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X-ray timing behaviour of Cygnus X-2 at low intensities

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ABSTRACT

It is known that the overall (mean) intensity of the low-mass X-ray binary Cyg X-2 varies on time-scales from a day to months, independently of the variations on time-scales of hours to a day by which the source moves between the horizontal, normal and flaring branches.

We present RXTE PCA observations of Cyg X-2, taken when its overall intensity was near its lowest values, in 1996 October and 1997 September. For the first time we perform a study of the fast timing behaviour at such low intensities. During the 1996 October observations, the source was in the left part of the horizontal branch, and during the 1997 September observations was most likely in the lower parts of the normal branch and flaring branch.

We find that the properties of the very low-frequency noise during the 1997 September observations are consistent with a monotonic decrease in its strength and power-law index as a function of overall intensity. In contrast, the strength of the normal branch quasi-periodic oscillations does not vary monotonically with overall intensity. They are strongest at medium overall intensity and weaker both when the overall intensity is low and when the overall intensity is high.

Key words: accretion, accretion discs – binaries: close – stars: individual: Cyg X-2 – stars: neutron – X-rays: stars.

1 INTRODUCTION

Cygnus X-2 is one of the brightest persistent low-mass X-ray binaries. It varies on time-scales from milliseconds to months (e.g. Kuulkers, van der Klis & Vaughan 1996; Wijnands, Kuulkers & Smale 1996; Wijnands et al. 1997a, 1998a). The primary is a neutron star, while the donor star is an A9 subgiant. They orbit each other with a period of $\sim 9.8$ d (Cowley, Crampton & Hutchings 1979; Casares, Charles & Kuulkers 1998). The mass accretion rate is high ($M \sim 10^{13}$ g s$^{-1}$), giving rise to near-Eddington X-ray luminosities (see Smale 1998). The source shows type I X-ray bursts (see Smale 1998 and references therein) and kiloHertz (kHz) quasi-periodic oscillations (QPO; Wijnands et al. 1998). Five other persistent high-luminosity neutron stars show similar X-ray behaviour. They are referred to as ‘Z’ sources, because of the Z shape of the tracks they trace out in the colour–colour diagram (Hasinger & van der Klis 1989).

The limbs of the Z are, from top to bottom, called horizontal branch, normal branch and flaring branch. It is thought that the mass-accretion rate increases from the horizontal branch, through the normal branch, to the flaring branch. In the horizontal branch and upper part of the normal branch QPO are present with frequencies varying between $\sim 15$ and $\sim 60$ Hz (called horizontal branch QPO or HBO) together with a noise component below $\sim 20$ Hz (called low-frequency noise or LFN). On the normal branch different QPO (called normal branch QPO or NBO) are present with frequencies of $5$–$7$ Hz. In the Z sources Sco X-1 and GX 17+2, the normal branch QPO merge smoothly into flaring branch QPO (called FBO) with frequencies of up to $\sim 20$ Hz on the lower part of the flaring branch. No such flaring branch QPO have been reported in Cyg X-2, although $\sim 26$ Hz QPO were seen when Cyg X-2 was in the upper part of the flaring branch, during an intensity ‘dip’ (Kuulkers & van der Klis 1995).

The Rossi X-ray Timing Explorer (RXTE) has opened up a new window on low-mass X-ray binaries in the millisecond regime. kHz QPO (for a review see e.g. van der Klis 1998) have been detected in all six Z sources (Van der Klis et al. 1996, 1997; Wijnands et al. 1997b, 1998a,b; Jonker et al. 1998; Zhang, Strohmayer & Swank 1998). The frequency of the kHz QPO increases with increasing mass-accretion rate.
Of the Z sources, Cyg X-2 displays the most noticeable variations in the X-ray intensity on long time-scales (days to months, e.g. Smale & Lochner 1992; Wijnands et al. 1996; see also Kong, Charles & Kuulkers 1998). These so-called secular variations (which have been empirically divided into three intensity intervals, called the low-, medium- and high-intensity states) recur on a time-scale of ~78 d and are associated with systematic changes in position and shape of the Z track in the colour–colour and hardness–intensity diagrams (Kuulkers et al. 1996; Wijnands et al. 1996, 1997a). They are clearly distinct from the process by which the source traces out the Z track itself on a time-scale of hours to a day. As the source goes from the medium-intensity to the high-intensity state (or vice versa) the fast timing properties in at least the normal branch change (Wijnands et al. 1997a).

On one occasion when Cyg X-2 was very faint in X-rays, no clear Z pattern was seen in the colour–colour and hardness–intensity diagrams, but only a long diagonal branch associated with flaring behaviour which is stronger at higher energies (see Kuulkers et al. 1996). Since the fast timing properties of the source in the low intensity state were unknown we proposed to observe the source in this rare state by using the RXTE All Sky Monitor (ASM) to trigger pointed observations. In this paper we report on the results of these observations.

2 OBSERVATIONS AND ANALYSIS

The RXTE Proportional Counter Array (PCA; Bradt, Rothschild & Swank 1993) obtained 'target of opportunity' observations of Cyg X-2 on 1996 October 31 05:29–08:00 UT (orbital phase according to Casares et al. (1998): $\phi_{\text{orb}} \sim 0.48–0.49$, where phase zero corresponds to X-ray source superior conjunction), 1997 September 28 09:24–18:13 UT ($\phi_{\text{orb}} \sim 0.22–0.26$) and 1997 September 29 04:36–13:42 UT ($\phi_{\text{orb}} \sim 0.30–0.34$), when the ASM rate dropped below ~20 count s$^{-1}$ SSC$^{-1}$. Most of the data were collected with all five proportional counter units (PCUs) on, simultaneously with a time resolution of 16 s (129 photon energy channels, effectively covering 2–60 keV) and down to 16 $\mu$s using various timing (event, binned and single-bit) modes covering the 2–60 keV range.

We constructed colour–colour and hardness–intensity diagrams from the 16 s data using the same energy ranges as Wijnands et al. (1998a). The intensity is defined as the 3-PCU count rate in the energy band 2.0–16.0 keV, whereas the soft and hard colours are defined as the logarithm of the count rate ratios between 3.5–6.4 and 2.0–3.5 keV and between 9.7–16.0 and 6.4–9.7 keV, respectively. All count rates were corrected for background.

Power-density spectra were made from the high time-resolution data using 16-s data stretches, also in the same energy range as...
Wijnands et al. (1998a), i.e., 5.0–60 keV. In order to study the low-frequency (≤100 Hz) behaviour, we fitted the 0.125–256 Hz power spectra with a constant representing the dead time modified Poisson noise, Lorentzians or exponentially cut-off power laws to describe peaked noise components, and a power law describing the underlying continuum (called very-low-frequency noise or VLFN). To search for kHz QPO, we fitted the 256–2048 Hz power spectra with a function described by a constant and a Lorentzian to describe any QPO. Errors quoted for the power spectral parameters were determined using $\Delta \chi^2 = 1$. Upper limits were determined using $\Delta \chi^2 = 2.71$, corresponding to 95 per cent confidence levels.

3 RESULTS

3.1 Colour–colour and hardness–intensity diagrams

In Fig. 1 we show the colour–colour diagram, and in Figs 2 and 3 the hardness–intensity diagrams of the individual observations (a–c) and combined (d) together with the data points of Wijnands et al. (1998a). All our data points correspond to X-ray intensities of ∼2000–2500 count s$^{-1}$ (3 PCUs), so we succeeded in catching the source at its lowest intensity levels. The observations obtained in 1996 October seem to be extensions towards lower intensity on the horizontal branch. This is apparent in both the hard hardness–intensity diagram and the colour–colour diagram by comparing with the data of Wijnands et al. (1998a). In the soft hardness–intensity diagram, however, the 1996 October data fall slightly below their horizontal branch.

The observations obtained in 1997 September, however, cannot be immediately placed within the general Z-pattern behaviour of the source as defined by the Wijnands et al. (1998a) data. In both hardness–intensity diagrams the 1997 September data describe a slightly curved branch, which does not fall on top of the earlier data points. In the colour–colour diagram the September 29 observations trace out a curved track; the September 28 observations fall on top of the September 29 data points and on top of the upper part of the normal branch of Wijnands et al. (1998a). It looks as if the curved track represents the lower part of the normal branch and flaring branch but shifted to higher soft and hard colours. However, in the hardness–intensity diagrams, no clear indications of ‘flaring’ or ‘dipping’ behaviour (see Kuulkers et al. 1996) can be found.

3.2 Power spectra

3.2.1 1996 October

The mean power spectrum (5–60 keV) of the 1996 October data (Fig. 4a; total of ∼6.3 ks) clearly showed horizontal branch QPO near ∼19 Hz together with a higher harmonic near ∼38 Hz on top

Figure 2. Soft hardness versus intensity diagram of data from (a) 1996 October 31, (b) 1997 September 28, (c) 1997 September 29, and (d) all observations together. The Wijnands et al. (1998a) data are represented by dots. All points are 64-s averages.
of a low-frequency noise component, confirming that the source is at the left end of the horizontal branch. A fit to this power spectrum (LFN + 2 QPO) resulted in a reduced $\chi^2$ of 1.72 for 114 degrees of freedom (d.o.f.). This is not a good fit; in fact, a close inspection of the power spectrum reveals that the harmonic is not well fitted with this model. We therefore added another cut-off power-law component with a cut-off near 20 Hz, i.e. a so-called high-frequency noise (HFN) component, which significantly improved the fit at high frequencies: reduced $\chi^2 = 1.42$ for 112 d.o.f. Moreover, the resulting fit seems to describe the second harmonic much better; the centroid frequency of the harmonic is $37.6 \pm 0.2$, compared to $36.5 \pm 0.3$ without the high-frequency noise component. The ratio of the harmonic frequency to the QPO frequency is $1.96 \pm 0.01$ (compare this with $1.90 \pm 0.01$ without the high-frequency noise component). The full width at half-maximum (FWHM) is $10$ Hz, compared to $20$ Hz without the high-frequency noise component. The resulting fit to the power spectrum including the high-frequency noise component is shown in Fig. 4(a).

The QPO and noise components are significant enough to divide the data up into two parts. We computed the $S_Z$ values which measure the position along the Z in the hard hardness–intensity diagram, using the Z track of Wijnands et al. (1998a). In Table 1 we give the results of fits to the power spectra corresponding to the two selected regions. As Cyg X-2 moves further on to the horizontal branch (to lower inferred mass-accretion rate), the frequencies of the horizontal branch QPO and the harmonic decrease, as expected.

We found no evidence for kHz QPO with upper limits of $\sim 3.4$ per cent, when fixing the FWHM at $150$ Hz. This is significantly different from earlier observations in the same part of the horizontal branch (see Section 4.3).

3.2.2 1997 September

The variability during both the September 28 and 29 observations was low. In Table 2 and Figs 4(b)–(d) we give the results of the fits to the power spectra for the September 28 and 29 observations.

The mean power spectrum of the September 28 observations (total of $\sim 22.6$ ks) showed weak power-law noise ($\sim 1.3$ per cent, Fig. 4b). Weak QPO near $\sim 40$ Hz are, however, discernable (see inset in Fig. 4b). We fitted these QPO and found that they were significant at the $\sim 4\sigma$ level as estimated from an F-test for the inclusion of QPO [$\chi^2$/d.o.f. = 104/97 versus $\chi^2$/d.o.f. = 130/100] and from the 68 per cent confidence error-scan of the integral power in the $\chi^2$-space, i.e. $\Delta \chi^2 = 1$. Taking into account the number of trials decreases the significance to $\sim 3\sigma$. A subdivision in the colour–colour and hardness–intensity diagram tracks of this observation did not show significant differences in the power spectral shapes.
Since the colour–colour diagram of the September 29 observations (total of ~21.0 ks) indicates the presence of two different branches, we decided to investigate the power spectra by selecting these branches as indicated by the two regions denoted ‘A’ and ‘B’ in Fig. 1(b). The power spectra are displayed in Figs 4(c) and (d), for regions ‘A’ and ‘B’, respectively. The mean power spectrum for region ‘A’ shows only a power-law noise component (rms ~ 1.4 per cent), whereas the mean power spectrum for region ‘B’ shows a weak peaked-noise component between ~2–20 Hz peaking near 6–7 Hz (rms ~ 3 per cent), on top of a power-law noise component (rms ~ 1 per cent).

Since the September 28 observation and part of the September 29 observations are parallel to the normal branch of the Wijnands et al. (1998a) observations, we investigated the power spectra for normal branch QPO. None was found with upper limits of ~1.3 and ~0.8 per cent, for the September 28 and 29 observations, respectively, with typical values for the frequency and FWHM of 5.5 and 2.5 Hz, respectively. The upper limits on normal branch QPO in regions ‘A’ and ‘B’ of the September 29 observation are ~0.8 and ~1.1 per cent, respectively. Upper limits on the strength of QPO in the September 29 observations, similar to those found in the February 28 observations near ~40 Hz, are ~1.3 per cent. We also searched the September 28 and 29 power spectra for the presence of kHz QPO but found none. Upper limits are ~3 and ~2.8 per cent, for the September 28 and 29 observations, respectively.

### 4 DISCUSSION

We performed RXTE observations when the ASM indicated that

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Table 1. 1996 October power spectral fit results.\(^a\)

| \( S_Z \) | LFN rms (%) | \( \alpha \) | \( \nu_L \) (Hz) | HBO rms (%) | \( \Gamma \) (Hz) | \( \nu \) (Hz) | harmonic rms (%) | \( \Gamma \) (Hz) | \( \nu_H \) (Hz) | HFN rms (%) | \( \chi^2_{\text{red}} \) d.o.f. |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| ~0.29 ± 0.04 | 7.8 ± 0.4 | ~0.11 ± 0.06 | 3.0 ± 0.4 | 8.7 ± 0.1 | 3.1 ± 0.1 | 18.39 ± 0.03 | 4.8 ± 0.3 | 8.8 ± 1.2 | 36.0 ± 0.3 | 10.5 ± 0.5 | 20.4 ± 1.5 | 1.13/112 |
| ~0.21 ± 0.04 | 8.0 ± 0.4 | ~0.08 ± 0.04 | 3.4 ± 0.5 | 8.3 ± 0.1 | 3.5 ± 0.1 | 19.73 ± 0.03 | 4.3 ± 0.3 | 8.8 ± 1.1 | 39.0 ± 0.3 | 10.2 ± 0.4 | 21.4 ± 1.7 | 1.39/112 |

\(^a\) VLFN and LFN/HFN rms (5–60 keV) integrated between 0.1–1 and 0.1–100 Hz, respectively. \( \alpha \) denotes the power-law index, \( \nu \) the cut-off frequency (noise) or centroid frequency (QPO), and \( \Gamma \) the FWHM (QPO).
Cyg X-2 was at overall low intensities. These were successfully performed in 1996 October and 1997 September. It appears that we obtained data in two different kinds of low intensity ‘states’ on the two occasions. In the next subsections we discuss the two observations separately, and investigate the kHz QPO properties.

### 4.1 1996 October

During our first observation in 1996 October we found the source in the colour–colour diagram and hardness–intensity diagrams and the presence of horizontal branch QPO at ~19 Hz and their harmonic at twice this frequency. Previous EXOSAT (Hasinger 1987) and RXTE (Focke 1996; Smale 1998) observations already showed horizontal branch QPO in the same frequency range. Assuming that the horizontal/normal-branch vertex is at the same location in the hard hardness–intensity diagram as derived by Wijnands et al. (1998a), the horizontal branch QPO frequencies found during the 1996 October observations are lower than expected at the same position in the Z. This most likely indicates that the Z track of our observation was shifted with respect to that of Wijnands et al. (1998a). This is supported by the fact that our observation is located below the horizontal branch of Wijnands et al. (1998a) in the soft hardness–intensity diagram, similar to what was seen in EXOSAT data by Kuulkers et al. (1996).

We found evidence for the presence of a cut-off power-law component in the power spectra with a cut-off frequency near 20 Hz. A similar component has been observed previously in Cyg X-2 (Hasinger & van der Klis 1989; Wijnands et al. 1997a) and in other Z sources (Hasinger & van der Klis 1989; Hertz et al. 1992; Kuulkers et al. 1994, 1997; Kamado, Kitamoto & Miyamoto 1997), and is mostly referred to as high-frequency noise. High-frequency noise is strongest in the horizontal branch. We note, however, that our observed high-frequency noise strength is higher than that reported previously for Cyg X-2. This may be a result of the higher energy range we investigated compared to that of Hasinger & van der Klis (1989) and Wijnands et al. (1997a). The high-frequency noise has been observed to become stronger at higher energies (e.g. Dieters & van der Klis 1999).

### 4.2 1997 September

The 1997 September observations do not show clear Z behaviour in the colour–colour diagram and hardness–intensity diagrams, although we cannot rule out the possibility that a ‘complete’ Z was traced out on a longer time-scale. However, the September 29 observations show a curved branch in the colour–colour diagram, which might be part of the Z, i.e. the lower normal branch and the lower flaring branch, but shifted to higher colour values. Moreover, the September 28 observation is aligned with the normal branch, suggesting that it is the same branch. It is known that the source hardens, i.e. the Z-pattern shifts to higher colour values, when it is at overall lower intensities (Kuulkers et al. 1996; Wijnands et al. 1996).

The situation is less clear for the hardness–intensity diagrams. The hardness–intensity diagrams of the September observations are more reminiscent of those reported by Vrtilek et al. (1986). Such shapes are seen when the source intensity is at an overall low level (see Kuulkers et al. 1996). Both the hardness–intensity diagrams and colour–colour diagrams of the September observations do not resemble, however, the large diagonal branch seen with EXOSAT in 1983 (see Kuulkers et al. 1996), which also occurred during a low intensity state.

For the first time we have been able to examine the rapid variability at low overall intensities. We find that the very low-frequency variability during the RXTE September observations is low, i.e. ~1.0–1.4 per cent (0.1–1 Hz, 5–60 keV). Such low variability was also found for the very low-frequency noise in the medium intensity level (1–20 keV; Wijnands et al. 1997a). Our observed very low-frequency noise component is unusually flat. Its index is α ~ 0.6–0.7, consistent with extrapolating the observed decrease in index in the normal branch (Wijnands et al. 1997a) from the high (α ~ 1.5–1.7) to medium (α ~ 1) intensity level down to the low intensity level.

In order to compare our RXTE observations with the 1983 ‘diagonal branch’ observations of Cyg X-2, we calculated power spectra of the EXOSAT data using 64-s data stretches. These data were obtained with a 0.25-s time resolution and no energy information (1–20 keV; so-called ‘i3’-data from the HER3 mode, see e.g. Kuulkers 1995). We used all data during which the collimator response was 100 per cent and all detectors were on source (total of ~16.5 ks). The resulting 0.02–2 Hz average power
spectrum corrected for instrumental noise (see Berger & van der Klis 1998) can be well described by a steep power law ($\alpha = 2.0 \pm 0.2$) with a 1.9 $\pm 0.1$ per cent rms (0.01–1 Hz). Clearly, during the 1983 observations the very-low-frequency noise was much steeper than during the 1997 September observations.

We found evidence for weak (~2 per cent, 5–60 keV) kHz QPO at ~40 Hz during the September 28 observations. Since it has been observed in Cyg X-2 (Wijnands et al. 1997a) that the horizontal branch kHz QPO frequency (and rms amplitude) decreases from the horizontal/normal-branch connection (~55 Hz) down the normal branch (down to ~45 Hz), we can interpret our observed QPO as horizontal branch QPO occurring in the lower/middle part of the normal branch. The fact that the horizontal branch kHz QPO on the normal branch has a similar width (i.e. 10–20 Hz FWHM; e.g. horizontal branch QPO occurring in the lower/middle part of the normal branch) (down to ~1 Hz) supports this identification.

Since the normal branch kHz QPO become more prominent when going from the high to the medium intensity, we searched for normal branch kHz QPO in our data. None were seen with upper limits of ~1 per cent (5–60 keV), which is below that seen in the normal branch of the medium intensity level (~1–2.5 per cent, 1–20 keV; Wijnands et al. 1997a). However, when during the September 29 observations the source went from the inferred normal branch to the inferred flaring branch, a broad (~13 Hz) noise component appeared, which peaked near 6–7 Hz. Interestingly, similar broad noise components have been reported in the lower part of the flaring branch of other observations, but with somewhat lower strength, i.e. ~2 per cent (1–20 keV; Hasinger & van der Klis 1989; Hasinger et al. 1990; Kuulkers & van der Klis 1995; Wijnands et al. 1997a) compared to ~3 per cent (5–60 keV). It is apparent from Wijnands et al. (1997a) that the strength of these ‘flaring branch kHz QPO’ becomes stronger from the high to the medium intensity level. Our observations extend this trend to lower overall intensities.

4.3 kHz QPO

No kHz QPO were found during the 1996 October observations with upper limits which are significantly lower (~3 per cent, 5–60 keV) than previously observed by Wijnands et al. (1998a) in the same part of the horizontal branch as inferred from the horizontal branch kHz QPO frequency (4–5 per cent, 5–60 keV). It is, however, consistent with the upper limits quoted by Smale (1998) when the source was also in the horizontal branch (~1 per cent, 4–11 keV), but at higher overall intensities. As noted by Smale (1998), this may indicate that the strength of kHz QPO (at the same position in the Z) changes as a function of the overall intensity level. Unfortunately, for our 1996 October observations we cannot infer the overall intensity level to which it corresponds.

During the 1997 September observations we found no indication for kHz QPO with upper limits of ~3 per cent (5–60 keV). This is consistent with the upper limits reported previously in the normal/flaring-branch region (2–4 per cent, 5–60 keV; Wijnands et al. 1998a).

5 CONCLUSION

Using RXTE we observed Cyg X-2 at low overall intensities, for the first time with sufficient time resolution. In 1996 October we found the source in the leftmost part of the horizontal branch. Our observations show horizontal branch kHz QPO properties which are generally consistent with earlier observations in this part of the Z track, but also indicate significant variations in the strength of the kHz QPO there. We conclude that we have seen parts of the normal branch and flaring branch during our 1997 September observations, when the source was seen at low overall intensities. These do not, however, resemble the behaviours seen during a rare low intensity state in 1983. Such a rare state may be observed when the overall intensity is even lower than during our observations. The properties of the very-low-frequency noise during our September low-intensity observations (low amplitude, flat power-law slope) are consistent with extrapolation from those seen in previous observations at higher intensity. However, the lack of normal branch kHz QPO during our observations is not consistent with the observed trends, and suggests that the normal branch kHz QPO amplitude is either non-monotonically related to intensity or varies independently from this parameter.

It has been suggested that obscurtion by the outer accretion disc of the inner accretion disc regions and neutron star causes the low overall observed intensities during certain times and the high to medium to low intensity level variations. Such a configuration might be due to the precession of a warped accretion disc, mainly based on the rather strict periodicity of the overall intensity variations on time-scales of months (see e.g. Wijnands et al. 1996; Wijers & Pringle 1999). We note that obscurtion effectively hardens the spectrum which leads to the changes in the position of the Z in the colour–colour diagram (see Kuulkers et al. 1996; Wijnands et al. 1996). Scattering in the outer disc would affect the variability amplitudes by light traveltime smearing down to a frequency of order 0.01 Hz. While this picture would explain the monotonic decrease in very low-frequency noise amplitude with decreasing intensity, it seems inconsistent with the flattening of its power-law index and the non-monotonic dependence of normal branch kHz QPO amplitude on intensity. A model in which the low intensity states are associated with changes in the character of the inner accretion flow itself seems therefore favoured.

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