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Author(s): V. A. McBride, J. Wilms, I. Kreykenbohm, M. J. Coe, R. E. Rothschild, P. Kretschmar, K. Pottschmidt, J. Fisher, T. Hamson

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On the cyclotron line in Cepheus X-4

V. A. McBride¹, J. Wilms^{2,3}, I. Kreykenbohm⁴, M. J. Coe¹, R. E. Rothschild⁵,
P. Kretschmar⁶, K. Pottschmidt⁵, J. Fisher³, and T. Hamson³

¹ School of Physics & Astronomy, University of Southampton, Highfield, SO17 1BJ, UK
e-mail: vanessa@astro.soton.ac.uk

² Dr. Karl Remeis-Sternwarte, Astronomisches Institut der Universität Erlangen-Nürnberg, Sternwartstr. 7, 96049 Bamberg, Germany

³ Department of Physics, University of Warwick, Coventry, CV4 7AL, UK

⁴ INTEGRAL Science Data Centre, 16 Ch. d'Écogia, 1290 Versoix, Switzerland

⁵ Center for Astrophysics and Space Sciences, University of California at San Diego, La Jolla, CA 92093-0424, USA

⁶ European Space Astronomy Centre (ESAC), European Space Agency, PO Box 50727, 28080, Madrid, Spain

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ABSTRACT

Context. Accreting X-ray pulsars provide us with laboratories for the study of extreme gravitational and magnetic fields, hence accurate descriptions of their observational properties contribute to our understanding of this group of objects.

Aims. We aim to detect a cyclotron resonance scattering feature in the Be/X-ray binary Cep X-4 and to investigate pulse profile and spectral changes through the outburst.

Methods. Spectral fitting and timing analysis are employed to probe the properties of Cep X-4 during an outburst in 2002 June.

Results. A previously announced cyclotron feature at 30.7 keV is confirmed, while the source shows spectral behaviour and luminosity related changes similar to those observed in previous outbursts. The long-term X-ray lightcurve shows a periodicity at 20.85 d, which could be attributed to the orbit in this Be system.

Key words. X-rays: binaries – stars: magnetic fields – stars: pulsars: individual: Cep X-4 – stars: pulsars: individual: GS 2138+56

1. Introduction

Cep X-4 was discovered as a transient source in 1972 June/July with *OSO 7* (Ulmer et al. 1973). In 1988 March it was detected with *Ginga* during a month long X-ray outburst (Makino & *Ginga* Team 1988a) and labelled GS 2138+56. During this outburst, where the source reached a maximum intensity of 100 mCrab, pulsations at 66.2490 ± 0.0001 s were detected (Koyama et al. 1991; Makino & *Ginga* Team 1988b) as well as a cyclotron resonance feature at 30.5 ± 0.4 keV (Mihara et al. 1991), leading to its classification as an X-ray binary pulsar. Using the *ROSAT* Position Sensitive Proportional Counter, Schulz et al. (1995) detected Cep X-4 in quiescence in 1993 January and in outburst in 1993 June. During outburst, the pulse period was measured at 66.2552 ± 0.0007 s. This observation led to a refinement of the source position, and a Be star at $\alpha_{2000} = 21^{\text{h}}39^{\text{m}}30^{\text{s}}.6$ and $\delta_{2000} = +56^{\circ}59'12''.9$ was proposed as the optical counterpart (Roche et al. 1997). Long slit optical spectroscopy of this proposed counterpart (Bonnet-Bidaud & Mouchet 1998) confirmed Cep X-4 as a Be/X-ray binary with a distance of 3.8 ± 0.6 kpc. In 1997 July and August, another outburst took place, this time observed by the Burst and Transient Source Experiment (*BATSE*) and the Rossi X-ray Timing Explorer (*RXTE*). Wilson et al. (1999) measured the pulsar spin down rate and placed constraints on the orbital period using *BATSE* and *RXTE* data from the 1993 and 1997 outbursts. The most recent outburst, occurring in 2002 June and lasting approximately one month, was observed by *RXTE* only.

In this paper, we describe the spectral and timing analysis of pointed *RXTE* observations during the 2002 June outburst. In Sect. 2 we present the observations and describe the reduction

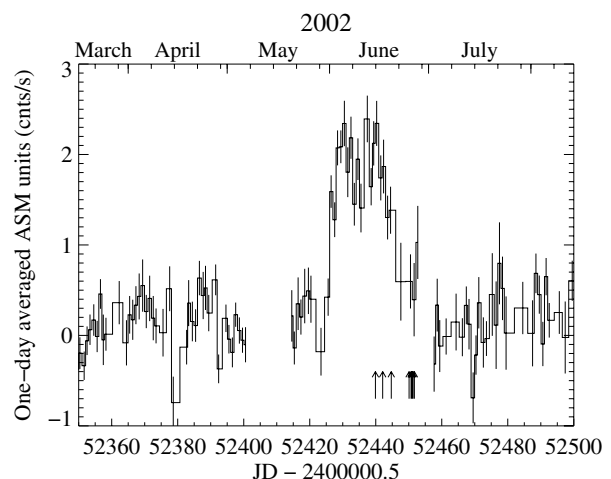


Fig. 1. The ASM lightcurve of Cep X-4 during the 2002 June outburst, re-binned to a resolution of 1 d and taking only one-day averages comprised of 10 or more dwells into account. Arrows indicate the dates of pointed *RXTE* observations.

techniques. Section 3 presents a possible orbital period in the long term lightcurve while in Sect. 4 we fit X-ray spectra from the 2002 outburst. In Sect. 5 the pulse profiles are introduced. Section 6 presents a discussion and interpretation of the data, while the results are summarised in Sect. 7.

2. Observations and data reduction

Figure 1 shows the *RXTE* All Sky Monitor (ASM) X-ray lightcurve of the month long outburst of Cep X-4 during the

Table 1. *RXTE* observations of Cep X-4 during 2002 June outburst. Luminosities are in the 2–10 keV range and are calculated using a distance of 3.8 ± 0.6 kpc (Bonnet-Bidaud & Mouchet 1998).

Obs ID	MJD	Exposure s	Luminosity $10^{36} \text{ erg s}^{-1}$	Period s
70068-11-				
01-00	52439.9	800	1.40	66.41(0.05)
01-01	52442.1	816	1.06	66.36(0.04)
01-02	52444.7	880	0.87	66.25(0.04)
02-01	52450.1	1552	0.41	66.35(0.02)
02-000	52450.7	19600	0.35	66.30(0.01)
02-00	52451.0	1456	0.31	66.33(0.03)
02-02	52451.3	8432	0.32	66.30(0.01)
02-03	52451.7	7088	0.27	66.296(0.004)

second quarter of 2002. Observations with *RXTE*'s pointed instruments were performed during the outburst (arrows in Fig. 1 and Table 1).

To increase the signal-to-noise we extracted data from only the top layer of the Proportional Counter Array (PCA Jahoda et al. 2006). As most of the source photons, but only half the instrumental background, is detected in this layer it is a good choice for a relatively weak source such as Cep X-4. These data are *Standard 2* mode data with 16 s time resolution and 128 channel energy resolution, and were employed to generate phase averaged spectra in the range 3.5–20 keV. We added systematic errors of 0.1% of the count rate in quadrature to all spectral bins across the energy range, as indicated by near contemporaneous fits to the Crab spectrum. For pulse profiles and timing analysis, top layer *Good Xenon* data with a time resolution of 0.03 s were used.

For all spectra we used the *E_8μs_256_DX1F* mode High Energy X-ray Timing Experiment (HEXTE Rothschild et al. 1998) data, which has a temporal resolution of 8 μs. In all cases, the signal-to-noise ratio was increased by adding together data from both HEXTE clusters. Data above 70 keV were not used due to rapid deterioration of the signal-to-noise at higher energies.

Analysis was done with *HEADAS* version 6.0.4 and spectral fitting with *XSPEC* version 11.3.1w (Arnaud 1996).

3. Long-term lightcurve

The archival *RXTE*-ASM data from MJD 50090 to MJD 53873 were filtered on the criterion that one-day averages should consist of 20 or more dwells to make a long-term lightcurve of time resolution one day. Without losing too many data points, this filtering gets rid of the very noisiest points, but includes data from both the 1997 and 2002 outbursts of Cep X-4. Figure 2 shows the Lomb-Scargle (Lomb 1976; Scargle 1982) periodogram of this X-ray lightcurve. To determine the significance levels of peaks in the periodogram, 10 000 Monte Carlo white noise simulations were generated with the same mean, variance and sampling as that of the ASM data. The 90% and 99% significance levels are shown in Fig. 2. A peak corresponding to a period at 20.85 d, with an error of 0.05 d is found above the 90% significance level.

Apart from this periodicity and red noise at low frequencies, no other significant long-term periodicities are found in 10–1000 d interval. This periodicity is not related to any systematic periods often present in ASM data (see Farrell et al. 2005; Benlloch 2004). We speculate that this period is caused by the orbit of the neutron star around its Be companion. It is very close to the lower limit of 23 d as proposed by Koyama et al. (1991),

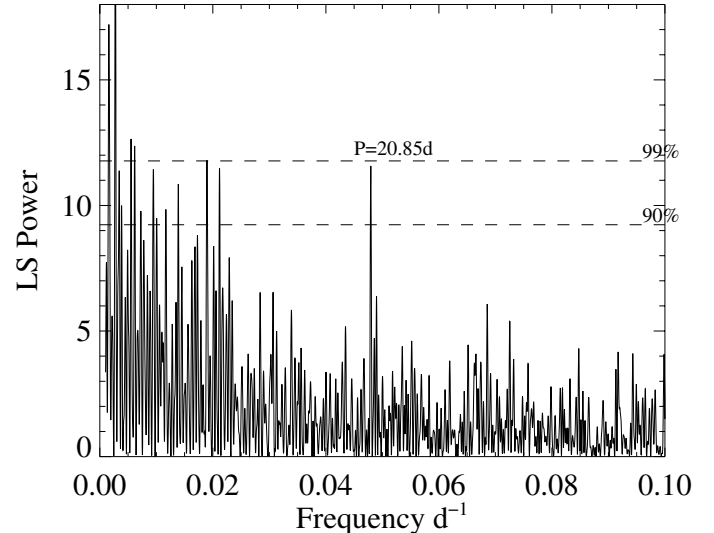


Fig. 2. Lomb-Scargle periodogram of the ASM lightcurve of Cep X-4.

assuming a circular orbit for the binary system. If the 1997 and 2002 outbursts are removed from the lightcurve, the 20.85 d period is still present, albeit with a reduced significance. The fact that inclusion of the outburst data boosts the signal is expected from a Be/X-ray binary, where it is common for outbursts to occur near periastron passage of the neutron star. However, if the orbital period of this system is 20.85 d then it is clear that we do not see bright outbursts at every periastron passage. After its initial discovery in 1972, Cep X-4 went into outburst every four to five years (1988, 1993, 1997, 2002). If this is a continuing trend, we may expect to see an outburst in 2007.

4. Spectral analysis

All observations from Table 1 were added to create the average outburst spectrum.

In the 3.5–70 keV energy range we used a power law with Fermi-Dirac cutoff to describe the continuum. This model has the analytical form

$$\text{FDCO}(E) = AE^{-\Gamma} \frac{1}{1 + e^{(E-E_{\text{cut}})/E_{\text{fold}}}} \quad (1)$$

and differs from the high energy cutoff model in that the transition from power law to exponential is smooth, i.e. without a discontinuity of the derivative at the cutoff energy. Although the high energy cutoff and NPEX (Mihara 1995) models also produced adequate fits to the continuum, the FDCO model provides both a lower χ^2_{ν} over the energy range and smaller uncertainties on the model parameters.

The cutoff energy was fixed at 17 keV from the fit with the lowest χ^2 as determined by Koyama et al. (1991) during the 1988 outburst of Cep X-4. This approach was deemed reasonable, as preliminary fits to the data converged at values close to this cutoff energy. In addition we modeled Fe K α emission with a Gaussian emission line, took into account photoelectric absorption using the *phabs* model in *XSPEC*, with photoelectric cross-sections from Balucinska-Church & McCammon (1992) and element abundances from Anders & Grevesse (1989). We added a ~ 5 keV wide emission line at $E_{\text{Gauss}} \sim 14$ keV to account for variation in the continuum over this energy range. This emission line is used to account for a feature noticed in spectra of a number of accreting X-ray pulsars, e.g. GS 1843+00 or

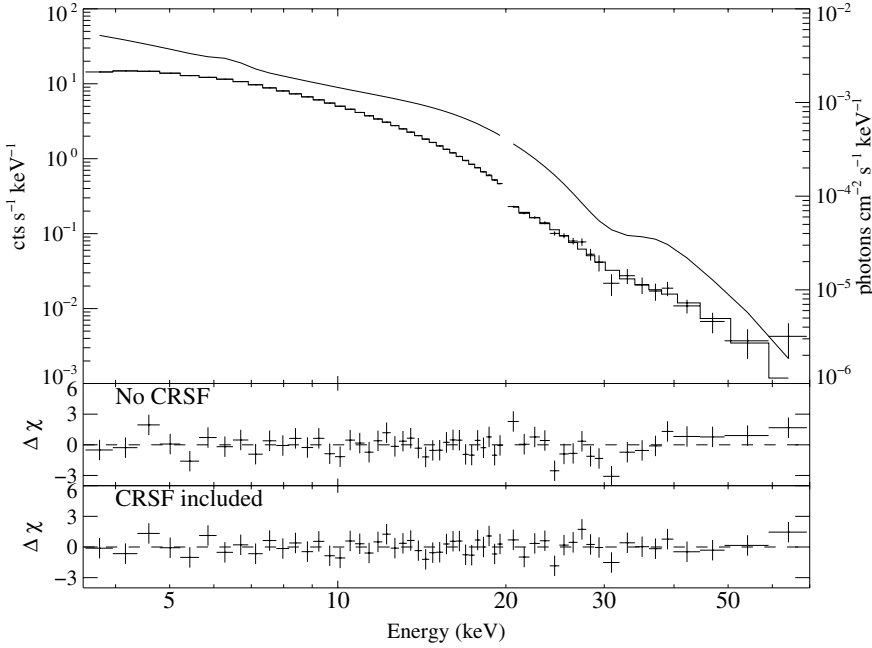


Fig. 3. The spectrum of Cep X-4 from 3.5–70 keV. The crosses show the data, the smooth curve shows the unfolded spectrum, and the histogram the model fit. In the second panel the residuals, plotted as $\Delta\chi$, are shown for the case in which no CRSF is included in the model. In the lower panel, these residuals are shown again – this time including a CRSF in the model.

Table 2. Spectral parameters for the average outburst spectrum. Errors indicate 90% confidence intervals.

Parameter	Value
Γ	$1.44^{+0.08}_{-0.05}$
E_{cut}	17 keV
E_{fold}	$10.9^{+0.8}_{-0.9}$ keV
N_{H}	$2.1^{+0.2}_{-0.1} \times 10^{22}$ cm $^{-2}$
E_{c}	$30.7^{+1.8}_{-1.9}$ keV
σ_{c}	$3.6^{+2.9}_{-1.5}$ keV
τ_{c}	$0.7^{+0.3}_{-0.2}$
E_{Fe}	$6.38^{+0.05}_{-0.06}$ keV
σ_{Fe}	$0.32^{+0.08}_{-0.10}$ keV
Fe EW	73.3 ± 0.1 eV
E_{Gauss}	$14.4^{+0.2}_{-0.1}$ keV
Gauss EW	$4.6^{+5.2}_{-1.6}$ keV
Flux (3.5–10 keV)	$1.8^{+1.3}_{-0.9}$ erg cm $^{-2}$ s $^{-1}$
χ^2_{ν} (d.o.f.)	0.74 (43)

Her X-1 (Coburn 2001). It is not an instrumental feature, as it has been observed with *RXTE*, *Ginga* (Mihara 1995) and *BeppoSAX* (Santangelo et al. 1998), and should be included in future models of pulsar X-ray continua. An absorption line with a Gaussian optical depth profile (Coburn et al. 2002, Eq. (6)) was used to model a weak cyclotron resonant scattering feature (CRSF) at 30.7 keV. The F -test probability of this improvement being by chance is 1×10^{-4} . See Protassov et al. (2002), however, for limitations of the F -test in these circumstances. The average outburst spectrum is shown in Fig. 3 while the model parameters are given in Table 2.

The average outburst spectrum is strongly influenced by the longest (20 ks) observation on MJD 52450.7. In order to see how well this spectrum represented individual observations we normalised the average outburst model to each individual observation by multiplying it by a constant. This allows us to notice

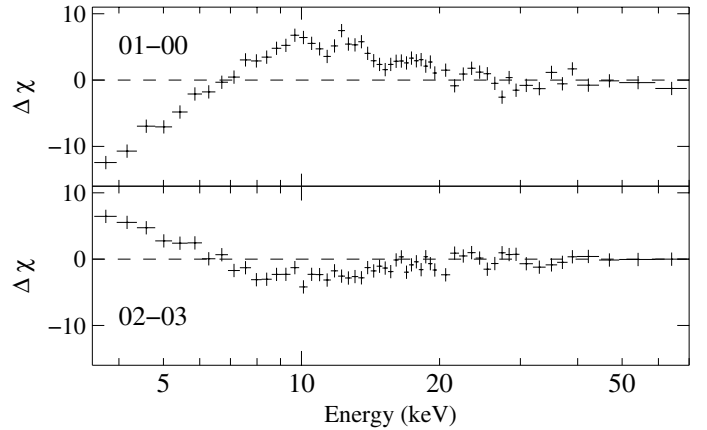


Fig. 4. Residuals, plotted as $\Delta\chi$, as a function of energy for the average outburst model compared to the spectra of observations 01-00 and 02-03.

broad changes across the spectrum. In earlier data (e.g., observations 01-00, 01-01) the model strongly overestimates the data at the soft end (<7 keV) of the spectrum. Whereas for later observations (e.g. 02-02, 02-03) the soft end is underestimated (see Fig. 4). To investigate this effect we fit the spectra of individual observations, this time allowing the normalisation parameters, the power law index and photoelectric absorption parameter to vary. Our fits show a clear steepening (from 1.19 ± 0.06 to 1.50 ± 0.04) of the power law as the outburst progresses, but the absorption column, although poorly constrained by the model, is consistently high ($\sim 2.5 \pm 0.3 \times 10^{22}$ cm $^{-2}$) through the outburst. This suggests that the spectrum becomes softer as the outburst progresses. There is, however, little variation around the energy range containing the cyclotron feature.

As cyclotron features are heavily dependent on the viewing angle and geometry of the line-forming region, a phase resolved study of Cep X-4 would be beneficial to understanding this system. However, the low count statistics in the region around the cyclotron line in this dataset make such a study unfeasible.

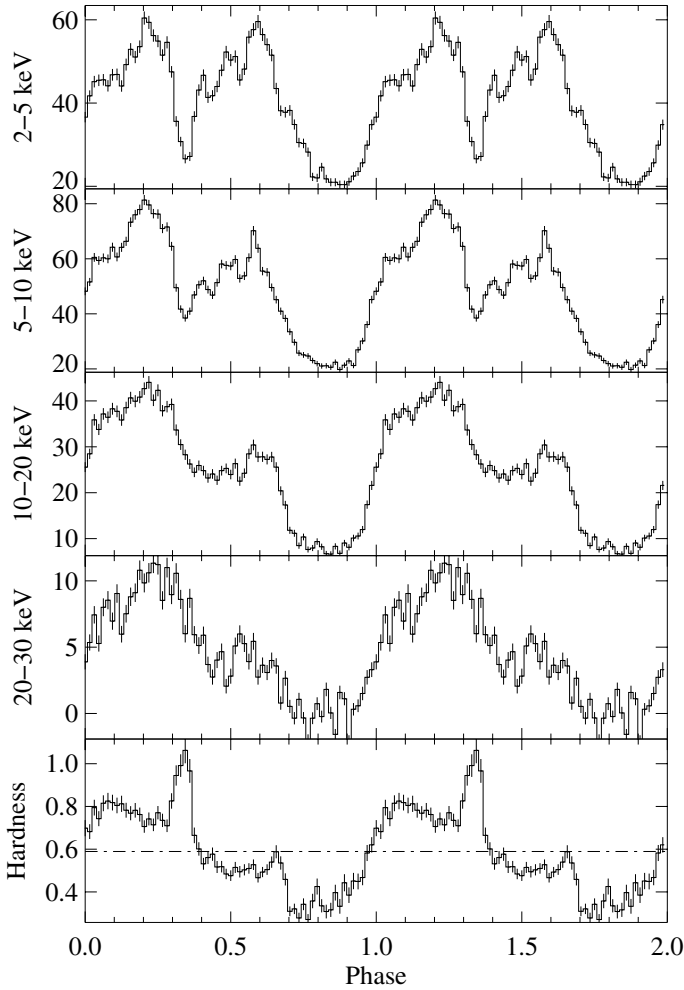


Fig. 5. Pulse profiles as a function of energy for observation 01-00 (MJD 52 439.9) shown in counts/s/PCU. Profiles are plotted twice for clarity. Hardness ratio is 10–20 keV band divided by the 2–5 keV band.

5. Pulse profiles

An epoch folding search (Leahy et al. 1983) was used to determine the source pulse period for each observation (see Table 1). The pulse profiles were generated by folding the lightcurves at a period of 66.30 s. The pulse profiles are double-peaked and complex through all energy bands (Fig. 5). Both of the peaks show additional structure which is prominent at low energies and becomes less coherent at higher energies. The pulse profile in the 2–5 keV energy band changes significantly as the source luminosity drops (see Fig. 6) with the second peak becoming weaker relative to the first as the outburst progresses.

The pulsed fraction, as defined by $(F_{\max} - F_{\min})/F_{\max}$, is shown in Fig. 7 and indicates an overall increase in softer bands (2–5 keV and 5–10 keV) as the outburst progresses. This is contrary to what was observed in the 1997 outburst, where Wilson et al. (1999) saw the pulsed fraction decreasing as the source luminosity dropped.

6. Discussion

6.1. Spectrum

A cyclotron line is identified in the average outburst spectrum at an energy of $30.7^{+1.8}_{-1.9}$ keV, confirming the cyclotron line discovered at this energy in the 1988 outburst of Cep X-4 by

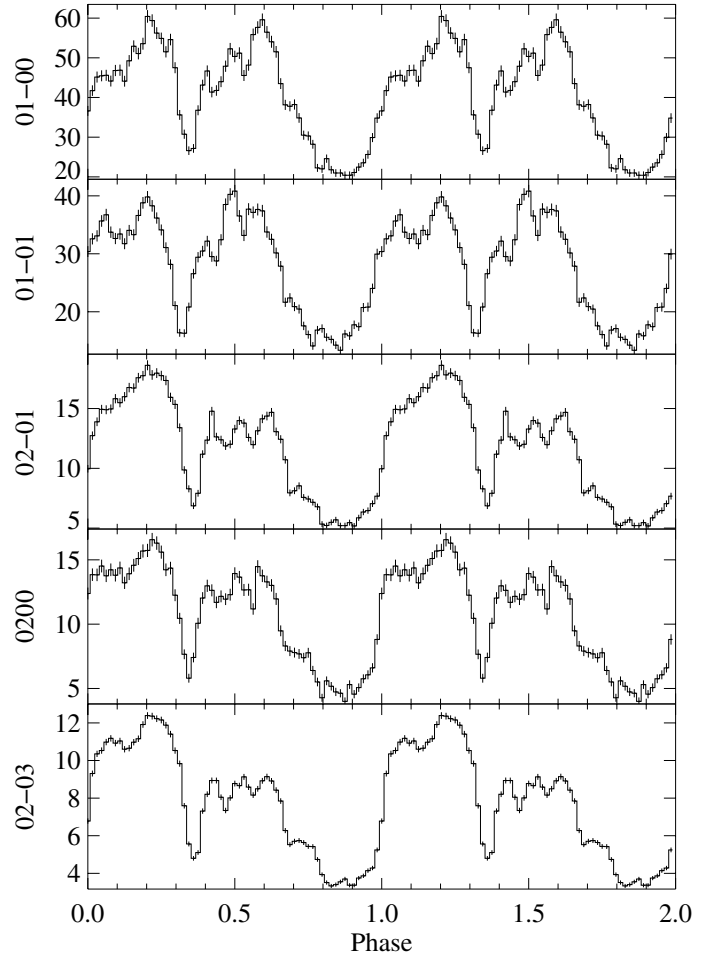


Fig. 6. Pulse profiles in the 2–5 keV energy band for a number of observations throughout the outburst. Luminosity decreases from the top to bottom panel. (See Table 1 for luminosity values.)

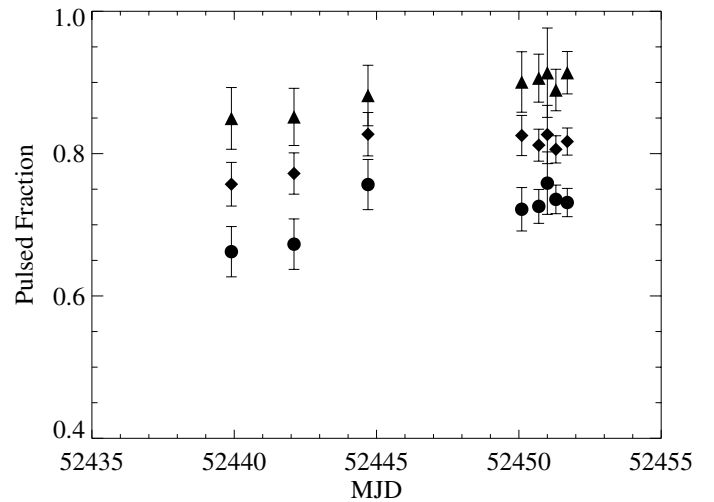


Fig. 7. Pulsed fraction through the outburst. Triangles represent the pulsed fraction in the 10–20 keV band, diamonds for the 5–10 keV band and circles for the 2–5 keV band.

Mihara et al. (1991) with *Ginga*. In the 2002 outburst, as in 1988, the cyclotron feature appears as an absorption line. With the intention of comparing the line properties between the 2002 and 1998 outbursts we fit the 2002 data with the CYCLABS model, which was used by Mihara et al. (1991). The line parameters for

the 2002 outburst, using the CYCLABS model are consistent, within errors, with those measured using the Gaussian optical depth model and given in Table 2. However, the overall model fit is slightly worse. We find values of the line depth and width that are around a factor three smaller than those measured in 1988 ($W_c = 15.0 \pm 1.4$ keV and $D_c = 2.93 \pm 0.10$, Mihara et al. 1991), but note that the cyclotron line was near the upper limit of the *Ginga* energy range. The observed energy of the cyclotron line is given by

$$E_c \approx 11.6 \text{ keV} \times \frac{1}{1+z} \times \frac{B}{10^{12} \text{ G}}. \quad (2)$$

Assuming that the observed feature is the fundamental ($n = 1$) and assuming a gravitational redshift $z = 0.3$ at the surface of a typical neutron star mass of $1.4 M_\odot$ and radius of 10 km, we can obtain the neutron star magnetic field to be $B \approx (3.4 \pm 0.2) \times 10^{12}$ G from Eq. (2).

The Fe $K\alpha$ line has an equivalent width of 73 eV which is within the range of the Fe line equivalent width during the 1988 outburst, and is of the same order as that of Fe $K\alpha$ emission lines observed in other accreting X-ray pulsars (Nagase 1989).

The N_H column density is more than double that noted before in any previous outburst of Cep X-4 (Koyama et al. 1991; Schulz et al. 1995) and also exceeds that derived from the reddening of the optical counterpart (Bonnet-Bidaud & Mouchet 1998). We interpret this increase in the column density as a local effect and ascribe it to possible increased mass transfer through the accretion stream or warping of the accretion disc.

The spectrum certainly changes with source luminosity, becoming softer as the luminosity fades. A similar effect occurred in the 1988 outburst with Koyama et al. (1991) reporting a change in the power law index from 1.10 ± 0.01 to 1.14 ± 0.01 over 10 days of the fading outburst. Although the change in power law slope occurs over a similar timescale in this latest data set, the change is more pronounced. This is in contrast to V0332+53, an accreting X-ray pulsar where the spectrum became harder through the decline of the outburst (Mowlavi et al. 2006). More observations, including data below 3 keV, will be useful in assessing whether both the power law and H I absorption change over the outburst.

6.2. Pulse profiles

For the 1997 outburst Wilson et al. (1999) describe the pulse profile using the model of Brainerd & Mészáros (1991) in which the total pulse profile is made up of two components. A hard pencil beam is caused by photons from one magnetic pole being upscattered through the accretion column. These photons contribute to the prominent peak in the hardness ratio around phase 0.3. Simultaneously, a soft, double-lobed peak originates from the antipodal magnetic pole when cyclotron photons are backscattered. These photons are backscattered into the neutron star or gravitationally focused around the neutron star to form a fan beam of soft photons.

The pulse profiles of Cep X-4 bear a striking resemblance to the complex pulse profiles of Vela X-1 (Kreykenbohm et al. 2002) in the soft X-rays. Both these accreting systems show two main pulses each subsequently made up of further structure. As with Vela X-1 this complexity disappears at higher energies leaving a clearly double-peaked profile. Interpretation of the complexity is uncertain, ranging from variable absorption over the neutron star spin phase (Nagase et al. 1983) to anisotropic emission through the accretion column at the polar cap.

The pulse profiles, especially those at lower energies, show clear evolution over the outburst. Over the 12 days covered by the *RXTE* pointed observations, the luminosity decreased by a factor of 5 and the two peaks in the double-pulsed profiles in the 2–5 keV band became distinctly more dissimilar to each other with the flux in one peak decreasing far more sharply with luminosity than the decrease in flux in the other pulse peak. Comparable changes were noted in the 1997 outburst of Cep X-4 (Mukerjee et al. 2000), where the relative strengths of the two pulses comprising the double-pulsed profile were reversed and the interpulse became stronger with decreasing source luminosity.

It is not uncommon for binary pulsars to show strong variations in their pulse profiles over the duration of an outburst. For EXO 2030+375, which also shows complex double-peaked profiles, a reversal of the dominant pulse was detected (Parmar et al. 1989). A simple geometric model comprising pencil and fan beams from two offset magnetic poles was employed. This interprets the above reversal as a switching of the dominant radiation from one magnetic pole to the other. Parmar et al. (1989) also showed that as the luminosity decreased by a factor of 100, the beam pattern changed from fan to pencil beam. Basko & Sunyaev (1976) propose that a fan beam will be the dominant pulse shape at higher luminosities ($>10^{37}$ erg s^{-1}) where the accreting matter forms a shock above the neutron star surface and radiation escapes predominantly from the side of the accretion column (Wang & Frank 1981). In lower luminosity scenarios, the infalling matter may be decelerated by Coulomb interactions at the neutron star surface (Basko & Sunyaev 1975; Kirk & Galloway 1981), giving rise to a pencil beam emission pattern.

The pulse profiles in Figs. 5 and 6 show behaviour similar to V0332+53 (Tsygankov et al. 2006) in its high luminosity ($\sim 10^{38}$ erg s^{-1}) states, i.e., a change in the relative heights of the double peaked profile with increasing energy as well as a marked change in the relative intensity of the peaks in the soft bands (3–6 keV and 6–10 keV) as the source luminosity decreases. Luminosities $>10^{37}$ erg s^{-1} are certainly not seen in this outburst of Cep X-4, yet it shows similar changes of the pulse profile. This may indicate that the soft pulse profile evolution in this source could be attributed to changes in the flux contribution from the two magnetic poles, although the prominent feature at phase 0.3 in the hardness profile (Fig. 5) is not obviously explained by such a scenario. Accurate orbital parameters for Cep X-4, which are not yet determined, together with modeling of the pulse profiles will help to highlight the geometry and clarify our understanding of the pulse profile behaviour.

7. Summary

1. We have confirmed the detection of a cyclotron line first noted by Mihara et al. (1991) in the 1988 outburst of Cep X-4.
2. We have observed a column density a factor of two higher than previously observed for this source. We attribute this increased density to an effect local to the Be/X-ray binary system of Cep X-4, such as possible partial obscuration by the accretion stream onto the neutron star.
3. We note changes in pulse profiles both with energy and with decreasing source luminosity. Although similar changes are noticed in the pulse profiles of other accreting X-ray pulsars there exists no global interpretation of these effects. Modeling of individual systems, incorporating the orbital parameters, can shed light on the pulsar geometry and emission patterns.

4. A softening of the source spectrum with decreasing luminosity, as was noted in a previous outburst of Cep X-4 (Koyama et al. 1991) is observed, in contrast to the hardening noticed during the outburst decay of V0332+53.
5. A tentative orbital period of 20.85 d for Cep X-4 is revealed in the long term X-ray lightcurve.

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