Black Hole X-ray Binaries
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Two-dimensional behaviour and high-frequency QPOs in the 1998 outburst of 4U 1630–47

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6.1 Introduction

Transient black hole X-ray binaries in outburst pass through a number of states, typically starting from a Low State (LS) during the early rise and proceeding to a Very High State (VHS), High State (HS), Intermediate State (IMS) and ultimately reaching the LS again at the end of the outburst. These states are characterized by their energy spectral and timing properties (for a recent review see for instance van der Klis 2004). An alternative definition for the black hole states, predominantly based on the energy spectral behaviour, is proposed by McClintock & Remillard (2004). They define most of the VHS as Steep Power Law (SPL) state, the LS as Hard State and the HS as Thermal-dominant (TD) state and propose an alternative definition for the intermediate state which they regard as a mix of the Hard State and the SPL state. At this moment no consensus has been reached regarding the definition of the canonical states, nor is it clear what the physical origin of these states are. In this paper we use the "old" canonical states and use the definitions as given by Homan et al. (2001).

State changes were originally hypothesized to originate mostly from changes in one parameter only: the mass accretion rate (eg. Tanaka & Lewin 1995; van der Klis 1995a; Esin et al. 1997, 1998). Recently, Homan et al. (2001), based on the spectral and temporal analysis of the 1999 outburst of XTE J1550–564, put forward a two-dimensional description of the black hole outburst behaviour. In their picture the position in the color-color diagram (CD) and the hardness-intensity diagram (HID) and the corresponding timing behaviour is determined by two parameters, which can to some extent vary independently from each
other. They suggest that high state – low state transitions occur at different mass accretion rates through the disk, one of their independent parameters, while the transitions itself are associated with another parameter (which could for instance be the size of the comptonizing region). As discussed by Homan et al. (2001) similar suggestions had been made on earlier occasions based on the two component decomposition of black hole X-ray spectra and on the differences in X-ray spectral and timing outburst behaviour between sources (Miyamoto et al. 1994; Nowak 1995; Rutledge et al. 1999). However, Homan et al. (2001) were the first to demonstrate the detailed and reproducible dependence of the timing properties on the position of the source in those two-dimensional diagrams.

The spectral and timing characteristics that establish the states and the transitions between them, are determined by the state of the accretion flow, which is suspected to be composed of a spectrally soft, geometrically thin accretion disk and a spectrally hard, geometrically thick corona-like object. While the spectral characteristics depend on parameters such as temperature and optical depth, the timing properties are nearly certainly determined by the short term motions (orbital, oscillatory, chaotic) of inhomogeneities in the accretion flow. Timing features manifest themselves in the power spectrum as broad or noise like features, referred to as Band Limited Noise (BLN), or as sharper more peaked features which are referred to as Quasi Period Oscillations (QPOs) (eg. van der Klis 2000). Several models have been proposed to explain the presence of both types of features (for a recent review see van der Klis 2004). But in the simplest picture a blob of material in a Keplerian orbit in the accretion disk causes the QPO (Bao & Ostgaard 1995, and references therein), while for instance “shot-noise” can produce both QPO and BLN features (eg. van der Klis 2000, and references therein). However, the spectrally hard component of the flow must be important as well. First of all the overall rms amplitude is correlated with the relative strength of the hard component, and secondly, most sources show a correlated behaviour between the spectral hardness and the frequency of the QPOs (eg. Sobczak et al. 2000; Remillard et al. 2002d).

The similarities between black holes and low magnetic field neutron stars in X-ray binaries from an observational point of view with respect to the energy spectra and, in particular, the power spectra were already pointed out by Hasinger & van der Klis (1989); Schulz et al. (1989); van der Klis (1994a,b). In the power spectra of black holes and neutron stars similar noise components and QPOs are detected, and similar correlations between these features are found to hold for all types of sources (including perhaps the white dwarf systems) over a large range in frequencies (Wijnands & van der Klis 1999; Psaltis et al. 1999; Belloni et al. 2002; Mauche 2002). This strongly suggests that most of the temporal characteristics arise in the accretion flows, largely independently of the presence or absence of a surface, boundary layer or (non-aligned) magnetic field. Recently, new attempts have been made to understand the X-ray spectral differences between the black holes and neutron stars. Done & Gierliński (2003) suggest that, based on the presence of a surface (and hence, a boundary
layer), neutron star outbursts show a different spectral evolution compared to those of black holes. They suggest that in some cases it is possible from the position in a color-color diagram (CD) to predict the nature of the compact object in the system. Sunyaev & Revnivtsev (2000) suggest that black holes and neutron stars can be identified based on the amount of power in the power spectra: sources that show significant power above ~ 500 Hz, should be considered neutron stars. In their view the difference is the result of the presence of a boundary layer, or a layer of spreading material on the surface of the neutron star, where most of the accretion energy is released. The absence of such layers in the case of the black holes results in the decline of the power spectra at frequencies above 10–50 Hz (Sunyaev & Revnivtsev 2000).

Neutron star sources are known to show sharp, strong QPOs at kHz frequencies (van der Klis 2000, for a review). In black holes the highest frequencies are detected around a few 100 Hz. The first features were detected in GRS 1915+105 (Morgan et al. 1997; Belloni et al. 2001; Remillard et al. 2002a; Strohmayer 2001b) and later similar ones were also found in for instance GRO J1655-40 (Remillard et al. 1999a; Strohmayer 2001a), XTE J1550-564 (Miller et al. 2001b; Homan et al. 2001; Remillard et al. 2002d) and XTE J1650-500 (Homan et al. 2003a). In some of these source two high-frequency features are present which seem to have a 2:3 ratio in frequency.

In this paper we present a study of the low and high-frequency QPOs that were detected during the 1998 outburst of the black hole X-ray transient 4U 1630–47. Our main goal is to relate their appearance and properties to the position and motion of the source through the HID. 4U 1630–47 was discovered with *Uhuru* (Jones et al. 1976) but already in 1969 *Vela* 5B had recorded the first X-ray outburst (Crudace et al. 1972). A infra-red counter part has been detected (Augusteijn et al. 2001), but no optical counterpart, and there is no mass estimate for the compact object. Based on the X-ray spectral and timing characteristics 4U 1630–47 has been classified as a black hole X-ray binary (White et al. 1984; Parmar et al. 1986; Kuulkers et al. 1997b). The first detection of the radio counterpart was during the 1998 outburst (Hjellming et al. 1999) and like other black hole X-ray binaries (eg. Fender et al. 2001), the 4U 1630–47 outbursts are accompanied by radio emission, most likely produced in a jet. Radio emission is a generic property of black holes in the hard spectral states (Fender 2001), however, some low magnetic field neutron stars show radio emission as well (eg. Hjellming & Han 1995). The detection of sporadic X-ray absorption dips has been interpreted in terms of an inclination angle of ~ 60–75° (Kuulkers et al. 1998). 4U 1630–47 is known for its somewhat regular outburst cycle: ~ 600–690 days (Jones et al. 1976; Friedhorsky 1986; Kuulkers et al. 1997a). However, more recent outbursts do not follow this cycle and at the of writing the source is in an extraordinary long outburst that started in September 2002 (Wijnands et al. 2002).

In previous reports (Hjellming et al. 1999; Dieters et al. 2000; Tomsick & Kaaret 2000; Trudolyubov et al. 2001) the radio, X-ray spectral and timing char-
acteristics of parts of the 1998 outburst have been discussed. In this paper we present a detailed analysis of the complete 1998 outburst of the black hole candidate 4U 1630-47. We discuss the behaviour in the HID and CD regarding the state transitions and show that the general behaviour is very similar to the two-dimensional behaviour seen by Homan et al. (2001) in XTE J1550-564. At frequencies below ~ 20 Hz several QPO features occur in the power spectra while in the range of ~ 20–200 Hz high-frequency features are detected during the rise and the early decay of the outburst. Furthermore, twin high-frequency features are detected on several occasions that have a ratio in frequency of 1:4. In this paper we will investigate the relation between the frequency of the features in the power spectra with the spectral hardness and count rate for 4U 1630–47. We focus on the two-dimensional behaviour and the corresponding power spectral changes and compare this with other black hole sources such as XTE J1550–564.

6.2 Data analysis

We analysed all Proportional Counter Array (PCA Zhang et al. 1993; Jahoda et al. 1996) Rossi X-ray timing Explorer (RXTE Bradt et al. 1993) observations of 4U 1630–47 made between February 11 1998 and June 8 1998; the data are from proposals 30172, 30178 and 30188, and the list of observation numbers is given in Table 6.1. Each observation, identified by its unique RXTE observation ID, consists of one or more intervals which are separated by Earth occultations and/or South Atlantic Anomaly (SAA) passages. Generally, for each observation we have about 2000 seconds of on-source data, and for a total of 101 observations we have ~ 200 ksec of data. For the timing study we used high time resolution data modes for all the available PCAs and performed time binning to obtain a uniform time resolution of 122 µs. Power spectra were created of data segments of 128s using the standard Fast Fourier Transform techniques (van der Klis (1988) and references therein). Detector drop-outs were removed but no background or deadtime corrections were performed prior to the production of the power spectra. The power spectra of each observation were averaged. We paid special attention to the possibility of detecting high-frequency features, similar to the ones found in for instance XTE J1550–564 (Miller et al. 2001b; Homan et al. 2001; Remillard et al. 2002d). In Appendix 6.8 we discuss the method we used to estimate the Poisson spectrum as accurately as possible. After considerable experimentation (App. 6.8) we produced the power spectra in channels 18–254 (7–104 keV, RXTE gain epoch 3; hereafter all energy ranges given correspond to gain epoch 3) for data from proposals 30178 and 30188, and channels 14–254 (5.5–104 keV) for proposal 30172. These ranges were chosen to eliminate an instrumental feature from the power spectra. We estimate the Poisson level using the model of Zhang (Zhang et al. 1995; Zhang 1995) with an additional small shift to fit the data at the highest frequencies.

The power spectra for each observation were fitted with a multi-Lorentzian model (e.g. Miyamoto et al. 1991; Olive et al. 1998; Nowak 2000) using the ap-
Table 6.1 — The observations covering the 1998 outburst of 4U 1630–47. We defined the following regions: A: observations 1–11; B: observations 12–26, 33, 47; C: observations 27–32, 34–36; D: observations 37–47, 48, 49; E: observations 50–90; F: observations 91–101.

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proach of Belloni et al. (2002) to assign characteristic frequencies to each component. In that approach the characteristic frequency, $\nu_{\text{max}}$, of a Lorentzian component is given by:

$$\nu_{\text{max}} = \sqrt{\Delta^2 + \nu_0^2}$$

(6.1)

with $\Delta$ the Half Width at Half Maximum (=HWHM) and $\nu_0$ the centroid frequency of the Lorentzian peak. The frequency trends reported in Section 6.4, are not affected by the frequency representation: in $\nu_0$ similar trends are observed. The peak width is parameterised by the quality factor $Q \equiv \nu_0/2\Delta$. At $\nu_{\text{max}}$ the Lorentzian attains its maximum in a frequency times power, $\nu P_\nu$, representation. Here we will use that representation with $P_\nu$, the rms normalised power, given by:

$$P_\nu = \left(\frac{B + S}{S^2}\right) \times P_0$$

(6.2)

with $S$ and $B$ the source and background count rates respectively and $P_0$ the Leahy power (see also van der Klis 1988).

We compared our fits with fits of the more "classical" model consisting of a broken power law and Lorentzians. Both models described the power spectra equally well (no significant differences in $\chi^2$ for a similar number of free parameters); for convenient comparison with recent studies we use the model consisting of only Lorentzians.

We only kept those Lorentzian components in the fits whose significance based on the error in the integrated power (from 0–$\infty$) is more than 3$\sigma$ or whose inclusion gave a significant (> 3$\sigma$) improvement of the $\chi^2$ of the fit. This is what henceforward we refer to as a significant feature. We find that for the observations in our data set, one to eight Lorentzians are necessary for an acceptable fit (reduced $\chi^2 < 2$). Most of the observations can be fitted using 2–3 zero centred (or broad, Q< 1) Lorentzians, together with 1–4 narrow (Q> 1) Lorentzians in the range 4–15 Hz to fit the QPOs. During the fitting occasionally the centroid frequency ($\nu_0$) of one or more Lorentzian components became negative (Q< 0). For numerical stability, these components were fixed at zero centroid frequency (Q=0) which did not significantly affect the $\chi^2$.

For the production of the light curves, color curves, HID s and CD s we used the Standard 2 data. Because proportional counter units (PCUs) 0, 1 and 2 were the only ones that were active during all the observations, we only used data from these PCUs. All the data were background subtracted but no deadtime corrections were made as the effect of deadtime can be neglected for our purposes (when using colors as defined below, deadtime effects are "divided out"). Also no Crab correction was made as we assume the gain changes to have a negligible effect and we always used the same PCUs. We define the soft color (SC) as the ratio of the count rates in PCA channel bands 13–39 (6.2–15.5 keV) and 4–13 (3.0–6.2 keV), while the hard color (HC) is defined as the ratio of the count rates in PCA channel bands 39–49 (15.5–19.2 keV) and 4–13 (3.0–6.2 keV). As a result of this definition of the colors, any linear combination of two spectral
6.3 The outburst behaviour

6.3.1 The CD and HID

In Figs. 6.1a, b and c we present the complete PCA light curve of the 1998 outburst of 4U 1630−47 in three different energy bands. In all the energy bands the source shows some resemblance with the Fast Rise Exponential Decay (FRED) light curve, found in many black hole transients. The outburst star-
ted at MJD 50853 and during the first ~ 10 days the intensity in all the energy bands increased rapidly while both the SC and HC decreased (Figs. 6.1e, f). The 1/128-1000 Hz rms amplitude (Fig. 6.1d) decreased rapidly by about a factor 3 during the first ~ 2 days, after which it remained constant at ~ 12% until day 10. Around day 10 the maximum of the outburst was reached as the count rate increased by about a factor 2, while at the same time the rms dropped to a level of ~ 5%. At day 16, marking the start of the decay, the count rate dropped again in all the energy bands, after which it decayed by a factor of ~ 10 in about 100 days. The luminosity decays exponentially with a characteristic time scale $\tau$ ($\propto e^{-t/\tau}$) of about 17 days. The decay was only interrupted by a secondary outburst that occurred around day 85 and which is particularly clear in the softer energy bands. At the end of the outburst, around day 100 a clear state change occurred as both the SC and HC and the rms amplitude increased again back to their original level (and even higher). The outburst behaviour is very similar to that of GS 1124-68 during its 1991 outburst (Ebisawa et al. 1994). In that case also a FRED type light curve is found, with a characteristic time scale for the exponential decay of ~ 30 days, slightly longer than 4U 1630-47, and a secondary outburst that occurred ~ 80 days after the start of the outburst. XTE J1550-564 also shows a FRED type light curve during the first part of its 1998-1999 outburst, and one might argue that the second part of the outburst in that case is actually the secondary outburst (Sobczak et al. 1999; Homan et al. 2001).

The HID and the CD of the outburst are shown in Figs. 6.2a and b. We use different symbols for six different regions (A–F) to be introduced in Section 6.3.2. During the rise of the outburst to its maximum (regions A to C) the source moves to the upper left part of the HID (Fig. 6.2a) as the count rate increases and the HC decreases. As the decay sets in the count rate drops gradually while the HC shows only small variations. At the end of the outburst, as the HC increases again and the count rate continues to drop, the source moves to the lower right part of the HID. In the CD (Fig. 6.2b) 4U 1630-47 moves mostly parallel to the power law and the disk blackbody lines (indicated with dashed lines in Fig. 6.2b), which means there is not straightforward interpretation in terms of variations in the relative strength of two such spectral components.

After the peak of the outburst (marked I in Figs. 6.1b and 6.2), a number of flares are found during the decay; these are most clearly visible in the light curve shown in Fig. 6.1b and in the HID shown in Fig. 6.2a, and are marked II–IX in both these figures. During a flare the source moves towards the upper right of the CD and HID: both colors and the count rate increase (Fig.6.2). The flares are also indicated in Fig. 6.1b: clearly during the flares the rms amplitude increases. We find that the flares are only found during observations in regions D, E and F and occur from various count rate levels covering a range of a factor ~ 7, but show show no preferential range in colors. For instance, the maximum of flare IV is equally hard as the minimum of flare III (Fig. 6.2a). Note, that some flares fall on top of each other in the CD, while the count rate difference makes them stand out more clearly in the HID.
6.3 The outburst behaviour

Figure 6.2 — The Hardness Intensity Diagram (HID; panel a) and the color-color Diagram (CD; panel b) of the outburst. For the HID we used the count rate in the 11.9–17.7 keV band. In both the HID and the CD the positions of the maximum I and flares II–IX are indicated. Also indicated in panel B are the lines for the power law and the disk blackbody components for different values of the power law index and the disk blackbody temperature, respectively. For the interstellar absorption a value of $3.5 \times 10^{22} \text{ cm}^{-2}$ was used. The increment in the power law index is 0.1 and that for the disk blackbody temperature is 0.2. In panel B the 6 regions (Section 6.3.2) are indicated by different symbols.
We return to the behaviour in the CD and HID in Section 6.5, where we show that during the flares, as the source moves in the CD and HID, a clear change in the power spectral behaviour is observed.

6.3.2 Power spectral shapes
In the CD and HID (Fig. 6.2) the 101 observations cluster together in different regions. For each of these regions we find that the observations belonging to it show very similar power spectra, while between the regions the power spectral characteristics are always found to be different: QPOs and BLNs change in frequency and strength and features appear or disappear, see below. Based on this we defined 6 regions A–F, as indicated in Fig. 6.2 using different symbols (see also Table 6.1 where we give the observation numbers belonging to each of the regions). Below we discuss the power spectral behaviour in each of the regions A–F, and show a characteristic example. Because all power spectra in one region are similar and adding observations increases the sensitivity, we produced average power spectra for each of the regions. These are also discussed below.

The average power spectra of regions A–F are shown in Fig. 6.3. Some are very complex, for instance region B requires 12 Lorentzians to obtain a reduced $\chi^2$ below 2. Although many of these components can also be identified in the individual observations, adding observations together produces power spectra with more power spectral components than in individual observations, due to both increased sensitivity and frequency shifts of components between observations. We deal with the lower frequency behaviour in detail in Section 6.4.1. The main purpose of adding the observations is to study the high-frequency features whose rms amplitudes and significance are summarised in Table 6.3, where we also give the $1/128$–100Hz rms amplitude for each region.

In the power spectra we identified the following components (in the average and individual observations; see for instance Fig. 6.3): from low to high frequencies we found two sharp QPOs ($L_{d1}$ and $L_{d2}$, they are referred to as the "dipping QPOs") that correspond to the dipping behaviour in the light curve (around 0.1 Hz Dieters et al. 2000), a BLN component ($L_b$) that is either represented by a broad or a peaked Lorentzian, one to three low-frequency QPOs around 10 Hz ($L_1$, $L_2$ and $L_3$) and a high-frequency feature ($L_{HF}$). We denote the frequencies of the components as $v_{d1}$, $v_{d2}$, $v_b$, $v_1$, $v_2$, $v_3$, $v_{HF}$, respectively.

In Figs. 6.3a and 6.4 we show the average power spectrum and a characteristic individual power spectrum of region A. The average power spectrum is dominated by a set of 4 low-frequency (LF) QPOs between 2–10 Hz, some of which appear to be harmonically related (Fig. 6.3a). In the individual observations we find either 2 or 3 QPOs which are harmonically related: $\sim 1 : 2$ and $\sim 1 : 1.5 : 3$ respectively. Because the frequencies of the LF QPOs shift slightly between the individual observations (the QPOs are found to increase in frequency during the first $\sim 4$ days; Section 6.4.1), the 4 QPOs in Fig. 6.3a are the result of adding all the observations together, as mentioned above. The high-frequency feature in the average power spectrum of group A is very broad
6.3 The outburst behaviour

Figure 6.3 — Average power spectra of the regions A–F. The regions are defined based on their position in the CD and HID as well as their behaviour in the power spectra. The power spectra shown in the different panels are a good representation for the power spectra of the individual observations. Note that a different binning was applied to the higher frequencies parts of the power spectra in order to better show the high-frequency features.
has a characteristic frequency of $164 \pm 10$ Hz and a rms amplitude of $\sim 6\%$ rms (see also Table 6.3). In the individual observations we find similar features, at frequencies between $\sim 70$–$200$ Hz, with $Q$ values between 0 and 1 and rms amplitudes of $4$–$9\%$ rms (see Table 6.2).

In Fig. 6.3b we show the average power spectrum of region B. The observations in this region are characterised by a strong QPO around 0.1 Hz (and in some cases harmonics at two times and four times that frequency) corresponding to the “dipping” behaviour reported by Dieters et al. (2000) and Trudolyubov et al. (2001), not to be confused with the absorption dips reported by Kuulkers et al. (1998). In the individual observation (Fig. 6.5) two strong dipping QPOs (Section 6.3.2) are detected. Around 10 Hz the average power spectrum shows four LF QPOs between 4 and 14 Hz, while the individual observations only show three QPOs (Fig. 6.5; in one observation only two are present) that appear to be harmonically related ($\sim 1 : 1.5 : 3$). However, Dieters et al. (2000) found that the lowest two LF QPOs of the triplet in the individual observations are not simultaneous: the QPO around 6–8 Hz drops to 4–5 Hz inside the dips. The fourth QPO in the average power spectrum is the result of either small frequency shifts or the enhancement in strength of a component as mentioned above.

At higher frequencies we find two features in the average power spectrum of region B (Fig. 6.3b), one at $v_{\text{max}}=49 \pm 3$ Hz ($Q=1.1, 2.1\%$ rms, 5.9$\sigma$) and one at $v_{\text{max}}=187 \pm 6$ Hz ($Q=1.1, 3.6\%$ rms, 10.3$\sigma$; see also Table 6.3). In the individual observations we find high-frequency features between 153 Hz and 279 Hz ($v_0$ between 85 and 179 Hz), which are either noise-like components ($Q<2$) or a QPO ($Q<2$; Table 6.2). Only during one observation in region B we find a significant feature at $\sim 45$ Hz simultaneous with a high-frequency feature at $\sim 178$ Hz (Section 6.4.2). In the other individual observations no significant detection was made of a similar feature at 45 Hz, but we did find relatively high 95% confidence upper limits of $\sim 2\%$ rms.

In regions A and B a low-frequency noise (or Band Limited Noise, BLN) component is found around $\sim 1$ Hz. This component is slightly stronger in region A ($\sim 10 \pm 1\%$) than in region B ($\sim 7 \pm 1\%$). Also, in both regions similar QPOs are found around 10 Hz and at high frequencies. The main difference between region A and B is the presence of the dipping QPOs (Section 6.3.2) and the feature at $\sim 45$ Hz in region B. The dipping QPOs are always observed in combination with a strong noise component between $\sim 0.1$–$0.5$ Hz; usually the dipping QPOs are found on top of this component, see for instance Fig. 6.5. For region A we investigated the possibility of detecting a feature similar as the 45 Hz feature found in region B. For both the average and the individual power spectra we did not significantly detect a similar feature, however, we did find high upper limits of 2–3% rms.

From Figs. 6.3c and 6.6 is is clear that compared to regions A and B, in region C the strength of the BLN is much reduced (about a few percent rms, see also Table 6.3), but that a relatively strong Very Low-Frequency Noise (VLFN)
6.3 The outburst behaviour

Figure 6.4 — A characteristic individual power spectrum of observation 7 (Table 6.1) in region A. The power spectrum consist of two noise components at low frequencies, a weak Very Low-frequency Noise (VLFN) component and stronger Band Limited Noise (BLN) component. There are two strong QPOs at ~ 5 and ~ 8 Hz and a high-frequency feature at ~ 150 Hz, detected at 5.2 σ with an rms amplitude of ~ 6%.

Figure 6.5 — A characteristic individual power spectrum of observation 13 (Table 6.1) in region B. The power spectra consist of a strong VLFN and BLN component, the “dipping” QPOs around 0.1 Hz and the three strong QPOs around 10 Hz. Region B is also characterized by the presence of high-frequency features, in this case a feature is detected at ~ 170 Hz (~ 5 σ, ~ 4% rms).
Table 6.2 — Frequencies of the $L_{\text{high}}$ components. The observation numbers in the first column correspond to the observation IDs of Table 6.1. For each component we give the $v_{\text{max}}$, Q and fractional rms.

<table>
<thead>
<tr>
<th>Obs nr.</th>
<th>$v_{\text{max}}$</th>
<th>Q</th>
<th>rms</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>$71.74_{-17.81}^{+22.72}$</td>
<td>0</td>
<td>$8.61_{-3.35}^{+3.44}$</td>
</tr>
<tr>
<td>3</td>
<td>$134.65_{-20.39}^{+23.55}$</td>
<td>$0.32_{-0.25}^{+0.32}$</td>
<td>$6.41_{-2.57}^{+2.64}$</td>
</tr>
<tr>
<td>4</td>
<td>$126.29_{-21.64}^{+28.93}$</td>
<td>$0.22_{-0.22}^{+0.20}$</td>
<td>$7.96_{-3.19}^{+3.32}$</td>
</tr>
<tr>
<td>5</td>
<td>$230.36_{-34.94}^{+56.40}$</td>
<td>$0.24_{-0.40}^{+0.41}$</td>
<td>$6.20_{-2.74}^{+2.85}$</td>
</tr>
<tr>
<td>6</td>
<td>$147.58_{-23.10}^{+33.86}$</td>
<td>$0.29_{-0.23}^{+0.22}$</td>
<td>$7.00_{-2.84}^{+3.04}$</td>
</tr>
<tr>
<td>7</td>
<td>$193.38_{-23.71}^{+32.40}$</td>
<td>$0.59_{-0.31}^{+0.35}$</td>
<td>$5.67_{-2.48}^{+2.69}$</td>
</tr>
<tr>
<td>8</td>
<td>$200.30_{-37.91}^{+45.92}$</td>
<td>$0.61_{-0.28}^{+0.36}$</td>
<td>$5.86_{-1.99}^{+2.99}$</td>
</tr>
<tr>
<td>9</td>
<td>$169.81_{-14.48}^{+18.23}$</td>
<td>$0.79_{-0.23}^{+0.28}$</td>
<td>$5.15_{-1.99}^{+2.08}$</td>
</tr>
<tr>
<td>10</td>
<td>$168.33_{-32.90}^{+39.37}$</td>
<td>$0.54_{-0.24}^{+0.28}$</td>
<td>$5.39_{-2.50}^{+2.64}$</td>
</tr>
<tr>
<td>11</td>
<td>$176.36_{-24.71}^{+24.22}$</td>
<td>$1.16_{-0.44}^{+0.60}$</td>
<td>$4.12_{-2.07}^{+2.21}$</td>
</tr>
<tr>
<td>13</td>
<td>$171.61_{-18.36}^{+22.38}$</td>
<td>$0.92_{-0.30}^{+0.41}$</td>
<td>$3.61_{-1.62}^{+1.68}$</td>
</tr>
<tr>
<td>14</td>
<td>$186.23_{-36.60}^{+55.00}$</td>
<td>$0.73_{-0.34}^{+0.51}$</td>
<td>$4.58_{-2.44}^{+2.57}$</td>
</tr>
<tr>
<td>15</td>
<td>$153.41_{-49.45}^{+50.56}$</td>
<td>$0.21_{-0.44}^{+0.35}$</td>
<td>$4.88_{-2.32}^{+2.42}$</td>
</tr>
<tr>
<td>16</td>
<td>$181.12_{-12.31}^{+53.80}$</td>
<td>$1.55_{-0.85}^{+1.19}$</td>
<td>$4.73_{-2.47}^{+3.03}$</td>
</tr>
<tr>
<td>17</td>
<td>$155.35_{-26.64}^{+26.42}$</td>
<td>$0.35_{-0.15}^{+0.14}$</td>
<td>$4.01_{-1.47}^{+1.56}$</td>
</tr>
<tr>
<td>18</td>
<td>$185.53_{-13.44}^{+19.55}$</td>
<td>$1.76_{-0.91}^{+1.46}$</td>
<td>$3.97_{-2.16}^{+2.42}$</td>
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<tr>
<td>19</td>
<td>$160.41_{-40.93}^{+44.96}$</td>
<td>$0.70_{-0.49}^{+0.70}$</td>
<td>$3.96_{-2.26}^{+2.46}$</td>
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<tr>
<td>21</td>
<td>$225.67_{-38.86}^{+52.83}$</td>
<td>$0.39_{-0.23}^{+0.24}$</td>
<td>$5.98_{-2.57}^{+2.72}$</td>
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<tr>
<td>24</td>
<td>$278.84_{-84.31}^{+209.93}$</td>
<td>$0.16_{-0.11}^{+0.31}$</td>
<td>$5.25_{-2.67}^{+3.30}$</td>
</tr>
<tr>
<td>25</td>
<td>$182.04_{-11.36}^{+16.42}$</td>
<td>$2.15_{-1.03}^{+2.02}$</td>
<td>$3.39_{-1.92}^{+2.11}$</td>
</tr>
<tr>
<td>26</td>
<td>$178.42_{-8.15}^{+8.45}$</td>
<td>$2.04_{-1.17}^{+0.72}$</td>
<td>$2.73_{-1.17}^{+1.23}$</td>
</tr>
<tr>
<td>26</td>
<td>$45.48_{-2.47}^{+2.70}$</td>
<td>$1.67_{-0.42}^{+0.42}$</td>
<td>$2.09_{-0.91}^{+0.95}$</td>
</tr>
<tr>
<td>32</td>
<td>$97.38_{-7.62}^{+5.89}$</td>
<td>$2.33_{-1.29}^{+2.12}$</td>
<td>$2.94_{-1.69}^{+1.93}$</td>
</tr>
<tr>
<td>33</td>
<td>$169.23_{-0.33}^{+6.79}$</td>
<td>$5.82_{-3.10}^{+4.41}$</td>
<td>$3.09_{-1.89}^{+2.19}$</td>
</tr>
<tr>
<td>42</td>
<td>$64.32_{-22.93}^{+36.19}$</td>
<td>$0$</td>
<td>$3.94_{-1.92}^{+2.02}$</td>
</tr>
<tr>
<td>46</td>
<td>$22.46_{-4.62}^{+12.00}$</td>
<td>$0$</td>
<td>$4.18_{-1.91}^{+1.90}$</td>
</tr>
<tr>
<td>48</td>
<td>$655.40_{-310.05}^{+800.74}$</td>
<td>$0$</td>
<td>$7.51_{-4.12}^{+5.38}$</td>
</tr>
</tbody>
</table>
6.3 The outburst behaviour

Table 6.3 — For the regions A–F we give the \( v_{\text{max}}, Q, v_0 \), fractional rms and the significance of the high-frequency features. In the last column we also give the fractional rms in the 1/128–100 Hz range. In regions B and D we detected two high-frequency features (see text). For regions E and F we could not detect a significant high-frequency feature. We only report the 95% upper limit (2 \( \sigma \)) found in region E, for region F no upper limit could be determined.

<table>
<thead>
<tr>
<th>Regions</th>
<th>( v_{\text{max}} ) (Hz)</th>
<th>Q</th>
<th>( v_0 ) (Hz)</th>
<th>rms (%)</th>
<th>Sig. (( \sigma ))</th>
<th>rms (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>164.3±9.8</td>
<td>0.33±0.07</td>
<td>90.5±18.7</td>
<td>6.2±1.5</td>
<td>17.7</td>
<td>14.7±1.8</td>
</tr>
<tr>
<td>B</td>
<td>49.3±3.0</td>
<td>1.2±0.26</td>
<td>45.5±4.1</td>
<td>2.1±0.9</td>
<td>5.9</td>
<td>18.6±1.8</td>
</tr>
<tr>
<td>C</td>
<td>187.4±6.5</td>
<td>1.09±0.18</td>
<td>170.2±11.0</td>
<td>3.6±1.1</td>
<td>10.3</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>262.2±45.5</td>
<td>0.56±0.28</td>
<td>195.6±68.8</td>
<td>3.3±1.5</td>
<td>4.9</td>
<td>4.1±1.0</td>
</tr>
<tr>
<td>E</td>
<td>38.06±7.3</td>
<td>0.67±0.37</td>
<td>30.5±12.5</td>
<td>2.1±1.1</td>
<td>4.0</td>
<td>5.79±1.2</td>
</tr>
<tr>
<td>F</td>
<td>179.3±5.7</td>
<td>4.6±2.2</td>
<td>178.3±6.8</td>
<td>2.0±1.1</td>
<td>3.8</td>
<td></td>
</tr>
</tbody>
</table>

1) 95% upper limit for Q=0 in the 50–1000 Hz range.

...component is present at frequencies below \( \sim 0.1 \) Hz. Also, the complex LF QPO features around 10 Hz are replaced by only one, much broader QPO. We tried fitting the structure in the average power spectrum with two Lorentzians but this did not significantly improve the fit. In the individual observations this LF QPO is also single (Fig. 6.6). In the average power spectra we find a strong (3.3% rms, 4.9 \( \sigma \)) rather broad (Q\~0.6) high-frequency feature at 262 \( \pm \)46 Hz, the highest frequency found in the average power spectra. In the individual observations this feature is not significantly detected, and only on one occasion a significant feature was detected at \( \sim 100 \) Hz (Table 6.2). We also looked for a similar feature as the 45 Hz one detected in region B. Again, in both the average power spectra and the individual ones we did not detect a significant feature, but did find a relatively high upper limit of 1.5% rms.

The average and the individual power spectra of region D are shown in Figs. 6.3d and 6.7. Compared to region C the BLN component is stronger (a factor \( \sim 2 \) in rms amplitude), and in the average power spectra two LF QPOs and two sharp high-frequency features are detected. Although the two LF QPOs seem to be harmonically related by a factor \( \sim 2 \), the 5.9 Hz QPO is only detected (together with the 11.3 Hz QPO) in one individual observation. In all the other individual observations only the 11.3 Hz QPO is significantly detected. The high-frequency feature in region D is the sharpest we detected in the average power spectra; we find a QPO at 179 \( \pm \)6 Hz with a Q value of \( \sim 5 \) (Table 6.3). In addition to that we also find a feature at \( \sim 40 \) Hz (Table 6.3). Just like in region B, the two QPOs have a frequency ratio of \( \sim 4 \). In the individual power spectra only occasionally high-frequency features are detected, see Table 6.2.

The average power spectrum of region E (Fig. 6.3e) shares some resemblance with those of regions C and D; we find strong VLFN and BLN components and
Figure 6.6 — A characteristic individual power spectrum of observation 27 (Table 6.1) in region C. This power spectrum has three relatively broad components, one at very low frequencies (the VLFN component, at ~ 0.01 Hz), one around 0.5 Hz (BLN) and one at ~ 10 Hz. The latter one is considered to be related to the QPO features detected around 10 Hz in regions A and B.

Figure 6.7 — A characteristic individual power spectrum of observation 39 (Table 6.1) in region D. This power spectrum is very similar to that of region C (Fig. 6.6), however, notice the stronger BLN component (about a factor 2 stronger in rms amplitude).
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one LF QPO around 10 Hz. However, no significant high-frequency feature was detected in the average power spectrum. We find a 95% confidence upper limit of 2.3% rms for a QPO with Q=12 and 2.9% rms for a feature with Q=0 in the 50–1000 Hz range. In the individual power spectra either no significant features are detected or only a broad noise component (BLN) is found, see Fig. 6.8.

The power spectra of the individual region F observations are characterized by a strong BLN component (10–20% rms) in combination with a sharp (Q~ 9) QPO, as shown in Fig. 6.9. In region F, during the decay of the outburst both the QPO and the BLN decrease in frequency: the QPO drops from ~ 4 Hz to about 0.1 Hz. Similar shifts in frequency have also been observed after the soft to hard state transition during the decay of outburst of the black hole candidates GRO 1655–40 (Mendez et al. 1998) and XTE J1650–500 (Kalemci et al. 2003). In the average power spectra of region F (Fig. 6.3e) these frequency shifts result in a broad feature around 2 Hz. In the high-frequency regime of the average and the individual power spectra no significant features are detected.

With respect to the high-frequency features in the average power spectra we find from Table 6.3 that as the sources moves from region A to C the frequency first increases (by about a factor 1.5) and then may decrease again in region D. The same trend is also observed for the high-frequency QPOs in the individual observations: an increase in the frequency with a maximum that is obtained in region B, followed by a decrease (see also Fig. 6.10).

6.3.3 The "canonical" states

Based on the characteristics given in the previous section we can identify the different regions A–F with the "canonical" black hole states (eg. Tanaka & Lewin 1995; van der Klis 1995a, 2004). Here we will use the definitions for these states as given by Homan et al. (2001).

For both region A and B the count rates are high and the spectrum is relatively hard, as can be seen from Figs. 6.1 and 6.2: A and B are part of maximum I. From Table 6.3 it is clear that the fractional rms amplitude is relatively high (15–19%). All this, together with the complexity of the power spectra leads us to conclude that the source is in the Very High State (VHS) or Intermediate State (IMS) in both regions A and B. This classification is similar to that of Dieters et al. (2000), however, Trudolyubov et al. (2001) report that while the power density spectra suggest the source is in the VHS/IMS the energy spectra are more consistent with the LS.

Based on the shape of the power spectra and the relatively low rms amplitude (~ 4–5%, see Table 6.3), we conclude that in regions C and D the source is still in the VHS/IMS, although the count rates are lower and the energy spectra softer. Region E is characterized by power-law noise type power spectra typical for the High State (HS). However, the relatively high rms amplitude (~ 5%) and the fact that in region E the source is on or close to the power law line in the CD, suggesting that the spectra are not dominated by the soft disk blackbody
Figure 6.8 — A characteristic individual power spectrum of observation 58 (Table 6.1) in region E. While most of the power spectra in this region show no significant features, some show a BLN component like the one shown here.

Figure 6.9 — A characteristic individual power spectrum of observation 93 (Table 6.1) in region F. All the power spectra in this region are characterized by a BLN component in combination with a QPO; both features decrease in frequency towards the end of the outburst.
component which is the general case for HS spectra, indicate the source never completely reaches the HS, but is close to it.

Towards the end of the outburst in region F, the spectrum hardens as the hard colour reaches a level about 2 times higher compared to the rise of the outburst (Figs. 6.1 and 6.2). The spectral hardening is accompanied by the increase in the rms amplitude to a relatively high level (~ 20%, see Table 6.3 and Fig. 6.2f). This suggests that in region F the source is in the Low State (LS). However, note that the power spectral shape is not typical of that of the LS: 4U 1630–47 in the LS shows only one BLN component at relatively low frequencies together with a sharp QPO, while for instance the LS power spectra of GX 339–4 and Cyg X–1 (Nowak 2000) show at least three BLN components up to ~ 100 Hz, sometimes together with a sharp QPO.

The identification into the canonical states for 4U 1630–47 gives the following sequence: VHS/IMS–“near-HS”–LS. Most likely, a LS during the initial rise is just missed by the observations presented here; the first two observations of the rise (region A) show VHS/IMS power spectra but the energy spectra are more LS-like (Trudolyubov et al. 2001). Remarkably, 4U 1630–47 never completely reaches the HS. 4U 1630–47 never becomes as soft as XTE J1550–564 did in its 1998/1999 outburst (Homan et al. 2001). During the decay of some black hole outbursts the transition from the HS to the LS goes via the IMS; here the power spectra are very similar to the VHS, but at much lower count rates. Although the sampling rate for the observations is similar in the decay as during the rest of the outburst, the points are further apart in the HID (Fig. 6.2) indicating the source moves faster here. Therefore, the IMS may have been missed during the 1998 outburst decay.

Like XTE J1550–564 (Homan et al. 2001), for 4U 1630–47 the same canonical state occurs at different count rate and HC levels: for instance regions A–C are all identified as VHS/IMS. All these four regions are found at different count rates and HC, show a behaviour in their power spectra that is also different, but yet are still identified as belonging to the same state. This shows that the classification into the canonical black hole states is not a fixed one, and that there are sub-states that in this case correspond to the regions A–F. The canonical states are a tool used to describe a continuum of behaviours of sources during outburst. However, this tool does not always work; sometimes a source is found to show characteristics that do not allow a straightforward classification into one of the canonical states. Most likely, this is also the case for the “near-HS” in region E: the source shows a HS-like behaviour which can only be classified as a sub-state of the canonical HS behaviour.

Note that the above depends on the classification of observations into the different canonical states. In that respect our identification as presented in Section 6.3.3, is similar to that presented in previous work (Dieters et al. (2000), Trudolyubov et al. (2001) and Tomsick & Kaaret (2000)), that involved both timing and energy spectral analysis.
Figure 6.10 — Here we show the frequencies of all the components as a function of time. We use the following symbols: a "★" is used for the high-frequency features (panel b), a "★" for L₁, a "⊙" for L₂, a "×" for L₃, a "□" for the break frequency (L₄; panel c), a "△" for L₅ and a "◊" for L₆ (panel d). The intervals corresponding to regions A–F are indicated at the top of panel a. Panel a shows the 11.9–17.7 keV light curve also shown in Fig. 6.1b. In panels b, c and d we show $v_{HF}$, $v_{br}$, $v_{1}$, $v_{2}$, $v_{d1}$ and $v_{d2}$ respectively, as a function of time (note that the time axis is logarithmic). Notice the clear rise of $v_{HF}$, $v_{br}$, $v_{1}$, $v_{2}$ and $v_{2}$ during the first ~4 days of the outburst.

6.4 Analysing the power spectra

In Fig. 6.10 we show the frequencies, in the $v_{max}$ representation, of all components in the power spectra of the 101 observations during the outburst as a function of time. Below we discuss the characteristics of these components and their relations with the HC and count rate in order of increasing frequency.

6.4.1 The low-frequency Lorentzians

The QPOs corresponding to the dipping behaviour (L₄₁ and L₄₂) are only present in regions B and C. The frequency of these QPOs is more or less constant in region B (with one exception for L₄₂) and we find that they are harmonically
related: \(v_{d1} : v_{d2} \approx 1 : 2\) as also found from the average power spectrum of region B (see Section 6.3). In region C we find on three occasions a \(v_{d1}\) that is a factor \(\sim 2\) lower than the one found in region B (Fig. 6.10d). The relation between the frequency and the HC and count rate for \(L_{d1}\) and \(L_{d2}\) is shown in Fig. 6.11. There is a clear correlation between \(v_{d1}, v_{d2}\) and the HC; linear correlation coefficients, \(r\), are 0.97 and 0.93 respectively. Here and hereafter we only report values for \(r\) when the confidence level for the correlation exceeds \(3\sigma\). For \(L_{d1}\) we find an anti-correlation between the frequency and the count rate \((r = -0.77)\), which is caused by the drop in \(v_{d1}\) in region C. \(L_{d2}\) is not detected in region C and shows no such anti-correlation.

The break frequency, \(v_b\), rises during the first 4 days from \(\sim 1\) Hz to about 3 Hz, then stays at this level until day 10 (Fig. 6.10c). After day 10 \(v_b\) shows erratic behaviour between \(\sim 0.3\) and 4 Hz (Fig. 6.10c). In Fig. 6.12 we show the relation between \(v_b\), HC and count rate. Clearly there is no overall correlation. However, we find a strong anti-correlation between the frequency and the HC \((r\) between \(\sim -0.7\) and \(-0.9)\) for regions A, E and F while regions A, D and F show a strong correlation with count rate \((r\) between \(\sim 0.87-0.93)\). For the other regions no significant correlations were found, although similar weak trends can not be
Figure 6.12 — The break frequency as a function of HC and count rate. For the different regions we use the same symbols as in Fig. 6.2. No overall correlation is found. However, in regions A, E and F there seems to be an anti-correlation between the break frequency and the HC (panel a) while regions A and F seem to show a correlation between the break frequency and the count rate (panel b).

We identified the LF QPOs, L₁, L₂ and L₃ in order of increasing frequency. During the first 4 days of the outburst ν₁, ν₂, and ν₃ increase by a factor ~ 2–3, and then stay at an almost constant level up to day ~ 10 (see Fig. 6.10c). In region B the LF QPOs in the individual observations are approximately harmonically related by 1 : 1.5 : 3, as also found for the average power spectra of region B (Section 6.3). After day 10 the source mostly shows only one QPO of this type, around 11 Hz, designated L₁ (which does not have to be the same as L₁ detected before day 10, see below). The only exception to this is found during observations 33 and 47 (Section 6.5), when a second QPO is detected. Higher resolution power spectra of these data show the presence of L₁, L₂ and L₃ in observation 47 (see also Tomsick & Kaaret (2000)) and of L₁ and L₂ in observation 33 (Fig. 6.18). Both these observations will be discussed in more detail in Section 6.5.

In regions C–F ν₁ remains relatively constant up to day ~ 50 at a level slightly higher than ν₂ in region B, and between day ~ 50 and ~100 it is not detected in the power spectra. In region F a LF QPO component designated L₁ is detected
Figure 6.13 — The frequency of L₁, L₂ and L₃ as a function of HC and count rate. For the different regions we use the same symbols as in Fig. 6.2. All three components show a similar behaviour with opposite correlations for count rate and HC (see text).

again, only now its frequency decreases to a level below $v_p$ (Fig. 6.10).

In Fig. 6.13 we show the relation between the frequency and the HC and the count rate for L₁, L₂ and L₃. $v_1$ and $v_3$ are anti-correlated with HC (Fig. 6.13a and e; $r \sim -0.5$ to $-0.99$) and for L₂ we see that in region A the frequency increases with HC, while in regions B and D it decreases with HC. $v_2$ and $v_3$ are strongly correlated with count rate, $r$ between 0.56 and 0.98 (Fig. 6.13d and f), while for L₁ the relation between the frequency and the count rate is more complex. L₁ shows a loop behaviour (see Fig. 6.13b): the source starts off around count rate $\sim 1000$ in the region A, moves to the upper right of the panel (region B and C) and when it enters region D moves to the left of the figure going all the way down to the bottom left part (region E and F). In this way, the highest frequencies are found when the count rate is dropping. Such hysteresis behaviour, which results in a parallel tracks in count rate vs. frequency plots, has already been found in for instance in the black holes GX 339–4 (Miyamoto et al. 1995; Smith et al. 2002), XTE J1550–564 (Homan et al. 2001) and the neutron star 4U 1608–52 (Méndez et al. 1999).

The identification of L₁, L₂ and L₃, is in increasing order of frequency. So what we call L₁ when only one or two LF QPOs are present, does not have
to be the same component as L₁ in an observation with three QPOs. In the
case of XTE J1550–564 similar LF QPOs are found, see for instance Homan et al.
(2001), which could be identified based on their time lag, energy dependence or
Q values (Remillard et al. 2002d; Homan et al. 2001). A time lag analysis of the
4U 1630–47 data shows that at least the L₁ components in regions A and B are
the same, both having a negative lag. However, no further conclusive evidence
was found for classifying the QPOs based on the time lag behaviour. The Q
values for the LF QPOs in the individual observations of 4U 1630–47 are all in
the same range and no clear pattern emerges when the energy dependencies
of the QPOs are analysed. So an unambiguous identification, similar to the one
used for XTE J1550–564, for the LF QPOs cannot be made. However, identifying
the group D LF QPO with L₂ or L₃ in Fig. 6.13 and not with L₁, leads to similar
correlations mentioned above.

6.4.2 The high-frequency Lorentzians

In 22 of the 101 individual observations we detect significant high-frequency
features (L_HF with frequencies v_HF). These features have Q values in the range
~ 0–6, rms amplitudes between 4–9%, frequencies between ~ 20–300, and all
have a single trial significance between 4 and 7 σ. Table 6.2 gives the complete
list of all the high-frequency features. Figures 6.4 and 6.5 show two examples
of L_HF in individual observations in regions A and B, respectively. Like also
found in the average power spectra (Fig. 6.3), the high-frequency features are a
dominant feature in the power spectrum.

The frequencies v_HF are plotted in Fig. 6.10b. Like in the case of the low-
frequency features (Section 6.4.1), L_HF increases in frequency during the first
~ 4 days (Fig. 6.10b) while in region B v_HF is relatively constant, at a level of
about 180 Hz. Apart from the last observation in region D which shows the
highest frequency measured in our data set at a frequency of 655^{+860}_{-310} Hz (Q=0,
3.3σ), v_HF shows a decreasing trend in regions C and D (Fig. 6.10b; note that all
the high-frequency features in region D are zero-centered). In regions E and F
no significant high-frequency features are detected.

In five individual observations (observations 2, 26, 32, 42 and 46) in regions
A, B, C and D we find components with frequencies between 20 and 100 Hz
(see Fig. 6.10b, and Table 6.2). Because these features are found well above v₁, v₂
and v₃, and are relatively broad (like the other high-frequency features) they are
also regarded as high-frequency features. Only on one occasion, in the power
spectrum of observation 26 (Fig. 6.14), we detected two high-frequency fea-
tures: one at ~ 45 Hz with a significance of 5.3 σ (2.1 % rms, Q=1.7) and a second
at ~ 178 Hz with a significance of 5.4 σ (2.7 % rms, Q=2.0). This is the first detec-
tion of two simultaneous high-frequency features in 4U 1630–47. In the average
power spectra of regions B and D we find similar features at ~ 38 Hz and ~ 49
Hz which occur simultaneously with features at ~ 187 Hz and ~ 179 Hz, re-
spectively (Fig. 6.3, Table 6.3). Also, for a lot of the individual power spectra in
regions A, B and C as well as for the average power spectrum of regions A and
6.4 Analysing the power spectra

Figure 6.14 — The two high-frequency features detected in an individual observation 26, (Table 6.1) during the 1998 outburst of 4U 1630-47. We find two features: one at 45±3 Hz and one at 178±8 Hz.

C we find high (~ 2%) 95% confidence upper limits for a similar feature around 45 Hz (Section 6.3.2). In all the cases when double high-frequency features are found, the ratio between their frequencies is about 4.

In Fig. 6.15a we show the relation between the frequency of the high-frequency features and the HC for both the individual observations and the average power spectra in regions A–F. A weak anti-correlation between $v_{HF}$ and HC is found, which becomes stronger when the L$_{HF}$ components with frequencies below 100 Hz are not taken into account. This weak trend is supported by the data from the average power spectra also plotted in Fig. 6.15a. The relation between $v_{HF}$ and the count rate is shown in Fig. 6.15b. For the individual observations there is only a weak correlation, which again is supported by a stronger one found in the average power spectra ($r= 0.97$).

Like in the case of $v_b$ in the previous section, $v_{HF}$ shows stronger correlations within regions than overall. Especially in region A we find a strong anti-correlation between $v_{HF}$ and the HC, and a correlation between $v_{HF}$ and the count rate ($r$ values of −0.84 and 0.80, respectively), representing the trends during the rise of the outburst.

The difference between the high-frequency features detected above and below ~ 100 Hz is apparent from Fig. 6.15: the features below ~ 100 Hz do not
Figure 6.15 — The frequency of the high-frequency feature found in the average and the individual observations as a function of HC (panel a) and count rate (panel b). In the top of panels a and b we show the symbols used for the average power spectra in the regions A–F and the individual power spectra, respectively.
follow the general trend and have no clear relation with the HC or the count rate. In Section 6.6.2 we show that, unlike the features with \( v_{\text{high}} > 100 \text{ Hz} \), those \(< 100 \text{ Hz} \) also do not follow the relation with the LF QPOs. We suggest that the \( L_{HF} \) components below \(~ 100 \text{ Hz} \) are different from the ones found above \(~ 100 \text{ Hz} \), and we discuss them in some more detail in Section 6.6.

Finally note, that for most of the correlations between the frequency of the different components in the power spectrum and the HC and count rate mentioned in this section, the strongest (most significant) relations are found in regions A and F. This is most likely directly related to the fact that these regions show large changes in HC and count rate, as can be found from Fig. 6.1.

### 6.5 The flares and a dip in the light curve: power spectral changes

As discussed in Section 6.3.1 flare I comprises the rise and maximum of the outburst, is associated with both changes in soft and hard flux and has smaller flares superimposed on it. In Fig. 6.16, which shows a zoom of the CD and HID (Fig. 6.2), we indicated these small flares. From this figure it is clear that during these flares the HC, SC and count rate increase and hence a movement to the upper right of the CD and HID occurs like in the case of the large flares II–IX (Section 6.3.1). However, the power spectra show no significant changes. This is most likely related to the relatively small changes in HC, SC and count rate compared to the changes during the large flares (Figs. 6.2 and 6.16) which do show power spectral changes, as will become clear below. The only significant change in power spectral behaviour during maximum I is found in observation 33 (Table 6.1; Figs. 6.16 and 6.17), which shows a drop in count rate.

During the outburst decay flares II–IX occur (Section 6.3.1; see also Figs. 6.1 and 6.2) which are associated to an increase in count rate, HC, SC (Fig. 6.2) and rms amplitude (Fig. 6.1). In the remainder of this section we discuss how the power spectra change during the flares and the observation associated to the drop in count rate.

#### 6.5.1 Flares II–VI and the drop in count rate

During the maximum of the outburst that occurred between days \( \sim 10–16 \) we find a peculiar drop in count rate around day 12 (observation 33), that is associated with an sharp increase in the rms amplitude. Figs. 6.17 and 6.16 shows a zoom of the 2.9–60.8 keV light curve, the rms amplitude and the HC and a zoom of the HID and CD, respectively. In the light curve (Fig. 6.17a) the dip caused by observation 33 is clearly marked. During the dip the colors, count rate and rms amplitude have values that are very similar to the values found before day 10. In the HID and CD (Fig. 6.16) this results in a position that is very close to that of the observations before day 10; before and after the dip the source is in
Figure 6.16 — A zoom of the HID (panel a) and the CD (panel b). In panel b we show the lines for the power law and the disk blackbody components for different values of the power law index and the disk blackbody temperature, respectively. Observations 33 and 47 (see text) are indicated with different symbols. Their position is close to that of the points corresponding to the first 10 days, which are indicated with triangles and classified as region B. Also indicated are the smaller flares that occur on top of I (the maximum of the outburst).
Figure 6.17 — A zoom of the light curve (panel a), the rms amplitude (panel b) and the HC (panel c). In panel b we show a typical error bar at day 20, in the other panels the error bars are too small to be visible. We indicated the position of the observations 33 and 47 with dashed lines. Both observations are associated with changes in the count rate, rms amplitude and HC; they (almost) reach the level they had in the first 10 days.
region C, during the dip the source is much closer to region B.

The proximity to region B is also reflected in the power spectrum. In Figs. 6.18a and b we show a power spectrum just before the drop in count rate (observation 31) and during the minimum (observation 33), respectively. The power spectrum before the dip is classified as region C (compare with Fig. 6.6), but in the dip as region B (compare with Fig. 6.5: observation 33 shows the characteristic dipping behaviour, LF QPOs, strong BLN component and a high-frequency feature.

Flares II–VI are similar in the sense that they show changes in the power spectra as the source moves in the HID and CD. The best example of that is flare III, which we will discuss in some more detail; the other flares show a similar behaviour although less clear.

From Fig. 6.16 it is clear that flare III corresponds to a loop in both the CD and the HID, moving to the upper right of the diagram in the direction of the region B points. In Fig. 6.18c we show the power spectrum of an observation at the beginning of the loop, while Fig. 6.18d shows the power spectra of observation 47, located closest to the region B points. This is not the peak of the flare in the light curve but is the point with the highest HC, see Fig. 6.17. While Fig. 6.18c is characteristic for the power spectra in region D, the power spectrum in Fig. 6.18d is very similar to those of region B (compare with Figs. 6.3b, d). Towards the maximum of the flare we find that the VLFN component increases in strength and more and stronger QPOs appear in the power spectrum around 10 Hz; essentially the power spectral behaviour changes from region D type outside the flare to region B type at the peak (in HC), indicating that the position in the CD and HID is related to a specific type of timing behaviour.

From the above it is clear that both an increase in count rate and a decrease give similar power spectral changes. This suggests that the location in the HID determines the timing properties. In both the flare and the dip the changes in power spectral behaviour leads us to classify them as belonging to another region. Note that, the changes in the power spectrum during flare III are not as large as those observed during the dip, and that latter is also located closer to region B. This suggests that the closer the source is to a certain region, the more similar the power spectra are to those found in that region.

During flares II and III, when the source is in region D outside the flares, the source shows power spectral behaviour similar to that of region B. For flares IV, V and VI when the source shows the region E behaviour (HS) outside the flares, the power spectral are similar to that of region D (IMS) at the peak of the flares.

### 6.5.2 Flares VII–IX

Flare VII is associated with the secondary maximum of the outburst, when the soft flux increases again. On top of this soft maximum a few small hard flares are visible during which, similarly to the ones found during flare I, no changes in the timing characteristics are found. For a large number of observations that cover flare VII no features are detected in the power spectrum; for flare VII no
Figure 6.18 — The changes in the power spectra during the dip (observation 33; panel a and b) and flare III (observation 47; panels c and d). In panels a and b we show the power spectra corresponding to an observation just before the dip and during the minimum of the dip, respectively. In this case the power spectra are characterized as region C outside the dip (compare with Fig. 6.6) and region B in the dip (compare with Fig. 6.5). Panels c and d show the power spectra just before and during the maximum of flare III, respectively. The power spectrum in panel a is classified as region D (compare with Fig. 6.7) and that in panel b as region B (compare with Fig. 6.5).
significant changes in the power spectra are found. Note that, as these flares are also found at lower count rates compared to the first ones, the lower statistics may prevent significant identifications of new or changing features.

Flares VIII and IX are found in region F at the end of the outburst decay, when the spectrum is hardening and the rms shows an increasing trend. While most of the observations in region E did not show any significant features, in region F the power spectra are characterised by a strong low-frequency noise and a QPO that is decreasing in frequency as the outburst proceeds. During flares VIII and IX no changes are found in the power spectra: the decaying trend of $\nu_1$ is not interrupted nor are changes found in the break frequency component.

6.6 Discussion

6.6.1 The relation between flares and state changes

The motion through the HID as presented in Fig. 6.2 is schematically shown in Fig. 6.19. As the outburst proceeds the source moves through the HID occupying specific regions that are associated with specific spectral and timing behaviour. During a flare, indicated by the arrows in Fig. 6.19, the source moves to a different location, changing its power spectral behaviour accordingly (Section 6.5). These flares can occur at different count rate and HC levels and occur in each of the regions A–F, but only some of them show associated changes in the power spectra.

Recently, Homan et al. (2001) suggested a two-dimensional behaviour in the HID, based on the 1998/1999 outburst of XTE J1550–564: the position in the HID depending on two parameters (the spectral hardness and the mass accretion rate) follows a track that can be described as a comb-like structure consisting of a spine representing a soft branch (HS) and the teeth that represent the flares. During these flares they found that changes in the power spectra occurred as QPOs changed in frequency and features appeared or disappeared: the flares are associated with transitions to and from harder states (IMS, VHS, LS; see figure 26 in Homan et al. (2001)).

The 1998 outburst of 4U 1630–47 strongly supports this. During flares the source shows changes not only in the rms amplitude but also in the number of (QPO-)features, in a way that strongly supports the idea that it is the position in the HID that determines the timing characteristics of the source. The behaviour during a dip (observation 33) strengthens this view, and shows that the occurrence of a specific type of behaviour can be initiated by the decrease in count rate (a dip) as well as by an increase in count rate (a flare).

Regarding the correlation between the position in the HID and the power spectrum a number of remarks are in order. First there are occasions, for instance in regions A and F, when the HC and count rate change over a large range, but no qualitative changes in the power spectrum are found: there are changes in the frequencies and also in the rms amplitude but the number of features in the
Figure 6.19 — A schematic view of the HID during the outburst, taken from van der Klis (2004). The dashed lines give an indication where the transitions between the states occur. The gray line gives the LS during the start of the outburst, that is most likely missed in the 1998 outburst of 4U 1630–47. As explained in Section 6.3.3 the real HS is never reached, hence the source does not cross the line indicating the transition between the VHS/IMS and HS. Also, the IMS during the decay is not observed. During a flare the source moves to a position that is associated with a different type of behaviour.
power spectra does not change, and all the power spectra are identified as part of one region. Secondly, there are transitions between regions that predominantly depend on only one parameter; the transition between regions B, C and D occur at almost constant HC. Finally, not all transitions between regions as we defined them here, are related to canonical state transitions. A clear example is the transition from region A to B, both of which are identified as VHS/IMS. This is related to the fact that a source can show variations on the canonical state behaviour as explained in Section 6.3.3: sometimes a mixture of two types of canonical state behaviour is observed, for instance during a transition from one state to another. Apparently, within a canonical state there are sub-types of behaviour that correspond to the regions we distinguished.

As mentioned before, the behaviour of 4U 1630–47 in the HID (and also CD) is very similar to that of XTE J1550–564 during its 1999/1998 outburst, however, from a comparison of the HID’s (compare Fig. 6.2 with figures 3a and 4 in Homan et al. (2001)) it is clear that XTE J1550–564 became much softer, almost reaching the disk blackbody line in the CD. For XTE J1550–564 the flares are all related to movements in the direction of the power law line, clearly suggesting an increase in the power law flux as their cause. In the case of 4U 1630–47 the source is still on the power law line even during its softest state, and the flares are related to movements along the power law line. So, 4U 1630–47 does not show as clear a HS as XTE J1550–564 does. The higher rms levels in the softest state of 4U 1630–47 are consistent with this.

The behaviour of XTE J1550–564 and 4U 1630–47 is consistent with the idea that each point in the HID has its own power spectral behaviour related to it. The track traced by the source in the HID during its outburst determines which power spectra it shows.

### 6.6.2 The high-frequency features

4U 1630–47 in its 1998 outburst shows prominent high-frequency features in the range between 20 and 300 Hz. The features are significantly detected, predominantly during the rise and the maximum of the outburst, in both the individual and the average power spectra (Section 6.4.2). Although most of the time only one high-frequency component is detected, occasionally two features are found. Remillard & Morgan (1999) already reported the detection of a high-frequency QPO during the 1998 outburst of 4U 1630–47. This feature was found at 184 Hz and was rather sharp (Q ~ 4). The features in the individual power spectra of regions A and B reported in Section 6.4.2, have comparable frequencies and Q values and are most likely similar to the one reported by Remillard & Morgan (1999).

The PBK relation

In Fig. 6.20a we show the relation between \( \nu_H \) and \( \nu_{LF} \), which are the lower kHz QPO and the lower frequency QPO for the neutron stars. In the original relation
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for the black holes a BLN component was used for the $\nu_l$, and a lower frequency QPO below the BLN for $\nu_{LF}$. Later, the high-frequency features found in black holes were also added to this (and used as $\nu_l$). Fig. 6.20a shows the recently updated version of this relation taken from Belloni et al. (2002) (which also employs the $\nu_{max}$ representation). In the same figure we also show the points of 4U 1630-47; for $\nu_{LF}$ we use the feature designated as L1 (with frequency $\nu_1$) and for $\nu_l$ we use L$_{HF}$. For both the individual power spectra (indicated with squares in Fig. 6.20a) and the average power spectra (indicated with big circles in Fig. 6.20a), we find that all the high-frequency features above 100 Hz fall on the lower branch of the PBK relation, coinciding with the points for XTE J1550-564 (1998/99 outburst; Homan et al. (2001)). Note that if we would have used L$_2$ or L$_3$ as the LF QPO, the 4U 1630-47 points would have shifted up about a factor 1.5-2 in frequency lying just below (in the case of L$_2$) or just above (in the case of L$_3$) the main PBK line.

The agreement of 4U 1630-47 with the PBK relation, and in particular with the measurements of XTE J1550-564, suggests that the high-frequency features detected in 4U 1630-47 are similar to those found in other black holes and show a correlated behaviour between $\nu_{hf}$ and $\nu_1$. However, we do not find a significant correlation (in the individual observations or the average power spectra) between these frequencies for 4U 1630-47. As mentioned in Section 6.4.2, this is may be related to the large errors on $\nu_{HF}$.

In the above we did not include the high-frequency QPOs, discussed in Section 6.4.2 which have a frequency below 100 Hz. These points are indicated in Fig. 6.20a with big stars for the individual observations and with big diamonds for the average power spectra in regions A–F. It is clear from Fig. 6.20a that these points do not follow the PBK relation (along any of the two tracks): $\nu_{HF}$ is lower but the corresponding $\nu_1$ is comparable with the ones found for the other high-frequency features. Because these features do not follow the PBK line, nor show some other kind of correlated behaviour, we regard them as different from the other L$_{HF}$ components.

The WK relation

In Fig. 6.20b we show the relation between the break frequency and the LF QPO (the Wijnands-van der Klis (WK) relation (Wijnands & van der Klis 1999)) for 4U 1630-47. The points of the original WK relation are taken from Belloni et al. (2002). From Fig. 6.20b it is immediately clear that neither with respect to the individual observations nor the average ones does 4U 1630-47 follow the WK relation. We find that the break frequency varies largely independently from the LF QPO: as the break frequency changes only by a factor ~ 2, $\nu_1$ changes by a factor ~ 10–100. These conclusions remain the same whether centroid ($\nu_0$) or $\nu_{max}$ values are used for the frequencies (see also Belloni et al. 2002).

A correlation between the break and the lower frequency QPO is found for regions A and F: we find $r$=0.7 and $r$=0.9 with a significance of 2.8$\sigma$ and 3.6$\sigma$, respectively. Within the other regions there is only evidence for a weak anti-
2-D behaviour and HF QPOs in 1630–47

Figure 6.20 — The Psaltis, Belloni, van der Klis relation (panel a) and the Wijnands-van der Klis relation (panel b). In panel a we show the black hole and neutron star sources from the PBK-relation (Belloni et al. (2002), shown in gray) together with the high-frequency QPO vs. the QPO1 for 4U 1630–47 (both for the individual observations and the average power spectra). In panel b we show the Wijnands-van der Klis relation. The original points are in the $v_0$ representation while the extra points added by Belloni et al. (2002) are given in $v_{\text{max}}$. For 4U 1630–47 the frequencies are given in $v_{\text{max}}$ and for the QPO above the break $L_1$ was used. The points corresponding to the individual observations are indicated using the same symbols as in Fig. 6.2.
correlation. Note that it is also in regions A and F that the break frequency shows an anti-correlation with HC and a correlation with count rate (Section 6.4.1).

The fact that 4U 1630–47 does not follow the WK relation might be related to the fact that Wijnands & van der Klis (1999) predominantly selected sources in the canonical LS with a QPO above the break (in their sample a few VHS/IMS ones might be present; Wijnands, private communication). In Fig. 6.20b we use power spectra during the whole outburst, changing between LS, HS and VHS/IMS. In the one case where we do classify 4U 1630–47 as LS, in region F, we find that those points do not fall on the WK relation (but do show a correlated behaviour between the break and the lower frequency QPO). However, the observations in this region are clearly different from the ones selected by Wijnands & van der Klis (1999): in the first observation the QPO is found above the break, for the rest it is found below it (Fig. 6.10; see also Tomsick & Kaaret (2000)).

Another possible explanation for the difference with the WK can be related to the fact that the noise component (break component) is relatively weak in 4U 1630–47, and hence more difficult to detect in the presence of the other features: Fig. 6.21 and the ones presented in Section 6.3.2 show that the break component is often found below much stronger QPO features, making an identification of the true break frequency more difficult.

**Double high-frequency features**

In the individual power spectra we find on one occasion, in region B, that the high-frequency feature is accompanied by another feature at ~ 4 times lower frequency (Fig. 6.14). In the average power spectra of regions B and D we find features at similar frequencies, again with a 1:4 ratio (Fig. 6.3 and Table 6.3). For other observations in region B we find a high 95 % upper limit of about 2% rms for a similar feature at 1/4 of the frequency of the high-frequency feature. Therefore, it is likely that the feature detected in the average power spectrum in region B at ~ 50 Hz is the result of several undetected ones in the individual observations. The features detected simultaneously in the individual and average power spectra have Q values between ~ 1 and 5 (see Tables 6.3 and 6.2), but when converted to the $v_0$ values the ratio of the frequencies is still consistent with being 1:4.

In Section 6.6.2 we showed that the features below 100 Hz do not follow the PBK relation, nor do they show a consistent relation with the lower frequency QPOs. Furthermore, the 1:4 relation between the double high-frequency features found for 4U 1630–47 is different from the relation found for double high-frequency features in other black hole sources, which is usually 2:3 (Remillard et al. 2002b). This suggests that the anomalous features detected below 100 Hz are not only different from the ones detected above 100 Hz, but they are also different from the lower of the two high-frequency features detected in other black hole sources.

However, during the outburst of other black hole sources, features similar to the ones we find below 100 Hz in 4U 1630–47 are in fact detected. For instance,
during the 2001 outburst of XTE J1650-500 a feature around 50 Hz was detected (Homan et al. 2003a; Kalemci et al. 2003). This feature is present simultaneously with features at higher frequencies (at twice or three times the frequency) and is broad (Q~ 0.2–0.5; Homan et al. (2003a)). Broad features at similar frequencies have been reported for Cyg X-1 and GX 339-4 (Nowak 2000). It is not clear whether these features are all the same, but they might be related to the "hectoHz" QPOs found in neutron stars as suggested by van Straaten et al. (2002). Although the anomalous features in 4U 1630–47 have similar Q and rms values compared to the hectoHz QPOs in for instance 4U 0614+09 and 4U 1728–34 (van Straaten et al. 2002), their characteristic frequencies show relatively large fluctuations compared to the hectoHz features which have a more or less constant frequency (Fig. 6.20a; van Straaten et al. (2002)).

The above shows that it is not clear if the double high-frequency features detected in 4U 1630–47 are similar to the ones found in other black hole sources, however, can a ratio of 1:4 be expected from theoretical arguments? In the disco-seismic model (Wagoner et al. (2001) and references therein) the preferred combination for two types of modes of oscillation is that between a g- (gravity mode) and c-mode (corrugation modes). From figure 1 in Wagoner et al. (2001) we find that a 1:4 ratio between the high-frequency features in 4U 1630–47 leads to the 45 Hz feature being related to a c-mode oscillation and the 178 Hz feature to a g-mode oscillation, with a corresponding mass of ~ 5 M⊙ and a spin of about 0.4. Note that the identification of the lower feature with a c-mode is different to what Wagoner et al. (2001) find for GRO 1655-40: they take the lower QPO to be the g-mode and the upper one to be the c-mode oscillation. Remarkably, Wagoner et al. (2001) report that a 1:4 ratio also occurs naturally if one takes into account non-axisymmetric oscillations (this ratio is almost constant for all values of the spin of the black hole Perez et al. 1997). Then there are two g-mode oscillations: one at the fundamental and one at 4 times that frequency.

In the model of Abramowicz & Kluźniak (2001) it is also possible to get a 1:4 ratio by putting the ratio between the relativistic epicyclic frequency and the relativistic Keplerian frequency equal to 1:4. In principle, only the 1:4, 1:3 and 3:4 resonances are capable of producing a 1:4 ratio in frequency (in the latter two cases we observe the beat between two resonances). All possible resonances give values for the black hole mass between 3 and 14 M⊙ for spins between 0 and 1. However, the larger the integer numbers in the ratio, the more unlikely it is for such a resonance to be observed (Kluźniak & Abramowicz 2002); in the case of the 1:4 ratio the 1:2 and 1:3 ones are likely to be stronger, but these are not observed in the power spectra.

Comparison with other sources

To date, 7 black hole sources are known to show high-frequency QPOs: GRO J1655-40 (Remillard et al. 1999a; Strohmayer 2001a), XTE J1650-500 (Homan et al. 2003a), XTE J1550-564 (Miller et al. 2001b; Homan et al. 2001; Remillard et al. 2002d), GRS 1915+105 (Morgan et al. 1997; Belloni et al. 2001; Re-
Discussions

6.6.1

millard et al. 2002a; Strohmayer 2001b), XTE J1859+227 (Cui et al. 2000; Markwardt et al. 2001a; Belloni et al. 2002), 4U 1630–47 and most recently H 1743–322 (IGR/XTE J1746–3213, Homan et al. (2003b)) was added to this list. In the previous sections we have already shown that, apart from the anomalous features, the high-frequency features detected during the 1998 outburst of 4U 1630–47 are very similar with respect to their frequency behaviour to the features detected in other black hole sources, and in particular to XTE J1550–564. But, where most of the sources that show multiple high-frequency features have 2:3 ratios, 4U 1630–47 shows a 1:4 ratio.

In Fig. 6.21 we compare a power spectrum of 4U 1630–47 in the VHS (observation 9, Table 6.1) with that of the black hole sources XTE J1550–564, GRS 1915+105, XTE J1650–500 in the VHS, and with two power spectra of the neutron star source 4U 1728–34 in the Extreme Island State (EIS) and Island State (IS) state. Panels a–d show very similar power spectra characterized by strong QPOs between 1 and 10 Hz, as often observed in the VHS. Remarkable is the fact that around a few tens of Hz the power, in $v$-$P_v$, increases again: all four black holes show relatively broad high-frequency features around 100–200 Hz. In that respect 4U 1630–47 is very similar to the other black hole sources (regarding the features found above 100 Hz).

For comparison, we also show two power spectra for 4U 1728–34 in the EIS and IS in Figs. 6.21e and f, respectively. The high-frequency end of these power spectra are characterized by broad or sharp features (kHz QPOs), that are found at higher frequencies and have higher rms amplitudes compared to the black hole sources. Sunyaev & Revnivtsev (2000) have recently shown that neutron star systems show more power compared to the black hole sources in the LS; they find that above 10–50 Hz the power spectra of the (LS) black holes decline, while neutron stars show significant power above ~ 500 Hz. We confirm this finding for 4U 1630–47 in the LS (Section 6.3.2), however, Fig. 6.21 not only shows that black holes in the VHS/IMS show an increase in power above 10–50 Hz, but also that they can have significant power up to ~ 200 Hz. Compared to the neutron stars in the EIS and IS (the states in which neutron stars are known to show their strongest high-frequency power) black holes are still different: their high-frequency components have lower rms amplitudes by up to a factor ~ 5 or so (Fig. 6.21), and peak at lower frequencies. A more detailed comparison between black holes and neutron stars will be presented in Chapter 7.

6.6.3 Low-frequency variability

Tomsick et al. (1998); Trudolyubov et al. (2001) and Dieters et al. (2000) already discussed the low-frequency variability of the 1998 outburst in more detail, and found similar changes in the power spectra and behaviour of the dipping and LF QPOs as described above. In this paper the changes in the low (and high) frequency variability in combination with the spectral changes are mainly used to show that the position in the HID determines the power spectral characteristics. For completeness we briefly compare the low-frequency variability to that
Figure 6.21 — A comparison between the power spectra of 4U 1630–47 (panel a, obsID 30178-02-01-01), the black hole sources XTE J1550–564 (panel b, obsID 30191-01-31-01), GRS 1915+105 (panel c, obs ID 20402-01-14-00), XTE J1650–500 (panel d, obs ID 60113-01-12-04) and the neutron star source 4U 1728–34 (panels e and f, obs ID 40033-06-01-00 and 40033-06-03-020, respectively). Notice the similarities between the power spectrum of 4U 1630–47 and that of XTE J1550–564 in panel b. The black hole spectra are obtained in the VHS, and the neutron star power spectra in the EIS (panel e) and the IS (panel f).
found in other sources.

Regarding its low-frequency variability, 4U 1630–47 is very similar to other black hole sources, see for instance Fig. 6.21. In a number of sources persistent low-frequency QPOs have been reported that might be very similar to the dip QPOs, found at ~ 0.1 Hz. In the black hole sources XTE J1118+480 (Haswell et al. 2000; Revnivtsev et al. 2000b; Wood et al. 2000), LMC X-1 (Ebisawa et al. 1989) and GRO J1655–40 (Remillard et al. 1999a) and GRS 1915+105 (Morgan et al. 1997) features are found at 0.07–0.15 Hz, 0.08Hz, 0.1 Hz and 0.067–1.8 Hz respectively. Also, as already mentioned by Dieters et al. (2000), the dip QPOs in 4U 1630–47 are also similar to the so called dips and flip-flops found in GS 1124–683 (Takizawa et al. 1997) and GX 339–4 (Miyamoto et al. 1991; Nowak et al. 1999). For the neutron star sources Her X-1 (Boroson et al. 2000), 4U 1323–62 (Jonker et al. 1999), EXO 0748–676 (Homan et al. 1999) and 4U 1746–31 (Jonker et al. 2000) similar features are found around ~ 1 Hz.

The 1998 outburst of 4U 1630–47 is the first to show strong QPOs around 2–14 Hz. These are very similar to the ones found in other black holes (Fig. 6.21). For instance, XTE J1550–564 (Homan et al. 2001; Remillard et al. 2002d), XTE J1650–500 (Kalemci et al. 2003; Homan et al. 2003a), GRS 1915+105 (Morgan et al. 1997; Munó et al. 1999), GS 1124–68 (Belloni et al. 1997c) and GRO J1655–40 (Mendez et al. 1998; Remillard et al. 1999a) are known to show these strong QPOs that are often found in the VHS/IMS.

The increase in frequency during the rise of the outburst, followed by a decrease during the late decay as found in 4U 1630–47, was also found in a number of other sources like XTE J1650–500 (Kalemci et al. 2003; Rossi et al. 2003) and GRO J1655–40 (Mendez et al. 1998). Assuming the QPO features are related to the Keplerian motion at the inner edge of the disc, this would suggest that during the early rise of the outburst the radius of the accretion disk decreases and the corona becomes less dominant, so that the spectrum softens. During the decay the reverse happens, resulting in lower frequencies and harder spectra (see also Trudolyubov et al. 2001).

In between the rise and decay of the outburst there is a plateau interval, during which all the components in the power spectra remain more or less constant in frequency. During that interval the count rate and rms amplitude remain constant as well, while the SC and HC only show a relatively small monotonic decrease. A similar plateau interval is also found for the 2001/2002 outburst of XTE J1650–500 (Rossi et al. 2003): after the initial increase the frequencies and the spectral index remain more or less constant for a period of several days.

With respect to the relations of the frequency with count rate and spectral hardness for the LF QPOs, XTE J1550–564 and GRO J1655–40 show opposite correlations (Sobczak et al. 2000; Remillard et al. 2002d), while similar QPOs as the dip QPOs reported here show no clear correlations for XTE J1118+480 (Wood et al. 2000) and GX 339–4 (Nowak et al. 1999). For 4U 1630–47 there is a clear difference in the correlations for the dip and the LF QPOs. The latter show a correlation between the frequency and the count rate, and an anti-correlation for
the frequency and the spectral hardness. The dip QPOs on the other hand, show an anti-correlation with count rate and a correlation with spectral hardness.

Although very similar to other black holes, the low-frequency variability could not be classified in the same way as for XTE J1550–564 (Homan et al. 2001; Remillard et al. 2002d). Apparently, the low-frequency behaviour of 4U 1630–47 is more complex than in the other sources.

6.6.4 QPO models

Most of the models that try to explain the QPO phenomenon are based on the assumption of a two-component accretion flow: a spectrally soft, geometrically thin accretion disk in combination with a spectrally hard, geometrically thick corona. Models suggested for the QPOs in black holes include hot blobs rotating at the innermost stable orbit (Morgan et al. 1997), frame dragging effects (Cui et al. 1998; Marković & Lamb 1998; Merloni et al. 1999), discoseismic oscillations (Nowak et al. 1997; Perez et al. 1997), and inertial acoustic instabilities (Milsom & Taam 1997; Honma et al. 1992). The accretion disk with its Keplerian orbits seems a likely location of origin. A link with the soft component is supported by the fact that the QPO frequency is sometimes found to increase with the inferred mass accretion rate through the disk (or the count rate, like in the case presented here). However, generally the QPOs are also related to the spectrally hard component: the strength of the variations (rms amplitude) is positively correlated with the hardness of the spectrum and the QPOs are found to have a hard spectrum. A dependence of the timing features on both the X-ray spectral components is found for many black hole sources, such as for instance XTE J1550–564, GRO J1655–40 (Sobczak et al. 2000) and GRS 1915+105 (Muno et al. 1999).

The fact that the dipping QPOs show different relations with respect to the HC and count rate (Section 6.4), compared to the other features in the power spectra, suggest that these features are produced by a different type of mechanism and/or are produced in a different region. This is supported by the average rms spectra of the dipping QPOs and the LF QPOs in region B, see Fig. 6.22. We calculated these rms values by adding up the individual rms amplitudes of the dipping QPOs and the LF QPOs for all the observations and then averaging this number. It is clear from Fig. 6.22 that the dipping QPOs have a softer spectrum compared to the LF QPOs. This suggests that the dip QPOs might be related to some kind of oscillation that occurs in the (spectrally softer) accretion disc.

As mentioned in Section 6.6.3 features similar to the dip QPOs have been reported in other sources as well. It was suggested by Titarchuk & Osherovich (2000) that these QPOs are caused by vertical oscillations in the disc, known as global disk mode (GDM) oscillations. Their model, which depends mostly on the mass of the compact object and the period of the binary, is capable of reproducing the QPO frequencies for the sources mentioned above (Titarchuk & Osherovich 2000), and it also predicts that the QPO frequency of such a feature is correlated with the spectral hardness.
Figure 6.22 — The average rms spectra of the dip QPOs, indicated with diamonds, and the LF QPOs, indicated with bullets. The figure clearly shows that the dip QPOs have a softer rms spectrum, showing less variation at higher energies compared to the LF QPOs.

For the dip QPOs in 4U 1630–47 we have not only found that the frequency is correlated with the HC, and therefore with the hardness of the spectrum, but also a preliminary analysis has shown that these features have a soft phase lag. In addition to that, we have found that the dip QPOs are present in all the energy bands of RXTE. These characteristics are all representative for the GMD oscillations (Titarchuk & Osherovich 2000) and, therefore, the dip QPOs could correspond to the GMD oscillations that take place in the (outer) soft accretion disc.

The GMD oscillations are vertical oscillations in the disk, hence their detection requires either a high inclination angle or X-ray reprocessing in the outer disk or deformation of the disk to occur (Titarchuk & Osherovich 2000). The relatively high inclination angle found by Kuulkers et al. (1998), implies that perhaps reprocessing is more important here.

The harder rms spectrum (Fig. 6.22) of the LF QPOs as well as the anti-correlation with HC for the LF QPOs, the BLN (break frequency) and the high-frequency features, suggests a relation to the spectrally hard corona. One way of producing such hard QPOs was suggested by Lehr et al. (2000). In their model a thin accretion disk is shrouded by a plane-parallel corona. Soft disk photons undergo repeated inverse Compton scatterings and escape the corona as higher energy photons. Variations, and hence QPOs, that are present in the soft disk flux emerge from the corona as hard-spectrum QPOs. The oscillation in the soft flux itself can still be the result from any of the mechanisms mentioned above,
but because of the much higher frequency the high-frequency features are related to, most likely, Keplerian orbits in the inner part of the soft accretion disk (see also Section 6.6.2).

6.7 Conclusions

We have analysed the complex timing and spectral characteristics of the 1998 outburst of 4U 1630–47 in light of the recently suggested two-dimensional outburst behaviour by Homan et al. (2001) based on the 1998/1999 outburst of XTE J1550–564. We analysed the power spectra of all the 101 individual observations, in order to follow the low and high-frequency behaviour during the outburst as the source moves through the HID and CD. We find that:

- We can classify the outburst into 6 different regions A–F, each one occupying a different location in the HID and CD, and each one characterized by their unique power spectral behaviour;

- During the course of the outburst the source switches between the basic canonical states (VHS/IMS-HS-IMS-LS) and changes its power spectral behaviour accordingly. We find that the canonical states show sub-states that correspond to the regions A–F; transitions between regions do not always correspond to transitions between the canonical states;

- During the decay of the outbursts, a number of flares are found during which the HC, SC and the rms amplitude increases. Most of these flares show changes in power spectra (in rms, frequency and the number of features) in such a way, that its power spectral characteristics are similar to that of another region. During the flares the source moves in the HID: the closer the flare gets to another region, the more similar its power spectrum is to that region;

- During a drop in the light curve, which is associated with an increase in rms and HC, we also find a change in the power spectral behaviour, suggesting that it is not the change in count rate that is important but rather the level it attains through that increase or decrease.

Based on this we conclude that 4U 1630–47 behaves similar to XTE J1550–564 showing an outburst behaviour that is completely determined by two parameters, the HC (or hardness of the spectrum) and count rate (or mass accretion rate). This strongly supports the two-dimensional behaviour suggested by Homan et al. (2001), and shows that it is the position in the HID (or CD but that is less clear) that determines the power spectral behaviour.

The 1998 outburst shows high-frequency features, predominantly found when the source is in the VHS/IMS. We find that:
• in 22 of the 101 individual power spectra high-frequency features are detected in the range of ~ 20–300 Hz, with Q values between 0 and 6 and rms amplitudes between 4–9%;

• the average power spectra also show high-frequency features, between ~ 40–260 Hz, with Q between ~ 0.3 and ~ 5 and 2–6% rms;

• on a few occasions we find two simultaneous high-frequency features, each time with a ratio in frequency of ~ 1 : 4;

• although this ratio is different from the 2:3 ratio that is found for a few other black holes, it can be reproduced in at least two of the models with reasonable assumption for the mass and the spin parameter for the black hole;

In all cases when two features are detected, the lowest ones are always found below 100 Hz. In some cases there are also single high-frequency features below 100 Hz. For all these components we find that they do not follow the PBK relation, while the high-frequency features detected above ~ 100 Hz do. The different ratio and the absence of any correlated behaviour with the lower frequency QPO suggest that the features below 100 Hz are different compared to both the features above 100 Hz in 4U 1630–47 but also compared to the lower of the two features detected in the other black hole sources. It is suggested that they might be related to the hectoHz QPOs.

When only taking the features above 100 Hz into account, we find that:

• the high-frequency features show a correlation with count rate and an anti-correlation with spectral hardness;

• although no significant correlation between the lower frequency QPO and the high-frequency feature was found, 4U 1630–47 does follow the BPK relation coinciding with the points for XTE J1550-564;

• this, together with a comparison with other black hole sources suggests that, 4U 1630–47 shows similar high-frequency features as the other black holes;

Compared to the neutron star sources, black holes show less power and peak at lower frequencies, however, unlike Sunyaev & Revnivtsev (2000) we find that black holes in the VHS/IMS show an increase in power above ~ 10–50 Hz and show significant power up to ~ 200 Hz. An increasing number of black hole sources is showing high-frequency features, but a remark is in order. It is of crucial importance to correctly determine the poisson noise spectrum in the power spectra, as the high-frequency features are only barely detected significantly above the noise. As explained in Appendix 6.8, we suggest a conservative way for determining the poisson spectrum, however, it remains unclear what the exact level must be. Therefore, all claims for significant high-frequency features should be regarded with great care.

Regarding the low-frequency variability we find that:
• 4U 1630–47 does not follow the Wijnands- van der Klis relation, however, on small time scales correlated behaviour between the break frequency and the LF QPO is present;

• With respect to the relations between the frequencies of the features and the HC and count rate, we find that there are two different types of features:

  I the so-called dip QPOs (at frequencies around 0.1 Hz) show a correlated behaviour with HC and an anti-correlation with count rate

  II the break frequency, the LF QPOs and the high-frequency features show an anti-correlation with HC and a correlated behaviour with count rate.

Moreover, we also found that the LF QPOs have a much harder rms spectrum compared to that of the dip QPOs. From this duality we suggest that the dip QPOs originate from global disk mode (GMD) oscillations in the outer thin accretion disc, while the other features most likely are related to some kind of oscillation in the inner part of the thin disk that are also subjected to Inverse Compton scatterings in a corona-type object. Most likely the corona-type object surrounds the inner accretion disk and causes the oscillations in the accretion disk to have a hard component in their spectrum. In this way the QPO features (and also noise components) have a natural dependency of both the soft accretion disk and the hard corona.

The most important result is the fact that the general outburst behaviour is two-dimensional, and that the position in the HID determines the power spectral behaviour. The analysis presented here has clearly shown that using the classification into regions in the HID, that are characterized by their own unique power spectral behaviour and can be considered as sub-canonical states, provides a more detailed view of the black hole transients during outburst.

6.8 Appendix: Noise levels at high frequencies

In the analysis presented here we are especially interested in features that appear in the power spectra at high frequencies (above ~ 100 Hz). In that range the contribution of the source power is usually low compared to that of the Poisson noise. The latter is influenced by the event and VLE (Very Large Events) deadtimes, which cause a detector to be effectively dead after detecting a valid event or an energetic particle, respectively. The Poisson noise spectrum depends on the count rates and the instrumental characteristics and could in principle be determined if the properties of the detectors and associated electronics were precisely known. The deadtime effects are different per detector and energy dependent.

Currently there are at least four different models that describe the Poisson noise spectrum. The model by Zhang (Zhang 1995; Zhang et al. 1995, 1996),
6.8 Appendix: Noise levels at high frequencies

gives the frequency dependent Poisson level \( P \), by:

\[
P_v = 2 - 4r_0t_d \left( 1 - \frac{t_d}{2t_b} \right) - 2 \left( \frac{N - 1}{N} \right) r_0t_d \times 
\left( \frac{t_d}{t_b} \right) \cos (2\pi vt_b) + 2r_{vle}t_{vle}^2 \left( \frac{\sin \pi t_{vle}v}{\pi t_{vle}v} \right)^2
\]  

(6.3)

Here \( P \), is the Poisson level at frequency \( v \), \( N \) is the number of points in the time series, \( t_d \) the event-deadtime, \( t_{vle} \) is the deadtime for the VLE events (the "VLE window"), \( r_0 \) the source count rate per detector, \( r_{vle} \) the VLE count rate per detector, and \( t_b = 1/2\nu_{nyquist} \) the time bin size. It is assumed that the event-deadtime is paralyzable, which means that each incident event causes a deadtime of the detector even if it is not detected, and also that \( t_b > t_d \). The event-deadtime for the proportional counters (PCUs) on board RXTE is supposed to be constant and usually is assumed to be \( t_d = 8.5\mu s \) (Jahoda, private communication). The Very Large Event (VLE)-window, \( t_{vle} \), is the deadtime for the VLE events. There are four different settings for the VLE-window: \( \sim 12, 60, 150 \) or \( 500 \mu s \) of which \( 150\mu s \) is the standard setting. The second and third term in formula 6.3 describe the effects of the event deadtime on the Poisson level, while the last term describes the effect of the VLE deadtime. In the model by Zhang, all the parameters are fixed.

In the model by Vikhlinin et al. (1994) the Poisson spectrum is calculated in a different way as in the Zhang model starting from very similar assumptions, and the results are virtually identical to those calculated with formula 6.3. A variation on this model was proposed by Revnivtsev et al. (2000a). They use the formula from Vikhlinin et al. (1994), however, besides the Good Xenon counts also the Remaining and Propane count rates are included in \( r_0 \), and \( r_{vle} \) is not fixed while fitting this function to the Poisson level (Revnivtsev et al. 2000a).

Finally, Jernigan et al. (2000) also use formula 6.3 but an extra term is added to take into account the oscillating power spectrum observed in background observations, which for low count rates might become an important effect. Jernigan et al. (2000) find that the contributions of this effect, which would manifest themselves with maxima around 4000 and 8000 Hz and minima at 2000 and 6000 Hz, are not a significant component. For the 1998 outburst of 4U 1630–47 the count rates are relatively high, and these oscillations are not evident. Therefore, we did not investigate this model further.

We compared the three remaining models by fitting them to the power spectra of Cyg X-3. For this source no significant source power is expected above \( \sim 1 \)Hz. We chose observations in the same period (P30082), with comparable count rates (on average \( \sim 2500 \) cnts/sec) and with similar settings (VLE window is \( 150\mu s \)) as for the 4U 1630–47 data presented here. We find that the model by Revnivtsev et al. (2000a) is not capable of describing the Poisson level: below \( \sim 2000 \) Hz the predicted level is too high and above \( \sim 2000 \) Hz, where no source power is expected, it is too low. Certainly, using the extra counts in the normalisation of the power spectrum, as suggested by Revnivtsev et al. (2000a)
cannot be correct: the normalisation of the power spectrum must be performed by the analysed count rate, which are only the Good Xenon counts. The predicted Poisson spectrum is more strongly curved than the actual data, which based on some experiments we attribute to including the extra counts as explained above. We fitted this model also to observations of 4U 1630–47 and found similar results. Based on this, we decided not to use this model. Note, that the fact that the model seems to work for Cyg X-1, as explained by Revnivtsev et al. (2000a), might be a coincidence precipitated by the fact that the Cyg X-1 observations had a different VLE window compared to the observations of Cyg X-3 and 4U 1630–47.

We will discuss the Vikhlinin model (Vikhlinin et al. 1994) and the Zhang model (Zhang 1995; Zhang et al. 1995, 1996) simultaneously as they give comparable results. We compared both models to the Cyg X-3 data with all the parameters fixed to their nominal values (the count rate, VLE rate, event dead time and VLE window are fixed to the values obtained from the data), and found acceptable $\chi^2_{\text{reduced}}$ of ~1. We also experimented with setting one or more parameters free to vary and performing a fit. This often resulted in the Poisson function fitting a local trend with unacceptable values for the parameters (changes by 30% or more) and/or a bad fit in the low-frequency range.

Next, we compared both the Zhang and the Vikhlinin models to the data of 4U 1630–47 in a frequency range that is free from source power. For this, the range 3000–4096 Hz was chosen. When evaluating the match to the 4U 1630–47 data in that range by the Zhang and the Vikhlinin models, we find that both describe the shape of the Poisson spectrum equally well. Figures 6.23a and b show that the difference between the unshifted models is very small: we find an effect on the rms amplitude for a high-frequency feature at 164 Hz with a rms amplitude of 6.2% in the order of 0.01 % rms. However, Figs. 6.23c and d show that the models have a small offset from the data. To correct for this, one of the parameters in the Poisson model could be set free to vary. For instance the count rate can introduce an overall shift. However, as we also found for Cyg X-3 setting one or more parameters free and then fit in the 3000–4096 Hz range resulted in fitting a local trend which gives unacceptable values for the parameters and/or an unacceptable fit in the low-frequency range. Hence instead we introduced a scaling factor, that introduces an overall shift without changing the shape of the Poisson spectrum. Fig. 6.23 shows how for the average power spectra of regions A and B, the Poisson model predictions can be shifted so that they match the data in the high-frequency end of the power spectrum, where no source power is expected. After shifting the Zhang and Vikhlinin model give comparable results (Figs. 6.23a, b). Only in the frequency range much below 3000 Hz the Zhang model dominates slightly. Because our aim is to find a conservative model for the Poisson spectrum, we prefer the shifted Zhang model over the shifted Vikhlinin model.

The scaling of the Zhang function is a purely empirical procedure based on the observation that the function predicts the correct shape of the Poisson spec-
### 6.8 Appendix: Noise levels at high frequencies

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**Figure 6.23** — A comparison between the Zhang and the Vikhlinin models fitted between 3000 and 4096 Hz for the average power spectra in region A (panel a) and B (panel b). In panels c and d we show the Zhang function (shifted and un-shifted) together with the data. Notice the difference in scaling used for the top and bottom panels.
trum, but with a slight offset. There is no apriori best way to perform this scaling. For instance one could scale only on the event deadtime effects or only on the VLE deadtime effects, and the scaling could be either additive or multiplicative. We find that these various scaling methods give differences in the final rms amplitude of much less than 1% of the source variability, and decided in favour of multiplicative scaling of the overall function. The scaling factor is always very small, between 0.998 and 1.0009.

From Fig. 6.23 it is clear that shifting the Zhang model makes the high-frequency features stronger. To investigate by how much we calculated the rms amplitude of the high-frequency features in the average power spectra in regions A and B using the original and the shifted Zhang function. For region A we find a feature at 164 Hz with an rms amplitude of 6.2% (Table 6.3). The shifted and unshifted Zhang model give a difference of ~ 0.05% rms in the amplitude of this feature, which is a change of less than 1%. In the case of region B, with a feature at 187 Hz and 3.6% rms, we find a difference in amplitude of about 0.54% rms: a change of about 14%. Only for region B, in both the average power spectrum and some of the individual power spectra, a change of this magnitude is found; for all the other regions and the individual power spectra the differences are smaller. On average we find a difference between the shifted and un-shifted Zhang model in the same order as for region A: a change in rms amplitude of less than 1%. We also found that the frequencies of the Lorentzian components were not affected by a significant amount.

Previous authors (Jernigan et al. 2000; Sunyaev & Revnivtsev 2000, eg.) have already suggested to ignore the lower (0-7) PCA energy channels to eliminate an instrumental feature from the power spectra. Indeed, after subtraction of the scaled Zhang function, the power spectrum of 4U 1630–47 shows high-frequency features that have different characteristics in different energy bands. We find in the lowest energy bands (PCA channels 0–13 or 0–17 corresponding to ~ 1.9–5.1 keV and ~ 1.9–6.5 keV) broad (Q~0–0.3), strong (5.8–7.8 % rms) features at characteristic frequencies ranging from 460 Hz to 1014 Hz. In the higher energy bands the overall trend is that all the frequencies are lower (between 60 and 260 Hz) and the features are more peaked (Q values ranging from 0 to 6). We compared the energy behaviour of the power spectra of two other sources, Cyg X-3 and GX 13+1, and selected observations with similar settings and count rates, all taken around the same time as the ones of 4U 1630–47. In Cyg X-3 we find a 9.9 % rms feature at \( v_{\text{max}} \sim 900 \) Hz in the band 0–13 when we determine the Poisson spectrum (with the shifted Zhang function) between 3000–4096 Hz. In the higher energy ranges we find no significant power with upper limits well below the 20–300 Hz features found in the same energy bands in 4U 1630–47. For GX 13+1 we find a 8.1% rms feature at \( v_{\text{max}} \sim 1960 \) Hz in the lowest energy band, while the highest energy bands again do not show significant features. The features found in the lowest energy bands in 4U 1630–47 share resemblance with those detected in Cyg X-3 and GX 13+1. Therefore, we also excluded PCA channels 0–13 for proposal P30172 and 0–17 for proposals P30178 and P30188, as the
Single Bit data that was used does not allow for smaller bands to be excluded.

To summarise, we used the following method for estimating the Poisson noise corrected power spectrum:

- ignore PCA channels 0–7, (in our case 0–13 and 0–17);
- evaluate the Zhang function (Zhang 1995; Zhang et al. 1995, 1996) to describe the effects of the event and VLE deadtime, using $8.5\mu s$ for the event deadtime, the value of the VLE window recorded in the satellite house keeping data, and using the Good Xenon count rates and VLE rates recorded in the high time-resolution data used for the timing analysis (Event, Single Bit or Good Xenon data);
- apply a multiplicative factor, scaling the Zhang function to the data in a range where no source power is expected, in our case 3000–4096 Hz.

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