Hard X-rays from the contact binary VW Cephei

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SUMMARY
We present *Ginga* observations of the contact binary VW Cep. The observed X-ray luminosity is $1.1 \times 10^{30}$ erg s$^{-1}$ in the energy range of 2–10 keV, assuming a distance of 31 pc. No evidence for X-ray orbital modulation or for flare events was seen. The observed X-ray spectrum is very hard, and can be represented well either by a thermal bremsstrahlung model with a temperature of $11.2^{+4.6}_{-2.3}$ keV or a power-law model with photon index of $\Gamma = 1.90^{+0.24}_{-0.36}$. These observational results are interpreted in terms of thermal emission from hot coronal plasma extending beyond the stellar size. However the observed upper limit on the iron K-line intensity is considerably below the theoretical prediction.

1 INTRODUCTION
One of the major results on stellar X-ray emission obtained with the *Einstein* observatory is the positive correlation between X-ray luminosity and rotation velocity in late-type stars, indicating that X-ray emission of late-type stars is due to coronal activity enhanced by the magnetic field which is produced by dynamo action in the convective zone (Pallavicini et al. 1981). However, systematically higher coronal X-ray activity is observed in RS CVn stars than in other normal, single, late-type stars. This observational result is regarded as a binary effect in that magnetic tubes connecting the two component stars enhance the coronal activity (Swank et al. 1981). Contact binaries have both rotational and binary effects, therefore it was expected that they would have high coronal activity and be strong X-ray sources. However the survey of contact binaries made by *Einstein* in the energy range of 0.1–4 keV showed a contrary result in that they have lower X-ray luminosity than might be expected from the correlations between X-ray luminosity and projected rotational velocity on single stars (Crudace & Dupree 1984). There is some possibility that the deficiency in X-ray luminosity is emitted in a harder energy band, to which the *Einstein* satellite had no sensitivity.

VW Cep is one of the brightest and best-studied eclipsing contact binaries of the W UMa type, and consists of a G8 and a K0 star, at a distance of 31 pc (Rucinski 1983). Its orbital period is $0.2783176$ d and its phase origin of JD45 636.3680 was obtained by Vilhu & Heise (1986). The first X-ray detection of VW Cep was made by *HEAO-1* at a flux level of about $6 \times 10^{-10}$–$4 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ at 0.1–10 keV (Carroll et al. 1980). *EXOSAT* has observed VW Cep twice. The first *EXOSAT* LE observation found orbital modulation and evidence that the contact region between the two stars is the preferred site of X-ray emission (Vilhu & Heise 1986), although no significant orbital modulation was seen in the other contact binaries observed in the same survey. However, the second observation of VW Cep did not detect the orbital modulation, but did observe flare activity in *EXOSAT* LE, ME and also in the VLA (Vilhu, Caillault & Heise 1988). The spectrum of VW Cep obtained by the *Einstein* SSS (Crudace & Dupree 1984) needs a hotter component whose temperature is above $3.5 \times 10^7$ K in addition to the cooler component with a temperature of $7 \times 10^6$ K. The result of the second *EXOSAT* observation was consistent with this.

The X-ray study of ‘normal’ stars including contact binaries has been so far focused on the X-ray luminosity, and on the search for the relation between X-ray luminosity and other parameters (see Rosner, Golub & Vaiana 1985). However, accurate spectral information on the coronal X-ray emission has been rather poor. VW Cep is one of several suitable targets for this study. The presence of very hot ($T \geq 10^7$ K) emission components has been suggested (e.g. Crudace & Dupree 1984), but their actual temperature has hardly been measured with past instruments. The sensitivity
of the Large Area proportional Counter (Turner et al. 1989) on board *Ginga* is several times higher than that of previous satellites in the hard (≥ 2 keV) X-ray energy band, and has enabled us to get the required information on the very hot corona of VW Cep for the first time.

2 OBSERVATIONS AND RESULTS

The present X-ray observations were carried out with the Large Area proportional Counter (LAC) on board the Japanese third X-ray astronomy satellite *Ginga* (Makino & the ASTRO-C team 1987). The LAC instrument has an energy range of 1–36 keV, an effective area of about 4000 cm², a field of view of 11° × 2° in FWHM, non X-ray background level as low as 3.5 × 10⁻⁴ counts cm⁻² s⁻¹ keV⁻¹, and an energy resolution of 18 per cent at 6 keV (Turner et al. 1989). VW Cep was observed from 1987 December 8.10 to 8.97 UT in the MPC-1 mode. Because of the Earth occultation and regions of high particle background, the net data coverage during these observations was typically 30–50 min out of each satellite orbit (95 min).

We accumulated all the on-source data into a single spectrum, from which the model background given by Hayashida et al. (1989) was subtracted. The mean count rate thus obtained in 2–10 keV with 1σ statistical error was 3.93 ± 0.07 counts s⁻¹, while the systematic 1σ error, which is determined by weak and unresolved sources in the LAC field of view, is 0.87 counts s⁻¹ in 2–10 keV (Hayashida et al. 1989). Therefore, the presence of an X-ray source in the LAC field of view is confirmed at a 5σ significance level. In the LAC field of view there are five sources catalogued by the *Einstein* IPC besides VW Cep. However, the flux levels of these sources are all less than 1/50 of VW Cep itself. Therefore, the X-ray flux observed by *Ginga* is for the most part due to VW Cep. The observed flux corresponds to a luminosity of 1.1 × 10³⁸ erg s⁻¹ in the energy range of 2–10 keV, assuming a distance of 31 pc (Rucinski 1983).

The background-subtracted and aspect-corrected light curve of VW Cep with 1σ statistical error is shown in Fig. 1. The accumulating time of each bin is 128 s. There is a possible slow decline in intensity toward the end of the observation. However, no significant flare or flare-like events were found and no fast X-ray variation was seen above an upper limit of 12 per cent on a time-scale of 128 s.

In order to search for modulation corresponding to the orbital period which was once reported in soft X-rays, we folded the light curve with the orbital period of 0.2783 d (Fig. 2). However, no orbital modulation was seen in the folded light curve [χ²/(degrees-of-freedom) being 2.2/9, assuming constant flux] above a 99 per cent upper limit of 1.2 counts s⁻¹, assuming sinusoidal modulation. This result suggests that the X-ray emitting region at 2–10 keV is larger than the stellar size of VW Cep.

The observed pulse-height spectrum of VW Cep (using the top layer of the LAC detectors) is shown in Fig. 3. We fitted the spectrum with a thermal bremsstrahlung model with Gaunt factor given by Karzas & Latter (1961), and with a power-law model. Considering the uncertainty in the background subtraction, a systematic error of 5 per cent is included for each pulse-height channel. The reduced χ² values of 1.48 and 1.56 for 20 degrees of freedom indicate that the models are acceptable at the 95 per cent confidence.
3 DISCUSSION

Ginga observations of VW Cep have detected a hard X-ray flux with a luminosity of $1.1 \times 10^{30}$ erg s$^{-1}$ in the energy range of 2–10 keV. The observed spectrum can be fitted by thermal bremsstrahlung with an electron temperature of $T_e = 111.2^{+2.4}_{-2.3}$ keV, or by a power-law model with photon index $\Gamma = 1.90^{+0.30}_{-0.29}$. The lack of a significant iron line at an energy $\sim 6.7$ keV might suggest a non-thermal origin (e.g., bremsstrahlung from high-energy particles) of the observed X-rays. Such non-thermal X-ray emission is present in some, if not all, solar flares (e.g., Tanaka 1987). However, the solar hard X-rays are detectable only during solar flares, and are hence highly time-variable, in contrast to the present results. Even if the apparently persistent X-ray emission from VW Cep was due to a series of small flares, high-energy particles should be thermalized quickly and give rise to thermal X-rays with a much higher luminosity than non-thermal X-rays. In addition, X-ray emission from stellar objects in the 2–10 keV band has in most cases been shown to be of thermal origin (Koyama 1985; White et al. 1986; Tsuru et al. 1989). We therefore presume that the observed X-rays are thermal bremsstrahlung emission from optically thin hot ($k_B T \sim 11$ keV) plasma. The volume emission measure of the plasma can be estimated to be $\sim 9 \times 10^{52}$ cm$^{-3}$ from the observed luminosity and temperature. This emission measure is 1–3 times larger than that of the cooler component with $T_e = 0.6–3$ keV observed by Einstein and EXOSAT in the softer energy band (Craddock & Dupree 1984; Vilhu et al. 1988).

The observed X-rays did not show significant time variability. In particular, the absence of an orbital modulation suggests that the emission region has a large vertical extent, although we cannot completely rule out a complex geometry involving low-scaleheight emission regions fairly uniformly spreading over both stars (see e.g., Vilhu & Heise 1985; Bradstreet & Guinan 1988). For simplicity we here assume that the emission region is larger than the stellar size of $2R_\odot$, presumably in the form of tall magnetic loops. However such loops should be confined within $\sim 3R_\odot$ of the system, because loops whose summits lie outside the Keplerian co-rotation radius, which is $3R_\odot$ for VW Cep, are expected to be unstable (Collier-Cameron 1988). Therefore we can put a constraint of $R = 2–3R_\odot$ on the X-ray emitting region of VW Cep. Then the electron density of the hot plasma can be esti-

![Figure 4](https://academic.oup.com/mnras/article-abstract/255/2/192/1254509)

**Figure 4.** The contour map of photoelectric absorption versus bremsstrahlung temperature, derived from the spectral fitting. The confidence limits are for two interesting parameters.

![Figure 5](https://academic.oup.com/mnras/article-abstract/255/2/192/1254509)

**Figure 5.** The contour map of iron-line intensity versus bremsstrahlung temperature, derived from the spectral fitting. The confidence limits are for two interesting parameters.

| Table 1. Summary of model fitting to the spectrum in Fig. 3. |
|----------------|----------------|----------------|
| **model**      | **Thermal Bremsstrahlung** | **Power Law** |
| $k_B T$ (keV) or Photon Index $\Gamma$ | $11.2^{+0.4}_{-0.3}$ | $1.90^{+0.24}_{-0.28}$ |
| reduced $\chi^2$ | 1.56 | 1.48 |
| degree of freedom | 20 | 20 |
| $N_H$ | $< 10^{20}$ | $< 10^{21.2}$ |
| $EW$ (keV) | < 0.24 | < 0.28 |

All the errors are 90 per cent confidence limits for a single parameter. The upper limit is defined at 99 per cent confidence. Equivalent width (EW) is for an emission line at 6.7 keV.
\[ n_e = 3 \times 10^9 \left( \frac{R}{2R_\odot} \right)^{-3/2} \eta^{-1/2} \text{ cm}^{-3}, \]

where \( \eta \) is a filling factor.

Since the magnetic field is considered to confine the hot corona, the pressure of the magnetic field \( B^2/8\pi \) must be larger than the gas pressure \( 2n_b k_b T \). Therefore, the lower limit on the magnetic field in the hot corona can be estimated as

\[ B > 50 \left( \frac{R}{2R_\odot} \right)^{-3/4} \eta^{-1/8} \text{ G}. \]

Here we have assumed that the plasma pressure varies little with height, which is justified by the fact that the pressure scaleheight \( H \) is as large as \( H/R_e = 10(R_e/R_\odot)(M_e/M_\odot)^{-1} \) due to the very high \( T_e \), where \( R_e \) and \( M_e \) are the radius and mass of the component star. The above field estimate is consistent with that given by Mullan (1975), and with the directly measured magnetic field of \( 1-3 \text{ kG} \) on the surface of late-type stars by Gray (1984) and Marcy (1984).

A hot \((T_e \sim 10 \text{ keV})\) thermal bremsstrahlung emission contributes comparable luminosities in the \textit{Ginga} band (e.g. 2-10 keV) and in the \textit{Einstein} soft X-ray band (typically 0.5-4 keV). The hot coronal component observed with \textit{Ginga} therefore implies a soft X-ray luminosity of order \( 10^{30} \text{ erg s}^{-1} \) as well, which is comparable to those actually measured with \textit{Einstein} and \textit{EXOSAT} LE. However, it is quite likely that the \textit{Einstein} and \textit{EXOSAT} LE data have been contributed mostly by the separate cooler \((T < 10^7 \text{ K})\) component. Therefore, we suggest that the corona of VW Cep consists of at least two separate components with similar bolometric luminosities but different temperatures. These estimates imply that inclusion of the detected hot coronal component does not increase the overall X-ray luminosity of VW Cep significantly. Therefore the previous conclusion, that luminosities of contact binaries are considerably less than those of other active stellar systems with comparable rotational velocities (e.g. Crudace & Dupree 1984), will still remain valid.

The observed coronal temperature of \( \sim 10 \text{ keV} \) is one of the highest values ever observed from stellar objects, including RS CVn stars and what is more remarkable, this high temperature was seen in the persistent emission rather than in flares. According to a study of coronal temperature with \textit{Einstein}, `single' main-sequence stars typically show much lower temperatures (Schmitt et al. 1990). Therefore, the extremely high temperature observed in VW Cep would result from a binary effect such as interaction between magnetic loops of the two component stars. It is not clear whether such a high coronal temperature is common to contact binaries in general. However if it is so, this observation presents the important issue that the temperature of hot corona of contact binaries is higher than that of RS CVn stars in spite of an order-of-magnitude lower X-ray luminosity as discussed above (Walter, Charles & Bowyer 1978; Walter et al. 1980; Swank et al. 1981; White et al. 1986). Further X-ray observations of other contact binaries are required for confirmation.

It is also puzzling that no significant iron-line emission was seen although the observed X-rays are considered to come from thin, hot plasma. The 99 per cent upper limit on the observed equivalent width of the iron line, 0.24 keV (Fig. 5), is well below the value of 0.6 keV expected for solar abundance. Relative metal underabundance would not be a correct account, because similar phenomena have been reported as well for many other objects including UX Ari (Walter et al. 1978; Tsuru et al. 1989), HR1099 (Koyama 1985), Algol (Stern et al. 1990), AB Dor (Vilhu, Tsuru & Collier-Cameron 1990), and II Peg (Doyle et al. 1991). Could it be that the iron atoms are not sufficiently ionized? For heavy ions to reach ionization equilibrium, the condition \( n_e \tau_i > 10^{32} \text{ s cm}^{-3} \) is required (Masai 1984), or in view of equation (1), \( \tau_i \) must exceed a critical value of

\[ \tau_i = 3 \times 10^9 (R/2R_\odot)^3 \eta^{3/2}, \]

where \( \tau_i \) is the particle or energy confinement time (whichever the shorter) for the ions. The radiative cooling time for electrons, \( -4 \times 10^9 \text{ s}, \) fully exceeds equation (2), but the plasma could cool more quickly via conduction due to the very high \( T_e \). In addition, any plasma instability would further decrease \( \tau_i \) possibly down to the level of equation (2). However, whatever determines \( \tau_i \), the luminosity required to replenish hot ions on the time-scale of equation (2) would amount to \( 10^{33} \text{ erg s}^{-1} \), almost comparable to the bolometric luminosity of VW Cep, on condition that the ion temperature \( T_i \) is as high as the measured \( T_e \). One possible solution might be to assume that the plasma in VW Cep is in a condition of \( T_i < T_e \) and \( \tau_i < \text{equation (2)} \), so that the heavy ions do not reach ionization equilibrium and the required iron-heating luminosity yet remains relatively small.

4 CONCLUSIONS

The \textit{Ginga} X-ray observation of VW Cep has shown the presence of a hot corona with a temperature of \( 11.2^{+5.0}_{-2.3} \text{ keV} \) and emission measure of \( \sim 9 \times 10^{53} \text{ cm}^{-3} \). This extremely high temperature compared to that of single main-sequence stars is thought due to a binary effect. There was no noticeable short-time-scale variability, nor orbital modulation. We interpret the results in terms of thin thermal emission from a hot plasma of density \( 10^{10} \text{ cm}^{-3} \) with a scale size of \( 2-3R_\odot \). The iron-line equivalent width is much lower than that expected for a solar abundance.

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REFERENCES


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