

## Soft X-ray observations of the binary $\sigma$ Cr B with *HEAO-1*

Prahlad C. Agrawal\* and Guenter R. Riegler

*Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA*

Gordon P. Garmire *California Institute of Technology, Pasadena, California, USA*

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**Summary.** A new soft X-ray source H 1613+33 has been detected with the Low Energy Detector 1 (LED1) of the *HEAO* A-2 experiment. The binary  $\sigma$  Corona Borealis ( $\sigma$  Cr B), the primary star (HD 143631) of which is a spectroscopic binary of period 1.1 day, lies near the centre of the error box of the source. On the bases of positional coincidence and the resemblance of the optical characteristics of HD 146361 with those of a RSCVn binary, we propose identification of H 1613+33 with HD 146361. The observed energy spectrum of the source is consistent with thermal emission from a hot plasma at a temperature of  $(6.3^{+9.5}_{-2.3}) \times 10^6$  K. The observed energy flux of  $1.7 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}$  in the 0.15–2 keV band corresponds to a luminosity of  $1.6 \times 10^{31} \text{ erg s}^{-1}$  for a distance of 23 pc. The characteristics of HD 146361 are compared with those of other X-ray emitting RSCVn binaries. It is suggested that the soft X-rays are probably of coronal origin.

### 1 Introduction

We report detection of X-ray emission in the 0.15–2 keV band from the vicinity of the radio-emitting binary star HD 146361 in the binary system  $\sigma$  Corona Borealis ( $\sigma$  Cr B) with low-energy detectors (LEDs) of the *HEAO* A-2 experiment. (The *HEAO* A-2 experiment is a collaboration led by E. Boldt of GSFC and G. Garmire of CIT with collaborators at GSFC, CIT, JPL and UCB.) HD 146361 is a spectroscopic binary with a period of 1.1 day and at a distance of 23 pc.

The X-ray emission from this object was discovered during a search of those binary stars from which radio emission has been detected by Spangler, Owen & Hulse (1977). In a survey of 145 close binary stars, Spangler *et al.* (1977) detected definite radio emission from 11 stars and possible emission from seven stars. One of these,  $\beta$  Persei (Algol), was detected as an X-ray source by Schnopper *et al.* (1976) from SAS-3. Detection of soft

\* NAS–NRC Senior Resident Research Associate on leave of absence from Tata Institute of Fundamental Research, Bombay, India.

X-ray emission from four other radio-emitting binaries (namely UX Ari, HR 1099, AR Lac and  $\lambda$  And) has been reported previously from the *HEAO* A-2 experiment (Garmire 1978; Walter, Charles & Bowyer 1978a). The detection of soft X-ray emission from  $\sigma$  Cr B reported here provides further evidence that radio-emitting binary stars are potential candidates as soft X-ray sources.

## 2 Observations

The observations were made with the low-energy detector 1 (LED1) of the *HEAO* A-2 experiment between 1978 February 7–12, during the normal scan-mode in which the detectors execute a great-circle scan of the sky in a plane perpendicular to the Earth–Sun line. For various reasons like occultation by the Earth, breakdown of the detector, etc, there were only 13 useful scans during this period. The LED1 (Rothschild *et al.* 1979) consists of a multi-layer collimated proportional counter equipped with a polypropylene window of thickness  $125 \mu\text{g cm}^{-2}$ . The data used in the present analysis are from only one-half of LED1, with a geometrical effective area of  $177 \text{ cm}^2$  and a field of view (FOV) of  $1^\circ.55$  FWHM along the scan direction and  $2^\circ.95$  FWHM perpendicular to it. The energy response of the LEDs is limited to the 0.15–3 keV range.

In Fig. 1 we show plots of count rate versus scan angle in  $0^\circ.5$  bins, obtained from superposition of the 13 source scans. Fig. 1(a) shows data in the 0.7–2.0 keV energy band and Fig. 1(b) contains data for the 0.15–0.4 keV band of the first layer of LED1. The new

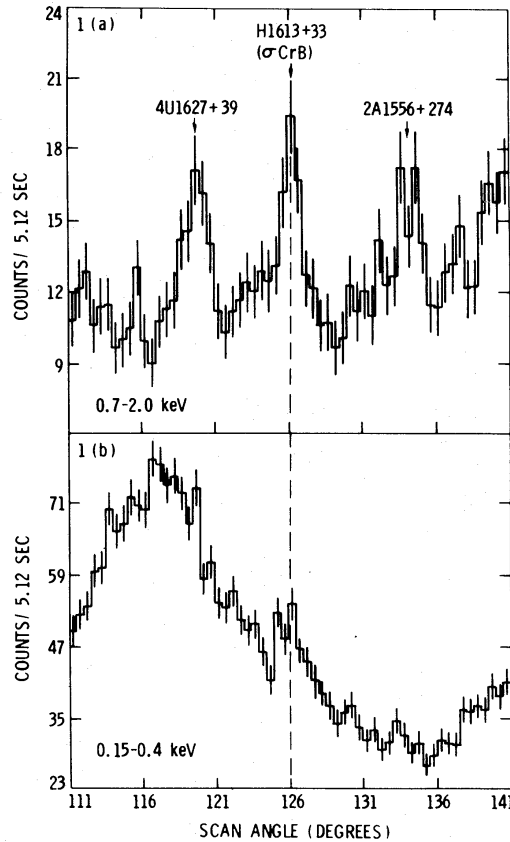


Figure 1. Plots of counts/5.12 s versus scan angle in two different energy bands of layer 1 of Low Energy Detector 1 (LED1). The plots are obtained by superposition of 13 scans of the source for the  $1^\circ.55$  field of view of LED1.  $1\sigma$  statistical error bars are indicated in the figures. The new source H 1613 + 33 is seen in both the plots at a scan angle of  $126^\circ.1$  and is indicated by an arrow.

source designated as H1613+33 is clearly seen in both the plots at scan angle  $126^\circ.1$ . As can be seen in Fig. 1(b), the new source is located in a region where the soft X-ray background (0.15–0.4 keV) is varying with the scan angle. The observed peak width is consistent with that expected for a point source. The other two peaks, at scan angles  $119^\circ.9$  and  $134^\circ$  can be identified with the known Abell cluster X-ray sources 4U 1627+38 (A2199) and 2A 1556+274 (A2142), respectively. The new source was detected at a significance level of  $>10\sigma$ . The observed excess counting rates of the source are  $(6.1 \pm 1.1)$  count/5.12 s and  $(4.0 \pm 0.7)$  count/5.12 s in the 0.15–0.4 and 0.7–2.0 keV bands, respectively. From the best-fitting energy spectrum, the energy flux due to the source is inferred to be  $1.7 \times 10^{-10}$  erg  $\text{cm}^{-2} \text{s}^{-1}$ .

### 3 Source position and identification

The position of the source along the scan direction can be determined to an accuracy of approximately  $0^\circ.2$  from the superposition data. The weak signal in individual scans as well as possible intensity variations make it difficult to locate the source position perpendicular to the scan plane. Constraints on the source location perpendicular to the scan plane can be obtained, however, by overlapping the  $2^\circ.95$ -FWHM detector FOV for the two extreme transits of the source. In Fig. 2 we show the error boxes for the first and the last transits of the source during which a positive signal was detected. The small error box shown by the heavy solid lines indicates the overlapping area of the two error boxes. The error-box width along the scan direction reflects the uncertainty at the 90 per cent confidence level in the determination of the scan angle from the superposition data. Our (1950.0) position for the new source is RA  $16^{\text{h}} 13^{\text{m}}.3$ , dec  $33^\circ 54'.4$ .

The binary system  $\sigma$  Cr B (RA  $16^{\text{h}} 12^{\text{m}} 48^{\text{s}}.25$ , dec  $33^\circ 59' 2''.62$ ) lies near the centre of the solid-line error box. A search through the *Variable Star Catalog* of Kukarkin *et al.* (1969) yielded no other optical candidate within the solid-line error box, although one star, SX Cr B (RA  $16^{\text{h}} 13^{\text{m}} 29^{\text{s}}$ , dec  $33^\circ 27'.3$ ), lies just outside the error box. A search through the catalogue of other likely optical objects such as RSCVn stars (Hall 1976), dwarf novae (Warner 1976), nearby spectroscopic binary stars (Batten 1967), white dwarfs (Giclas, Burnham & Thomas 1965; Giclas, Burnham & Thomas 1967), and bright UV stars (Jamar *et al.* 1976) failed to indicate any other optical candidate.

The energy spectrum of the source, described in a later section, is quite soft ( $kT = 0.54$  keV for a thermal fit), as is confirmed by the failure to detect it above 2 keV with the medium- and high-energy detectors (MED and HED) of the *HEAO A-2* experiment (Marshall, private communication). Almost all the extragalactic X-ray sources like BL Lac objects, Seyfert galaxies and quasars, some of which have been detected as soft X-ray sources, have relatively hard spectra ( $kT \geq 1$  keV). The soft spectrum of the source therefore

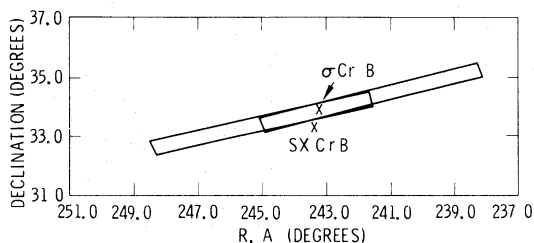


Figure 2. The error boxes derived from the first and last sightings of the source. The heavy solid-line error box represents the overlapping region of the two error boxes as explained in the text. Positions of the candidate objects  $\sigma$  Cr B and SX Cr B are shown.

argues against an extragalactic identification of the object, and we conclude that H1613+33 is most likely to be a galactic object. In view of this, no search was made for an optical or radio counterpart in catalogues of extragalactic objects.

SX Cr B is a variable of spectral type M5, whose photographic magnitude varies between 9.8 and 10.3. It has been classified as a slowly varying irregular variable star of late spectral type and is probably a giant (Kukarkin *et al.* 1969). To the best of our knowledge there are no unusual characteristics associated with this star. Since red giant stars of late spectral type have not been observed as soft X-ray sources, we consider it unlikely that SX Cr B is the optical counterpart of H1613+33.

On the other hand  $\sigma$  Cr B is a well-studied binary system which consists of a primary (HD 146361) of spectral type dF6 with a magnitude  $m_V = 5.76$  and a companion (HD 146362) of  $m_V = 6.66$  and spectral class dG1. The separation between the two stars is about 5.3 arcsec (Hoffleit 1964). The primary is a double-line spectroscopic binary with a period of 1.14 day (Batten 1967). Optical variability is also suspected in  $\sigma$  Cr B (Kukarkin *et al.* 1972). Variable radio emission with average flux of 8 mJy has been detected from HD 146361 by Spangler *et al.* (1977). Young & Koniges (1977) have reported detection of strong *H* and *K* emission lines of Ca II from both components of HD 146361. This indicates considerable chromospheric activity in the system. The observed optical characteristics of HD 146361 bear a strong resemblance to those of RSCVn binaries, as outlined by Hall (1976). Six of the stars classified as RSCVn-type systems (with periods in the range 1–14 day) have been detected as soft X-ray sources by Walter *et al.* (1978a). Variable radio emission has also been detected from four of these latter (Spangler *et al.* 1977; Gibson & Newell 1979). The observed optical and radio characteristics of HD 146361 resemble the characteristics of those binary systems which have been identified as soft X-ray sources. This provides strong support for the identification of HD 146361 with the new soft X-ray source. Based on this consideration as well as good agreement in the positions of H1613+33 and HD 146361, we propose that HD 146361 is the optical counterpart of H1613+33.

#### 4 Energy spectrum

The energy spectrum of the source has been measured using pulse-height data available from 7 of the 13 scans of the source. A spectral fit was attempted with a power-law spectrum as well as a thermal bremsstrahlung spectrum (Gaunt factor included), and we find that both

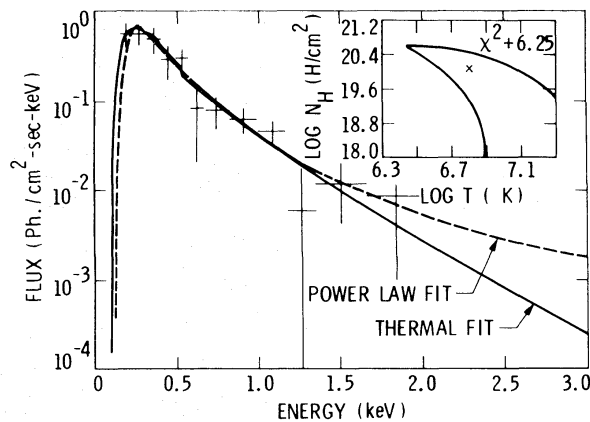


Figure 3. The best-fitting thermal and power-law energy spectra of the source. The flux values observed near the Earth, corrected for detector response for the thermal fit, are also shown. In the insert is shown a 90 per cent confidence  $\chi^2$ -contour of  $\log N_H$  versus  $\log T$  for the fit of a thermal spectrum. The spectrum plotted is marked by  $\times$  in the insert.

types of spectra provide statistically acceptable fits to that observed. In Fig. 3 we have shown the best-fitting power-law and thermal bremsstrahlung spectra, along with the flux values, corrected for detector response for a thermal spectrum, observed near the Earth. Also shown in the insert is a 90 per cent confidence  $\chi^2$ -contour for the fit with a thermal spectrum. This contour has been derived using the criterion of  $\chi^2_{\min} + 6.25$  given by Lampton, Margon & Bowyer (1976) for three free parameters. Our best-fitting thermal spectrum gives  $\chi^2$  per degree of freedom ( $\chi^2/\text{dof}$ ) = 0.62 for a temperature of  $6.3 \times 10^6$  K ( $kT = 0.54$  keV) and a column density ( $N_{\text{H}}$ ) =  $1.3 \times 10^{20}$  H atom  $\text{cm}^{-2}$ . The power-law spectrum yields  $\chi^2_{\min}/\text{dof} = 0.60$  for a spectral slope  $\alpha = -(2.9^{+0.8}_{-1.0})$  and  $N_{\text{H}} = 3 \times 10^{20}$  H atom  $\text{cm}^{-2}$ . The errors quoted on  $T$  and  $\alpha$  are  $1\sigma$  errors obtained using the criterion of Lampton *et al.* (1976). No error has been quoted on  $N_{\text{H}}$  because, as can be seen from the 90 per cent  $\chi^2$  contour in the insert of Fig. 3, the observed spectrum is consistent with an  $N_{\text{H}}$  value as low as  $10^{18}$  H atom  $\text{cm}^{-2}$ . The derived value of  $N_{\text{H}}$  therefore represents only an upper limit to the column density to the source.

On the basis of our data alone, we are unable to distinguish between thermal and non-thermal models. The power-law model can, however, be ruled out on the basis of an upper limit derived from the MED data (Marshall, private communication), which falls a factor of 4 below the flux predicted by the power-law model but is consistent with the best-fitting thermal spectrum. The X-ray flux from H1613+33 is therefore almost certainly of thermal origin.

The observed  $N_{\text{H}}$  value of  $\leq 1.3 \times 10^{20}$  H atom  $\text{cm}^{-2}$  is consistent with the distance of 23 pc and average interstellar density  $\langle n_{\text{H}} \rangle = 0.34$  derived by Bohlin, Savage & Drake (1978) from Ly  $\alpha$  absorption measurements in the spectra of stars.

## 5 Discussion

According to Hall (1976), RSCVn systems exhibit three common optical characteristics: (i) orbital periods in the range of 1–14 day, (ii) hotter components of spectral type F or G and luminosity class V or IV, and (iii) the presence of strong  $H$  and  $K$  emission lines of Ca II outside eclipse. As described earlier, all these three characteristics are present in HD 146361. Most RSCVn systems also have a mass ratio near unity. The mass ratio for the two stars in HD 146361 is estimated to be 1.14 (Tanner 1949), and it is therefore likely that HD 146361 may be a RSCVn-type binary. From their analysis of detached binaries with and without emission lines, Popper & Ulrich (1977) have proposed that RSCVn stars are in the post-main-sequence evolutionary phase, the evolution of the stars being accelerated due to mass exchange in the binary via a stellar wind emanating from the more evolved cooler components. The value of colour index ( $B-V$ ) for HD 146361 is 0.5 and indicates that it is a system of earlier type than the RSCVn binaries, for which the colour index is about unity. Therefore, unlike RSCVn binaries, HD 146361 is probably a less evolved system still on the Main Sequence. A search for the  $H\alpha$  emission from HD 146361 by Bopp & Talcott (1978) has given negative results. This is, however, not inconsistent with HD 146361 being an RSCVn system, since continuous or sporadic  $H\alpha$  emission has been detected in only six RSCVn systems (Bopp & Talcott 1978).

If identification of H1613+33 with HD 146361 is correct, as seems highly likely, and if it is a RSCVn type binary, then this will make it the seventh RSCVn binary detected as an X-ray source. The other six are: HR 1099, RSCVn, UX Ari, AR Lac, LX Per and RW UMa (Walter *et al.* 1978a). Soft X-ray emission has also been detected from four long-period RSCVn-like binaries, namely  $\alpha$  Aur (Catura, Acton & Johnson 1975),  $\lambda$  And,  $\sigma$  Gem and HK Lac (Walter *et al.* 1978a). Detection of HD 146361 as a soft X-ray source provides further support for the conclusion of Walter *et al.* (1978b) that RSCVn binaries constitute a



class of soft X-ray sources. The observed X-ray luminosity ( $L_x$ ) of these objects ranges from  $1 \times 10^{31} \text{ erg s}^{-1}$  for HR 1099 to  $\approx 10^{32} \text{ erg s}^{-1}$  for RSCVn. Using a distance of 23 pc and observed energy flux of  $1.7 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}$  for HD 146361, we estimate  $L_x = 1.6 \times 10^{31} \text{ erg s}^{-1}$  in the 0.15–2 keV range. Besides HD 146361, the only other RSCVn X-ray source with available spectral data is UX Ari, for which Walter *et al.* (1978b) have derived a temperature of  $10^7 \text{ K}$ . None of these objects has been detected by the medium- and high-energy detectors of the *HEAO A-2* experiment (F. Marshall, private communication). This implies that all the RSCVn sources have soft spectra during quiescent emission. Emission lines of oxygen, neon, magnesium and silicon, and *L*-transition lines of the various ionic states of iron at  $\approx 0.9 \text{ keV}$ , are the most prominent features in the X-ray emission spectrum of a hot plasma in the temperature range of  $(4\text{--}16) \times 10^6 \text{ K}$  (Raymond & Smith 1977). If the X-ray emission from HD 146361 is indeed of thermal origin and it has normal elemental abundance, then these X-ray lines should be observable with the solid-state spectrometer of the *HEAO-2* observatory. Because of the limited number of counts in our observations, we are unable to make any inference about the presence of lines.

With the exception of LX Per and RW UMa, radio emission has been detected from all the five other X-ray emitting RSCVn binaries. The radio emission in each is variable over periods of a few days, and at least one of them, HR 1099, exhibits strong radio flaring (Feldman *et al.* 1978). HD 146361 is one of the least luminous radio sources, its average flux density being  $\approx 8 \text{ mJy}$ , which implies a radio luminosity ( $L_R$ ) of  $\sim 8 \times 10^{15} \text{ erg s}^{-1} \text{ Hz}^{-1}$ . An X-ray flare coincident with a radio flare has also been detected from HR 1099 by White, Sanford & Weiler (1978). We have searched for X-ray intensity variations in H1613+33 and place an upper limit of a factor of 2 on the variations in X-ray flux over a period of one day.

Hall (1972) and Eaton & Hall (1979) have explained the variations of the light curve and other related optical features of RSCVn binaries in terms of a starspot model. In this model, a very large fraction of the surface of one hemisphere of the cooler star in the binary is covered with spots which are similar to sunspots. These starspots give rise to the optical variations and observed chromospheric activity in the RSCVn binaries. Walter *et al.* (1978b) have explained X-ray emission from UX Ari as coronal emission from a plasma of temperature  $\sim 10^7 \text{ K}$  and have suggested that activity associated with starspots can provide enough energy to maintain such a corona around the star. It is possible that the observed X-ray emission from HD 146361 is also of coronal origin. The value of the observed X-ray luminosity ( $1.6 \times 10^{31} \text{ erg s}^{-1}$ ) and the volume emission measure ( $\sim 4 \times 10^{53} \text{ cm}^{-3}$ ) are consistent with such a coronal model.

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### Note added in proof

Walter, Charles & Bowyer have also reported detection of  $\sigma$  Cr B as an X-ray source (Walter, F., Charles, P. & Bowyer, S., 1978. *Astr. J.*, **83**, 1539).