The re-occurrence of mHz quasi-periodic oscillations in Cygnus X–3

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ABSTRACT

We have re-analysed archival RXTE data of the X-ray binary Cygnus X–3 with a view to investigate the timing properties of the source. As compared to previous studies, we use an extensive sample of observations that include all the radio/X-ray spectral states that have been categorized in the source recently. In this study we identify two additional instances of quasi-periodic oscillations that have centroid frequencies in the mHz regime. These events are all associated to a certain extent with major radio flaring, which in turn is associated with relativistic jet ejection events. We review briefly scenarios whereby the quasi-periodic oscillations may arise.

Key words: accretion, accretion discs – binaries: close – stars: oscillations – X-rays: binaries – X-rays: individual: Cygnus X–3 – X-rays: stars.

1 INTRODUCTION

Cygnus X–3 is a well-known X-ray binary (XRB) located in the plane of the Galaxy at a distance of approximately 9 kpc (Dickey & Lockman 1990; Predehl et al. 2000). Its discovery dates back to 1966 (Giacconi et al. 1967) but the intrinsic nature of the system remains a mystery despite extensive multiwavelength observations through the years. A truly puzzling feature of Cygnus X–3 is that the 4.8-h periodicity in the X-ray light curve (Parsignault et al. 1972) attributed to orbital modulation is characteristic of typical low-mass XRBs, but infrared observations suggest the mass-donating companion to be a Wolf–Rayet (WR) star (van Kerkwijk et al. 1992), characteristic of high-mass XRBs.

Unlike most other XRBs, Cygnus X–3 is relatively bright in the radio virtually all of the time (≥100 mJy), with periods of quenched or quiescent radio emission punctuated by giant outbursts of the type not seen in classical radio-emitting XRBs (Waltman et al. 1996). During these outbursts there is strong evidence of relativistic jet-like structures (Mioduszewski et al. 2001; Miller-Jones et al. 2004).

Surprisingly, given the wealth of available timing data, the X-ray timing properties of Cygnus X–3 are not particularly well studied. Thus, apart from the strong orbital modulation present in the X-ray light curve, the timing properties of Cygnus X–3 appear remarkably non-descript. The power density spectrum (PDS) of Cygnus X–3 was studied in Willingale, King & Pounds (1985) and was found to be well described by a power law of index β = −1.8 in the frequency range of 10−5 to 0.1 Hz. This result has been more or less verified in further studies by Choudhury et al. (2004; β ≈ −1.5) and Axelsson, Larsson & Hjalmarsdotter (2009; β ≈ −2 in the canonical, disc-dominated soft X-ray state and −1.8 in the canonical, Comptonization-dominated hard X-ray state). The PDS has no power above 0.1 Hz, a result that has been discussed in Berger & van der Klis (1994; they placed an upper limit of 12 per cent rms above 1 Hz) and subsequently in Axelsson et al. (2009). This is believed to be an effect of scattering in the nearby surrounding medium (Zdziarski, Misra & Gierliński 2010). However, van der Klis & Jansen (1985) found short intervals (5–40 cycles) of mHz quasi-periodic features in the PDS during the soft state and possibly also during the hard state in EXOSAT/ME data. A mHz feature in the Cygnus X–3 hard X-ray light curve was also found in a balloon flight study by Rao, Agrawal & Manchanda (1991). However, no quasi-periodic oscillations (QPOs) were found in the RXTE/PCA study in Axelsson et al. (2009) in either the soft or the hard spectral states of the source. It is important to note that all of these previously studied PDSs are indicative of red noise (the ‘leakage’ of power in low-frequency features to higher frequencies) dominated PDSs. The discrepancies between the reported results clearly show that these transient features are short-lived and sporadic or time-sensitive events. Interestingly, the previously discovered QPOs appear to occur following major radio flaring episodes (Koljonen et al. 2011).

In this Letter we study the PDS of Cygnus X–3 using the extensive archive of RXTE/PCA timing data including pointings during and after major radio flaring events. We introduce the data and the analysis method in Section 2 and present our results in Section 3. In Section 4 we briefly review the possible causes for the QPOs in Cygnus X–3 and summarize the Letter in Section 5.

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2 OBSERVATIONS AND METHOD FOR CURRENT STUDY

2.1 Observations

We analysed, following standard procedures using FTOOLS v6.9, the archived RXTE observations from 1997 to 2011 totalling 172 pointings and more than 0.7 Ms of data, covering all the spectral states as defined in Koljonen et al. (2010; hereafter K10), and orbital phases. The RXTE/PCA light curves were extracted using the generic binned data with a time resolution of 4 ms from channels 0–35 corresponding approximately to the energy range of 2–15 keV (epoch-dependent). Subsequently, the light curves were binned to a 100-ms resolution. We verified our results by comparing the outcome to Standard 1 data that have a time resolution of 125 ms. In order to gauge the X-ray spectral state of the source during the selected pointings (if not already done so in K10), we extracted light curves from channels 3–11 and 24–37 corresponding to energy ranges 3–6 and 10–15 keV using the Standard 2 data products and compared the resulting hardnesses and intensities of these bands to the hardness–intensity diagram presented in K10.

Furthermore, in order to identify the correct radio/X-ray state, simultaneous radio observations were inspected using archival data from the Green Bank Interferometer (GBI), Ryle/AMI-LA and RATAN-600. To follow the overall evolution of the radio/X-ray spectral states within the context of the selected pointings containing the QPOs, the monitoring data from RXTE/ASM, Swift/BAT and CGRO/BATSE were used in the phase-selected format as in K10 in addition to the radio light curves from the above-mentioned radio observatories.

2.2 Timing analysis

The timing analysis in this study was undertaken using ISIS (Interactive Spectral Interpretation System, Houck & Denicola 2002) with the SITAR timing analysis module. The usual procedure for searching for quasi-periodic phenomena in light curves is to construct a PDS and search for sharp peaks in this spectrum. To construct a PDS we prepared the 100 ms time resolution light curves (done separately for each pointing) and calculated the PDS for segments of length 8192 bins over the whole light curve rejecting the segments with data gaps and finally averaging the PDS over the whole light curve. To determine the significance level of the possible QPO detections, we followed the Monte Carlo analysis of Benlloch et al. (2001) which relies on simulating random red-noise-dominated light curves with the algorithm described in Timmer & Kögig (1995). First, we performed simple fits to the PDS with ISIS (with a high degree of binning), where we include a simple power law for modelling the low-frequency noise and a constant for modelling the Poisson noise. Then 5000 light curves were simulated, using the model of the PDS ensuring that the generated light curves had the same length and mean counts as the original observations. Based on the distribution of the resulting PDSs from simulated light curves for each frequency bin, 95, 99 and 99.9 per cent confidence intervals were obtained. Also, root mean square values were obtained from the dynamically calculated PDSs from a frequency range of 0.004–0.1 Hz using the same segment length over the light curves as above.

3 RESULTS

3.1 Previous detections of QPOs

QPOs have been detected at least six times according to the literature in the first studies dedicated to this topic (Table 1). EXOSAT/ME observations exhibited QPOs with amplitudes between 5 and 20 per cent of the 1–10 keV flux and periods in the range of 0.7–15 mHz (50–1500 s) which persisted for 5–40 cycles and occurred in the phase interval of 0.0–0.75 (van der Klis & Jansen 1985). A balloon study (Rao et al. 1991) showed a QPO in the 100–1 keV light curve with a frequency of 8 mHz (125 s), a pulse fraction of 40 per cent and a duty cycle of 60 per cent during maximum brightness.

A later study based on RXTE pointing data from 1996 through 2000 was conducted by Axelsson et al. (2009) and, as mentioned above, they found no evidence of QPOs on any time-scale. Specifically, on the shorter time-scales (>10^{-3} Hz) they did not detect QPOs at all and the power density spectrum is well described by a power law of index ~2, while on the longer time-scales (~10^{-3} Hz) they found that the variability is dominated by the state transitions. However, as Scott, Finger & Wilson (2003) point out in their study of the timing noise in the Crab, random walk processes will yield a power-law index of ~2. This suggests that the flaring in Cygnus X−3 produces the red noise that essentially mimics a random walk process and thus hides any potential intrinsic variability.

3.2 Current study

Our study yielded only two PDSs that show clear peaks above the 99.9 per cent confidence limit, as described below. However, we would like to note that while the PDSs are consistent with power-law noise with β ~ −1.5–2.5 with a mean value of ~2.0, there are pointings that exhibit more structure in the PDS around 0.01 Hz with multiple peaks just below the 99.9 per cent significance level.

To identify the state of the system when these PDSs arise, we calculated the fraction of data as a function of phase whose root mean square values are above the level of a standard deviation + the median rms value of all the data (see Fig. 1, black histogram). In addition, each fraction was further divided among different radio/X-ray states (coloured histograms in Fig. 1). Quiescent radio/X-ray states are not shown in Fig. 1 as they have lower rms values. Fig. 1 shows that most of the rms variation is due to the rms–flux relation (tracing the orbital modulation), but two anomalous peaks show up at phases 0.3–0.4 and 0.6–0.7. The first peak is due to only the FHXR state and the second peak results from the excesses in the FIM/FSXR states. These states and related phases are the same states and phases where the QPOs discussed in this Letter are found.

Fig. 2 and Table 2 show the PDSs and significances (based on the Monte Carlo analysis referred to in Section 2) respectively of the QPOs we have identified in this subset of RXTE data with Fig. 3 highlighting the data from the 2000 April 3 observation. As noted in Table 2, the QPOs occurred during the flaring states – particularly in the FSXR/FHXR states. In the context of phase, we note that the QPOs occurred between phases 0.2 and 0.7. Interestingly, the QPOs discussed in van der Klis & Jansen (1985) all appear exclusively in the phase interval 0.0–0.75 that corresponds to the rising branch and top of the phase-folded X-ray light curve (Vilhu et al. 2003).

The orbital phase of each of the individual segments of light curves was determined using a cubic ephemeris (Singh et al. 2002).
Table 1. Log of QPOs identified from Cyg X–3 in previous studies.

<table>
<thead>
<tr>
<th>Mission</th>
<th>ID Date</th>
<th>MJD</th>
<th>Phase (d)</th>
<th>TSMF (d)</th>
<th>Centroid freq. (mHz)</th>
<th>X-ray state</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>1983 October 22</td>
<td>45629.11–45629.18</td>
<td>0.41–0.75</td>
<td>11.5</td>
<td>2.6</td>
<td>High</td>
</tr>
<tr>
<td>E</td>
<td>1983 November 5</td>
<td>45643.01–45643.15</td>
<td>0.14–0.54</td>
<td>25.5</td>
<td>2/15</td>
<td>High</td>
</tr>
<tr>
<td>E</td>
<td>1983 December 18</td>
<td>45686.14–45686.22</td>
<td>0.13–0.37</td>
<td>68.6</td>
<td>1.7</td>
<td>High</td>
</tr>
<tr>
<td>E</td>
<td>1984 January 3</td>
<td>45702.55–45702.73</td>
<td>0.18–0.64</td>
<td>84.9</td>
<td>0.7/3.4</td>
<td>High</td>
</tr>
<tr>
<td>E</td>
<td>1984 May 21</td>
<td>45841.64–45841.92</td>
<td>0.00–0.13</td>
<td>1</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>1986 March 18</td>
<td>46507.1</td>
<td>–</td>
<td>–</td>
<td>8</td>
<td>–</td>
</tr>
</tbody>
</table>

a E, EXOSAT (1–10 keV); B, balloon flight (20–100 keV).

b Time Since Major Flare. ‘−’ corresponds to not known.

Table 2. Log of QPOs identified from Cyg X–3 in this study.

<table>
<thead>
<tr>
<th>ObsID</th>
<th>Date</th>
<th>MJD</th>
<th>Phase</th>
<th>TSMF (d)</th>
<th>X-ray state</th>
<th>Obs. length (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50062</td>
<td>2000 April 3</td>
<td>51637.53–51637.62</td>
<td>0.33–0.78</td>
<td>2.16</td>
<td>FSXR</td>
<td>4526.6</td>
</tr>
<tr>
<td>94328</td>
<td>2009 August 9</td>
<td>55052.82–55052.84</td>
<td>0.22–0.34</td>
<td>17.0</td>
<td>FHXR</td>
<td>1974.0</td>
</tr>
</tbody>
</table>

No. PDS on ave. | Model $\beta$ | Model $\chi^2$/d.o.f. | Centroid freq. (mHz) | Significance |
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</tr>
</thead>
<tbody>
<tr>
<td>50062</td>
<td>3</td>
<td>–2.0</td>
<td>41.7/27</td>
<td>8.5/30</td>
</tr>
<tr>
<td>94328</td>
<td>2</td>
<td>–1.8</td>
<td>22.5/27</td>
<td>9/21/31</td>
</tr>
</tbody>
</table>

a Time since major flare.

b Classification of K10 where FSXR/FHXR refer to the ‘high’ state in the canonical nomenclature.
3.2.2 2009 August 9

This pointing occurred 17 d after a major flare event (∼1.5 Jy in the 15 GHz band). During this pointing the 15 GHz radio flux density is ∼ 50 mJy and the source is in the FHXR state. There is a strong 21 mHz (∼50 s) QPO lasting about 20 cycles corresponding to a 2 per cent rms in the PDS. In the PDS there are also two peaks with lower significances that correspond to the frequencies of 9 and 31 mHz.

4 DISCUSSION

An in-depth analysis is beyond the scope of this Letter. Here we speculate briefly on the origin of the QPOs found in this study.

(i) QPOs and the geometry of the system. If we assume that the QPOs are X-ray emitting blobs or regions in orbit around the compact object, the possible time-scales are determined by the innermost stable circular orbit (ISCO, highest frequency) and the Roche Lobe radius or the bow shock that is formed as the compact object ploughs the stellar wind of density $\rho$. During this pointing the 15 GHz radio flux density is ∼ 50 mJy and the source is in the FHXR state. There is a strong 21 mHz (∼50 s) QPO lasting about 20 cycles corresponding to a 2 per cent rms in the PDS. In the PDS there are also two peaks with lower significances that correspond to the frequencies of 9 and 31 mHz.

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(ii) QPOs as disc oscillations? In the literature there are several methods to investigate how low-frequency QPOs can be invoked in an accretion disc, e.g. low-frequency ‘dynamo cycles’ in the azimuthal magnetic field (O’Neill et al. 2011) or accretion–ejection instability (Varni`ere & Tagger 2002) to name a few. However, the geometry of the system might present a challenge to disc-based phenomena. If the accretion disc is perpendicular to the jet and if the jet is inclined ∼14° to the line of sight (Mioduszewski et al. 2001), then we should be viewing the disc face-on. The problem then arises as to how the actual modulation can be seen at all. A further interesting question is, how would the simultaneous frequencies observed in the 2000 April 3 pointing arise in the disc, especially when they seem to be producing a clear pattern? Are they causally linked and/or produced by the same underlying mechanism? Interestingly, the 2009 August 9 pointing indicates that the peaks in the PDS form a 3:2:1 frequency relation, the same relation as has been reported on Sgr A* (Aschenbach et al. 2004).

(iii) QPOs as coronal oscillations? As the QPOs appear to be present in energy bands of 2–15 keV and as they appear to arise in flaring radio/X-ray states that can be modelled solely with a Comptonization component (K10), this could imply that the actual component causing the Comptonization of soft photons is oscillating. An oscillating corona due to a magneto-acoustic wave propagating within the corona producing multiple QPOs has been theoretically discussed in Cabanac et al. (2010).

(iv) QPOs as oscillations due to the jet? As the QPOs appear to occur after major radio flares, the latter most likely signalling a jet ejection event, the two are probably linked. This connection could be two-fold: either the jet is shadowing, therefore modulating, an underlying oscillation/emission from the disc or corona, or the QPOs are caused by some structure in the jet (emitting X-rays, e.g. a shock). The latter scenario is discussed for blazars in Rani et al. (2010); it could occur in a turbulent region behind a shock where dominant eddies with turnover times corresponding to the QPO periods could explain the short-lived, quasi-periodic fluctuation. It is also possible that the jet possesses a helical structure, and a relativistic shock propagating down the jet encounters regions of enhanced magnetic field and/or electron density intensifying the emission and causing fluctuations.

(v) QPOs as oscillations due to the wind? Similarly to the jet case, clumps in the Wolf–Rayet companion’s stellar wind could cause a shadowing effect on an underlying oscillation/emission. The pointings that exhibit QPOs are often accompanied by sudden drops in intensity (van der Klis & Jansen 1985; their 1983 November 5 observation). A quite similar 15 per cent drop in the light curve can be seen in Fig. 2(a). The light-crossing time in this drop is about 16 s and implies an upper limit on the size of the emission region radius of $< 2.4 \times 10^{14}$ cm. This value is remarkably close to the separation between the components $a \approx 3 \times 10^{14} (M/30 M_\odot)^{1/3}$ cm, and thus could be produced by a light-blocking clump. A clumpy wind was established in Szostek & Zdziarski (2008).

5 SUMMARY

In this Letter, we reported on the detection of QPOs in Cygnus X–3. In this initial study, we found two occasions in the RXTE data where QPOs were present, and these followed major radio flares. We speculated on various scenarios that may explain the QPOs, but a more in-depth study is necessary to single out a favoured one.

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