Chandra HETGS Observations of the Active Binary σ² Coronae Borealis

R. A. Osten, A. Brown, T. R. Ayres

Center for Astrophysics and Astronomy, University of Colorado, Boulder, CO 80309-0389, USA

J. L. Linsky

JILA, University of Colorado, Boulder, CO 80309-0440 USA

Abstract. We describe Chandra observations of the active binary system σ² CrB taken in 2000 June as part of a coordinated multi-wavelength campaign. The 86 ks (≈ 24 hours) Chandra observation showed steady emission for the first 78 ks, followed by the rise, peak, and initial decay of a moderately large flare. Spectra extracted from the quiescent and flaring portions of the observation reveal numerous emission lines from O, Ne, Mg, Al, Si, S, and Fe as well as a strong continuum. A time-resolved analysis of spectral line variations through the observation reveals no evidence for either star dominating the coronal emission, and is consistent with both stars in the binary system being active coronal emitters. We also find no evidence of flare-related mass motions in the X-ray spectrum. We describe the spectral analysis technique we have developed to measure emission line fluxes and continuum fluxes, determine the distribution of plasma with temperature, and derive abundances relative to hydrogen in a self-consistent manner. The coronal iron abundance of σ² CrB appears to be less than the solar photospheric value, and does not show any dramatic variation from quiescence to flare.

1. Introduction

At a distance of 21 pc, σ² CrB (TZ CrB; HD 146361) is one of the nearest RS CVn binaries and the third brightest detected in the ROSAT All-Sky Survey (Dempsey et al. 1993). With a rotational/orbital period of 1.14 days, σ² CrB belongs to the category of tidally locked short-period RS CVn binaries. Since both components are dwarfs (F6V+G0V), σ² CrB is an interesting case for studying the coronae of hyperactive Sun-like stars. The system has a low inclination (i ≈ 28°; Bakos 1984) and thus does not eclipse; the mass and radius ratios of the two stars are nearly unity and approximately solar (Barden 1985).

Previous observations of σ² CrB have spanned the electromagnetic spectrum, from radio (21 cm) to hard X-rays. Variability is a common factor in all these observations. Agrawal, Rao, & Riegler (1986) detected a flare on the system during an Einstein pointing with a total energy release of 2 × 10³⁴ erg, decay time ≥ 34 minutes, and peak flare temperature 25 MK, compared to a qui-
escent temperature of 6 MK. In a 28 hour EXOSAT observation, van den Oord, Mewe, & Brinkman (1988) observed a flare lasting two hours with a 28 minute decay time, peak flare temperature of 95 MK, and quiescent temperature of 22 MK. Osten et al. (2000) reported a long pointing with the Extreme Ultraviolet Explorer (EUVE) which showed four flares over the course of a 4.5 day look, occurring in two groups of two, approximately two orbital periods apart from each other, with no sustained quiescence between the end of the first flare and beginning of the second flare in each group. Spectra from the observation reveal the brightening of Fe XXIV emission lines during flare intervals compared with quiescence, indicating the presence of hotter plasma during the flares. In the radio, significant variability has been observed at 5 GHz (Morris & Mutel 1988) with undetected circular polarization. Both components are active stars: they each exhibit strong Ca II H and K emission (Bakos 1984; Fernández-Figueroa et al. 1994; Strassmeier et al. 1990) and variable excess Hα emission (Montes et al. 1995; Eker, Hall, & Anderson 1995).

Stern et al. (1992) obtained multi-wavelength observations of α2 CrB over 2.5 days using the Ginga, IUE, and VLA observatories in 1988 June. The Ginga light curve varied continuously, and three X-ray flares were detected. During the flares the temperature of the hotter component in a two-temperature fit increased from 24 to 32 MK. One X-ray flare also was detected in the ultraviolet and radio spectral regions. The timing of the radio flare peaks was frequency dependent (see Fig. 10 of Stern et al. 1992), and the radio peaks preceded the X-ray peak by at least one hour. Osten et al. (2000) described a later multi-wavelength campaign, using the X-ray telescopes ASCA and RXTE and the VLA radio observatory during 2.5 days in 1997 March. They detected a large X-ray flare, with a coincident radio flare which appeared to peak after the X-ray flare. The rise phase of the X-ray event showed the presence of extremely hot, (∼100 MK) plasma. During the decay phase of the flare, the temperature displayed a progressive settling from the peak back to the distribution seen during the initial non-flaring segment. During the flare, dramatic abundance variations are evident during the rise phase: the iron abundance increased by a factor of four compared to the quiescent value.

2. Observations

The Chandra observations occurred from 2000 June 18 through June 20, with an exposure time of 86 kiloseconds. The observations were made using the High Energy Transmission Grating Spectrometer (HETGS) in conjunction with the AXAF CCD Imaging Spectrometer–Spectroscopy (ACIS-S) detector array. The HETGS provides an image in undispersed light, as well as dispersing photons through two concentric sets of gratings: the Medium Energy Grating (MEG) covers the wavelength range 1.7–40 Å in first order, while the High Energy Grating (HEG) covers the wavelength range 1.7–20 Å in first order, with almost twice the spectral resolution of the MEG in the regions of overlap. The observation utilized the Timed Exposure mode, in which the CCD events are accumulated over a frametime of 3.2 seconds before being read out.

The X-ray pointing was part of a multi-wavelength campaign to study coronal variability. One moderately large flare occurred at the end of the Chandra
observation. The ~1 day Chandra observation was situated in the middle of an 8.3 day look with the Extreme Ultraviolet Explorer (EUV E) which covers the 80-380 Å region and provides a broader temporal context of the coronal activity the system was experiencing during the shorter X-ray stare. Five flares occurred within the span of two days in the EUVE light curve, the first of which was seen with Chandra. The 10.5 hour VLA observation (~0.4 days) took place before the flare seen with Chandra and EUVE and did not record any radio outbursts.

![Light curve from Chandra MEG and HEG spectrometers during the observation. Each bin represents 5 minutes of data. The rise, peak, and initial decline of a moderately large flare, with an enhancement at peak of 3.7 times the non-flaring count rate, is visible.](image)

We processed the data using CIAO threads to eliminate bad aspect times, filter events based on energy and event grades, and eliminate "streak" events. This removes the majority of non-stellar events. The events were resolved into spectral events with wavelength, order, and grating attributes using region filtering and order separation. We generated light curves of the data by binning the MEG and HEG events in five minute time intervals. The 1σ error bars were calculated using Poisson statistics. The light curves from the MEG and HEG data are shown in Fig. 1. For the first 78 ks of the observation, both light curves show remarkably steady emission, with an average MEG count rate of 1.79±0.11 counts s⁻¹. During the last 8 ks, the count rate increased to a peak of nearly a factor of 4 over the non-flaring value, and the rise, peak, and initial decay of a moderately large flare can be seen.

The MEG spectra extracted from the quiescent and flaring intervals are shown in Fig. 2. Features seen in both spectra include the hydrogen- and helium-like lines of O, Ne, Mg, Al, Si, and S. Numerous lines of iron are present in the spectrum, ranging from ionization stages Fe XVII–Fe XXIV (the line of Fe XXV
Figure 2. Spectra extracted from quiescent and flaring time intervals, of the Chandra MEG spectrum. This is a spectrum typical of a hot coronal object: lines of O, Ne, Mg, Al, Si, S, and Fe are present, as well as a strong underlying continuum.

indicated in the plot is not a detection). Also evident is significant continuum emission underlying the emission lines; this is most clear in the flare spectrum, where the increase of flux towards the short wavelength end of the spectrum belies a strong continuum.

Because the Chandra observation of 86 ks spanned nearly one complete orbital period of the binary system (98 ks), we searched in the spectral data for any variations of line widths or offsets that could be related to orbital phase, and also for any flare-associated motions. We extracted spectra in one- and two-hour intervals, and examined the bright lines Ne X λ12.14 Å, Mg XII λ8.42 Å, and O VIII λ18.97 Å. For each line and time interval, we fitted the line profile as a Gaussian with all three parameters (width, centroid, and peak) allowed to vary, then plotted the variations of the integrated line flux, FWHM, and average velocity offsets versus time. The integrated line flux increases in response to the flare only. The line widths are constant with time. The lines are unresolved; the expected thermal line width due to Neon at 5 MK would be \( \sim 60 \text{ km s}^{-1} \), and the observed FWHM is a factor of 10 larger due to the instrumental resolution (\( \lambda / \Delta \lambda \approx 500 \) at 12 Å in the MEG). The maximum velocity separation of the two stars in their orbit around each other is \( \approx 120 \text{ km s}^{-1} \). The velocity offsets of the line profile indicate no bulk motions present during the observation. There is no evidence that either star dominates the emission; the offsets are consistent with equal contributions from both stars in the binary system. There is likewise no evidence of velocity deviations associated with the flare.
3. Data Analysis

In order to proceed further, we first identified bright lines and possible blends in the spectrum. Using the APEC v1.10 linelist (Smith et al. 2001), we visually identified moderate and strong features in the HEG and MEG spectra. In addition, we also noted emission lines whose peak emissivities in the APEC linelist were comparable to those of the visually identified lines. In this way we generated a smaller list of \( \sim 390 \) lines and blends from the much larger linelist contained in the APEC data. We also used the APEC linelist to identify “line-free” regions where the individual lines had peak emissivities less than \( 10^{-18} \) photons cm\(^3\) s\(^{-1}\), approximately three orders of magnitude smaller than that of the brightest lines. Under the assumption that the observed emission in these wavelength regions is dominated by continuum emission rather than weak line emission, we can average the flux in these bins and determine the shape of the continuum spectrum.

![Normalized Emissivity vs Temperature](image)

Figure 3. The temperature sensitivity of lines in the Chandra spectrum. Note the “gap” between Fe XVII and O VII, O VIII and Ne IX.

With the assumption that the observed emission is effectively thin, the measured line and continuum fluxes can be related to the elemental abundance and an integral involving the differential emission measure, DEM(T), which specifies the amount of plasma emitting at a given temperature. In our subsequent analysis we used iron lines to constrain the shape of the DEM, because iron has the widest coverage in temperature of the abundant species, and its line emissivities are more peaked in temperature than those of the H- and He-like ions, which tend to have broad high temperature tails. Using a single element removes any influence uncertainties in relative abundances might have in constraining the shape of the DEM. Figure 3 illustrates the temperature coverage of the emission.
lines detected in the *Chandra* spectra. The continuum spectrum also is sensitive to temperature in a manner that is depicted in Figure 4. For a given DEM (in the case of Fig. 4, assumed to a power law), the shape of the continuum spectrum at short wavelengths is sensitive to the maximum temperature present in the DEM, allowing us to constrain the presence of hotter temperatures better than we could using only the emission lines.

![Figure 4](image)

Figure 4. The sensitivity to temperature of the X-ray continuum spectrum. Inset shows the assumed shape of the DEM used to predict the continuum spectra; it is a power-law up to a maximum temperature $T_{\text{max}}$. Continuum spectra were generated using the same DEM, but different values of $T_{\text{max}}$.

We developed the following analysis scheme: starting with the observed *MEG* and *HEG* spectra, we measured line features from our linelist and extracted line fluxes. The three brightest unblended lines of each iron ionization stage were used to constrain the shape of the DEM, which is then used to estimate the continuum flux. There is an interaction between matching the high temperature cutoff in the DEM with the observed continuum shape. Once that was satisfactory, the predicted continuum flux was scaled to the observed continuum flux and subtracted, yielding a first estimate of a "continuum-free" spectrum. The procedure was iterated until the observed spectrum showed no influence of continuum emission. At that point, the continuum spectrum and emission line spectrum could be treated separately. A final determination of the DEM using Fe lines was made, without the contaminating influence of continuum flux in measuring the line fluxes. That allowed us to estimate abundances of other elements whose emission lines are present in the spectrum relative to Fe. The scaling of the observed and predicted continuum spectra gives a determination of the Fe/H ratio, and allows the relative abundances of other elements to be converted to absolute
abundances with respect to hydrogen. Once that has been done, the abundance estimates then can be used in the continuum estimation in the next iteration. The continuum emissivities, like the line emissivities, come from APEC/APED and include bremsstrahlung, bound-free, and two-photon continuum processes tabulated for 14 elements. While hydrogen and helium continua dominate, emissions from other elements can contribute substantially to the total continuum spectrum, particularly if the elemental abundances are significantly enhanced over solar. The oxygen component, in particular, can be a major contributor to the total.

![Continuum spectra in the quiescent (top) and flare (bottom) intervals. Points indicate measured continuum fluxes, under the assumption that these wavelength bins are dominated by continuum emission and not by weak lines. Black curves are predicted continuum emissions from the DEM, scaled to the Fe/H ratio.](image)

Figure 5. Continuum spectra in the quiescent (top) and flare (bottom) intervals. Points indicate measured continuum fluxes, under the assumption that these wavelength bins are dominated by continuum emission and not by weak lines. Black curves are predicted continuum emissions from the DEM, scaled to the Fe/H ratio.

In our initial analysis of the Chandra data, we constrained the shape of the DEM to be a power-law, and minimized the $\chi^2$ statistic between observed and predicted iron line fluxes to determine the parameters of the DEM. As Fig. 3 shows, ionization stages Fe XVII–XXIV cover the temperature range 5–30 MK, which spans the temperature sensitivity of lines from most of the other elements. The notable exception is O, and the helium-like lines of Ne. In order to constrain adequately the shape of the DEM using iron lines at these lower temperatures, it is necessary to have access to lower ionization stages of iron. Using simultaneously obtained EUVE data accomplishes this: the Medium Wavelength spectrometer (180–380 Å) contains emission lines of Fe XIV, XV, and XVI which fill in the temperature coverage of iron down to 1 MK. Results of the detailed Chandra and EUVE analysis will be presented in Osten et al. 2001 (in prep.). Fig. 5 depicts the continuum spectra in the quiescent and flare
intervals, along with the predicted continuum shape. The analysis shown in Fig. 5 has been performed assuming the DEM has a broken power law shape and using only Chandra data and suffers from the caveats mentioned before about temperature coverage. Nevertheless, the general results are consistent with those obtained from a more detailed analysis involving Chandra and EUVE data. The scaling of the predicted continuum flux to the observed continuum spectrum implies an iron to hydrogen ratio that is less than the solar photospheric value of Anders & Grevesse (1989) and does not appear to change substantially in the flare interval compared with the quiet interval. The DEM in quiescence indicates temperatures up to 30 MK, while in the flare spectrum additional material out to 50-60 MK is required.

Acknowledgments. This work was supported by NASA grants NGT5-50241, and NAG5-3226 to the University of Colorado and NASA grant H-04630D to the University of Colorado and NIST. RAO is grateful for the support of a GSRP fellowship.

References

Strassmeier, K. G, et al. 1990, APJS, 72, 191