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CONTACT BINARY STARS. I. AN X-RAY SURVEY

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ABSTRACT

A survey of W UMa-type contact binary stars has been made, using the *Einstein Observatory* with the Imaging Proportional Counter (IPC) in the focal plane. In the sample of 17 stars observed, all the W-type systems were found to be X-ray sources, and an X-ray flux was detected from five of the sample of eight A-type systems. The measured X-ray luminosities (L_x) fall in the range 8×10^{28} to 2×10^{30} ergs s^{-1} (0.1–4 keV). Although the longer-period A-type tend to have lower luminosities than the shorter-period W-type systems, no clear correlation of L_x with stellar properties is apparent in the results. There is some evidence for a correlation between L_x/L_{bol} and the period of revolution P, which, taken with the results of Solid State Spectrometer (SSS) observations of VW Cep and 44i Boo, suggests the existence of a hot corona. This correlation does not fit an extrapolation of the correlation obtained for longer-period RS CVn and single stars, and it is possible that the function $L_x/L_{bol}(P)$ may turn over at low periods.

The SSS observations revealed spectra similar to those of RS CVn stars. Acceptable fits were obtained using models of an optically thin plasma containing at least two components. In the case of both VW Cep and 44i Boo the best-fitting temperatures for a two-component model were 6.5×10^6 and approximately 3.5×10^7 K.

Subject headings: stars: coronae — stars: W Ursae Majoris — X-rays: binaries

I. INTRODUCTION

The first detection of X-ray emission from a contact binary star was made by the *HEAO 1* satellite (Carroll *et al.* 1980). Shortly after it was turned on in 1977 August the large-area sky survey instrument (A-1) detected VW Cephei, and analysis of the results determined that the luminosity (0.1–10 keV) was between 3×10^{30} and 4×10^{31} ergs s^{-1}. In addition there was some marginal evidence for modulation of the flux in synchronism with the binary revolution (period = $0\overset{d}{.}278$). The uncertainty in the luminosity was due to lack of knowledge of the source temperature, which was assumed to lie between 10^6 and 10^8 K.

The *HEAO 1* discovery was followed quickly by spectroscopic observations of 44i Boo and VW Cep by *IUE* (Dupree, Hartmann, and Raymond 1980), which established the presence of high-temperature chromospheric and transition region emission lines, in particular multiplets of O I λ1302, C II λ1335, Si IV λ1400, C IV λ1550, N V λ1240, and He II λ1640, in the spectra of these stars. These *HEAO 1* and *IUE* results implied that the processes causing X-ray emission from VW Cep might be similar to those energizing the solar corona, although in greatly enhanced form, and that X-ray emission might be a common occurrence among contact binary stars. Therefore, a series of observations of these stars was undertaken using the *HEAO 2* (*Einstein*) *Observatory.* In this paper we shall present the results of these observations, and assess their implications with regard to the nature of contact binary stars. In particular, we shall compare our results with similar *HEAO 2* studies of coronal X-ray sources in the local region of the Galaxy (Vaiana *et al.* 1981; Pallavicini *et al.* 1981), in the Hyades (Stern *et al.* 1981), and in RS CVn and other rapidly rotating systems (Walter and Bowyer 1981; Walter 1981, 1982). Although the X-ray characteristics of these stars resemble those of contact binaries in a number of respects, significant differences have been found. These *may* be linked to the peculiar evolution of contact systems, in which the rapid thermal and dynamic interaction couples strongly the evolution of one star with that of the other.

II. OBSERVATIONS

The *HEAO 2* observations which are summarized in Table 1 comprised 16 short points with the *Einstein* Imaging Proportional Counter (IPC), two long IPC points designed to search for variation of X-ray flux with phase, and two long points using the Solid State Spectrometer (SSS). In this paper we will deal with the characteristics of contact binary stars as a class of X-ray source, omitting any discussion of the more careful scrutiny of VW Cep, 44i Boo, and V566 Oph made during the long IPC and SSS observations. The latter will be described in a subsequent paper (Paper II: Dupree and Cruddace 1984).

In Table 2 we have assembled the X-ray fluxes and luminosities of the observed binaries, the ratio of the X-ray to the bolometric luminosity, the binary phase at the midpoint of the observation, and some other pertinent characteristics of the stars. As is evident in Table 2, we chose a sample of binaries which are near the Sun, which embraced wide ranges of spectral classes and periods, and which contained a balanced mixture of W and A types. A thorough search was made for recent measurements of binary periods and times of minimum, because shifts in period can invalidate estimates of phase if extrapolations from one epoch to another extend over a period longer than a few years. The results of optical observations were used throughout, except in the case of ε CrA where we relied on recent *IUE* photometric measurements (Dupree and

TABLE 1

SUMMARY OF *EINSTEIN* OBSERVATIONS OF CONTACT BINARY STARS

Binary	Date[a] (Mo.day.yr; hr:m:s)	Duration[b] (s)	Focal-Plane Instrument	Average[c] Count Rate (ct s^{-1})
44i Boo	7.11.79, 16:39:55	4079	IPC	1.506 ± 0.001
44i Boo	7.26.79, 23:57:20	8300	SSS	0.450 ± 0.007
VW Cep	2.27.79, 19:24:37	32525	IPC	0.468 ± 0.008[d]
VW Cep	7.28.79, 03:03:12	7600	SSS	0.296 ± 0.006
XY Leo	5.10.80, 00:12:06	1647	IPC	0.129 ± 0.003
TW Cet	6.21.80, 18:21:48	2253	IPC	0.0362 ± 0.0012
SW Lac	1.9.80, 17:56:53	2220	IPC	0.173 ± 0.003
YY Eri	2.25.79, 19:08:44	2826	IPC	0.0702 ± 0.0016
W UMa	4.30.80, 01:15:28	580	IPC	0.179 ± 0.018
AM Leo	12.13.80, 21:36:37	1808	IPC	0.0217 ± 0.0015
V839 Oph	10.8.80, 11:45:16	1821	IPC	0.0343 ± 0.0019
V566 Oph	3.23.80, 08:48:11	1876	IPC	0.0357 ± 0.0018
V566 Oph	4.7.81, 07:46:25	10098	IPC	0.0602 ± 0.0030
AK Her	3.8.80, 05:29:16	4820	IPC	0.0398 ± 0.0010
AW UMa	12.14.79, 18:58:10	1493	IPC	<0.0055
V502 Oph	3.1.80, 08:07:24	2005	IPC	0.0832 ± 0.0091
ε CrA	4.6.80, 17:09:47	2150	IPC	0.0388 ± 0.0025
V535 Ara	3.11.80, 17:31:27	3067	IPC	<0.0072
S Ant	6.13.80, 03:28:52	1617	IPC	0.0199 ± 0.0019
GK Cep	12.18.79, 02:55:16	2162	IPC	<0.0046

[a] Start of observation, UT.

[b] Useful time for image processing (IPC) or spectral analysis (SSS).

[c] Uncertainties are based on the square root of the total source counts. No statistically significant short-term (< 1000 s) flux variations have been found. Energy band is 0.1–4 keV for the IPC, 0.5–4 keV for the SSS.

[d] Variations in the flux from VW Cep were observed during this long observation (Dupree and Cruddace 1984). This count rate corresponds to a well-defined "low state" during the observation.

TABLE 2

SUMMARY OF THE PROPERTIES OF THE OBSERVED CONTACT BINARY STARS

Binary	Spectral Class[a]	Type[b]	Period[c] (days)	Binary Phase of Midpoint of Observation[c]	Distance[d] (pc)	Energy Flux at the Earth, 10^{-12} ergs cm^{-2} s^{-1} (0.1–4 keV)	X-Ray Luminosity, 10^{29} ergs s^{-1} (0.1–4 keV)	L_x/L_{bol} (10^{-4})	Complete (C) or Partial (P) Eclipse[e]
44i Boo	G2+G2	W	0.2678	0.75	12.2 ± 0.3	30.9 ± 0.1	5.3– 5.8	2.32	P
VW Cep	G8+K0	W	0.2783	[f]	23.2 ± 1.0	9.6 ± 0.2	5.7– 6.7	2.47	P
XY Leo	K2+K3	W	0.2841	0.58–0.60	43	2.64 ± 0.06	5.8– 6.1	4.87	P
TW Cet	G5+G5	W	0.3169	0.38–0.39	65	0.742 ± 0.025	2.6– 2.8	0.94	P
SW Lac	G3+G3	W	0.3207	0.55	65 ± 11	3.55 ± 0.02	12.6–25.2	3.31	P
YY Eri	G5+G5	W	0.3215	0.53–0.54	55 ± 2	1.44 ± 0.03	4.8– 5.8	0.96	P
W UMa	F8+F8	W	0.3336	0.375	46 ± 4	3.67 ± 0.37	7.1–12.3	1.69	C
AM Leo	F8	W	0.3658	0.55–0.60	110	0.445 ± 0.031	6.2– 7.1	0.78	C
V839 Oph	F8	A	0.4090	0.06–0.09	110	0.703 ± 0.039	10.0–11.1	0.73	P
V566 Oph	F0+F4	A	0.4096	0.69–0.70	74 ± 4	0.732 ± 0.037	4.2– 5.7	0.256	C
AK Her	F2+F6	A	0.4215	0.21–0.22	89 ± 6	0.816 ± 0.021	6.8– 9.3	0.81	C
AW UMa	F0+F2	A	0.4387	0.40	65 ± 6	<0.113	<0.70	<0.0281	C
V502 Oph	F9+G2	W	0.4534	0.83–0.86	69	1.71 ± 0.19	8.9–11.1	1.32	P
ε CrA	F0	A	0.5914	0.98–0.02	29	0.795 ± 0.051	0.76–0.86	0.0286	C
V535 Ara	A5[g]	A	0.6293	0.92	61	<0.148	<0.67	<0.0284	C
S Ant	A9+F4	A	0.6483	0.24–0.35	63	0.408 ± 0.039	1.8– 2.2	0.0527	P
GK Cep	A0+A0	A	0.9362	0.06–0.12	171	<0.0094	<3.5	<0.0177	P

[a] Obtained from Binnendijk 1970, Wood *et al.* 1980, Tapia and Whelan 1975, Koch and Shanus 1978, and Schöffel 1979.

[b] Obtained from Binnendijk 1977.

[c] Sources of periods and times of minimum are summarized in the Appendix.

[d] Sources of information discussed in the text.

[e] Obtained from Binnendijk 1970.

[f] VW Cep was observed during two revolutions of the binary. See note (d) to Table 1.

[g] The spectral class of this star has been quoted often as A3, for example by Binnendijk 1970 and Wood *et al.* 1980. On the other hand, Eggen 1978 classified it as A8. We use what appears to be the most recent result, reported by Schöffel 1979, obtained from spectroscopy observations made at the ESO in 1976.

Dussault 1984) of the time of primary minimum. Wherever it was appropriate we used the results of several observers in making phase estimates (see Appendix), and this has resulted in the uncertainties shown in Table 2. Consequently, we are confident that the phases shown in this table are correct, except in the cases of V535 Ara and S Ant. Schöffel's (1979) ephemeris for V535 Ara relies on observations made before 1970. In the case of S Ant, the most recent measurement we could find of the time of minimum was made in 1976 March, and for the period we had to use the average value between 1948 and 1976. The time of minimum is consistent with a measurement made using the optical and ultraviolet light curves obtained during an *IUE* observation of S Ant (Dupree and Dussault 1984).

Distance estimates were based primarily on the distance moduli provided by Eggen (1967). In some cases, revealed in Table 2 by the stated uncertainties, averages were taken of these results and similar photometric distance estimates made by Ruciński and Kaluzny (1981). TW Cet, V535 Ara, and GK Cep were not considered by Eggen (1967), and in these cases we have made estimates using $B-V$ colors provided by Binnendijk (1970), Mauder (1972), and Mochnacki (1981), respectively, and blue magnitudes provided by Binnendijk (1970). The distances of VW Cep and 44i Boo are based on trigonometric parallax measurements. For VW Cep we have averaged the parallaxes reported by Eggen (1967) and Hershey (1975), and the distance of 44i Boo was obtained as the mean of the measurements reported by Eggen (1967) and Gliese (1969).

X-ray sources were associated with 14 of the 17 contact binary stars observed by the *HEAO 2* IPC. Inspection of the IPC fields in the total X-ray band (0.15–4.5 keV) showed that the average discrepancy between the X-ray and optical positions of the detected stars was 24″. This is comparable to the standard deviation of IPC observations of point sources, 36″.1 and 14″.0, respectively, for the soft (0.15–0.5 keV) and hard (0.5–4.5 keV) X-ray bands (Van Speybroeck 1982). The count rate of a source was derived by counting events within a circle of radius 30 pixels (4′.0), centered on the source position, and subtracting from it the estimated number of background counts. The background count rate was obtained by counting events in a concentric annulus with radii of 40 pixels (5′.3) and 60 pixels (8′.0). The upper limit quoted for a nondetection was obtained by first counting the background events in six equal boxes grouped around the expected position of the source near the field center. Then the upper limit was set at one standard deviation of this sample, normalized to the area of a circle of radius 30 pixels.

The energy fluxes in Table 2 have been calculated using a conversion factor of 2.05×10^{-11} ergs cm^{-2} s^{-1} per IPC count s^{-1}. This number was obtained by folding the measured X-ray spectra of 44i Boo and VW Cep through the response of the IPC. The spectra were derived by fitting models to the data resulting from the long SSS observations (Table 1 and Fig. 1) of these two sources. Satisfactory fits were possible neither with continuum models nor with a model assuming emission from a thin, isothermal plasma with solar abundances of the constitutents. In the latter case the best fits to the 44i Boo and VW Cep data (Fig. 1) had χ^2 values of 2.48 and 1.46, respectively, per degree of freedom. When two components of differing temperature were allowed, the fits improved, although the poor statistics of the data above 2 keV provided no useful constraint upon the temperature of the hotter component. Therefore, the best fits shown in Figures 1*a* and 1*b* were obtained with this temperature fixed at 3 keV ($T = 3.5 \times 10^7$ K). Table 3 summarizes the results of the spectral analysis. The model of the cooler component contains a number of strong emission lines, for example several lines of highly ionized iron appearing at energies between 0.5 and 1 keV, and the Si XIII line at 1.86 keV. The hotter component is more prominent in VW Cep than in 44i Boo, which may be seen both in Figure 1 and in the emission measure estimates given in Table 3. Further, in VW Cep the temperature of this component appears to be significantly greater than 3 keV. This is apparent in Figure 1*b*, in which at energies above about 2.5 keV the measured count-rate is underestimated by the model.

Some caution is needed in using our IPC and SSS observations of 44i Boo (ADS 9494), which is a multiple system (Batten, Fletcher, and Mann 1978) comprising the contact binary (ADS 9494B) and an F5 V star (ADS 9494A). The A and B components form a visual binary with a period of 225 yr. Hoffleit (1982) reports a stellar rotational velocity of ≤ 16 km s^{-1} for this system, which presumably applies to the F star. Therefore, it is possible (e.g., see Fig. 4*b*) that it contributes significantly to both the X-ray flux and the X-ray spectrum of the 44i Boo system.

In calculating X-ray luminosities we applied small corrections, less than 5% in all cases, to the measured energy fluxes to allow for interstellar extinction. The spectral analysis was able to set an upper limit only to the amount of extinction in the lines of sight to 44i Boo and VW Cep. The limit corresponds to a hydrogen column density of 10^{18} cm^{-2}. Therefore, we have estimated the interstellar extinction, using a gas density of 0.05 cm^{-3}, in computing the luminosities quoted in Table 2.

TABLE 3
RESULTS OF ANALYSIS OF THE SSS SPECTRA OF 44i BOOTIS AND VW CEPHEI

		Temperature (K)		Emission Measure (cm^{-3})	
Binary	χ^2/d.o.f. of the Fit	Cool Component	Hot[a] Component	Cool Component	Hot Component
44i Boo ...	1.18	6.35×10^6	3.5×10^7	8.6×10^{51}	6.8×10^{51}
VW Cep ..	1.01	6.66×10^6	3.5×10^7	1.33×10^{52}	1.44×10^{52}

[a] Temperature fixed during spectral fitting: see discussion in text.

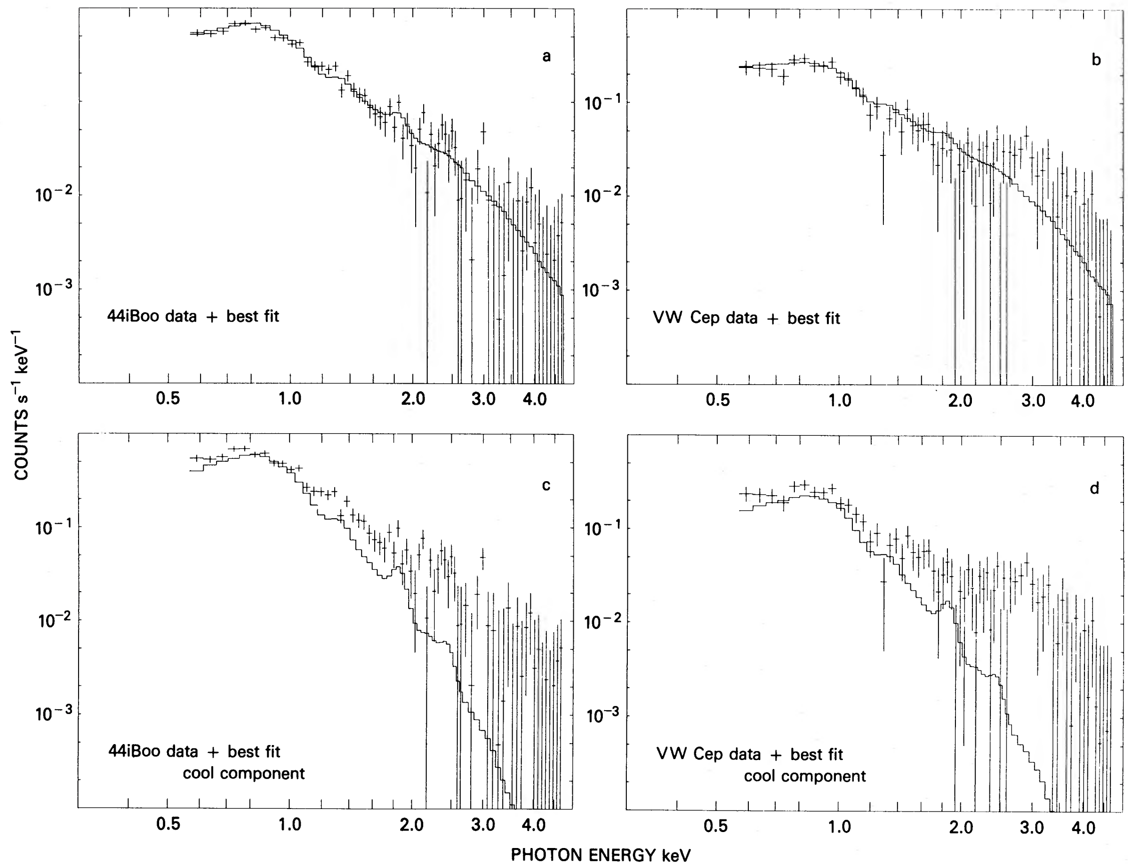

FIG. 1.—X-ray spectra of two contact binary stars, obtained by the *Einstein Observatory* Solid State Spectrometer. In each of the upper figures, (*a*) and (*b*), the solid line is the best fit to the data, and represents two thin-plasma components at different temperatures. The solid lines in (*c*) and (*d*) represent the cooler components of the two best fits.

The bolometric luminosity, $L_{\rm bol}$, in the ratio $L_x/L_{\rm bol}$, was calculated using the equations:

$$(M_{\rm bol})_\odot - M_{\rm bol} = 2.5 \times \log_{10} (L_{\rm bol}/L_\odot) , \quad (1)$$

$$M_{\rm bol} = m_v - {\rm DM} - {\rm BC} , \quad (2)$$

where m_v is the apparent visual magnitude of the binary at maximum, DM is the distance modulus obtained from Table 2, and BC is the bolometric correction, obtained from the correlation between BC and $B-V$ color (Allen 1973).

III. ANALYSIS AND DISCUSSION

a) *The Nature of the X-Ray Emission*

The dominant source of X-ray emission in late-type contact binary stars appears to be a hot corona. Two positive pieces of evidence support this point of view, although they are not strong enough to exclude models which consider other possible sources of X-ray emission, such as colliding shock waves or the impact of gas streams with the stellar surface. First, *IUE* spectra of a number of these systems reveal strong chromospheric and transition region emission lines. Second, the X-ray spectra of 44i Boo and VW Cep (Fig. 1) have been fitted satisfactorily only by models containing hot, optically thin plasmas. The emission regions appear to be distributed over a major fraction of the stellar surface and to extend a significant distance above the photosphere, instead of being concentrated in some local emission volume. Such a region, which might arise, for example, at the impact point of a high-velocity stream moving between the stars, or at the contact point in the system, should be eclipsed at some point during the revolution of the binary. We have examined the distribution of the X-ray luminosities with respect to the phase of the observation, considering the W- and A-type systems separately, and have found no sign of any correlation with phase. However, although this limited sample of observations has revealed no evidence for a dominant, local source of X-rays, it may not be concluded that the emission in contact binary stars is either uniform or steady. In our second paper (Dupree and Cruddace 1984) we shall present evidence that neither condition obtains in the VW Cep system.

Finally, we should make an observation concerning SW Lac. This star is unusual in regard to both the degree of activity evident from optical observations (for example, see Ruciński 1973), and the high mass ratio ($q = 0.87$). In addition its X-ray luminosity, as observed by *HEAO 2*, was significantly greater, by approximately a factor 2, than that of other W-type systems. This may reflect a greater degree of activity in the binary.

b) Correlations of X-Ray Luminosity with Rotation Parameters

Our sample of binaries was chosen with no strong bias beyond the selection of nearby objects. As noted earlier, the selection attempted to cover a wide range of spectral types and periods of revolution, and to include roughly equal numbers of W and A types. Therefore, the results of the observations probably are characteristic of contact binaries. Some caution is necessary, because in all likelihood the X-ray luminosity depends on a number of variables, including phase, spectral type, period and W/A type, and a larger sample will have to be examined in future observations in order to verify and elucidate the trends we have found.

A comparison of the X-ray luminosities shown in Table 2 with the luminosities of F, G, and K stars observed in the *HEAO 2* survey of nearby stars ("pointed survey," Vaiana *et al.* 1981), suggests that contact binaries are unusually luminous when compared with most main sequence stars of similar spectral type. All the G and K stars in Table 2 have luminosities close to 10^{30} ergs s^{-1} (0.1–4 keV), with the exception of TW Cet (2.7×10^{29} ergs s^{-1}), whereas the *HEAO 2* distribution has a mean which is below 10^{29} ergs s^{-1}. The F stars in our sample span the same range of luminosity, approximately 10^{28}–10^{30} ergs s^{-1}, as the *HEAO 2* survey distribution, but there appears to be a higher proportion of contact binaries with luminosities close to 10^{30} ergs s^{-1}. These results are not surprising within the context of current theories of coronae around late stars, which suppose that magnetic fields provide the energy for heating the corona. These fields are generated and amplified by dynamo action in the differentially rotating convective layer, and then rise above the photosphere as loops which thread the corona. Although no reliable quantitatively predictive model of this process exists, simple models of the dynamo predict an increase in poloidal field strength as the rotation rate increases. This may increase both the heating power in the corona, and the density of coronal gas contained by loops, so that a correlation of X-ray luminosity, L_x, with the speed of rotation is expected. Such correlations have been found by Walter and Bowyer (1981) and Walter (1981, 1982), who correlated L_x with the period, P, for samples of RS CVn binary and single stars, and Pallavicini *et al.* (1981), who correlated L_x with the projected rotational velocity, $v \sin i$, using primarily the results of the *HEAO 2* survey reported by Vaiana *et al.* (1981). In what follows we examine similar correlations, which include the results of the contact binary survey. It should be borne in mind, in considering correlations with period, that implicit in a correlation concerning binary systems is the assumption that the rotation period of a star is equal to its period of revolution in the binary orbit. This is a good approximation in short-period systems such as contact and RS CVn binaries, where strong tidal forces couple the dynamics of the two stars.

Examining the dependence of L_x upon the period of revolution, P, we find a trend in which L_x is lower in the longer period systems (Fig. 2). However, the correlation is far from smooth. The luminosities cluster around a value of roughly 10^{30} ergs s^{-1} for periods less than about $0^{\rm d}.45$, and then decline rapidly at longer periods. All the W types, and three A types (V839 Oph, V566 Oph, and AK Her) which are characterized by a relatively short period and a bias toward being later F stars, fall in this cluster near 10^{30} ergs s^{-1}. As noted earlier, the lower luminosities of the longer period systems may in some cases be due to eclipsing effects, but this appears unlikely.

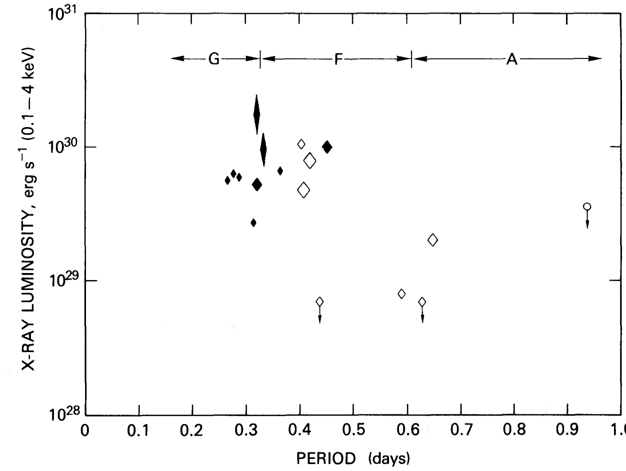

FIG. 2.—The measured X-ray luminosities of contact binary stars plotted against binary period. Black diamonds represent W-type binaries, white diamonds represent A-types, and the circle designates an early-type contact binary. The vertical length of the symbol represents the uncertainty in the luminosity, arising principally from uncertainty about the distance of the star.

In order to compare the coronae of contact binaries with those of other stars, we use the parameter $L_x/L_{\rm bol}$, which has the advantages that it is a better measure of coronal activity per unit surface area than L_x, and that it is insensitive to uncertainties in distance estimates. In Figure 3, we have attempted to correlate $L_x/L_{\rm bol}$ with P, comparing our result with the correlation established by Walter and Bowyer (1981) for RS CVn stars, and by Walter (1981, 1982), who included a sample of binary and single stars of spectral class F0–K7. Two results are apparent immediately. First, the contact binaries fall below the extrapolation of this correlation to periods of less than 1 day. Three stars in Walter's sample have periods of less than 1 day, the low-mass binary V471 Tau (Van Buren, Charles, and Mason 1980), RW CrB, and ER Vul. We might suspect V471 Tau, the black square in Figure 3, of not being a coronal X-ray source, because one component of the binary is a white dwarf. The other two may be part of a "bridge" between the contact binaries and the longer period stars. Therefore, two explanations of the position of the contact systems on the ($L_x/L_{\rm bol}$, P)-diagram appear equally likely. Either the coronae of these binaries are intrinsically different from those of single stars or stars in detached binary systems, or the relation between $L_x/L_{\rm bol}$ and P turns over at short periods. The second result we obtain from Figure 3 is the rapid decline in $L_x/L_{\rm bol}$ with increasing period, at a rate significantly greater than that obtaining for the longer period stars. A simple interpretation of this behavior is that it is the combination of two effects. One is the decrease in L_x with increasing period, which is characteristic of stars in a given spectral class. The other is the trend among contact binaries for longer period systems to be of earlier spectral type. This influences $L_x/L_{\rm bol}$, which for stars of a given period is greater for the later stars. For example, in Figure 3 the three groups of stars studied by Walter (1981, 1982), which fall in the spectral class ranges F0–F8 (*white squares*), F9–G7 (*dots*), and G8–K7 (*black squares*), may be

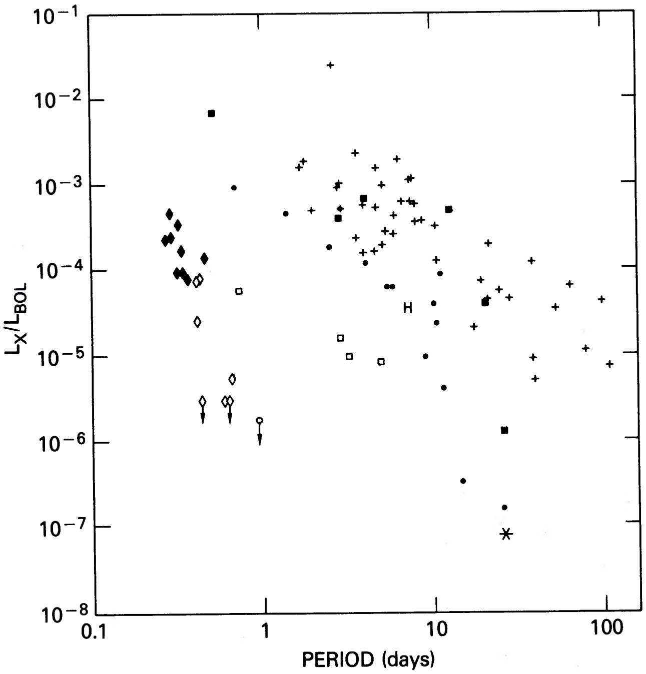

FIG. 3.—The ratio of the X-ray to the bolometric luminosity, L_x/L_{bol}, plotted against period. This is either the period of revolution of a binary star, or the rotation period of a single star. The meanings of the symbols are as follows: ◆, W-type contact binary. ◇, A-type contact binary. ○, Early-type contact binary. +, RS CVn system (Walter and Bowyer 1981). ■, Stars later than G7 (Walter 1981, 1982). ●, Stars F9–G7 (Walter 1981, 1982). □, Stars earlier than F9 (Walter 1982). H, Hyades stars (Stern *et al.* 1981; Walter 1982). *, Sun (Walter 1982).

fitted by three curves. These curves are displaced systematically to higher values of L_x/L_{bol} as the spectral classification becomes later.

However, this explanation of the rapid decline in L_x/L_{bol} may not be complete. If we consider only those contact binaries, of both W and A types, for which L_x/L_{bol} is greater than 10^{-5} (Fig. 3), it is plausible to argue that they lie on (L_x/L_{bol}, P)-correlations which turn over at short periods, the correlations being displaced upward for stars of later spectral type. The contact binaries for which L_x/L_{bol} is less than 10^{-5}, on the other hand, do not fit this pattern. This may be illustrated by comparing (Fig. 3, Table 2) AW UMa with V839 Oph and AK Her, all of which have periods between $0^d.41$ and $0^d.44$, and also by comparing ϵ CrA ($P = 0^d.59$), V535 Ara ($P = 0^d.63$), and S Ant ($P = 0^d.65$) with the short-period F star considered by Walter (1981, 1982), RW CrB (F0, $P = 0^d.72$). We believe that in these four stars, AW UMa, ϵ CrA, V535 Ara, and S Ant, evolution of the system may have modified the structure of the corona significantly. This will be considered further in the last section.

In the above arguments, we have not considered the point represented by the open circle in Figures 2 and 3, the upper limit for GK Cep. This star, of spectral type A0, is earlier than the rest of our sample, and has an appreciably longer period. More significantly, there is some evidence that it is different in an evolutionary sense from the other longer period A-types in our sample, AW UMa, ϵ CrA, V535 Ara, and S Ant. These evolved systems are characterized by large fill-out factors and low mass-ratios (Mochnacki 1981), whereas GK Cep has a low fill-out factor ($F = 1.0$) and a high mass ratio ($q = 0.89$). GK Cep may comprise two relatively young stars with a radiative envelope. The upper limit for its X-ray luminosity (Table 2) is consistent with the correlation, $L_x/L_{bol} \approx 10^{-7}$, which has been established for the coronae of early stars (Pallavicini *et al.* 1981).

The current understanding of stellar dynamos does not make it clear whether the rotation period or the equatorial velocity is the more appropriate measure of the processes of loop formation and expansion into the corona, which result in plasma heating and X-ray emission. Therefore in Figure 4 we compare our results with the correlations of L_x with the projected rotational velocity, $v \sin i$, established by Pallavicini *et al.* (1981). We have calculated the projected equatorial velocities, v_e, using a simple model in which two stars in contact revolve in circular orbits. It is assumed that each star rotates with the same period as the revolution of the binary. Each velocity, v_e, may be expressed as a proportion of the amplitude, K, of the orbital velocity measured spectroscopically, so that no terms in "sin i" appear:

$$v_{e1}/K_1 = (q + 1)/q(k + 1) , \quad (3)$$

$$v_{e2}/K_2 = k(q + 1)/(k + 1) . \quad (4)$$

Here the subscripts 1 and 2 refer to the primary and secondary, respectively, and $q = m_2/m_1$, $k = r_2/r_1$, where m and r are the stellar mass and radius. The results of the calculations are shown in Table 4, which also describes the sources of the information used. In particular, all the K's are measured values, except those of the secondaries of AK Her and ϵ CrA, for which we used the relation, $K_2 = K_1/q$.

Pallavicini *et al.* (1981) divided late stars into two groups, A9–F8 and F7–M5, which we have represented in Figures 4*a* and 4*b*, respectively. The conclusions to be drawn from Figure 4 lie closely in parallel with what is apparent in Figure 3. First, the shorter-period contact systems, composed predominantly of W-type stars of spectral class G and K, do not fit the correlation obtained for longer period systems (Fig. 4*a*). Second, the A-type stars which we believe to be evolved systems, AW UMa, ϵ CrA, V535 Ara, and S Ant, have somewhat low X-ray luminosities, given their high rotational velocities (Fig. 4*b*).

c) Conditions in the Corona

We examine a model, similar to that discussed by Walter (1981) and Swank *et al.* (1981) in their discussion of RS CVn stars, in which the X-ray–emitting plasma is contained by loop-like magnetic field structures. It should be emphasized that this is a simplification, both from the point of view that it cannot represent the evident complexity of the solar corona, and in regard to one distinct difference between the corona of the Sun and those of the contact binaries and RS CVn stars. The emission measure of the solar corona declines rapidly at temperatures greater than about 7×10^6 K (Underwood *et al.* 1978), whereas the emission measure of 44i Boo and VW Cep is roughly constant between 6×10^6 K and 3×10^7 K (Table 4).

We consider VW Cep as an example, using the temperatures and emission measures (E cm^{-3}) given in Table 3. The length of a magnetic loop (l) may be related to the temperature and pressure of the contained gas by the expression (Rosner,

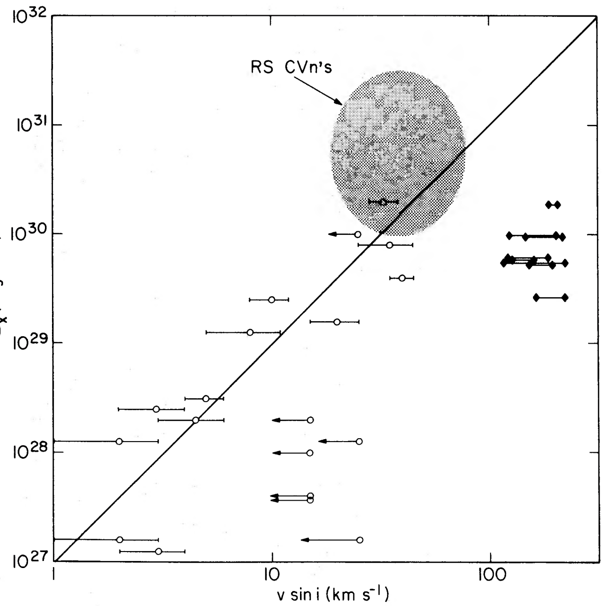

FIG. 4*a*

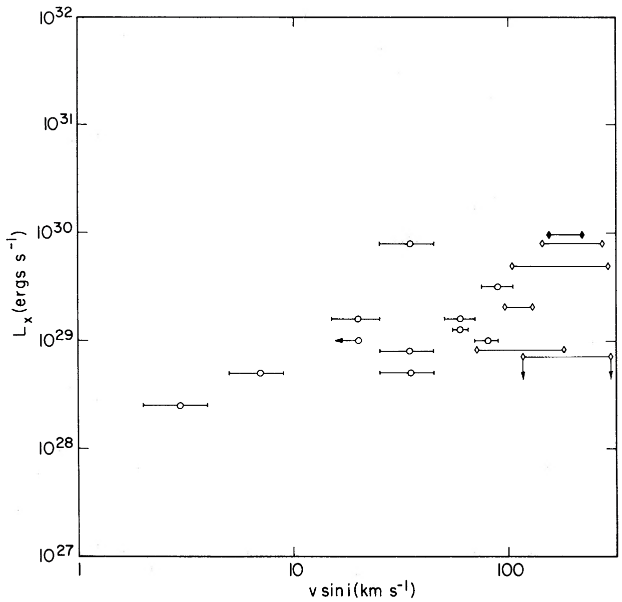

FIG. 4*b*

FIG. 4.—Correlation of the X-ray luminosity with $v \sin i$, the projection of the velocity of rotation upon the sky. The circles represent the sample of stars sampled by Pallavicini *et al.* (1981), and the black and white diamonds represent W-type and A-type contact binaries respectively: (*a*) Spectral class F7–M5. (*b*) Spectral class A9–F8. The straight line in Fig. 4*a* is the relation $L_x \propto (v \sin i)^2$ established by Pallavicini *et al.* (1981).

Tucker, and Vaiana 1978):

$$T_7 = 1.4 \times 10^{-4}(pl)^{1/3} , \quad (5)$$

where l is in cm, p is the pressure in dyn cm^{-2}, and T_7 is the temperature in units of 10^7 K. Using this equation, it is a simple task to derive the following expression for L_x/L_{bol}:

$$L_x/L_{bol} = 9 \times 10^{17} fpT_7 \epsilon , \quad (6)$$

where f is the fraction of the stellar surface area intercepted by loops and the temperature-dependent function ϵ is given by:

$$L_x = E\epsilon \text{ ergs s}^{-1} . \quad (7)$$

The value of ϵ in the 0.5–4 keV band is 2.4×10^{-23} ergs cm^3 s^{-1} for the soft spectral component and 1.1×10^{-23} ergs cm^3 s^{-1} for the hard spectral component (Raymond 1981). Hence, using

TABLE 4

ROTATIONAL VELOCITIES ($K_{1,2}$), MASS RATIOS (q), RATIOS OF THE STELLAR RADII (k), AND EQUATORIAL VELOCITIES ($v_{e1,2}$) OF 13 CONTACT BINARY STARS OBSERVED BY *HEAO 2*

Binary	K_1[a] (km s^{-1})	K_2[a] (km s^{-1})	q[b]	k[b]	v_{e1} (km s^{-1})	v_{e2} (km s^{-1})
44i Boo	127	202	0.50	0.73	220	128
VW Cep	90	220	0.41	0.63	186	123
XY Leo	135	170	0.79	0.90	161	144
TW Cet	135	255	0.53	0.74	224	166
SW Lac	185	210	0.87	0.94	205	190
YY Eri	130	220	0.59	0.79	196	154
W UMa	131[c]	243[c]	0.54	0.76	212	149
V566 Oph	84	246	0.238	0.53	286	105
AK Her	78	335[d]	0.233	0.52	270	143
AW UMa	29[e]	423[e]	0.076	0.34	304	115
V502 Oph	85	250	0.34	0.61	203	124
ϵ CrA	26[f]	230[d]	0.113	0.39	184	72
V535 Ara	71[g]	237[g]	0.30[g]	0.59[g]	194	114
S Ant	81	148	0.55[a]	0.74[a]	131	98

[a] Values obtained from Binnendijk 1970, except where indicated.
[b] k, q obtained from Mochnacki 1981, except where indicated.
[c] K_1 and K_2 from Worden and Whelan 1973.
[d] K_2 obtained from the relation, $K_2 = K_1/q$.
[e] K_1 and K_2 obtained from McLean 1981.
[f] K_1 obtained from Tapia and Whelan 1975.
[g] K_1 and K_2 obtained from Schöffel 1979.

TABLE 5

ESTIMATES OF THE SCALE AND PRESSURE OF MAGNETIC LOOPS CONTAINING HOT CORONAL GAS AROUND VW CEPHEI

Coronal Component	$f^a \times p$ (dyne cm^{-2})	Loop Length l/R
Cool (6.7×10^6 K)	14	$1.6/p$
Hot (3.5×10^7 K)	3	$220/p$

[a] f is the fraction of the stellar surface generating loops.

this result and Table 3, and assuming $L_x/L_{bol} \approx 3 \times 10^{-4}$ (Table 2), we obtain:

$$(L_x/L_{bol})_{soft} \approx 2 \times 10^{-4} \; ; \quad (L_x/L_{bol})_{hard} \approx 1 \times 10^{-4} \; . \quad (8)$$

In calculating L_{bol} we have assumed a radius for the primary of 1 $R_\odot$ and an effective temperature of 5550 K, which yields the total rate of energy generation of the primary (Mochnacki 1981).

Using the values of ϵ and T_7 for the cool and hot components of the plasma, obtained from the spectral analysis of the SSS data, we have used equation (6) to obtain an estimate of the product ($f \times p$), and equation (5) to derive the loop length as a function of the pressure p (although the temperature of the hot component is outside the range of validity of eq. [5], the accuracy is adequate for our purposes). The results are shown in Table 5. Considering first the cooler component of the X-ray emitting gas, we find that the high emission measure ($\sim 10^{52}$ cm^{-3}, Table 3) implies pressures at the base of the corona in excess of 10 dyn cm^{-2}, more than two orders of magnitude greater than the solar coronal pressure. In this model the scale of the loops is no more than 20% of the stellar radius, and the magnetic field strength should be at least an order of magnitude greater than the average field strength at the base of the solar corona.

As illustrated in Table 5, these pressures and field strengths become larger, and the loop size becomes smaller, if it is supposed that the loops cover only a small fraction of the stellar surface ($f \ll 1$). However, our observations may provide

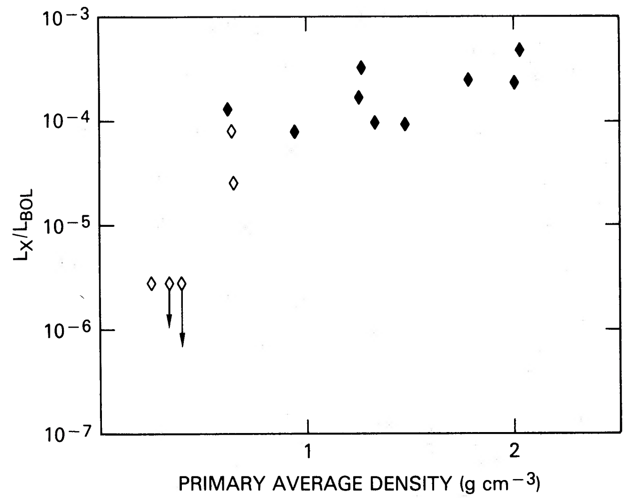

FIG. 5.—The ratio of the X-ray to the bolometric luminosity, L_x/L_{bol}, plotted against the average density of the primary star. W-type and A-type binaries are represented by black and white diamonds, respectively.

some evidence that, at least as far as the W-type and the more luminous A-type stars are concerned, f may be close to unity. The "turnover" in the correlations between L_x and either P (Fig. 3) or $v \sin i$ (Fig. 4*a*) may signify a limit at which the X-ray luminosity can rise no further because the whole stellar surface is covered by loops. This hypothesis requires also some upper limit to the pressure, and hence the density, of the gas in the corona. It is possible that this limit is approached as tidal forces interfere with the differential rotation in each star.

The hotter component revealed by the X-ray spectra of VW Cep and 44i Boo is difficult at this stage to understand. It appears to have no solar analog, for its emission measure is equal to that of the cooler component, whereas the solar emission measure declines rapidly above 10^7 K. A magnetic loop model, if appropriate, would imply magnetic field structures (Table 5) commensurate in scale with that of the whole binary system. The SSS results placed few restraints on the

TABLE 6

COMPARISON OF W-TYPE AND A-TYPE CONTACT BINARY STARS

Characteristic	W Type	A Type
1. Spectral type	$>$F9[a]	$<$F9[a]
2. Ratio of stellar masses ($q < 1$)	0.33–0.88[b] 0.30–0.87[c]	0.08–0.54[b] 0.08–0.37[c]
3. Average density of the primary	high mostly >0.7g cm^{-3}[c]	low mostly <0.7 g cm^{-3}[c]
4. Period	changing constantly	many systems have a relatively stable period
5. Optical activity	many systems show rapid changes in the ratio of the heights of the two maxima, and in the shape of the light curve.	many systems have stable light curves
6. Mass transfer between the stars, $M_\odot$ yr^{-1}	$\sim 10^{-7}$[a]	$\sim 10^{-8}$[a]

[a] Ruciński 1974.
[b] Ruciński 1973.
[c] Mochnacki 1981.

spectrum of this component, and consequently other possible sources of the X-ray emission should be explored.

d) Evolutionary Considerations

It has been argued (Lucy 1976; Robertson and Eggleton 1977; Mochnacki 1981; Vilhu 1981) that many A-type systems are in a late stage of evolution, moving along an evolutionary track on which at some earlier epoch they were W-type binaries. These two phases are summarized in Table 6. As a W-type the binary is later in spectral class ($\lesssim$F9), has a higher mass ratio (q), shows signs of continuing activity in its light curve, and has a shorter period. Studies of the light curve have revealed variations which have been interpreted in terms of variations of the binary period. This would imply relatively rapid mass exchange between two stars ($\sim 10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$). On the other hand, the A-type tends to be bluer and have a

TABLE 7

Binary	Time of Minimum[a] Reference	Date	Julian Date	Period Determination Reference[b]	Date	Period (days)
44i Boo	1	1979 Jul	2444061.75540	1	1979 Jul	0.26781580
VW Cep	2	1978 Jul	2443706.82454	2	1978 Jul	0.2783152
XY Leo	3	1956 Jan	2435484.0222	4−3	1956 Jan–1978 Mar	0.28410335
	4	1978 Mar	2443572.7288	5−3	1956 Jan–1978 Mar	0.28410324
	5	1978 Mar	2443587.783	6−3	1956 Jan–1978 Apr	0.28410339
	6	1978 Apr	2443606.396			
TW Cet	7	1979 Dec	2444210.322	11	before 1950	0.31685260
	8	1980 Oct	2444523.370	8−7	1979 Dec–1980 Oct	0.3168502
	9	1980 Oct	2444523.374	9−7	1979 Dec–1980 Oct	0.3168543
	10	1980 Oct	2444523.379	10−7	1979 Dec–1980 Oct	0.3168593
SW Lac	12	1980 Sep	2444499.52716	12	1980 Sep	0.3207186
YY Eri	13	1977 Sep	2443398.5500(S)	15	1973 Dec	0.32149644
	14	1979 Jan	2443889.316	14−13	1977 Sep–1979 Jan	0.32149754
W UMa	16	1980 Apr	2444312.41662	16	1980 Apr	0.3336380
AM Leo	17	1968 Mar	2439936.8337	18−13	1977 Mar–1980 Apr	0.36580123
	13	1977 Mar	2443218.3973	18−17	1968 Mar–1980 Apr	0.36579817
	18	1980 Apr	2444705.379	13−17	1968 Mar–1977 Mar	0.36579686
V839 Oph	19	1958 Jun	2436361.73170	19	1958 Jun	0.4089946
	20	1978 Sep	2443756.363	20−19	1958 Jun–1978 Sep	0.4089951
	21	1979 Jul	2444059.429	21−19	1958 Jun–1979 Jul	0.4089951
V566 Oph	22	1969 Jul	2440418.4931	22	1969 Jul–1975 Jun	0.40964431
	13	1977 May	2443281.5037	24−13	1977 May–1978 Jun	0.40964607
	23	1978 Jun	2443671.8964	23−13	1977 May–1978 Jun	0.40964616
	24	1978 Jun	2443676.4026			
AK Her	25	1974 Jun	2442220.195	25	1974 Jun	0.42152421
	26	1980 May	2444372.4713	26−25	1974 Jun–1980 May	0.42151906
	27	1980 Aug	2444475.3248	27−25	1974 Jun–1980 Aug	0.42151959
AW UMa	41	1979 Mar	2443941.7717	41	1979 Mar	0.43873212
V502 Oph	13	1978 May	2443292.4761	30	1967 May–1978 Jun	0.45339293
	28	1979 Jun	2444076.391	28−13	1978 May–1979 Jun	0.45339208
	29	1980 Jul	2444446.374	29−13	1978 May–1980 Jul	0.45339800
ε CrA	31	1972 Sep	2441582.5135	33	1967 Aug	0.5914264
	32	1980 Jun	2444417.2673	32−31	1972 Sep–1980 Jun	0.5914362
V535 Ara[c]	34		2439292.9353	34		0.62929
S Ant	35	1948 Jan	2432921.939	35	?	0.6483321
	36	1975 Feb	2442445.496	36−35	1948 Jan–1975 Feb	0.6483462
	36	1975 Feb	2442458.434	36−35	1948 Jan–1975 Feb	0.6483442
	37	1976 Mar	2442838.387	37−35	1948 Jan–1976 Mar	0.6483457
GK Cep	38	1964 Oct	2438694.7075	38	1964 Oct	0.936175
	39	1975 Sep	2442685.5421	39−38	1964 Oct–1975 Sep	0.936156
	40	1978 Mar	2443590.360	40−39	1975 Sep–1978 Mar	0.936180

[a] Times of primary minimum, except where indicated. Times of secondary minimum are followed by (S).

[b] Where periods are derived by comparing times of minimum obtained by different workers, $m - n$ means that the time obtained from reference n was subtracted from that given in reference m.

[c] Schöffel (1979; reference 34) gives the ephemeris as a quadratic in the epoch, E: Time of primary minimum = 2,439,292.9353 + $0.62929677E - 4.4 \times 10^{-11}E^2$.

References.—(1) Stoeckley and Carroll 1979. (2) Linnell 1979. (3) Gehlich *et al.* 1972. (4) Koch and Shanus 1978. (5) Hebron and Shegelski 1980. (6) Pohl and Gulman 1981. (7) Locher 1980*a*. (8) Locher 1980*b*. (9) Stoikidis 1980. (10) Parris 1980. (11) Cillié and Bok 1951. (12) Mikolajewska and Mikolajewska 1981. (13) Ebersberger *et al.* 1978. (14) German 1979. (15) Strauss 1976. (16) Tümer *et al.* 1980. (17) German 1981. (18) Binnendijk 1969. (19) Binnendijk 1960. (20) Diethelm 1978. (21) Diethelm 1979. (22) Dawson and Narayanaswamy 1977. (23) Maddox and Bookmyer 1979. (24) Niarchos 1979. (25) Karetnikov 1979. (26) Diethelm 1980. (27) Demetrius 1980. (28) Troispoux 1980. (29) German 1980. (30) Maddox and Bookmyer 1978. (31) Tapia and Whelan 1975. (32) Dupree and Dussault 1984. (33) Tapia 1969. (34) Schöffel 1979. (35) Wood *et al.* 1980. (36) Locher 1975. (37) Locher 1976. (38) Gleim 1967. (39) Dworak 1976. (40) Penna 1978. (41) Hrivnak 1980.

longer period, exhibits less optical activity, and has a lower mass ratio. The period appears to be more stable, and the implied mass exchange rate in the binary is smaller ($\sim 10^{-8}$ $M_\odot$ yr^{-1}). Of particular interest is the average density of the primary star, which may be related directly to the age of the system. The average density of the primary in some A-type binaries is unusually low, suggesting the development of a dense core (Mochnacki 1981). These systems are found to have low mass ratios. Prominent examples which were observed during our survey are AW UMa, ϵ CrA, and V535 Ara. Their mass ratios are 0.076, 0.113, and 0.30, and their primary average densities are 0.39, 0.25, and 0.33 g cm^{-3}, respectively. These numbers are at the low ends of the ranges of mass ratio and primary density in A-type binaries (Table 6).

In Figure 5 we have plotted $L_x/L_{\rm bol}$ against the primary average density, using values for the latter derived by Mochnacki (1981). The correlation in Figure 5 suggests that evolutionary factors *may* be responsible for the tendency, evident in Figures 3 and 4, for some A-type stars to have unusually low coronal X-ray luminosities. In what manner does the evolution of the binary influence the corona? An important clue may be provided by our observation that, when comparisons are made with W-type stars, the low X-ray luminosities of the A-types ϵ CrA and S Ant are not accompanied by any reduction in the luminosity of ultraviolet emission lines. The ultraviolet emission may be distributed over the whole surface, whereas it is known that the X-ray brightness of the Sun is diminished over coronal holes, where mass loss occurs. Also, in bright stars lower X-ray luminosities are encountered when massive winds are present (Dupree 1981). Therefore the decline in X-ray luminosity of contact binaries during their evolution may be due to the growth of regions analogous to coronal holes. The corresponding growth in stellar wind mass loss is consistent with the hypothesis, advanced by Mochnacki (1981), that loss of angular momentum occurs during evolution toward the A-type system, and that magnetic braking is responsible.

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APPENDIX

Table 7 gives a collation of periods and times of minimum of the contact binaries observed in the X-ray survey. This information was used in estimating the binary phase of each X-ray observation.

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