THE PUZZLING HARMONIC BEHAVIOR OF THE CATHEDRAL QPO IN XTE J1859+226

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ABSTRACT

We present a spectral and temporal analysis of the Cathedral quasi-periodic oscillation (QPO) detected in the power density spectra of the black hole binary and microquasar XTE J1859+226, obtained using Rossi X-Ray Timing Explorer. This type of QPO has been seen on two occasions (MJDs 51574.43 and 51575.43) during the 1998 outburst of this source. It manifests as two peaks with similar amplitudes (∼3% and ∼5%) and harmonically related centroid frequencies (∼3 and ∼6 Hz). The temporal properties of these two peaks are different: the amplitude of the ∼3-Hz feature varies, in anticorrelation with the count rate, by ∼50%. The ∼6-Hz feature, on the other hand, shows a slight increase (∼7%) in its amplitude with the count rate. The rms spectra of the two peaks are also quite different. The ∼3-Hz feature is softer than the other one, and, although its rms amplitude increases with energy, it shows a cutoff at an energy of ∼6 keV. The rms of the ∼6-Hz feature increases with energies up to at least 20 keV. We also study the bicoherence $b^2(\mu, \nu)$ of both observations. At the diagonal position of the peaks, the values $b^2(\sim3, \sim3)$ and $b^2(\sim6, \sim6)$ are rather high and similar to those reported for type C QPOs of GRS 1915+105. In comparison with the latter source, the bicoherence of the ∼3-Hz feature is higher than that of the other peak, which may indicate that the ∼3-Hz feature is the fundamental QPO and the other is its first harmonic. The value of $b^2(\sim3, \sim6)$ is, however, very low and therefore indicates a behavior different from that seen in the type C QPO of GRS 1915+105. We discuss the implications of these differences in the context of a harmonic relationship between the peaks, and suggest that, rather than pure harmonics, we may see different modes of the same underlying phenomenon competing to produce QPOs at different frequencies.

Key words: accretion, accretion disks – black hole physics – stars: individual (XTE J1859+226, XTE J1550–564, GRS 1915+105) – X-rays: stars

1. INTRODUCTION

Black hole binaries (BHBs; see, e.g., Remillard & McClintock 2006 for a review) transit through different “spectral states” during outbursts. These are defined both by the spectral and temporal parameters obtained through analyses of their energy spectra and power density spectra (PDS). In the soft state, where emission is dominated by a bright and warm (∼1 keV) accretion disk, the level of variability is weak, and the PDS is similar to a power law. On the other hand, in the hard state, when the disk is much colder (≤0.5 keV) and thought to be truncated at a large distance from the accretor, the level of variability is much higher and shows a band-limited noise component. Other states exist and can be seen as intermediate stages between the hard and soft states (see, e.g., Remillard & McClintock 2006; Homan & Belloni 2005 for recent reviews and precise classifications of BHB states). Furthermore, quasi-periodic oscillations (QPOs) in the “low-frequency” range (0.1–20 Hz, hereafter referred to as LFQPOs) are seen in the hard and intermediate states. On the basis of their typical frequencies, total rms amplitude, and time lags, these LFQPOs have been further classified into types A, B, or C (e.g., Remillard et al. 2002; Casella et al. 2005). We have recently proposed a tentative classification of states based on the presence of the different types of QPOs (Varnière et al. 2011a).

The exact origin of QPOs is still a matter of debate: They could arise from global oscillations of the disk (e.g., Wagoner et al. 2001 and references therein), Lense–Thirring precession (e.g., Ingram et al. 2009 and references therein), oscillating shocks (e.g., Molteni et al. 1996 and references therein), or MHD instability (Tagger & Pellat 1999). From the observational side, it seems clear that the inner disk somehow sets the frequency of LFQPOs (e.g., Muno et al. 1999; Rodriguez et al. 2002a, 2002b, 2004a; Mikles et al. 2009). LFQPOs are, however, strong when a strong, hard component is seen in the energy spectra and their frequencies are correlated with the power-law photon index (e.g., Vignarca et al. 2003; Shaposhnikov & Titarchuk 2007). The last point would tend to indicate an origin in relation to the corona. The amplitude of the QPO increases up to a variable cutoff energy (Rodriguez et al. 2004b, 2008).

These LFQPOs usually manifest in the PDS as a powerful peak, referred to as the fundamentals and a series of (sub-)harmonics of much fainter amplitudes. So far, very little attention has been paid to these harmonics, even if it is clear that they do not completely share the same properties as the fundamental. They can show different signs for their time lags, as in the case of type B QPOs (Casella et al. 2004), and different shapes of the rms spectra (Cui 1999; Homan et al. 2001; Rao et al. 2010). The true identification of the fundamental has recently been contested (e.g., Rao et al. 2010), which raises questions related to the genuineness of the harmonic relationship of the peaks.

XTE J1859+226 was discovered on 1999 October 9 by the Rossi X-Ray Timing Explorer (RXTE) All Sky Monitor (Wood et al. 1999), as it was entering its outburst. It is a microquasar, deduced from the observations of relativistic ejections in radio waves (Brocksopp et al. 2002), and the observations of low- and high-frequency QPOs led Cui et al. (2000) to classify it as a possible BHB. An extensive timing analysis of this source is presented by Casella et al. (2004). Similar to XTE J1550–564, XTE J1859+226 displays all three types of LFQPOs. In two particular observations during the 1999 outburst, Casella et al. (2004) observed the presence of two peaks with harmonically related frequencies but, unlike any other cases, similar rms amplitudes. These are referred to as the
“Cathedral” QPOs (Casella et al. 2004): the strongest peak (and highest in frequency) has hard lags (the hard X-rays lag behind the soft X-rays) and is interpreted as the fundamental peak, while the lowest-frequency peak has soft lags and is the sub-harmonic. Interestingly, these two observations are separated by about a day and by an observation showing another type of QPO indicative of a spectral transition (Casella et al. 2004).

The existence of the Cathedral QPOs showing two harmonically related peaks of similar amplitude raises challenging questions for all theoretical models. To obtain a clearer view of the properties of these peaks, we performed a complete study of the QPO structure from these two observations, and compared the temporal and spectral behaviors of the two peaks. The organization of the paper is as follows: we start by presenting the observation IDs and data reduction methods. We then describe the results in Section 3, including the temporal evolution of the source, the fit to the broadband PDS, the energy dependences of the QPOs, and the bicoherence of the observations. We discuss our findings in the last section.

2. OBSERVATIONS AND DATA REDUCTION

We focus on RXTE observations 40124-01-24-00 (Obs. 1) and 40124-01-27-00 (Obs. 2), respectively made on 1999 October 23 (MJD 51474.43) and 24 (MJD 51475.43) near the peak of the 1999 outburst. The entire process of the RXTE/Proportional Counter Array (PCA) data reduction was carried out with the HEASOFT v6 9 software package. We reduced the Binned and Event mode data following standard procedures (see, e.g., Rodriguez et al. 2008) to obtain light curves filtered by low elevations above the Earth, large offset from the source, and Proportional Counter Unit breakdown. We extracted 7.8125 × 10−3 s binned light curves in several energy ranges, used for fine timing analysis, and a ∼2–15 keV light curve from the binned data with a time bin of 8 s (Figure 1) to characterize the overall behavior of the source over the observations. Note that this range contains most of the counts emitted by the source. PDS were then produced with Powspec v1.0 at intervals of 16 s in the range of 0.0625–64 Hz; all intervals were further averaged before the fitting process. To study the variations in the QPOs over time, a dynamical PDS (DPDS) was also computed between 0.25 and 64 Hz (Figure 1). The PDS were fitted between 0.0625 and 40 Hz in XSPEC v12.6.0. The background rate was taken into account when estimating the rms amplitudes of the different features, following $A_{\text{net}} = A_{\text{raw}} \times \frac{S_r B}{S}$, with $A$ being the amplitude, $S$ being the source net rate, and $B$ being the background rate (Berger & van der Klis 1994; Rodriguez et al. 2004b, 2008).

3. RESULTS

3.1. Time Evolution of the Source: Light Curve and Dynamical PDS

The 2–15 keV XTE J1859+226 PCA light curve binned at 8 s and the DPDS of Obs. 1 are reported in Figure 1. Large variations around a mean raw (net) count rate of 5700 counts s$^{-1}$ (5676 counts s$^{-1}$) are clearly visible. We especially note the presence of two rather broad dips lasting, respectively, ∼100 s and ∼50 s near relative times 1350 s and 1775 s, and a third occurring near the end of the observation (at $t \sim 2050$ s). The DPDS shows the presence of two strong features (relative to the overall noise) around 3 and 6 Hz. These features are quite thin and indicate the presence of QPOs at these frequencies. Interestingly, the two QPOs seem to behave differently over time (Figure 1): The QPO with the smallest frequency is, on average, much weaker than the other one, and is strong only when the count rate is around its mean value. It is particularly weak during the small flares and is not visible during the three dips. The highest-frequency QPO, on the other hand, seems, in terms of power, more stable and to vary significantly only during the dips (Figure 1). The feature seems rather broad around ∼6 Hz, which may indicate some rapid variations in frequency or simply an intrinsically low-coherence QPO. A very similar behavior (not shown) is also seen in both the light curve and DPDS of Obs. 2.

3.2. Broadband PDS

We started by fitting the large-band PDS. We did not subtract the white noise but preferred to add a constant to our fit model to account for this component. Following Casella et al. (2004), we fitted the continuum with the sum of three broad and three narrow Lorentzians (Figure 2) on top of the white-noise component. This model yields a good fit, with $\chi^2_r = 1.13$ (1.09) for 118 degrees of freedom (dof) for Obs. 1.
The parameters of the three thin peaks are reported in Table 1 for both observations. The parameters of all three peaks are compatible between the two observations, which lends credence to their complete similarity. In the remainder of the paper, only the results of Obs. 1 are precisely described and presented in the figures. Note that in all cases the same analysis was performed on Obs. 2, and the results and trends observed are consistent with those of Obs. 1. The third peak is compatible with $4 \times \nu_1$, and $2 \times \nu_2$ at the $\sim 2\sigma$ level, and is likely to be a harmonic of one of the two main peaks. In the remainder of this paper, we will refer to either peak 1, 2, or 3, or QPO1, QPO2, or QPO3, for the peaks at $\sim 2.9$, $\sim 5.8$, and $\sim 11.2$ Hz, respectively.

Although the fit statistic is quite good, we observe some residuals on the lower shoulder of QPO2. This effect is also mentioned by Casella et al. (2004) in Obs. 2, and these authors added a Gaussian to better represent the peak. In our case, the addition of another thin Lorentzian at $\sim 5.5$ Hz improves the fit to $\chi^2 = 0.90$ for 137 dof, and corrects the defect previously present in the residuals. The feature is, however, poorly defined, and its parameters are badly constrained. We verified that it had no significant impact on the other peaks, and therefore it was omitted from the study.

As mentioned in the previous section, QPO1 seems more intermittent than the second peak (Figure 1). In order to quantify and study any possible dependence of the QPOs’ amplitudes on the count rate (Section 3.1), we followed a procedure similar to that presented in Heil et al. (2011). Each observation was separated into 10 count rate intervals of equal width. Each interval therefore has a width equal to $\frac{\text{Max}(CR) - \text{Min}(CR)}{10}$ counts s$^{-1}$. Due to short accumulation times, and thus poor statistical quality of the resulting PDS, some pairs of intervals were combined. In Obs. 1, this rebinned intervals 1–4. The final division of Obs. 1 is represented in Figure 1. We then extracted a $7.8125 \times 10^{-3}$ s binned light curve from the time interval of 8 s, and produced PDS from all light curves. Individual PDS belonging to the same count rate interval were averaged to produce the final count rate-dependent PDS. The latter were then fitted to estimate the parameters of the peaks, with a special focus on their rms amplitudes. No specific trend is seen between the frequency and the coherence of either peak with the count rate. In order to simplify the comparison of the QPOs of XTE J1550–564 (Heil et al. 2011), we represented the evolution of the absolute rms (in terms of counts s$^{-1}$) of the two peaks with the count rate in Figure 3 for the particular case of Obs. 1. The amplitude of QPO1 decreases with an increasing count rate, while that of QPO2 increases slightly (Figure 3) and shows a possible linear trend. Between the first real detections of the two peaks (in the second count rate bin) and the last bin, QPO1 varies from an rms amplitude of $2.7 \pm 0.3\%$ to $1.35 \pm 0.34\%$ (a variation of $50\%$ in amplitude), while QPO2 varies from $0.90 \pm 0.02$ to $1.10^{+0.3}_{-0.3}$.

| Obs. No. | $\nu_1$ (Hz) | $Q_1^a$ (%) | $A_1^b$ (%) | $\nu_2$ (Hz) | $Q_2^a$ (%) | $A_2^b$ (%) | $\nu_3$ (Hz) | $Q_3^a$ | $A_3^b$ (%) |
|----------|--------------|-------------|-------------|--------------|-------------|-------------|--------------|--------|-------------|
| 1        | 2.94 ± 0.02  | 5.9         | 2.8 ± 0.1   | 5.828 ± 0.025 | 7.3         | 4.7 ± 0.1   | 11.2±0.3    | 9.5    | 1.1±0.3     |
| 2        | 3.00 ± 0.04  | 5.2         | 2.9 ± 0.2   | 5.86 ± 0.04   | 6.5         | 4.6±0.2     | 1.15 ± 0.3  | 8.3    | 1.5±0.3     |

Notes. The errors are given at the 90% level.

$^a Q = \nu$/FWHM.

$^b A$ stands for rms amplitude.

To study the energetic dependence of the QPOs and produce the rms spectra (Figure 4), we fitted each energy-dependent PDS with the statistically required number of broad features to account for the continuum. These features also have complex energetic dependences, and thus the different fits require one, two, or three broad Lorentzians. The study of these is, however, beyond the scope of this paper and not discussed further. We then added the thin Lorentzians to account for the QPO. The third peak is undetectable most of the time, and no spectrum can be acquired for it. The resultant rms spectra for QPO1 and QPO2 from Obs. 1 are reported in Figure 4. An almost identical behavior is seen in the QPO spectra obtained from Obs. 2 (not shown).

The two QPOs share a common trend: their amplitudes first increase with energy before reaching a plateau. Such QPO spectra are common for all types (A–C) of LFQPOs in this source (Casella et al. 2004) and have also been seen, for example, in GRS 1915+105 (Rodriguez et al. 2004b, 2008) and XTE J1550–564 (Homan et al. 2001; Rodriguez et al. 2004a). That the normalization of the spectra is different is not unexpected because the two peaks have different total amplitudes. The precise shape and typical parameters (such as energy of the break and slope) are, however, different (Figure 4). This is illustrated in the right panel of Figure 4, where we normalized the rms spectrum of QPO2 by that of QPO1. This representation also clearly shows that QPO2 has a steeper (harder) spectrum than QPO1. The latter first increases to $\sim 5.7$ keV and then remains flat until $\sim 20$ keV. QPO2 is undetectable in the first energy bin (and is thus fainter than QPO1). It increases to $\sim 20$ keV, where its plateau is reached.
The bispectrum and the related bicoherence permit any possible coupling between the different components of the PDS to be studied, and thus allow one to go beyond the diagnosis brought out by the PDS (see, e.g., Maccarone et al. 2011 and references therein for a thorough discussion on these aspects). Dividing the light curve in \( K \) segments of equal length, the bicoherence is expressed as

\[
b^2(\nu, \mu) = \frac{\sum_{i=0}^{K-1} X_i(\nu)X_i(\mu)X_i(\nu+\mu)^2}{\sum_{i=0}^{K-1} |X_i(\nu)|^2 \times \sum_{i=0}^{K-1} |X_i(\mu + \nu)|^2},
\]  

where \( X_i(\nu) \) is the \( \nu \) component of the discrete Fourier transform of the \( i \)th interval (see, e.g., Maccarone & Coppi 2002; Uttley et al. 2005; Maccarone et al. 2011 for the description, restriction, interpretation, and applications to various astrophysical sources, including BHs). We calculated the 2–15-keV bicoherences of XTE J1859+226 between 6.25 \( \times \) 10\(^{-2} \) Hz and 16 Hz, with a frequency resolution of 0.0625 Hz. Figure 5 shows a zoomed-in view of the bicoherence plot obtained for Obs. 1 (the plots and results obtained for Obs. 2 are almost identical). Note that, by definition, the bicoherence is symmetrical with respect to the first diagonal (\( b^2(\nu, \mu) = b^2(\mu, \nu) \)). The highest values of the bicoherence are reached in a region around \((\nu_1, \nu_1)\) (the latter being indicated by the white box close to the bottom left corner in Figure 5, between \( \sim 2.8 \) and \( \sim 3.2 \) Hz along the first diagonal (Figure 5), with a slight broadening at low frequencies. A local maximum is also reached around the frequency of QPO 2 (illustrated by the second white box in Figure 5). Note that the mean value of \( b^2 \) calculated in the white regions represented in Figure 1 is higher around QPO 1 than around QPO 2. The mean value of \( b^2 \) over the 0.0625–16 Hz range is 0.008, with an rms of about 0.008. The value of \( b^2 \) around \((\nu_2, \nu_1)\) (black box in Figure 5) is quite low. At the position of the two peaks, we obtain \( b^2(\nu_2, \nu_1) \sim 0.01 \), a value within the statistical fluctuations around the mean of \( b^2 \) and clearly compatible with “noise.” Note that the same results are obtained when looking at the mean value of \( b^2 \) in broad (e.g., \( 5 \times 5 \) frequency-pixels) regions centered on \((\nu_2, \nu_1)\). Overall, this tends to show either that the two peaks are not coupled or that their coupling is very weak.

4. DISCUSSION AND CONCLUSIONS

We presented an analysis of some of the properties of the peculiar “Cathedral” QPO (Casella et al. 2004) seen in XTE J1859+226. Although we mainly focused on Obs. 1 to illustrate our analysis, similar results and trends were obtained from Obs. 2, allowing us to use these two observations in our argument. The Cathedral QPO manifests as two apparently harmonically related peaks with similar amplitudes in the PDS (Figure 2). Casella et al. (2004) concluded that QPO 2 is the fundamental feature, while QPO 1 is its “sub”-harmonic. From this conclusion, and the fact that QPO 2 shows hard time lags while QPO 1 shows soft time lags, they classified the Cathedrals as type B QPOs (Casella et al. 2004).

Although QPO 1 and QPO 2 seem to be harmonically related and have been classified as harmonics, their overall behavior is quite different. We summarize the main differences:

1. Their amplitudes have a different temporal evolution. QPO 2 is present during the entire observation (apart from the three dips mentioned in Section 3.1), while QPO 1 is only intermittently seen. Our analysis shows that it undergoes larger variations in amplitude than QPO 2 (Section 3.1).

2. The rms spectra of these two peaks are clearly different in shape, normalization, and typical parameters (Figure 4).
In particular, the characteristic energy at which their spectra flatten is different by about a factor of $\geq 3$: QPO1 reaches its peak at around $\sim 6$ keV, while QPO2 is much harder and peaks at $\geq 20$ keV.

3. The time lags of the two peaks are different: QPO1 has soft lags (the soft X-rays lag behind the hard ones), while QPO2 has hard lags (Casella et al. 2004). This property is typical of type B QPOs (e.g., Remillard et al. 2002; Casella et al. 2005).

4. The value of the bicoherence $b^2(v_2, v_1)$ is compatible with statistical noise, which tends to indicate a very weak or nonexistent coupling between the features at $v_2$, $v_1$, and $v_1 + v_2$.

Although points 2 and 3 have been mentioned about other BHBs (e.g., Homan et al. 2001; Rao et al. 2010; Cui 1999, for XTE J1550−564 and GRS 1915+105), in addition to XTE J1859+226 (Casella et al. 2004), to our knowledge, this is the first time that points 1 and 4 have been reported for any BHB. In XTE J1550−564, Heil et al. (2011) reported a positive linear rms–flux relation for (type C) QPOs with a frequency smaller than $\sim 4$ Hz, and a negative rms–flux trend at higher frequencies. Here, the situation is reversed. QPO2, which has the highest frequency, shows a linear relation and QPO1 shows a negative trend (Figure 3). This could be the signature of a new fundamental difference between type B and C QPOs.

For XTE J1550−564, Rao et al. (2010) mentioned that the difference in energy spectra of the two peaks, especially when the fundamental has a higher amplitude at high energies, can indicate a more sinusoidal signal at higher energies. In this respect, the fact that QPO1 is stronger at low fluxes could also indicate a more sinusoidal signal in the peaks. This explanation, although simple and tempting, does not account for the different signs of the time lags of the two peaks, since in the case of a non-purely sinusoidal signal, all components are expected to undergo the same physical processes and thus show similar lags. In addition, Rao et al. (2010) concluded that the peak referred to as sub-harmonic in XTE J1550−564 could in fact be the true fundamental feature. In this case, the “more sinusoidal” explanation does not hold because any longer, since the harmonic (and therefore the peak with the highest frequency) should then disappear first and show a softer spectrum, which is clearly opposite to what is seen here.

Note that the bicoherence behavior of the two peaks (at $(v_1, v_1)$ and $(v_2, v_2)$) is similar to that of the type C QPOs for GRS 1915+105 (Maccarone et al. 2011), where $b^2$ reaches a high value close to the frequencies of the peaks. In GRS 1915+105, $b^2$ is high at the (bi-)position of the fundamental and much lower in the harmonic (Maccarone et al. 2011). Pursuing the comparison with GRS 1915+105, in XTE J1859+226, the values of $b^2$ indicate that QPO1 is the fundamental and QPO2 is its harmonic. In GRS 1915+105, however, different global patterns have been identified in the bicoherence plot. In all cases (where a strong harmonic is seen), a strong coupling is seen between the fundamental and the harmonic (e.g., the “web” or “cross” patterns; Maccarone et al. 2011), and even between the noise component and the QPO. This was not observed in the case of XTE J1859+226 (Figure 5).

Simplistic interpretation of the four points above would be that the two peaks have absolutely no relation and that the apparent harmonic relation of their frequencies is coincidental. This seems difficult to reconcile with the fact that similar behavior is seen in Obs. 1 and 2, which are separated by roughly a day and underwent transition from one state into another (Casella et al. 2004). In addition, point 2 for type C QPOs and points 2 and 3 for type B QPOs have been reported in this and other objects (Cui 1999; Homan et al. 2001; Remillard et al. 2002; Rodriguez et al. 2002b; Casella et al. 2004; Rao et al. 2010). It is more likely that the two peaks are somehow related or that, at least, a possible common mechanism sets their frequencies to be integer multiples, with the two features not being harmonics in a physical sense.

Hard lags are usually easy to understand in the context of Comptonization of soft photons in a hot and tenuous medium (e.g., the so-called corona; e.g., Cui 1999). As discussed in Cui (1999) and Gierliński & Zdziarski (2005), the energy dependences of the QPO and/or the continuum are indicative of variations in physical parameters: the favored ones are the temperature and/or optical depth of the corona (Cui 1999), the temperature of the soft photons, or a variable power of the Comptonized component (Gierliński & Zdziarski 2005). In this respect, however, the different time dependences of the two peaks and the opposite sign of their time lags are difficult to understand.

Other families of models involve precession at the inner boundary of the disk, but here the fundamental and harmonics are produced at the same location and should “see” the same environment. In the framework of Comptonization, the time lags, rms spectra, and bicoherence of the different features should be the same.

A way to possibly reconcile the four points summarized above could be that the peaks are not harmonics in the usual sense but that they represent different modes of the same mechanism favored at different moments, depending on some (unknown) parameter(s) in the corona–disk–jet system. This hypothesis has the advantage of providing an explanation for the time behavior of the two peaks, and permits in particular that they do not necessarily appear at the same time, but rather enter into a sort of competition. The competition has also been mentioned for other types of QPOs in XTE J1859+226 by Casella et al. (2004), and in XTE J1550−564 by Remillard et al. (2002), although it has never been explored further. The physical states of the disk–corona–jet system might then set the conditions for one or the other peak to dominate. We explore this from a particular theoretical standpoint in Varnièvre et al. (2011b). With respect to the rms–flux relation and the bicoherence behavior, the behavior observed in the Cathedral QPO is different from that of the type C QPO of GRS 1915+105 (Heil et al. 2011; Maccarone et al. 2011). This may, however, represent a fundamental property of type B QPOs in general. In any case, the new model-independent observational facts presented here should be taken as strong constraints to any attempt to model LFQPOs in BHBs.

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