**XMM-Newton** observations of UW CrB – detection of X-ray bursts and evidence for accretion disc evolution

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**ABSTRACT**

UW CrB (MS1603+2600) is a peculiar short period X-ray binary that exhibits extraordinary optical behaviour. The optical light curve shape of the system changes drastically from night to night, without any changes in overall brightness. Here we report X-ray observations of UW CrB obtained with **XMM-Newton**. We find evidence for several X-ray bursts confirming a neutron star primary. This considerably strengthens the case that UW CrB is an Accretion Disc Corona (ADC) system located at a distance of at least 5–7 kpc, (3–5 kpc above the galactic plane). The X-ray and optical monitor (UV+optical) light curves show remarkable shape variation from one observing run to another, which we suggest are due to large scale variations in the accretion disc shape resulting from a warp which periodically obscures the optical and soft X-ray emission. This is also supported by the changes in phase-resolved X-ray spectra.

**Key words:** Accretion discs – X-rays: binaries, bursts – Binaries: close – Stars: Individual: UW CrB.

1 INTRODUCTION

UW CrB (previously known as MS1603+2600) was discovered by Morris et al. (1990) in the *Einstein* medium sensitivity X-ray survey. They identified the optical counterpart with a blue, emission-line only object close to the X-ray position. Subsequent optical photometry revealed a period of 111 minutes. Morris et al. (1990) also noted UW CrB’s key distinguishing feature of an optical light curve that changes dramatically from one night to another. UW CrB is located at a high galactic latitude of 47°, which, together with its low X-ray flux, suggests that either the source is underluminous in X-rays for a low mass X-ray binary (LMXB) or that it is actually located in the galactic halo.

Hakala et al. (1998) published the results of further optical photometry together with the ROSAT observations. They confirmed the extreme variability seen in the optical light curve pulse shapes. Even if there are dramatic changes in the optical light curve shape, the overall optical flux levels do not vary significantly. ROSAT data showed that the soft X-ray spectrum of UW CrB can be modelled with a single blackbody component, with a temperature of \(kT \sim 0.24\) keV. As expected at this galactic latitude, the spectra showed no significant interstellar absorption.

Earlier models for UW CrB have invoked both LMXB and magnetic CV (cataclysmic variable) explanations (Morris et al. 1990, Ergma & Vilhu 1993). Hakala et al. (1998) compared the ROSAT spectra of UW CrB with soft X-ray spectra of various types of interacting binaries. Their conclusion was that the only class where the spectral fits seemed to match those of the source was the (black hole) soft X-ray transients in quiescence. This could also have explained the relatively low \(F_X/F_{\text{opt}}\) ratio (\(\sim 15\)) observed. In addition, Hakala et al. (1998) report a negative result from their search for circular polarisation.

Mukai et al. (2001) presented ASCA observations of UW CrB. They claim to see a single type I X-ray burst, which would rule out both black hole and white dwarf explanations for the accreting component in the system. They proposed instead that UW CrB is a short period X-ray dipper, similar to X1916-05. They also note that the system would probably in this case have to reside in the galactic

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The background subtracted unfolded EPIC pn 0.2–10 keV light curves from epoch 1 (top, 2003 Jan 20) and epoch 2 (bottom, 2003, Jan 22). The time resolution is 10 sec. Several X-ray bursts are seen during each observation.

Figure 1. The background subtracted unfolded EPIC pn 0.2–10 keV light curves from epoch 1 (top, 2003 Jan 20) and epoch 2 (bottom, 2003, Jan 22). The time resolution is 10 sec. Several X-ray bursts are seen during each observation.

halo, and could have formed in the globular cluster Palomar 14, which is located 11° from UW CrB and at a distance of 73.8 kpc.

Recently Jonker et al. (2003) report the results from Chandra observations of the source. They conclude that depending on the nature of the single burst event detected by ASCA (Mukai et al. 2001), UW CrB could be either a "nearby" quiescent transient or an ADC source at 11–24 kpc distance. They consider the dipper interpretation of Mukai et al. (2001) to be unlikely, mainly on the basis of optical brightness (eg. the system would be intrinsically much brighter in the optical than other, longer period LMXB's that have a larger disc). Quite recently, Muhli et al. (2004) reported that the optical light curves of UW CrB show optical bursts. This has now also been confirmed by Hynes et al. (2004).

In this paper we will present new results of UW CrB taken using XMM-Newton and discuss the nature of the source in light of these extensive new data.

2 OBSERVATIONS

UW CrB was observed by XMM-Newton on 2003 Jan 20 and 22. The two datasets produced a total integration time of 38.8 ksec. However, the particle background was high for around half of observation. The observations were processed using SAS v5.4.1. and the light curves and background subtracted spectra were extracted using XMMSELECT. Response files prepared by the XMM-Newton Project Team were downloaded and used in the EPIC pn spectral analysis, which was carried out using XSPEC. We only used events with flag=0 and pattern=0–4 in the spectral analysis, whilst events with pattern=0–12 were included in the light curves. The spectra were binned using GRPPHA with a minimum requirement of 30 counts per spectral bin. The light curves were also background subtracted.

3 LIGHT CURVES AND BURSTS

3.1 X-ray and UV-optical light curves

The unfolded X-ray lightcurves are shown for the two epochs in Figure 1. There are two main features in the light curves that characterize the variability. Firstly, at least 5–6 short, type I-like, X-ray bursts are seen during both of the epochs. Furthermore, it is clear from the unfolded time series that the light curves have changed within the 2 days that separate the two observing runs. Whilst the light curve of the first observation shows only a moderate modulation over the 111 minute orbital period, such a modulation is prominent in the second dataset, as is more clearly demonstrated in the phase-folded light curves (Figure 2). These show that the orbital modulation, while present in both observations, has changed remarkably from one observation to another. The
modulation is most pronounced at lower energies and UV-optical (OM white light \(\sim 2000\text{–}7000\) Å). The cause for the orbital modulation will be discussed in more detail in the Discussion section.

3.2 X-ray bursts

The candidate X-ray bursts seen in the raw X-ray time series are, at least sometimes, also evident in the OM white light data. There are at least 5–6 candidate bursts in our data. However, the start time can be determined only for the strongest (first) burst. An analysis of that burst revealed that, based on our 1 sec time resolution light curves, the burst seems to start about 2 sec later in UV-optical, than it does in the X-rays (Figure 3). Given the 111 minute orbital period, this roughly corresponds to the light crossing time of the system. This burst happened at an approximate binary phase of 0.1, which implies that the UV-optical burst could occur as a result of reprocessing in the parts of the disc "behind" the compact object. We must note though...
that the binary phase here is not entirely certain, but based on the deepest minimum in the OM light curve (see Figure 2). It is possible that, given the extent of the changes in the light curve shapes of UW CrB, the deepest minimum does not always occur when the compact object is closest to be eclipsed.

The peak EPIC pn count rate of our best (first) X-ray burst is 6 cps, this together with the powerlaw spectral model in the 1–10 keV range (photon index 1.74 from the summed spectrum for epoch 1) yields $2.44 \times 10^{-11}$ ergs cm$^{-2}$ s$^{-1}$ using PIMMS. Now if we assume a conservative burst peak flux of $10^{37}$ ergs s$^{-1}$, this would imply a distance of 60 kpc, and this would still be a lower limit, as $10^{37}$ ergs s$^{-1}$ is on the low side of estimated type I burst peak fluxes (Lewin et al 1995). In addition we are using the brightest of our candidate bursts for this estimate. Based on burst fluxes at different energies we conclude that their spectrum could be characterized by a 1.5–2 keV blackbody, which is fairly typical for type I bursts. The fact that bursts are not seen below 1 keV is a natural consequence of their X-ray spectrum.

It is possible, that if UW CrB really is an ADC source, as suggested by Jonker et al. (2003), then the scattered flux we see from the burst could be only a fraction of the intrinsic flux. Assuming we detect only $\sim$1% of the total flux implies the derived minimum distance estimate would reduce to about 6 kpc. However, there is a problem with this interpretation in that we are still seeing a sharp burst rise of duration less than 1 sec and we would expect the scattering ADC to smooth this out. Having said that, we think this does not entirely rule out the ADC scattering scenario. UW CrB is a short period system, and an ADC could have a diameter with light crossing time of less than 1 sec, in which case the smearing of pulse could not be detected in our data. There is some additional support for the ADC model from the burst data in that the bursts during the first run, when there is little orbital modulation, have a peak flux of $\sim$ 6 cps, whilst the bursts during the second run have a peak flux of only 2–3 cps. This suggests that we are not seeing the bursts directly, but maybe only the scattered X-rays from an ADC, which is more obscured during the second epoch. This is also supported by the fact that the orbital X-ray modulation is more pronounced during the second epoch.

### 4 X-RAY SPECTRA

The X-ray spectra of UW CrB have been previously interpreted using a variety of models. Hakala et al. (1998) showed that the ROSAT spectra could be modelled using either a 0.24 keV blackbody, or a 1.0 keV thermal bremsstrahlung model. Jonker et al. (2003) fitted their Chandra data using a powerlaw with photon index 2.

Our summed EPIC pn spectrum from the first observing run is plotted in Figure 4, and the resulting spectral fit parameters, together with those for the second observing run, are shown in Table 1. All spectra were extracted only from times of low background and have integration times of 6.1 and 6.9 ksec for the two epochs respectively. We find that in order to be able to fit the spectra, a rather complex model is required. The whole 0.2–10.0 keV EPIC pn spectrum cannot be fitted with a single blackbody model nor a powerlaw model. Even the combination of these two models, previously used to model the ROSAT and Chandra spectra, cannot produce an adequate fit. As a result we show that an additional thermal plasma component is required in order to fit the spectra.

We have also looked at the MOS1 spectra from the
EPIC pn spectral fits to the two summed spectra and to the “high” and “low” phase spectra of epoch 2. The corresponding \( \chi^2 \) values are 1.21, 1.22, 1.23, 1.14. The values shown for different parameters indicate 90% confidence intervals.

| Spectrum       | \( N_H \times 10^{22}\text{cm}^{-2} \) | \( kT_{BB} \text{ (keV)} \times 10^{-5} \) | norm. (BB) | \( kT_{mekal} \text{ (keV)} \times 10^{-4} \) | norm. (MEKAL) | \( \alpha \text{ (pl)} \) | norm. (pl) |
|----------------|----------------------------------------|------------------------------------------|------------|------------------------------------------|---------------|----------------|-----------|
| Obs. 1         | 0.076-0.152                            | 0.098-0.142                              | 0.93-3.18  | 0.996-1.199                              | 1.37-2.43     | 1.477-1.659  | 3.42-4.29  |
| Obs. 2         | 0.083-0.197                            | 0.089-0.125                              | 0.78-3.88  | 1.030-1.215                              | 1.38-2.35     | 1.190-1.433  | 1.50-2.03  |
| Obs. 2 (high)  | 0.075-0.181                            | 0.084-0.118                              | 1.09-5.75  | 0.944-1.098                              | 1.93-3.30     | 1.410-1.784  | 2.08-3.16  |
| Obs. 2 (low)   | 0.073-0.360                            | 0.082-0.196                              | 0.05-4.62  | 1.041-1.510                              | 0.42-1.92     | 0.944-1.435  | 0.81-1.52  |

Figure 5. The “high” and “low” phase EPIC pn spectra from the second epoch (together with a spectral model fit to the “high” spectrum).

first observing run. Fitting the MOS1 spectra we get somewhat different results than from the pn spectra. Especially the derived spectral components that dominate at the low energy range (photoelectric absorption and the blackbody temperature) are different. The MOS1 fits yield blackbody temperatures above 0.2 keV and \( N_H \) values less than 0.05\( \times 10^{22} \) cm\(^{-2}\), whilst the pn spectrum (taken simultaneously) implies \( T_{BB} < 0.15 \) keV and \( N_H > 0.07 \times 10^{22} \) cm\(^{-2}\) respectively (99% limits). The remaining spectral components (MEKAL and powerlaw) seem to match. It is known that the EPIC MOS and EPIC pn count rates differ by 10–15% (Jimenez-Garate et al., 2002). We think that the differences in spectral fits can probably be explained by such systematic calibration effects. Furthermore, fitting first the hard part (above 2 keV) of the MOS spectrum with just a powerlaw, fixing its value, and then adding a blackbody component fixed to the best fit value from the pn spectrum and fitting the whole spectrum yielded \( \chi^2 = 1.76 \). Adding a MEKAL component and letting the powerlaw to change freely brought the \( \chi^2 \) value down to 1.11, which is a reasonable fit. With this fit (blackbody temperature still fixed to 0.1 keV) all the spectral parameters agree with the pn data.

The spectral fits to the datasets from the two epochs give very similar results, in spite of the totally different light curves. This is because most of the flux in both spectra is contributed to by the “high” part of the light curves, and thus the effect of phase-dependent absorption is diminished. There is a slight difference in the powerlaw photon index though. However, the phase-resolved spectra extracted separately during the low and high parts of the light curve (phases 0.6–0.9 and 0.1–0.35 respectively) from the second epoch do show a clear difference (Figure 5). The fits to these spectra are also included in Table 1. We fitted the higher signal to noise spectrum (“high” spectrum ) first, and then fixed all the other fitting parameters except for the column density and the normalizations for the fitting of the “low” spectrum. We determined that the changes over orbital phase can be well reproduced by simply changing the overall flux of each component (i.e. through their normalisations). While we had not anticipated this given the energy dependence of the X-ray orbital modulation (which had suggested that the most likely cause for the modulation would be through a changing \( N_H \) with orbital phase), a closer inspection of Figure 5 does show that the low energy spectral shape remains roughly constant while decreasing by a factor \( \sim 5 \) in flux.

We suggest that this is most likely caused by changing partial covering effects across the disc by very thick matter. The normalisations of all three spectral components are affected by this, even though it is strongest in soft X-rays. An obvious cause for such an effect could be the raised rim (or warp) in a non-axisymmetric accretion disc. This “rim asymmetry”, combined with an extended X-ray emission source (ADC) is the most likely cause for the orbital modulation.

The fact that the powerlaw component appears steeper during the “high” spectrum suggests that the ADC is likely to be hotter in its outer regions than near the disc surface. Such effect has been theoretically predicted by Ko & Kallman (1994). In summary, the main difference for the the “high” and “low” spectra is in the normalisation of the components. However, the powerlaw component of the “high” spectrum is somewhat steeper than in the “low” spectrum indicative of a temperature gradient within the ADC. This is also supported by the integrated spectra from the two epochs. The powerlaw at epoch 1 (when there is less orbital modulation, and thus less obscuration of the inner disc on the average) is somewhat steeper than at epoch 2.

We have also inspected the RGS spectra, but due to the low count rates the spectra cannot be analyzed in detail. However, there is evidence for emission lines at around 0.5 keV and possibly also near 0.65 keV. These could correspond to NVII and OVIII Ly\(_\alpha\) type lines. These lines have also been seen for instance in the RGS spectra of Her X-1 (Jimenez-Garate et al., 2002).

5 DISCUSSION

Perhaps the most intriguing result coming out of our study is the huge variation in the amount and shape of the X-
ray modulation between the two epochs. It is well known from previous optical studies by Morris et al. (1990) and Hakala et al. (1998) that the optical light curve shape varies even from night to night. Our study here demonstrates that similar variability is also seen in X-rays.

It is evident from both the X-ray modulation shape (and its variability) and phase-resolved X-ray spectra, that the most likely cause is the changing total column depth of the binary system rotates. This is most simply produced by non-axisymmetric vertical structure in the outer parts of the accretion disc. Observational evidence for such structure has been reported in many LMXBs like X1822-371 (Mason & Cordova 1982, Hellier & Mason 1989), X1916-05 (Callanan 1993; Homer et al 2001), AC211 (Ilovaisky et al 1993) and X1957+115 (Hakala, Muhli & Dubus, 1998). Similar structure has also been seen in supersoft sources such as CAL 87 (Schandl et al. 1997). Sufficiently thick disc rims are almost impossible to produce theoretically, so an alternative explanation for the X-ray (and optical) modulation is the warped disc model, where a thin disc is warped out of the orbital plane due to radiation pressure effects (Pringle, 1996). The precession of such a warped disc could then manifest itself through the changing light curve shape over a (longer) precession period. However, calculations by Ogilvie & Dubus (2001) show that radiation-induced warping is not very likely to happen in short period LMXBs like UW CrB. Instead they suggest that the likely cause for long term variability in short period systems is the change in accretion rate through the disc. It is, however, hard to reconcile how such an effect could produce the observed X-ray and optical light curves, which clearly favour an explanation, where a non-axisymmetric, vertically extended obscuring structure is required. In fact our recent optical work on UW CrB (Hakala et al. in prep.) suggests that there could be another (about 5d) period in UW CrB, over which the optical light curve shape seems to be repeating. Now, our two sets of XMM-Newton observations presented here were taken 2d apart, very close to half of this suggested periodicity. This could explain the very different X-ray light curve shapes reported here.

During the first epoch we see the dip or partial eclipse at phase 0.0 predominantly in the soft band. This implies, together with less X-ray orbital modulation, that we can see the inner disc (or parts of it) directly. There is an additional dip at phase 0.5, which seems to imply extra (obscuring) matter at 180° from the secondary. Similar features have been seen in optical light curves of X1916-05 (Callanan 1993). The OM light curves during this epoch are very similar in shape to the soft X-ray light curves. This implies that both are probably dominated by the emission from the inner disc. The hard X-rays are not affected by the disc structure. During the second epoch the soft X-ray light curve is more sinusoidal with a minimum just before phase 0.0. This is what would be produced by a thick disc rim that has a bulge on the side where the stream hits the outer disc. This time no eclipse is seen in soft X-rays or UV-optical, which could be a result of the outer disc obstructing our view of the inner disc. The fact that we see a large smooth X-ray modulation over the orbital period is a hallmark of ADC systems.

6 CONCLUSIONS

Using our XMM-Newton data, we find evidence for evolving vertical disc structure (either warped or an asymmetric flared disc). This is evident from the strong X-ray modulation over the orbital period, that has changed amplitude and shape over the 2 day period separating the two epochs. The nature of X-ray and UV-optical modulation also suggests that UW CrB is most likely an ADC source. The detection of several X-ray bursts confirms that the compact object in UW CrB is a neutron star. However, as we probably only see scattered X-rays from the ADC, the bursts luminosities cannot be used as a direct tool for distance estimates. Assuming that we would only see about 1 % of the total burst flux then we can estimate that the minimum distance to the source would be ~ 6 kpc. This would place the source at about 4 kpc above the galactic plane.

ACKNOWLEDGMENTS

PJH, PM and DH are supported by the Academy of Finland.

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