EXOSAT observations of Z sources
Kuulkers, E.

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Detection of 26 Hz QPO in the Flaring Branch of Cygnus X–2

E. Kuulkers & M. van der Klis


Abstract

We report the detection of 26 Hz quasi-periodic oscillations during an 800s intensity dip in the low-mass X-ray binary Cyg X–2 in the flaring branch state. The quasi-periodic oscillations have properties that are different from those of flaring branch quasi-periodic oscillations seen in other Z sources, which are often ascribed to oscillations in a radial inflow of matter. The fact that the 26 Hz quasi-periodic oscillations occur during a dip suggests that they arise in a medium that partially obscures the X-ray emission. We interpret the new quasi-periodic oscillations phenomenon in terms of a model involving a radial flow and a thick, torus-like inner disk.

5.1 Introduction

The six brightest low mass X-ray binaries trace out Z-shaped patterns in X-ray colour-colour diagrams (CDs) and hardness-intensity diagrams (HIDs) as a function of accretion rate $\dot{M}$ (Hasinger & van der Klis 1989). The three limbs of the Z define three source states. At the lowest $\dot{M}$, in the upper limb of the Z, called the “horizontal” branch (HB), quasi-periodic oscillations (QPO) occur with central frequencies of 15–55 Hz which are ascribed to interaction between a magnetosphere and matter in the inner disk (Alpar & Shaham 1985, Lamb 1989, Gosh & Lamb 1992). At higher $\dot{M}$, in the middle limb, the “normal” branch (NB), another type of QPO appear that have a stable frequency of $\sim$6 Hz. As $\dot{M}$ increases further, a Z source enters the lower limb of the Z, the “flaring” branch (FB). In this branch, but so far only in the sources Sco X–1 (see Dieters & van der Klis 1995, and references therein) and GX 17+2 (Penninx et al. 1990) QPO are seen as well. The frequency of these QPO increases along the FB from $\sim$6 Hz up to $\sim$20 Hz.

Since the NB QPO (NBO) merge smoothly with the FB QPO (FBO), these two types of QPO are thought to have a common origin. NBO and HB QPO (HBO), on the other hand, have been found to occur simultaneously (GX 5–1: e.g. Lewin et al. 1992; Cyg X–2: e.g. Hasinger et al. 1990), so there is no doubt that different mechanisms underlie these two types of QPO.
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Models for N/FBO make use of the fact that Z sources are accreting at near-Eddington rates (Fortner et al. 1989, Alpar et al. 1992).

In some Z sources, notably Sco X-1, GX 17+2 and GX 349+2, the motion of the source “up” the FB (away from the NB) corresponds to strong X-ray flares. In other Z sources, in particular Cyg X-2 and GX 340+0, motion up the FB can correspond to X-ray dips. In the HID, this translates into very different FB shapes in these various sources: FBs sticking out up and to the right in Sco X-1, GX 17+2 and GX 349+2 (see Schulz et al. 1989, Hasinger & van der Klis 1989), one that “turns around” halfway in GX 340+0 (Penninx et al. 1991), one that usually points to the left in Cyg X-2 (see Kuulkers et al. 1995c [Chapter 4] and references therein). In GX 5–1 the FB is a small limb with different orientations (Kuulkers et al. 1994a, Chapter 3).

Although Cyg X-2 has a well-pronounced FB (Schulz et al. 1989, Hasinger & van der Klis 1989, Hasinger et al. 1990, Kuulkers et al. 1995c [Chapter 4]), to date no QPO had been found in that branch. We report the discovery of QPO in a small part of the FB from data obtained with EXOSAT. The circumstances under which the QPO appear provide a strong hint as to their origin, and as to the causes of the different FB shapes in the HID in different Z sources.

5.2 Observations and results

Cyg X–2 was detected to be in the FB during part of a 12-hr observation on 1985 day 318/319 (see Kuulkers et al. 1995c [Chapter 4] and references therein) with the EXOSAT ME instrument (Turner et al. 1981, White & Peacock 1988). The data were obtained in the HER2 (full spectral resolution over 1–20 keV, 1 s time resolution), HER7 (4 spectral channels over 1–20 keV, ~4 ms time resolution) and HTR5 (one channel covering 5–35 keV, ~4 ms time resolution) modes.

In Figs. 5.1a and b we show the CD and the HID, based on the HER2 data. The diagrams
5.2 Observations and results

Figure 5.2. EXOSAT light curve showing the dip in the light curve in the four HER7-mode bands at a 10 s time resolution. The intensities are the count rates in the 0.9–3.1 keV, 3.1–4.7 keV, 4.7–6.3 keV and 6.3–19.7 keV bands (a–d), corrected for background, dead time and collimator response. We used the new collimator responses as determined by Kuulkers et al. (1994a, see Chapter 1). The start of the light curves corresponds to 1985 day 318 (Nov 15) 04 h 38 m (UT).

...clearly show the presence of a NB and a FB (see also Kuulkers et al. 1995c [Chapter 4], and references therein). In Fig. 5.2 we show a section of the corresponding light curves in the four HER7 bands. A clear dip can be seen with a duration of ~800 s. The data during the dip correspond to the upper FB (see Fig. 1a and b, open circles). The dip is deepest at the lower energies, which corresponds to spectral hardening when Cyg X–2 enters the dip. The colours suddenly increase, as the intensity drops. This corresponds to jumps from the middle FB to the upper FB in the CD and HID (Fig. 1a,b); the open circles in Fig. 1a and b are therefore disconnected in both the CD and HID. It is clear that the intensity does not “flare”, but “dips”...
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in the upper part of the FB. After the dip, Cyg X–2 undergoes a rapid transition, within 7 min, out of the dip, through the middle and lower FB, into the NB.

In order to investigate the fast timing behaviour we performed 16 s FFTs of the data for the four HER7 channels summed. The power spectra show very-low-frequency noise (VLFN) and QPO, which we modeled with a power law and a Lorentzian peak, respectively. The HER7 data suffer strong dead time effects. We therefore used the Poisson level as a free parameter in the power spectral fits, which gives a good estimate of the true Poisson level (see Kuulkers et al. 1994a [Chapter 3], 1995b [Chapter 4]).

When the source is in the NB, clear NBO near 6 Hz are present with a fractional rms amplitude of ~2.7% and a FWHM of ~2 Hz. The NBO vanish when the source approaches the FB. Broad NBO is still visible in the lower FB (2.7±0.5%, FWHM 6±1 Hz and centroid frequency of 6.9±0.6 Hz). No significant QPO (<1% rms up to ~40 Hz for 90% confidence) are found in the power spectra when the source is in the middle FB. However, when the source enters the dip shown in Fig. 5.2, a ~3 sigma\(^1\) QPO peak near ~26 Hz suddenly appears. The power spectrum of the data in the dip is shown in Fig. 5.3. The QPO has an integral Leahy-normalized power of 1.0±0.3 corresponding to a fractional rms amplitude of 3.9±0.5%, a FWHM of 5±3 Hz and a central frequency of 26.1±1.0 Hz; the fit had a \(\chi^2/\text{dof}\) of 57.6/46.

We found no significant difference in QPO parameters between subsegments of the dip; the uncertainties are large. We also performed 16 s FFTs for the HTR5 and for each HER7 channel separately in order to investigate the energy dependence of the QPO. For the HTR5-mode data the Poisson levels could be determined from known dead-time relations (see Berger & van der Klis 1994, and references therein). In the power spectral analysis of these data the QPO peak was fixed at 26 Hz with a FWHM of 5 Hz. The results are given in Table 5.1. There is some indication that the QPO are soft (larger fractional amplitude at lower photon energies than at higher energies; Table 5.1); we can exclude that it is as hard as the FBO seen in Sco X–1 and GX 17+2, and the dependence of the QPO amplitude on photon energy is consistent with being the same as that of the dip depth. We attempted to measure QPO phase lags between the various energy channels (see e.g. van der Klis et al. 1987c), but no meaningful limits could be set.

\(^1\)The significance was estimated from an F-test for the inclusion of the QPO-peak, and from the 90% confidence error-scan of the integral power in the \(\chi^2\)-space (\(\Delta\chi^2=1\)).
Table 5.1: 26 Hz QPO energy dependence

<table>
<thead>
<tr>
<th>energy (keV)</th>
<th>rms (%)</th>
<th>error$^d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9–19.7</td>
<td>3.9</td>
<td>0.5</td>
</tr>
<tr>
<td>0.9–3.1$^b$</td>
<td>4.8</td>
<td>1.0</td>
</tr>
<tr>
<td>3.1–4.7$^b$</td>
<td>2.7</td>
<td>2.9</td>
</tr>
<tr>
<td>4.7–6.4$^b$</td>
<td>1.6</td>
<td>4.2</td>
</tr>
<tr>
<td>6.4–19.7$^b$</td>
<td>−8.7$^c$</td>
<td>2.3</td>
</tr>
<tr>
<td>5–35$^d$</td>
<td>0.2</td>
<td>0.1</td>
</tr>
</tbody>
</table>

$^a$ Errors are determined from an error scan through the $\chi^2$ space using $\Delta\chi^2 = 1$.

$^b$ QPO frequency and FWHM fixed (see text).

$^c$ Negative rms arises from uncertainty in the Poisson level.

$^d$ Xenon energy range (Turner et al. 1981).

5.3 Discussion

We have for the first time observed QPO in the flaring branch (FB) of Cyg X–2. When the source enters the uppermost part of the FB, a QPO peak appears with a central frequency of about 26 Hz. This part of the FB corresponds to a dip in the light curve.

Although these QPO are observed in the FB, they exhibit a number of clear differences with FBO such as observed in Sco X–1 and GX 17+2. In those two sources, there is a continuous transition between NBO and FBO, the QPO frequency steeply rising near the NB/FB transition, but never disappearing. In our data clear NBO near 6 Hz are seen in the NB (which becomes broadened in the lower FB), but no QPO in the middle FB. Only in the upper FB do QPO appear once again. In Sco X–1 and GX 17+2 the QPO appear in the lower ~10% of the FB (see Dieters & van der Klis 1995, Penninx et al. 1990), in Cyg X–2 in the upper ~20% of the FB. The QPO frequency we see in Cyg X–2 is 26 Hz, the highest ever seen in the FB in any Z source, with a FWHM of only 5±3 Hz; in Sco X–1 and GX 17+2 FBO can be traced up to frequencies of ~20 Hz as the source moves up the FB, but at that point the peak has usually already become quite broad (~10 Hz, see e.g. Dieters & van der Klis 1995), and further up the FB it merges into the background noise components (Middleditch & Priedhorsky 1986). FBO, where seen, have a hard spectrum, whereas the QPO we see seem to have a soft spectrum. We note that Hasinger et al. (1990) reported some excess power between 5 and 20 Hz during a dip in the FB, which they interpreted as possible FB QPO. This excess may be due to the broad NBO in the lower FB (such as present in our dataset), which “contaminates” the power spectra at these frequencies.

In view of the differences in the properties of the FB, we suggest that the 26 Hz QPO we see in the FB, may be caused by a different mechanism than the usual N/FBO. Significantly, the QPO only appear when Cyg X–2 enters into an intensity dip, and immediately disappear when the source emerges from the dip. This suggests that during the dip the emission is diminished by the introduction into the line of sight to the source of an absorbing or scattering medium, that at the same time attenuates the observed flux and causes the QPO by oscillating near 26 Hz. This interpretation is strengthened by the fact that the energy spectra of the QPO and dip are consistent with being the same.

According to the model for N/FBO of Fortner et al. (1989), NBO arise due to a feed-back
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loop between the radiation force and the accretion rate in an approximately radial inflow fed by matter that was initially in the accretion disk, but has lost its angular momentum due to photon drag. In this model, FBO are assumed to also originate in oscillations in this radial flow, at super-Eddington accretion rates. (One possible explanation for the increase in QPO frequency up the FB is that when \( L_x \gtrsim L_{\text{Edd}} \), the flow is no longer stable against matter/radiation separation, and the infall velocity and therefore also the QPO frequency in the matter-dominated parts of the flow increase. In this regime the coherency parameter Q of the oscillations diminishes rapidly due to the inhomogeneity of the flow.)

Independently of this idea of a radial flow, it has been pointed out by various authors that near to the Eddington limit the inner, radiation-pressure dominated part of the disk might puff up to a torus-like shape which for certain inclinations could partially obscure the X-ray emitting regions, and that oscillations in such a torus could provide an alternative explanation for N/FBO (e.g. van der Klis et al. 1987b, Alpar et al. 1992). An argument against this is that this would work only for a rather restricted range of geometrical configurations where the observer, the edge (or semi-transparent part) of the torus and the emitting region are on one line (Lamb 1989).

We submit that the Fortner et al. (1989) radial-flow model explains the usual N/FBO, but that oscillations in a thick, torus-like inner disk that partially obscures the emitting region explains the 26 Hz QPO that we have found in the upper FB of Cyg X–2. This type of QPO would be expected to be relatively rare and usually not very persistent because of the required line-up of observer, torus and emitting region; this is in accordance with our observation of only one such a QPO peak during 800 s in all EXOSAT Cyg X–2 observations (a total of \( 4 \times 10^{5} \) s). The fact that the intensity shows a dip when the QPO appear is in accordance with the torus entering into the line of sight to the source. The QPO frequency of 26 Hz corresponds to the Kepler frequency at a distance of \( \sim 190 \) km from the neutron star, consistent with the position of the outer regions of the radiation pressure dominated region (see Frank et al. 1992) and of the radial flow region (see Lamb 1989).

Combining the Fortner et al. (1989) radial-flow model with a torus-like shape for the inner disk when the source becomes near-Eddington can also explain the differences in the shape of the FB in the HID between different Z sources and the correlated differences that are observed in N/FBO properties (see Kuulkers et al. 1994a, Chapter 3). All these may be due to differences in binary inclination (Fig. 5.4, see Kuulkers et al. 1994a [Chapter 3] and references therein).

We suggest that the sequence of events that is observed to take place when the source approaches the Eddington limit is mostly due to two gradual processes: a gradual increase in the geometrical thickness of the inner disk torus, and a gradual increase in the fraction of the total accretion flow carried by the radial flow (Fortner et al. 1989). Due to the presence of the torus-like inner disk, the region in which the radial flow takes place is not spherical, but cone-like in shape. The opening angle of the cone decreases when \( \dot{M} \) increases.

What the observer sees depends on binary inclination \( i \). At low \( i \), the torus never comes near to the line of sight, so that a FB results on which the X-ray intensity \( I_x \) always increases and the N/FBO are seen all the way between 6 and 20 Hz (Sco X–1, GX 17+2). At somewhat higher \( i \), the FB starts out in the direction of increasing \( I_x \), but then the torus enters into the line of sight and the FB turns around to lower \( I_x \) (GX 340+0). At even higher \( i \) (Cyg X–2), the FB would be directed towards lower \( I_x \) right away. It seems likely that when the surface of the torus is near to the line of sight no strong N/FBO will be seen, as in this region the flow will

\( ^2 \)Although the number of power spectra we have analysed during studies of EXOSAT-data is large (i.e. a large number of trials, which may indicate the QPO being pure coincidence), we note that only two such dips in the FB have been observed with EXOSAT, and so are rare phenomena (1983 day 258 and 1985 day 318/319; the ME-data of the 1983 day 258 data could, however not be used due to problems in the Analog to Digital Converter (ADC) onboard EXOSAT[see Chiapetti et al. 1990]).
Figure 5.4. A simple representation of the shape of the disk during the HB, NB and FB. As a Z-source moves from the HB, through the NB, to the FB, the inner disk starts to puff up, influencing the extent of the radial flow. In the upper panel (HB) we schematically indicate the probable inclinations of the Z-sources as inferred from various observations (see text). In the middle panel (NB) we show how the strength of the NBO can be affected by the viewing geometry of the radial inflow (see text). In the lower panel (FB) clear flaring branch QPO (which originate from the NBO) are seen in the low inclination sources (in these sources the intensity flares: "flaring" FB, or "FFB"), whereas this QPO is hidden from our view in the high inclination sources. In exceptional cases one may see a QPO when the inner torus intercepts our line of sight to the inner disk region, and therefore causes dips in intensity ("dipping FB", or "DFB").
not be radial but mostly perpendicular to the torus' surface. This is the region where the radial flow is fed (see Fig. 5.4). Indeed, no FBO have been seen in GX 340+0 and Cyg X-2. The most extreme case might be GX 5–1, where the NB is relatively short, the FB peculiar (Kuulkers et al. 1994a, Chapter 3), and where the 6 Hz NBO are weak. In this source i may be so high, that the torus already comes into the line of sight when the source is still on the NB.

This scenario leads to a number of predictions. Examples of QPO such as the 26 Hz QPO that we have reported here should occur when the torus comes into the line of sight, so when the FB turns to lower $I_x$. No steady progression of N/FBO peaks should be observed through such a bend-back of the FB to lower $I_x$. Rather the N/FBO should become weak and then disappear.

Binary inclinations of Z sources should rank from Sco X–1, GX 17+2, GX 349+2 (lowest) via GX 340+0 and Cyg X–2 to GX 5–1 (highest). In the case of a precessing disk the point where the N/FB bends back to lower $I_x$ might depend on phase in the precession cycle.