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

Pasi Hakala,[1]★ Gavin Ramsay,[2] Panu Muhli,[1] Phil Charles,[3] Diana Hannikainen,[1] Koji Mukai[4] and Osmi Vilhu[1]

[1]*Observatory, PO Box 14, University of Helsinki, FIN-00014 University of Helsinki, Finland*
[2]*Mullard Space Science Laboratory, University College London, Holmbury St Mary, Dorking, Surrey RH5 6NT*
[3]*School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ*
[4]*Laboratory for High Energy Astrophysics, NASA/GSFC, Code 662, Greenbelt, MD 20771, USA*

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ABSTRACT

UW CrB (MS 1603+2600) is a peculiar short-period X-ray binary that exhibits extraordinary optical behaviour. The shape of the optical light curve 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 system located at a distance of at least 5–7 kpc (3–5 kpc above the Galactic plane). The X-ray and Optical Monitor (ultraviolet–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 that 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, accretion discs – binaries: close – stars: individual: UW CrB – X-rays: binaries – X-rays: bursts.

1 INTRODUCTION

UW CrB (previously known as MS 1603+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 object close to the X-ray position. Subsequent optical photometry revealed a period of 111 min. Morris et al. (1990) also noted the key distinguishing feature of UW CrB, namely 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 either that 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 shape of the optical light curve, the overall optical flux level does *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 cataclysmic variable (CV) 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_{opt} ratio (∼15) observed. In addition, Hakala et al. (1998) report a negative result from their search for circular polarization.

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 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 accretion disc corona (ADC) source at 11–24 kpc distance. They consider the

★E-mail: pahakala@astro.helsinki.fi

dipper interpretation of Mukai et al. (2001) to be unlikely, mainly on the basis of optical brightness (e.g. the system would be intrinsically much brighter in the optical than other, longer-period LMXBs 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, Robinson & Jeffery (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 January 20 and 22. The two data sets produced a total integration time of 38.8 ks. However, the particle background was high for around half of the observations. 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 ultraviolet–optical light curves

The unfolded X-ray light curves are shown for the two epochs in Fig. 1. There are two main features in the light curves that characterize the variability. First, at least five or six 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 d that separate the two observing runs. Whilst the light curve of the first observation shows only a moderate modulation over the 111 min orbital period, such a modulation is prominent in the second data set, as is more clearly demonstrated in the phase-folded light curves (Fig. 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 [Optical Monitor (OM) white light ∼2000–7000 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 five or six 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 s time-resolution light curves, the burst seems to start about 2 s later in UV–optical than it does in the X-rays (Fig. 3). Given the 111-min 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 Fig. 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.

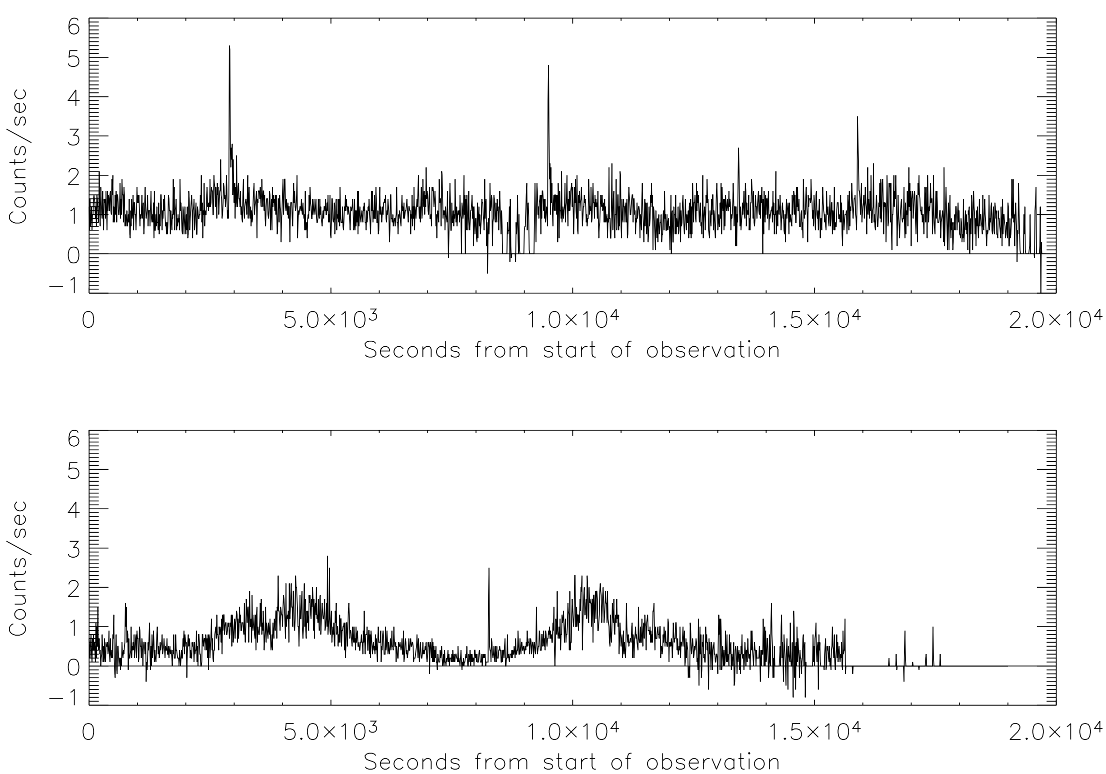

Figure 1. The background-subtracted unfolded EPIC pn 0.2–10 keV light curves from epoch 1 (top, 2003 January 20) and epoch 2 (bottom, 2003 January 22). The time-resolution is 10 s. Several X-ray bursts are seen during each observation.

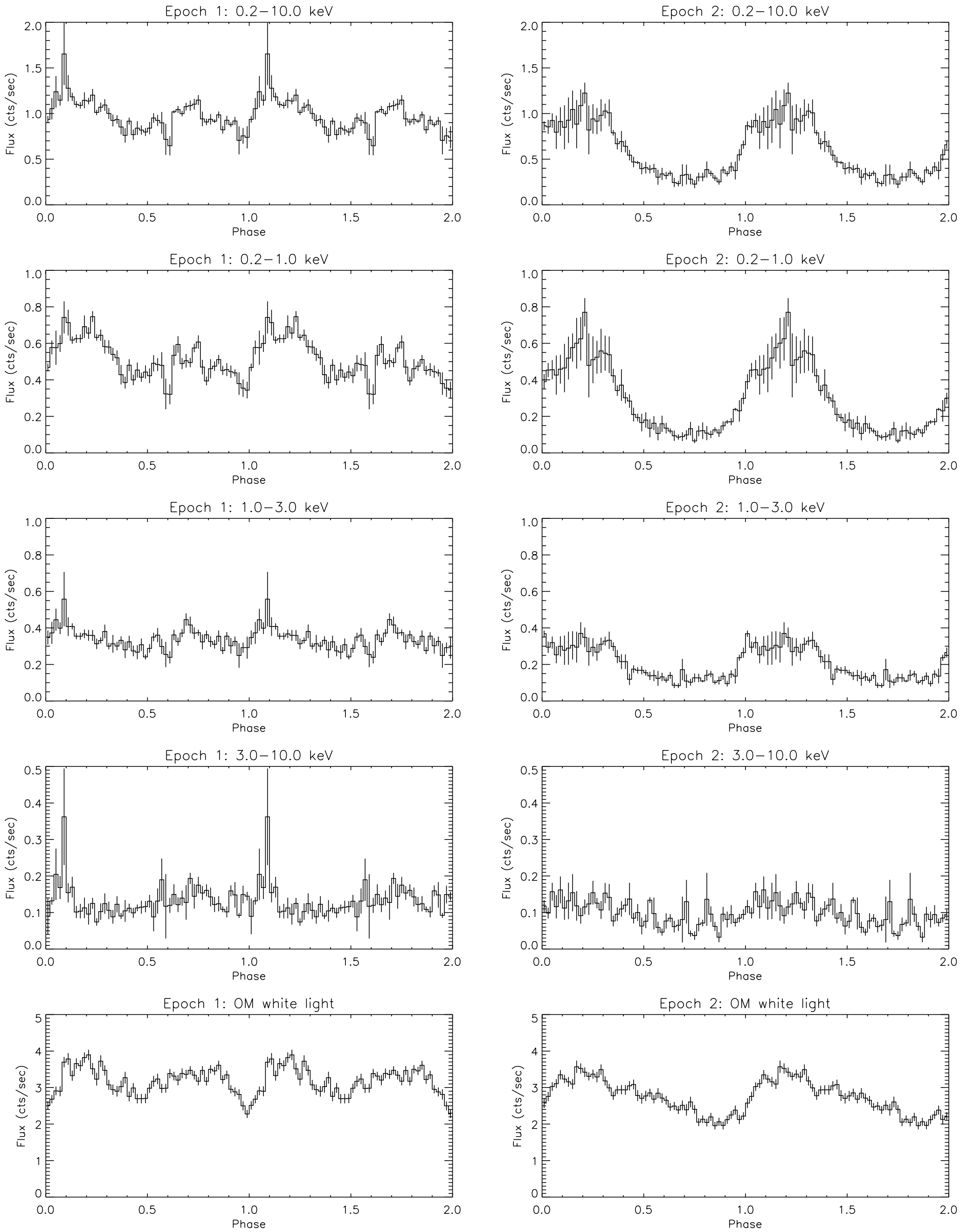

Figure 2. The phase-folded EPIC pn and OM light curves. From top to bottom: 0.2–10.0 keV, 0.2–1.0 keV, 1.0–3.0 keV, 3.0–10.0 keV and OM white light. The left panel is epoch 1 and the right panel epoch 2. The 0.0 phase is arbitrary and taken from the main sharp minimum of epoch 1 OM light curve.

The peak EPIC pn count rate of our best (first) X-ray burst is 6 count s^{-1}, which together with the power-law spectral model in the 1–10 keV range (photon index 1.74 from the summed spectrum for epoch 1) yields 2.44×10^{-11} erg cm^{-2} s^{-1} using PIMMS. Now if we assume a conservative burst peak flux of 10^{37} erg s^{-1}, this would imply a distance of 60 kpc, and this would still be a lower limit, as 10^{37} erg s^{-1} is on the low side of estimated Type I burst peak fluxes (Lewin, van Paradijs & Taam 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 ∼1 per cent 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 s, 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 s, 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

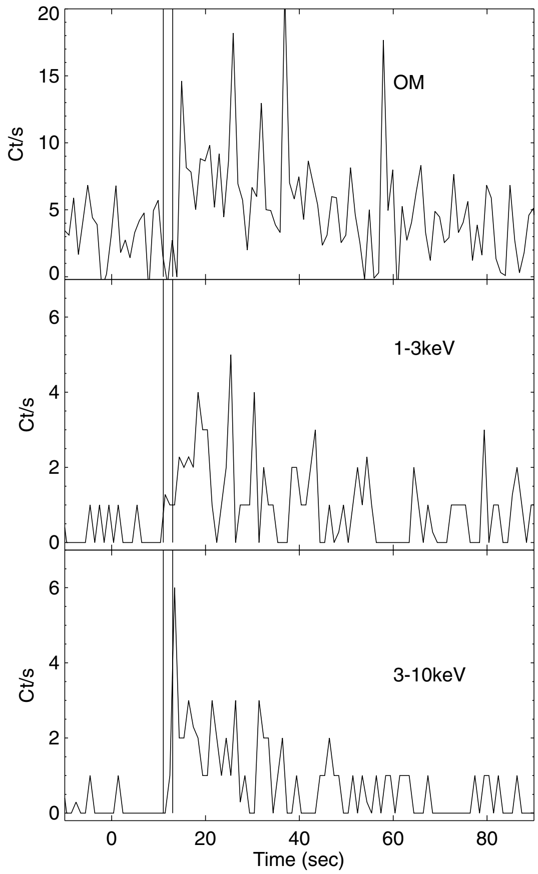

Figure 3. The best (first) burst of the first run at different energies. There is no detection in the 0.2–1 keV band.

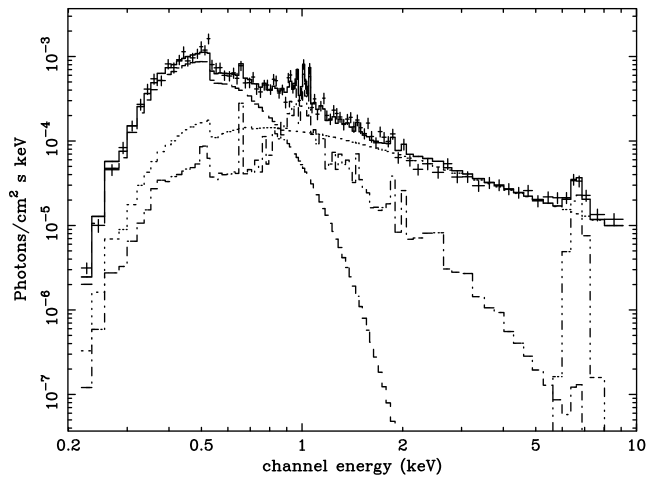

Figure 4. The summed EPIC pn spectra of epoch 1.

there is little orbital modulation, have a peak flux of ∼6 count s^{-1}, whilst the bursts during the second run have a peak flux of only 2–3 count s^{-1}. 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 power law with photon index 2.

Our summed EPIC pn spectrum from the first observing run is plotted in Fig. 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 ks, respectively, for the two epochs. 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 power-law 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 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 $N_{\rm H}$ values less than 0.05×10^{22} cm^{-2}, whilst the pn spectrum (taken simultaneously) implies $T_{\rm bb} < 0.15$ keV and $N_{\rm H} > 0.07 \times 10^{22}$ cm^{-2} respectively (99 per cent limits). The remaining spectral components (MEKAL and power law) seem to match. It is known that the EPIC MOS and EPIC pn count rates differ by 10–15 per cent below 0.7 keV (Kirsch et al. 2004). 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 power law, fixing its value, and then adding a blackbody component fixed to the best-fitting value from the pn spectrum and fitting the whole spectrum yielded $\chi^2_\nu = 1.76$. Adding a MEKAL component and letting the power law change freely brought the χ^2_ν 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.

Table 1. EPIC pn spectral fits to the two summed spectra and to the 'high' and 'low' phase spectra of epoch 2. The corresponding χ^2_ν values are 1.21, 1.22, 1.23 and 1.14. The values shown for different parameters indicate 90 per cent confidence intervals.

Spectrum	$N_{\rm H}$ ($\times 10^{22}$ cm^{-2})	$kT_{\rm bb}$ (keV)	Norm. (BB) ($\times 10^{-5}$)	$kT_{\rm mekal}$ (keV)	Norm. (MEKAL) ($\times 10^{-4}$)	α (pl)	Norm. (pl) ($\times 10^{-4}$)
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

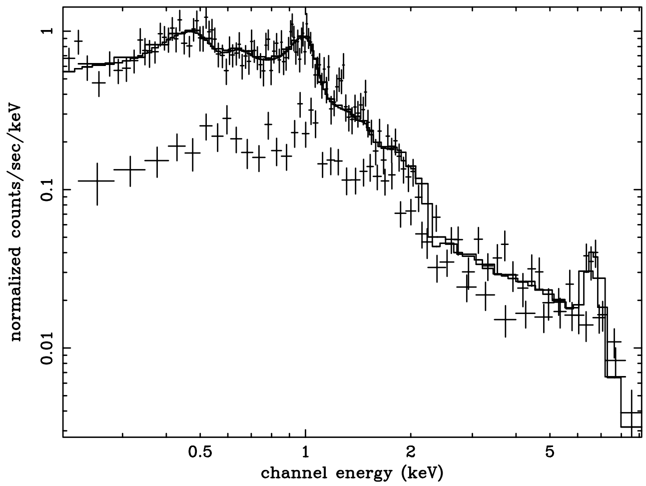

Figure 5. The 'high' and 'low' phase EPIC pn spectra from the second epoch (together with a spectral model fit to the 'high' spectrum).

The spectral fits to the data sets 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 power-law 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 (Fig. 5). The fits to these spectra are also included in Table 1. We fitted the higher signal-to-noise ratio 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 normalizations). 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 $N_{\rm H}$ with orbital phase), a closer inspection of Fig. 5 does show that the low-energy spectral shape remains roughly constant while decreasing by a factor ~5 in flux.

We suggest that this is most likely caused by changing partial covering effects across the disc by very thick matter. The normalizations 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 power-law 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 an effect has been theoretically predicted by Ko & Kallman (1994).

In summary, the main difference for the 'high' and 'low' spectra is in the normalization of the components. However, the power-law 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 power law 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 analysed 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 N VII and O VIII Lyα 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 as 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 et al. 1998). Similar structure has also been seen in supersoft sources such as CAL 87 (Schandl, Meyer-Hofmeister & Meyer 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 preparation) suggests that there could be another (about 5 d) 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 2 d 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, which has changed amplitude and shape over the 2 d 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 burst luminosities cannot be used as a direct tool for distance estimates. Assuming that we would only see about 1 per cent of the total burst flux, then we can estimate that the minimum distance to the source would be $\sim$6 kpc. This would place the source at about 4 kpc above the Galactic plane.

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