Low- and high-frequency variability as a function of spectral properties in the bright X-ray binary GX 5–1

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ABSTRACT

We report on a detailed analysis of data obtained over nearly four years with the Rossi X-ray Timing Explorer of the Z source GX 5–1. From a spectral analysis using a hardness–intensity diagram it was found that the source traced out the typical Z-shaped pattern. The study of the power spectral properties showed that when the source moved on the horizontal branch towards the normal branch the fractional rms amplitudes and time-scales of all variability decreased, while their FWHMs increased. The frequency separation of the two kHz QPO peaks decreased from 344^12 to 232^13 Hz, while the frequency of the lower and upper kHz QPO increased from 172^10 to 608^6 Hz and from 516^10 to 840^12 Hz, respectively. At low frequencies, besides the horizontal branch oscillation (HBO) and its second harmonic, two additional broad Lorentzian components were needed to obtain acceptable fits. These broad Lorentzians have Q-values of ~1–2 and frequencies 0.5 and 1.5 times the HBO frequency. When interpreted as being related to the HBO, they seem to favour disc models for the HBO over the magnetic beat-frequency model. The frequency of the normal branch oscillations changed slightly and non-monotonically, while on the normal branch between ~6 Hz at both ends and 5.25 ± 0.05 Hz near the middle of the branch. It evolved into a flat-topped noise component on the flaring branch. We compared the timing properties of the some of the Z sources. We also compare the timing properties and colour–colour diagrams (CDs) of GX 5–1 with those of the back hole candidate XTE J1550–564 and the atoll source 4U 1608–52. The CDs are strikingly similar when a colour scheme commonly employed in back hole studies is used. However, this may be a degeneracy as the CDs turn out to be more complicated when colours common in neutron star studies are employed. Apart from some remarkable similarities between the CD of XTE J1550–564 and that of 4U 1608–52, several differences can be seen between these CDs and that of GX 5–1. Conclusions on spectral states or properties based solely on the use of CDs using the ‘black hole scheme’ should be regarded with caution.

Key words: accretion, accretion discs – stars: individual: GX 5–1 – stars: neutron – X-rays: stars.

1 INTRODUCTION

Low-mass X-ray binaries (LMXBs) are systems where the compact object, either a neutron star or a black hole, accretes matter from a companion with a mass of less than 1 M\(_\odot\). The neutron-star LMXB systems are subdivided on the basis of the pattern they trace out in an X-ray colour–colour diagram or a hardness–intensity diagram (CD or HID, respectively) in atoll and Z sources (Hasinger & van der Klis 1989). The X-ray flux measurements combined with the knowledge of the distance have shown that Z sources have a high luminosity (~L\(_{\text{Edd}}\)) and accrete at a rate close to the Eddington accretion rate, whereas atoll sources...
have typical luminosities and inferred accretion rates 5–100 times lower (see, e.g., the compilation of source luminosities by Ford et al. 2000). The three branches of the Z traced out in a CD or HID by Z sources are called (from top to bottom) horizontal branch, normal branch and flaring branch.

Studies of the X-ray variability of Z sources revealed two types of quasi-periodic oscillations (QPOs) with frequencies less than 100 Hz (horizontal branch oscillations, HBO, and normal branch oscillations, NBO), twin kHz QPO peaks, and three types of rapid flickering (‘noise’), the very low-frequency noise (VLFN), the low-frequency noise (LFN), and the high-frequency noise (HFN) (see van der Klis 1995, 2000 for reviews). The properties of noise features and the HBOs, such as the central frequency and the fractional rms amplitude, are strongly correlated with the position of a source along the horizontal branch. These correlations, together with the observed increase in the ultraviolet flux in the Z source Sco X-1 (Vrtilek et al. 1991) when the source moves from the horizontal branch via the normal branch to the flaring branch lend support to the idea that the mass accretion rate increases from the horizontal branch via the normal branch to the flaring branch (see van der Klis 1995).

However, recent observations Wijnands et al. 1996; Di Salvo et al. 2000; Homan et al. 2002), together with problems noted before (most notably secular motion of the Z track; Kuulkers et al. 1994), show that the situation may be more complex (e.g. van der Klis 2001).

KHz QPOs have now been seen in just over 20 LMXBs, including all Z sources (van der Klis 1998, 2000). Potentially they can provide a key to measure the basic properties of neutron stars (spin rates and perhaps magnetic field strengths, radii and masses) and thereby constrain the equation of state of ultradense matter, and to verify untested general relativistic effects by tracing space–time just above the neutron star surface (e.g. Kluzniak 1993; Kaaret, Ford & Chen 1997; Zhang, Strohmayer & Swank 1997; Miller, Lamb & Psaltis 1998; Stella & Vietri 1999; Psaltis & Norman 2001). The discovery of kHz QPOs in GX 5–1 was reported by Wijnands et al. (1998). The HBOs were discovered by van der Klis et al. (1985), and the NBOs in GX 5–1 by Lewin et al. (1992). The source was also detected at radio (Braes, Milely & Schoenmakers 1972) and infrared wavelengths (Jonker et al. 2000). In this paper we present an analysis of all RXTE observations of GX 5–1 obtained before 2001. We show for the first time that the kHz QPO separation frequency is not constant in GX 5–1. We show that besides the two harmonically related low-frequency QPOs found previously on the horizontal branch, two additional harmonically related broad Lorentzian components are needed to obtain a good fit. We discuss the power spectra and CDs of the black hole candidate XTE J1550–564, the Z source GX 5–1, and the atoll source 4U 1608–52, and conclude that there are some remarkable similarities and differences that have not been appreciated in the past due to differences in analysis conventions between, in particular, neutron stars and black hole candidates.


2 OBSERVATIONS AND ANALYSIS

GX 5–1 was observed 76 times in the period spanning 1996 July 27 to 2000 March 3 with the proportional counter array (PCA; Jahoda et al. 1996) on board the Rossi X-ray Timing Explorer (RXTE) satellite (Bradt, Rothschild & Swank 1993). A log of the observations is presented in Table 1. The total observing time was \( \approx 564 \) ks. During \( \approx 40 \) per cent of the time only a subset of the five detectors was active. Two short observations (2 and 4) were omitted from our analysis due to data overflows. Data were always obtained in a mode providing 16-s time resolution and a high spectral resolution (129 channels covering the effective 2–60 keV range; the Standard 2 mode). In addition, a variety of high time-resolution modes was used in the various observing campaigns; for all observations data with a time-resolution of at least \( 2^{-11} \) s were obtained in the energy band spanning 2–60 keV.

From the Standard 2 data we computed HIDs. We only used data obtained with the two detectors (proportional counter units 0 and 2) that were always operational, since each detector has a slightly different energy response. The background was subtracted using the standard PCA background subtraction model version 2.1e, where we used the version of the skyvle model appropriate for data from each epoch. The hardness, or hard colour, and intensity are defined as the logarithm of the 10.2–17.5/6.5–10.2 keV count rate ratio and as the count rate in the 2.5–17.5 keV band of a 16-s average, respectively, \( \text{RXTE} \) energy channels 25–44/14–24 and 3–44, respectively. The high voltage setting of the PCA detectors was changed on 1999 March 22 (i.e., the gain changed). Combined with the finite energy resolution this forced us to use somewhat different energy boundaries in our computation of the HID for data obtained after 1999 March 22 (i.e., 10.1–17.6 keV/6.6–10.1 keV for the hard colour and 2.6–17.6 keV for the intensity for observations 42–76; we used \( \text{RXTE} \) energy channels 20–36/11–19 and 2–36, respectively). Besides the gain change the energy response of the detectors changed slowly with time. These various changes have been partially corrected for using the Crab pulsar as a reference, under the assumption that the spectrum of the Crab pulsar does not vary. This correction is perfect only if the spectral shape of GX 5–1 is equal to that of the Crab (the steps involved in this correction were outlined in Di Salvo et al. 2001 and Jonker et al. 2001). So, a small systematic error is introduced both by the correction for the drift in detector response and the slightly different energy boundaries which we used as a result of the gain change. Together with the secular variation of the source (Kuulkers, van der Klis & Vaughan 1996) this led us to compute five separate HIDs combining observations 1–7, 8–18, 19–26, 27–41, 42–76 (see Fig. 1, left-hand panel, and Table 1).

In Fig. 1 (right-hand panel) the five HIDs are overplotted. The source was found on the horizontal branch, normal branch and flaring branch in four of the five HIDs; for the HID of observations 42–76 the source was not found on the horizontal branch. The position of the source along the Z track is characterized by a parameter called \( S_z \) representing curve length along the track (Hasinger et al. 1990; Hertz et al. 1992). The Z tracks were parametrized by fitting a spline through manually selected points along the track in each of the five HIDs separately. The \( S_z \) values are determined using the logarithm of the colours and count rate (Wijnands et al. 1997b) and normalized by assigning the hard vertex (the horizontal branch–normal branch junction) the value ‘1’ and setting the soft vertex (the normal branch–flaring branch junction) to ‘2’. This defines the measure of curve length, and therefore \( S_z = 0 \) and \( S_z = 3 \) are not special points or vertices. We applied this parametrization to the HID obtained from each of the subsets. The track traced out by the source during observations 42–76 only covers part of the Z. In order to calculate the \( S_z \) values along this track, we assumed that the hard vertex in that data set was at the same position relative to the soft vertex as in the HID of observations 27–41.

**Figure 1.** Left-hand panel: Hardness–intensity diagrams for observations 1–7, 8–18, 19–26, 27–41, 42–76. Right-hand panel: Hardness–intensity diagram of all observations combined. The hard colour is the logarithm of the 10.2–17.5/6.5–10.2 keV count rate ratio for observations 1–41 and that of the 10.1–17.6 keV count rate ratio for observations 42–76. The intensity is the 2.5–17.5 keV (observations 1–41), and the 2.6–17.6 keV (observations 42–76) count rate. The data were background-subtracted and corrected for changes in the energy response of the PCA detectors (see text), but no deadtime corrections were applied (the deadtime correction is \(<4\) per cent). Typical error bars (not including systematic errors) are shown at the bottom right of the figure in the right-hand panel.
Using the high time-resolution data we calculated power-density spectra (2–60 keV) of data stretches of 16 s, up to a Nyquist frequency of 2048 Hz, using a Fast Fourier Transformation algorithm. The power spectra were normalized to fractional rms amplitude squared per Hz, added, and averaged according to their position along the Z track (the selection method will be described in detail below). Due to the relatively low amplitude of the variability in the high-frequency part of the power spectrum, simultaneous fits of the entire frequency range would not constrain the properties of the high-frequency part. Therefore we fitted the low (1/16–128 Hz) and high (∼128–2048 Hz) frequency parts of the power spectra separately. The low-frequency part of the average power spectra was fitted with a function consisting of an exponentially cut-off power law to describe the noise at low frequencies (LFN) and at most five Lorentzians to fit the QPOs. The component arising in the power spectrum due to the Poisson counting noise was subtracted. For values of \( S_z > 1.0 \) a power law was added to the fitted function to fit the very low-frequency noise (VLFN). The function used to describe the high-frequency part of the average power spectrum was built up out of two Lorentzians describing the kHz QPOs. Contrary to when we fit the low-frequency part, the continuum due to Poisson noise was not subtracted prior to fitting, and so we included a constant to account for this Poisson noise. Sometimes also a power-law component was added to account for the slope of the underlying continuum, caused by the high-frequency tail of one of the low-frequency components. The high-frequency tail did not systematically influence our fit parameters.

From previous studies of GX 5–1 and other Z sources it is known that the frequency of the QPOs on the horizontal branch (the HBOs and the kHz QPOs) increases with \( S_z \) (Wijnands et al. 1998; Dieters & van der Klis 2000; Jonker et al. 2000b; Homan et al. 2002). For all but the HID of observations 42–76 (when the source was not found on the horizontal branch or the upper part of the normal branch and therefore no HBOs were present in the power spectra; see Fig. 1, left-hand panel) we studied the relation between \( S_z \) and HBO frequency. These relations, plotted in Fig. 2, have two notable properties. First, the relation found for observations 27–41 is clearly offset from the other relations. This is an effect of secular motion of the source during the gap between the observations 27–35 and 36–41. During the first nine observations (27–35) the source was found on the horizontal branch, whilst, after a 9-day gap, during observations 36–41 the source traced a part of the horizontal branch close to the normal branch, the normal branch, and the flaring branch. We checked the vertices of the five HIDs to search for additional evidence of secular motion but, in view of the uncertainties involved in their manual selection, we conclude that the vertices of the five HIDs were not significantly different. The second notable property involves the jump in HBO frequency near \( S_z \sim 1 \) (see also plots in Wijnands et al. 1998). To investigate the nature of the jump further, we plotted the hard colour versus the frequency of the HBO. A discontinuity in the rate of change in frequency as a function of hard colour was also observed in the hard colour versus frequency plot at a frequency of ∼50 Hz. Therefore the jump in frequency when plotted versus \( S_z \) is not an artefact of the \( S_z \) parametrization. We investigated whether a similar jump was present in the frequencies of the kHz QPOs, but we lacked sufficient signal-to-noise ratio to conclude on this.

In order to combine all power spectra with similar HBO frequencies, we shifted all \( S_z \)–HBO frequency relations to one ‘parent’ relation. To this end, we fitted a polynomial to the relation between \( S_z \) and HBO frequency for each of the HIDs separately.

We included only measurements for \( S_z < 1.0 \) in the fit. The order of the polynomial was determined such that the reduced \( \chi^2 \) of the fit was ∼1. The parent relation for \( S_z < 1.0 \) is the best linear fit to the \( S_z – \)HBO frequency relation for all the HIDs combined (\( \chi^2 \) = 9.9 + 36.8 \( S_z \)); the drawn line in Fig. 2). The shifting procedure works as follows: given the \( S_z \) value (\( S_z^{\text{initial}} \)) obtained from the HID corresponding to the observation from which the power spectrum is calculated, the HBO will have a certain predicted frequency which follows from the \( S_z – \)HBO frequency relation found for that HID. That predicted HBO frequency corresponds, the given \( S_z – \)HBO frequency parent relation, to a \( S_z^{\text{parent}} \). This \( S_z^{\text{parent}} \) is then assigned to the power spectrum instead of \( S_z^{\text{initial}} \) (the change of \( S_z \) corresponds to a horizontal shift in Fig. 2). This shifting procedure was done for each 16-s power spectrum separately. Finally, all power spectra were selected according to their \( S_z^{\text{parent}} \) values for \( S_z < 1.0 \); the selection bin width was 0.1. For \( S_z > 1.0 \) the unshifted values obtained from each separate HID were used in the selection, since both the secular motion and the effects of the changes in the response move the Z track in a direction nearly perpendicular to the normal branch. Here the selected bin width was 0.05. The selected power spectra were averaged and fitted with the function described above.

The errors on the fit parameters were determined using \( \Delta \chi^2 = 1.0 \) (1σ, single parameter). The error on \( S_z \) is the standard deviation of the distribution of \( S_z \) values in one selection bin. In cases where components were not significantly detected, 95 per cent confidence upper limits were determined using \( \Delta \chi^2 = 2.71 \). The full-width at half-maximum (FWHM) of the Lorentzians was fixed at 10 Hz in case an upper limit was determined to the sub-HBO, its third harmonic or the second harmonic of the HBO, and at 30 Hz in case...
of the first harmonic (which is the fundamental) of the HBO. The frequency of the component for which an upper limit was determined was not fixed, but restricted to a range of values around that expected on the basis of the observed trends. Upper limits to the presence of kHz QPOs were determined using a FWHM of 75 Hz.

3 RESULTS

3.1 Spectral states

The source was found on the horizontal branch, normal branch and flaring branch. Note the clear ‘dipping flaring branch’ trailing the flaring branch (see Fig. 1 and also Kuulkers et al. 1994). GX 5–1 was found to reside most often on the normal branch during the time of our observations (see Fig. 3, upper panel). The average velocity along the Z track (defined as the average of $V_z(i) = S_z(i + 1) - S_z(i - 1)/T(i + 1) - T(i - 1)$; Wijnands et al. 1997b; Fig. 3, lower panel) was approximately constant for $S_z < 1$, but gradually increased for $S_z > 1$, i.e., in anticorrelation with the time the source spent in each part of the Z diagram, although the product of the two is not exactly constant. Note that the average velocity along the Z track also increased towards the lowest $S_z$ values.

3.2 Low-frequency power spectra

We found two new components in the averaged power spectrum of GX 5–1. One of these components was located at frequencies consistent with half the frequency of the HBO, the so-called sub-HBO. This component was reported before in the Z sources Sco X-1, GX 340+0, and GX 17+2 with RXTE (Wijnands & van der Klis 1999; Jonker et al. 2000b; Homan et al. 2002). The second new component has a frequency which is consistent with 3 times the frequency of the sub-HBO (or 1.5 times the frequency of the HBO; see Fig. 4). Fitting the average low-frequency (1/16–256 Hz) power spectrum of $S_z = 0.60 \pm 0.03$ with a function consisting of a cut-off power law (LFN), and three Lorentzians (sub-HBO, HBO, and 2 second harmonic of the HBO) a $\chi^2$ of 383 for 209 degrees of freedom was obtained. Adding a fourth Lorentzian component at frequencies $\sim 3$ times the frequency of the sub-HBO gave a $\chi^2$ of 314 for 206 degrees of freedom. An $F$-test (Bevington & Robinson 1992) to the $\chi^2$ of the fits with and without the fourth Lorentzian revealed that the probability that the reduction in $\chi^2$ could be achieved by a random process is $6.5 \times 10^{-3}$, i.e., the significance of the addition of the fourth Lorentzian component is $\sim 6\sigma$. For the other power spectra where this component was found a similar value was obtained. Although this component is too broad to

Figure 3. Upper panel: Percentage of the total observing time spent in each $S_z$ interval as a function of the $S_z$ value. During our observations the source spent most of the time on the normal branch ($S_z$ values between 1 and 2). Lower panel: The average velocity (see text) of the source along the Z track. The average velocity was approximately constant for $S_z < 1$ (except towards the lowest $S_z$ values where it increased), but steadily increased for $S_z > 1$.

Figure 4. Left-hand panel: The frequencies of the four Lorentzian components used to fit the average power spectra for $S_z < 1.5$, plotted against the frequency of the HBO. The lines represent 0.5 (dashed line overlaying the crosses), 1.0 (drawn line overlaying the filled circles), 1.5 (dot-dashed line overlaying the plus symbols), and 2.0 (dotted line overlaying the squares) times the HBO frequency. Error bars are plotted, but in several cases they are smaller than the size of the symbols. Right-hand panel: The $Q$-values of the four harmonics. The HBO and its second harmonic have $Q$-values near 5 over the range where they are detected simultaneously; thereafter the HBO coherence drops steadily. The $Q$-values of the sub-HBO and its third harmonic are around 1, with only a slight increase between $S_z \sim 0.1$ and $S_z \sim 0.8$. Error bars are omitted for clarity, but they are a few times larger than the size of the symbols. The same symbols as in the left-hand panel have been used.
Table 2. Best-fitting parameters of the Lorentzian components of the low-frequency power spectra (2–60 keV) as a function of $S_z$.

<table>
<thead>
<tr>
<th>$S_z$ value</th>
<th>Freq. sub. (Hz)</th>
<th>HBO freq. (Hz)</th>
<th>FWHM HBO (Hz)</th>
<th>HBO rms. amp.</th>
<th>LFN hr. freq. (Hz)</th>
<th>LFN rms. amp.</th>
<th>LFN FWHM (Hz)</th>
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<tr>
<td>0.12 ± 0.03</td>
<td>2.5 ± 0.2</td>
<td>7.0 ± 1</td>
<td>7.0 ± 1</td>
<td>0.02 ± 0.01</td>
<td>3.0 ± 0.1</td>
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<td>0.31 ± 0.03</td>
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<td>7.3 ± 0.4</td>
<td>12.0 ± 0.5</td>
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Parameter fixed at this value. $^a$Parameter is the weighted average of two Lorentzians (see text). $^b$The error on $S_z$ is the standard deviation of the distribution of $S_z$ values in the selection bin.

The fractional rms amplitude (integrated between frequencies ranging from 0 to $\infty$) of all the low-frequency Lorentzian components (excluding the NBO) decreased as a function of $S_z$ (see Fig. 6, upper panels, and Table 2). For $S_z = 1.0\sim 1.5$ the frequency and the fractional rms amplitude of the HBO were consistent with being constant at $\sim 50$ Hz and $\sim 2$ per cent, respectively. For $S_z > 1.5$ the HBO was not detected with an upper limit of 1.2 per cent. The FWHM of the Lorentzian components increased as a function of $S_z$ (see Fig. 6, lower panels, and Table 2).

The fractional rms amplitude of the LFN (0.1–100 Hz) decreased from $7.4 \pm 0.3$ to $3.38 \pm 0.02$ per cent as $S_z$ increased from 0.12 ± 0.03 to 1.01 ± 0.02 (Table 3). The LFN component could not be measured for $S_z > 1$. The LFN power-law index increased from $0.07 \pm 0.05$ to $0.41 \pm 0.01$, while the cut-off frequency increased from 2.9 ± 0.5 Hz to $\sim 60$ Hz. For $S_z > 1$ we added a power law to the fit function to represent the power at frequencies below 1 Hz, the VLFN. The VLFN fractional rms amplitude (0.001–1 Hz) increased from less than 1 per cent at the hard vertex to more than 20 per cent at $S_z > 3.0$. This increase was gradual for $S_z < 2.0$ but steep for $S_z > 2.0$ (see Fig. 7 and Table 3). The VLFN power-law index gradually increased to 1.5 and remained constant for $S_z < 2.0$, for $S_z > 2.0$ the power-law index was consistent with 2.
The fractional rms amplitude is anticorrelated with the frequency $\nu$:

\[
\nu \propto S_z^{-3}
\]

The frequency of the NBO decreased from $6.1 \pm 0.3$ Hz at $S_z = 1.07 \pm 0.02$ to $5.25 \pm 0.05$ Hz at $S_z = 1.33 \pm 0.02$, before it increased again to $6.1 \pm 0.1$ Hz at $S_z = 1.82 \pm 0.03$. For $S_z > 1.9$ its frequency could not be determined with high accuracy, since the FWHM increased to 8 Hz. The fractional rms amplitude of the NBO varied between $1.69^{+0.05}_{-0.09}$ and $2.38 \pm 0.03$ per cent for $S_z = 1.07 \pm 0.02$ and $S_z = 1.52 \pm 0.02$, respectively, but it decreased to $\sim 1.14 \pm 0.05$ per cent at $S_z = 1.95 \pm 0.05$. The somewhat erratic behaviour in the fractional rms amplitude of the NBO between $S_z = 1.3$ and 1.5 can be explained by the fact that the HBO was very broad and had power in the same frequency range as the NBO. The fractional rms amplitude is anticorrelated with the frequency and FWHM of the NBO (see Fig. 8). At $S_z < 1.0$, stringent upper limits on the presence of the NBO were derived.

At $S_z > 2.0$ the NBO was not detected, but instead a cut-off power law was fitted to represent the power at frequencies comparable to the NBO frequencies. This cut-off power law was peaked (power-law index of $-0.9 \pm 0.2$) near the soft vertex, with power-law index $-0.9 \pm 0.2$ and evolved into a flat-topped noise component at $S_z = 2.15 \pm 0.05$ with a typical power-law index of 0.3. The cut-off frequency increased from $4.3 \pm 0.6$ to $25.1 \pm 3$ Hz. The fractional rms amplitude ($0.001$–100 Hz) increased from $1.68 \pm 0.07$ per cent at $S_z = 2.05 \pm 0.05$ to $2.07 \pm 0.05$ per cent at $S_z = 2.15 \pm 0.05$. For $S_z > 2.15$ the fractional rms

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Table 3. Best-fitting parameters of the cut-off power law, the power law, and the NBO component of the low-frequency power spectra (2–60 keV) as a function of $S_z$.  

<table>
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<tr>
<th>$S_z$ value&lt;sup&gt;a&lt;/sup&gt;</th>
<th>LFN frac. rms amp. (%)</th>
<th>Power law index</th>
<th>Cut-off freq. (Hz)</th>
<th>VLFN frac. rms amp. (%)</th>
<th>Power law index</th>
<th>NBO frac. rms amp. (%)</th>
<th>FWHM NBO (Hz)</th>
<th>Freq. NBO (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.12 ± 0.03</td>
<td>7.4 ± 0.3</td>
<td>7e-2 ± 2e-2</td>
<td>2.9 ± 0.5</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>0.21 ± 0.03</td>
<td>7.57 ± 0.06</td>
<td>2e-2 ± 1e-2</td>
<td>2.97 ± 0.1</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>0.31 ± 0.03</td>
<td>7.29 ± 0.06</td>
<td>1e-2 ± 2e-2</td>
<td>3.43 ± 0.1</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>0.40 ± 0.03</td>
<td>7.06 ± 0.06</td>
<td>7e-2 ± 2e-2</td>
<td>4.32 ± 0.2</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>0.50 ± 0.03</td>
<td>6.83 ± 0.05</td>
<td>0.11 ± 1e-2</td>
<td>5.4 ± 0.2</td>
<td>...</td>
<td>...</td>
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<td>...</td>
<td>...</td>
</tr>
<tr>
<td>0.60 ± 0.03</td>
<td>6.48 ± 0.05</td>
<td>0.20 ± 1e-2</td>
<td>7.4 ± 0.3</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>0.70 ± 0.03</td>
<td>5.42 ± 0.07</td>
<td>0.26 ± 1e-2</td>
<td>8.7 ± 0.5</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>0.80 ± 0.03</td>
<td>4.81 ± 0.09</td>
<td>0.37 ± 1e-2</td>
<td>15 ± 1</td>
<td>&lt;0.4</td>
<td>1&lt;sup&gt;a&lt;/sup&gt;</td>
<td>&lt;0.4</td>
<td>10&lt;sup&gt;a&lt;/sup&gt;</td>
<td>...</td>
</tr>
<tr>
<td>1.01 ± 0.03</td>
<td>4.65 ± 0.02</td>
<td>0.48 ± 1e-2</td>
<td>68 ± 2</td>
<td>&lt;0.5</td>
<td>1&lt;sup&gt;a&lt;/sup&gt;</td>
<td>&lt;0.7</td>
<td>10&lt;sup&gt;a&lt;/sup&gt;</td>
<td>...</td>
</tr>
</tbody>
</table>

<sup>a</sup> Parameter fixed at this value.  
<sup>b</sup> Fitted with a cut-off power law; FWHM stands for power-law index, and frequency stands for cut-off frequency.  
<sup>c</sup> The error on $S_z$ is the standard deviation of the distribution of $S_z$ values in the selection bin.

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**Figure 5.** Average 2–60 keV power density spectrum for $S_z = 0.60 \pm 0.03$. The best-fitting and the individual components used in this fit are indicated; the dashed line represents the LFN, the dotted line the HBO, the dot-dashed line the sub-HBO, the solid line its third harmonic, and the dash–three dots line the second harmonic of the HBO. The component arising in the power spectrum due to Poisson noise was subtracted.
amplitude was consistent with 1.6 per cent. The noise component
became undetectable at an $S_z$ value of $2.64 \pm 0.06$ with an upper
limit of 1.2 per cent, where the vertex between the flaring branch
and the ‘dipping flaring branch’ is at $S_z \approx 2.5$. The fit
parameters of the cut-off power law are marked with a $b$ in Table 3.

3.3 KHz QPOs

The lower and upper kHz QPO were detected at frequencies
ranging from $156 \pm 23$ to $627 \pm 13$ Hz and from $478 \pm 15$ to
$866 \pm 23$ Hz, respectively (dots and crosses, respectively upper
panel, Fig. 9A). The peak separation ($\Delta f$) was not constant; the fit
of a constant to the peak separation ($325 \pm 10$ Hz) versus $S_z$
resulted in a $\chi^2_{\text{red}}$ of 7 for 10 degrees of freedom, an unacceptable
fit. We tried various other functions (see, e.g., Fig. 9, lower panel,
and Table 5). From an $F$-test it was clear that the use of a broken
function or a parabola significantly reduced the $\chi^2_{\text{red}}$, indicating that
$\Delta f$ is decreasing towards higher $S_z$ at a rate that is not constant but
increases. The data indicate a decrease in FWHM of the lower kHz
QPO towards larger $S_z$, but the scatter is large. The FWHM of the
upper kHz QPO varies between 100 and 247 Hz (see crosses
Fig. 9B, top panel). The fractional rms amplitude of the lower kHz
QPO decreased gradually from $3.6 \pm 0.4$ to $0.5 \pm 0.1$ per cent; that of the upper kHz QPO first increased slightly from $2.0 \pm 0.4$ to
$2.6 \pm 0.1$ per cent to decrease gradually to $0.9 \pm 0.1$ per cent (see
dots and crosses respectively, Fig. 9C top panel). The $S_z$ changed
from $-0.1$ to $1.1$ over the plotted interval. All fit results are given
in Table 4.

Motivated by the results on GX 17+2 (Homan et al. 2002), we
plotted the frequency of the kHz QPOs and their separation
frequency as a function of $n_{\text{HBO}}$ (Fig. 10). Near $n_{\text{HBO}} \sim 45$ Hz the peak separation starts to decrease, most likely due to an increase in the rate at which the frequency of the lower kHz QPO increases with $n_{\text{HBO}}$. This $n_{\text{HBO}}$ is consistent with the jump at $n_{\text{HBO}} \sim 44–
\sim 47$ Hz in a $n_{\text{HBO}}$ versus $S_z$ plot (see Section 2).

4 DISCUSSION

A detailed analysis of all RXTE observations obtained to date of
GX 5–1 has been presented. The main result of our high-frequency
variability study is that the kHz QPO peak separation is not constant in GX 5–1. The low-frequency power spectra for $S_z < 1.0$ are complex and can best be described by four harmonically related Lorentzians, in addition to the LFN. Two of these Lorentzians were not known previously in GX 5–1. At $S_z > 1.9$ a new component was found in the power spectra. Below we discuss these findings and compare the timing properties and CDs of GX 5–1, the black hole candidate XTE J1550–564, and the atoll source 4U 1608–52.

4.1 kHz QPOs

We showed that the kHz QPO peak separation is not constant. The data are consistent with a constant peak separation followed by a steep decrease for $S_z \sim 1.0$, or a parabolic relation between the peak separation and $S_z$. A decrease in peak separation was previously found in Sco X-1 (van der Klis et al. 1997), 4U 1608–52 (Méndez et al. 1998a), 4U 1728–34 (Méndez & van der Klis 1999), 4U 1735–44 (Ford et al. 1998), 4U 1702–43 (Markwardt, Strohmayer & Swank 1999) and GX 17 + 2 (Homan et al. 2002). We found that in GX 5–1 the rate of increase in frequency of the lower kHz QPO changes near $n_{\text{HBO}} \sim 45$ Hz, causing the peak separation to decrease.

The frequencies of the kHz QPOs of GX 5–1 are low in comparison with the other kHz QPO Z sources (the lowest frequencies of the lower and upper kHz QPO we found are 156 ± 23 and 478 ± 15 Hz, respectively). The lowest upper kHz QPO frequency found so far in an atoll source (449 ± 20 Hz for 4U 0614 + 09; van Straaten et al. 2000) is at the low-frequency limit (~500 Hz for the upper kHz QPO; Miller, Lamb & Psaltis 1998) imposed by the sonic point beat frequency model. The cause of the lower bound on the Keplerian frequency in the sonic point beat frequency model is that the radiation drag of the luminosity produced near the surface of the neutron star can only remove the required amount of the specific angular momentum of the gas to make it fall to the neutron star when the gas is close to the neutron star (Miller et al. 1998). Unlike 4U 0614 + 09, in the case of GX 5–1 QPOs with still lower frequency did not occur because the source was not found at lower $S_z$ values but not because the QPO disappeared. Therefore, observations of kHz QPOs in GX 5–1 at even lower $S_z$ values will provide a strong test of the sonic point beat frequency model.

In the so-called two-oscillator model (Titarchuk, Lapidus & Muslimov 1998; Osherovich & Titarchuk 1999) the angle $\delta$ is defined as

$$\delta = \arcsin\left[\left(\frac{n_{\text{upper}}}{n_{\text{lower}}} - 1\right)^2 - \frac{1}{2}\right]^{0.5},$$

where $n_{\text{lower}}$ is the frequency of the lower kHz QPO, $n_{\text{upper}}$ is the frequency of the upper kHz QPO, and $n_{\text{HBO}}$ is the frequency of the HBO; $\delta$ is the angle between the magnetosphere equator and the disc plane in the model. The current version of the theory predicts $\delta$ to be constant. However, the measurements of Homan et al. (2002) for GX 17 + 2 and the our measurements for GX 5–1 show that $\delta$ versus the frequency of the lower kHz QPO changes is not constant (see Fig. 11). A fit of a constant gives $\delta = 6.1 \pm 0.2$ and a $\chi^2$ of 377 for 9 d.o.f. for GX 17 + 2 and $\delta = 6.3 \pm 0.1$ and a $\chi^2$ of 95.2 for 9 d.o.f. for GX 5–1.

4.2 Comparison with other Z sources

We have detected a sub-HBO component similar to the component in the Z sources Sco X-1 (Wijnands & van der Klis 1999), GX 340+0 (Jonker et al. 2000b) and GX 17 + 2 (Homan et al. 2002). Furthermore, we found a fourth Lorentzian component whose frequency was consistent with 1.5 times the frequency of the HBO. If we interpret the sub-HBO as the fundamental frequency, then the HBO would be the second harmonic, the newly found peak at 1.5 times the HBO frequency the third harmonic, and the second harmonic of the HBO the fourth harmonic. In such a scheme the odd harmonics should either be formed less coherently than the even harmonics, or an additional broadening mechanism has to be invoked which broadens the odd harmonics more than the even harmonics (see Fig. 4, right-hand panel). This harmonic structure could be explained in a scenario where the HBO is caused by a

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**Figure 9.** The kHz QPO properties as a function of $S_z$. The measurements presented in the upper panel are dependent points since data have been used from partially overlapping bins. Upper panel A: The frequencies of the lower (dots) and upper kHz QPO (crosses), the same symbols for the lower and upper kHz QPO are used throughout the figure. Upper panel B: The FWHM of the kHz QPO pair. Upper panel C: The fractional rms amplitude (2–60 keV) of the kHz QPO pair. Lower panel: The peak separation as a function of $S_z$. The dot-dashed line represents the best-fitting constant, the drawn line represents the fit to the data of a parabola, and the dashed line represent a fit using two straight lines joined at the break with slope fixed to zero below the break at $S_z = 0.93$ (for the fit parameters see Table 5). Error bars are plotted, but the errors in the upper panel can be smaller than the size of the symbols.
increase in the lower kHz QPO frequency and therefore also in the peak
to HBB. The rate of
The dots represent the lower kHz QPO, and the crosses the upper kHz QPO.

Table 4. Best-fitting parameters (2–60 keV) of the lower ($v_{\text{low}}$) and upper ($v_{\text{up}}$) kHz QPO as a function of the source position along the Z track. Note that overlapping selections in $S_z$ have been used.

<table>
<thead>
<tr>
<th>$S_z$ value</th>
<th>Fractional rms ampl. $v_{\text{low}}$</th>
<th>FWHM lower kHz QPO (Hz)</th>
<th>Frequency lower kHz QPO (Hz)</th>
<th>Fractional rms ampl. $v_{\text{up}}$</th>
<th>FWHM upper kHz QPO (Hz)</th>
<th>Frequency upper kHz QPO (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.12 ± 0.03</td>
<td>3.6 ± 0.4</td>
<td>317 ± 77</td>
<td>156 ± 23</td>
<td>2.0 ± 0.4</td>
<td>103 ± 47</td>
<td>478 ± 15</td>
</tr>
<tr>
<td>0.18 ± 0.03</td>
<td>3.3 ± 0.2</td>
<td>214 ± 36</td>
<td>172 ± 10</td>
<td>2.3 ± 0.2</td>
<td>155 ± 29</td>
<td>515 ± 9</td>
</tr>
<tr>
<td>0.21 ± 0.03</td>
<td>2.7 ± 0.1</td>
<td>148 ± 15</td>
<td>183 ± 3</td>
<td>2.6 ± 0.1</td>
<td>199 ± 23</td>
<td>521 ± 8</td>
</tr>
<tr>
<td>0.24 ± 0.03</td>
<td>2.5 ± 0.1</td>
<td>130 ± 19</td>
<td>192 ± 4</td>
<td>2.6 ± 0.2</td>
<td>217 ± 27</td>
<td>530 ± 10</td>
</tr>
<tr>
<td>0.31 ± 0.03</td>
<td>1.4 ± 0.2</td>
<td>61 ± 15</td>
<td>215 ± 4</td>
<td>2.6 ± 0.2</td>
<td>208 ± 30</td>
<td>549 ± 10</td>
</tr>
<tr>
<td>0.35 ± 0.03</td>
<td>2.3 ± 0.2</td>
<td>179 ± 42</td>
<td>232 ± 7</td>
<td>2.9 ± 0.2</td>
<td>247 ± 32</td>
<td>562 ± 11</td>
</tr>
<tr>
<td>0.40 ± 0.03</td>
<td>2.1 ± 0.2</td>
<td>162 ± 28</td>
<td>258 ± 7</td>
<td>2.6 ± 0.1</td>
<td>210 ± 23</td>
<td>584 ± 8</td>
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<tr>
<td>0.45 ± 0.03</td>
<td>2.1 ± 0.2</td>
<td>192 ± 32</td>
<td>277 ± 9</td>
<td>2.2 ± 0.1</td>
<td>170 ± 18</td>
<td>623 ± 7</td>
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<tr>
<td>0.50 ± 0.03</td>
<td>2.0 ± 0.1</td>
<td>177 ± 29</td>
<td>280 ± 8</td>
<td>2.2 ± 0.1</td>
<td>163 ± 19</td>
<td>637 ± 7</td>
</tr>
<tr>
<td>0.55 ± 0.03</td>
<td>2.1 ± 0.2</td>
<td>241 ± 62</td>
<td>282 ± 12</td>
<td>2.1 ± 0.2</td>
<td>183 ± 29</td>
<td>645 ± 10</td>
</tr>
<tr>
<td>0.60 ± 0.03</td>
<td>1.5 ± 0.2</td>
<td>128 ± 35</td>
<td>355 ± 10</td>
<td>2.0 ± 0.2</td>
<td>182 ± 30</td>
<td>668 ± 11</td>
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<tr>
<td>0.65 ± 0.03</td>
<td>1.8 ± 0.1</td>
<td>152 ± 28</td>
<td>356 ± 8</td>
<td>1.9 ± 0.1</td>
<td>151 ± 23</td>
<td>677 ± 8</td>
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<tr>
<td>0.70 ± 0.03</td>
<td>1.4 ± 0.2</td>
<td>125 ± 32</td>
<td>377 ± 10</td>
<td>1.7 ± 0.1</td>
<td>139 ± 27</td>
<td>696 ± 8</td>
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<td>0.76 ± 0.03</td>
<td>1.7 ± 0.1</td>
<td>197 ± 45</td>
<td>391 ± 19</td>
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<td>726 ± 6</td>
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<td>148 ± 26</td>
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</tr>
<tr>
<td>0.85 ± 0.03</td>
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<td>438 ± 7</td>
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<td>764 ± 10</td>
</tr>
<tr>
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<td>165 ± 39</td>
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<td>1.1 ± 0.1</td>
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<td>485 ± 12</td>
<td>1.2 ± 0.1</td>
<td>101 ± 28</td>
<td>801 ± 8</td>
</tr>
<tr>
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<td>1.0 ± 0.1</td>
<td>135 ± 34</td>
<td>535 ± 20</td>
<td>1.1 ± 0.1</td>
<td>131 ± 33</td>
<td>828 ± 11</td>
</tr>
<tr>
<td>1.10 ± 0.03</td>
<td>0.5 ± 0.1</td>
<td>45 ± 20</td>
<td>608 ± 6</td>
<td>1.0 ± 0.1</td>
<td>126 ± 31</td>
<td>840 ± 12</td>
</tr>
<tr>
<td>1.15 ± 0.02</td>
<td>&lt;0.7</td>
<td>75^b</td>
<td>...</td>
<td>&lt;0.9</td>
<td>75^b</td>
<td>...</td>
</tr>
<tr>
<td>1.22 ± 0.02</td>
<td>&lt;0.8</td>
<td>75^b</td>
<td>...</td>
<td>&lt;0.8</td>
<td>75^b</td>
<td>...</td>
</tr>
</tbody>
</table>

^a The error on $S_z$ is the standard deviation of the distribution of $S_z$ values in the selection bin.
^b Parameter fixed at this value.

Figure 10. The kHz QPO properties as a function of the HBO frequency. The dots represent the lower kHz QPO, and the crosses the upper kHz QPO. The frequency of the peak separation is indicated with stars. The rate of increase in the lower kHz QPO frequency and therefore also in the peak separation frequency changes near $\lambda_{\text{HBO}} \approx 45$ Hz.

Table 5. Fit parameters of different functions describing the peak separation as a function of $S_z$. The broken functions are two straight lines concatenated at the break. The last row contains the $\chi^2$ and the degrees of freedom (d.o.f.) of the fit. Note that, unlike in the top panel of Fig. 9, only independent measurements have been used in the bottom panel.

<table>
<thead>
<tr>
<th>Constant</th>
<th>Linear</th>
<th>Parabola</th>
<th>Broken</th>
<th>Broken</th>
</tr>
</thead>
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<td>369 ± 21 Hz</td>
<td>291 ± 29 Hz</td>
<td>334 ± 4 Hz</td>
</tr>
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<td>Slope</td>
<td>...</td>
<td>−70 ± 30</td>
<td>259 ± 109</td>
<td>−69 ± 15</td>
</tr>
<tr>
<td>Quadratic/break</td>
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<td>−275 ± 90</td>
<td>$S_z = 0.93 ± 0.06$</td>
<td>$S_z = 0.94 ± 0.05$</td>
</tr>
<tr>
<td>Slope after Break</td>
<td>...</td>
<td>...</td>
<td>−832 ± 483</td>
<td>−832 ± 439</td>
</tr>
<tr>
<td>$\chi^2$/d.o.f.</td>
<td>66.8/9</td>
<td>39.9/8</td>
<td>15.0/7</td>
<td>7.8/7</td>
</tr>
</tbody>
</table>

^a Parameter fixed at this value.
The angle $\delta$ (defined by Osherovich & Titarchuk 1999) for GX 5–1 (grey diamonds) and GX 17+2 (black dots) as a function of the lower kHz QPO frequency.

1994) were fitted using only the even harmonics (the HBO and its second harmonic) and an additional high-frequency noise (HFN) component. Now, using the larger collecting area of RXTE, we find that the HFN in GX 5–1 is better described by two Lorentzian components which have centroid frequencies of 0.5 and 1.5 times that of the HBO.

The same function we used for our analysis of GX 5–1 was used in the analysis of the similar Z source GX 340+0 (Jonker et al. 2000b). There no third harmonic of the sub-HBO was found. Instead, we found excess power (a shoulder) close to the HBO and the second harmonic) and an additional high-frequency noise (HFN) component. Now, using the larger collecting area of RXTE, we find that the HBO was asymmetric. In GX 340+0 both the HBO and the NBO peak became asymmetric when they were strongest. Similar behaviour was found in GX 5–1, where for $S_2 < 0.5$ four of the five HBO measurements were done using two Lorentzians with centroid frequencies up to 2 Hz apart with similar FHMs but different strengths, indicating that the HBO was asymmetric. However, unlike in our analysis of GX 340+0 where the data were selected according to HBO frequency, in the case of GX 5–1 this asymmetry could be an artefact of the selection method, as explained in Section 3.2. An attempt to fit the average power spectra of GX 17+2 (Homan et al. 2002) with the same fit function as that of GX 5–1 did not lead to the detection of a third harmonic to the sub-HBO. The asymmetry of the HBO found in GX 340+0 and the third harmonic of the sub-HBO found in GX 5–1 could be two different components, one of which is detected in each source because of the special circumstances affecting detections in each case: the larger amplitude of the HBO in GX 340+0 than in GX 5–1 allows us to detect a strong asymmetric (shoulder) component, whereas the higher signal-to-noise ratio in GX 5–1 than in GX 340+0 (due to the fact that GX 5–1 is several times brighter than GX 340+0) leads to the detection of the broad third harmonic. New observations with higher signal-to-noise ratios can reveal whether both components are present in both sources or whether they represent power provided by one single component.

The low-frequency power spectra of the three Z sources discussed above (GX 17+2, GX 340+0 and GX 5–1) are quantitatively different. In Sco X-1 and GX 17+2 a QPO is found when the source is on the flaring branch (the FBO; Haslinger, Priedhorsky & Middleditch 1989; Penninx et al. 1990). Such a QPO is absent in GX 340+0, GX 5–1, GX 349+2 and Cyg X-2. The new component we found in the power spectrum of GX 5–1 with frequencies similar to those of the FBO when the source is on the flaring branch is much broader than the FBO in Sco X-1 and GX 17+2. The second harmonic of the HBO is relatively strong in GX 17+2, while for GX 5–1 and GX 340+0 only weak harmonics have been detected (see Haslinger & van der Klis 1989 and van der Klis 1989). Furthermore, the fractional rms amplitude of the HBO is highest in GX 340+0, and lowest for GX 17+2. The HBO frequency in GX 17+2 was found to decrease on the normal branch (Wijnands et al. 1997a; Homan et al. 2002), whereas in GX 340+0 and GX 5–1 the frequency is consistent with being constant (Jonker et al. 2000b). Besides the Lorentzians the LFN is also different; it is always peaked in GX 17+2, whereas this is never the case in GX 5–1 and GX 340+0 (see Haslinger & van der Klis 1989, van der Klis 1989, Jonker et al. 2000b and Homan et al. 2002). The dependence of the HBO, lower and upper kHz QPO $Q$-values on $S_2$ is shown in Fig. 12. The HBO $Q$-value decreases gradually for $S_2 > 0.5$, while that of the kHz QPOs increases. This is opposite to what was found for GX 17+2 (Homan et al. 2002), where the $Q$-value of the HBO and that of the kHz QPOs increased as a function of $S_2$.

4.3 Comparing GX 5–1 with XTE J1550–564 and 4U 1608–52

In the power spectra of black hole candidates low-frequency QPOs with harmonics are occasionally found in the low, intermediate and very high states (e.g. GS 1124–68, Belloni et al. 1997b; GX 339–4, Mendèz & van der Klis 1997; XTE J1550–564, Homan et al. 2001; Sobczak et al. 2000). Sometimes these black hole candidate QPOs have asymmetric profiles. We found a similar harmonic structure of QPOs in the Z source GX 5–1. The $Q$-values of the harmonics for XTE J1550–564 are similar to those found for GX 5–1: low $Q$-values for the odd harmonics and high $Q$-values for the even harmonics (Homan et al. 2001). However, we checked the energy dependence of the QPOs in GX 5–1, and there are no indications of changes in the $Q$-values with energy, as were found in XTE J1550–564 (Homan et al. 2001). In general, the energy dependence and time-lag behaviour of the QPOs in GX 5–1 (Vaughan et al. 1999) are different from what was found in XTE J1550–564 (Wijnands, Homan & van der Klis 1999). On the flaring branch, similar to the high state in black hole candidates, the fractional rms amplitude of the variability is low, and QPOs are weak or absent (in GX 17+2 and Sco X-1, just as in XTE J1550–564 a QPO with a centroid frequency of $\sim 18$ Hz is found, but whether they are related is unclear). The similarities between the horizontal branch variability and that of the intermediate/low state have been pointed out before (van der Klis 1994a,b; Wijnands & van der Klis 1999). Furthermore, the trend of a decrease in variability time-scale as the source approaches the flaring branch/High State is the same in black hole candidates as in GX 5–1 and 4U 1608–52 (cf. Mendèz, van der Klis & van Paradijs 1998b; Homan et al. 2001).

To further investigate the similarities between a black hole candidate (XTE J1550–564), a Z source (GX 5–1), and an atoll source (4U 1608–52) we created CDs for the three sources in two ways. First, we used the colour definitions commonly used for atoll and Z sources (soft and hard colour were defined as the logarithm of the 3.6–6.2/2.5–3.6 keV and 9.8–16/6.2–9.8 keV count rate ratio, respectively). These CDs are shown in the left-hand panels of Figs 13, 14 and 15. Second, we created CDs in a similar way as van
Teeseling & Verbunt (1994), an approach often used for black hole candidates (Belloni et al. 1997a; Homan et al. 2001; although see also Miyamoto et al. 1991). We defined the hard and soft colour as the 9.7–16.0/2–6.4 keV and 6.4–9.7/2–6.4 keV count rate ratio for observations 1–41, respectively, and that of the 9.7–15.8/2–6.6 keV and 6.6–9.7/2–6.6 keV count rate ratio for observations 42–76, respectively (Fig. 13, right-hand panel). In the case of the right-hand panels of Figs 14 and 15, the hard and soft colour were defined as the 16.0–19.4/2–6.2 keV, and 6.5–15.7/2–6.2 keV count rate ratio, respectively. Note that in the right-hand panels the soft colour is plotted versus the hard colour, since the convention, introduced by (Ostriker 1977), to plot hard colour versus soft colour was abandoned in some of the recent black hole work. In the right-hand panels the points have been connected by a line. Lines bridging different parts of the diagrams do not reflect sudden jumps or changes in source state, but are due to gaps introduced by observational windowing.

A similar structure as for XTE J1550–564 was found in the CD of GX 5–1 (Figs 13 and 14, right-hand panel). The flaring branch is now vertical and located at the left-hand side of the figure, similar to the high state in XTE J1550–564. The normal branch connects to the flaring branch and points towards the upper right corner of the diagram (both the hard colour and the soft colour increase as the source moves up the normal branch). The horizontal branch is a continuation of the normal branch, with only a slight bend at the normal branch–horizontal branch junction. (It is interesting to note that there is also no vertex present in GX 17+2 at the Horizontal–normal branch junction at energies above 14.8 keV; see fig. 3C of Homan et al. 2002.) The ‘Dipping’ flaring branch is parallel to the normal branch, but directed towards the lower left corner. The ‘Dipping’ flaring branch has been found in the Z sources Cyg X-2, GX 5–1 and GX 340+0 (Kuulkers et al. 1994; Kuulkers et al. 1996; Jonker et al. 2000b). The CD of the atoll source 4U 1608–52 again shows a similar structure as found for XTE J1550–564 (Figs 14 and 15, right-hand panels). The island state is found at the top right corner of the right-hand panel of Fig. 15, whereas the lower banana branch connects to the upper banana branch at the lower left corner. The upper banana branch seems similar to the black hole candidate high state and the Z source flaring branch.

The CD of the black hole candidate XTE J1550–564, plotted using colours typically applied for neutron star sources is reminiscent of that of an atoll source, although more structure is observed (Fig. 14, left-hand panel). The source was first found in the upper right part of the CD as the outburst started. The path traced by the source as the outburst progressed is indicated with arrows. For a complete description of the outburst of XTE

Figure 12. The Q-values of the HBO (diamonds), the lower (crosses), and the upper kHz QPO (filled squares) as a function of $S_\nu$. The Q-values of both kHz QPOs increase with increasing $S_\nu$, while that of the HBO decreases for $S_\nu > 0.5$. Error bars have been omitted for clarity. The errors of the diamonds (HBO) are $\sim 1.5$ times the size of the symbols. The errors of the crosses and squares (lower and upper kHz QPO, respectively) are of the order of the amplitude of the scatter in measurements close together in $S_\nu$.

Figure 13. Left-hand panel: Colour–colour diagram of observations 19–41 where the soft and hard colour were defined as the logarithm of the energy of the photons in keV (or $q_{2002}$). Each dot is a 64 s average. Right-hand panel: Colour–colour diagram of the 9.7/15.8–6.4 keV (or 6.6–9.7/2–6.6 keV for observations 42–76; soft colour) count rate ratio versus the 9.8–16.0/2–6.4 keV (or 9.7–15.8/2–6.6 keV for observations 42–76; hard colour). Each 512 s average is connected to the next by a line. The lines in the right-hand panel indicate what RXTE would have seen if the source spectrum had consisted of only a blackbody (top), a thermal bremsstrahlung (middle), or a powerlaw (bottom line) spectrum. In this Figure as well as in Figs 14 and 15 error bars were omitted for clarity; data were background subtracted but no deadtime corrections were applied (the deadtime was in all cases less than 4 per cent).
J1550–564 we refer to Cui et al. (1999), Sobczak et al. (2000) and Homan et al. (2001).

The similarities between the CDs of the Z source GX 5–1, the atoll source 4U 1608–52, and the black hole candidate XTE J1550–564 strengthen the idea that some of the spectral properties of LMXBs originate in the accretion disc and do not depend on the presence of a solid surface. However, our analysis also indicates that differences between spectral properties of the neutron star Z and atoll sources and the black hole candidates do exist (e.g., the left-hand panels of Figs 13, 14 and 15), but may not clearly show up in representations of the CD commonly used for black hole candidates. The explanation for this could be that in the ‘black hole colour scheme’ only three independent colours are defined, whereas in the ‘neutron star colour scheme’ four colours are usually defined.

So, although the CDs of a Z or atoll source and that of a black hole candidate appear similar in shape when plotted using colours typical for black hole studies, their appearance is both dissimilar and more complicated when plotted using colours typical for neutron star studies. Whether the complications can be ascribed to the unique nature of the sources considered can only be checked by comparing more sources, but the conclusion that dissimilar CDs can appear more similar than they really are in the ‘black hole’ representation can already be drawn. Conclusions regarding the
spectral state or properties of the source based on the colours commonly used in black hole candidates should be regarded with caution, since an other choice of colours may lead to a qualitatively different CD.

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