On the kHz QPO frequency correlations in bright neutron star X-ray binaries

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ABSTRACT
We re-examine the correlation between the frequencies of upper and lower kHz quasi-periodic oscillations (QPO) in bright neutron star low-mass X-ray binaries. By including the kHz QPO frequencies of the X-ray binary Cir X-1 and two accreting millisecond pulsars in our sample, we show that the full sample does not support the class of theoretical models based on a single resonance, while models based on relativistic precession or Alfvén waves describe the data better. Moreover, we show that the fact that all sources follow roughly the same correlation over a finite frequency range creates a correlation between the linear parameters of the fits to any subsample.

Key words: accretion, accretion discs – stars: neutron – X-rays: binaries.

1 INTRODUCTION
Thanks to the Rossi X-Ray Timing Explorer (RXTE), the past decade has seen the discovery of high-frequency quasi-periodic oscillations (QPOs) in neutron star X-ray binaries (see van der Klis 2006, for a review). These oscillations often appear in pairs, with frequencies ranging from a few hundred Hz to more than 1 kHz, hence the name kHz QPOs. Such fast variability provides a probe into the accretion flow very close to the compact objects and is a powerful tool to observe effects of general relativity. The frequencies of the kHz QPOs are strongly correlated with other timing and spectral features (see Ford & van der Klis 1998; Psaltis, Belloni & van der Klis 1999; Belloni, Psaltis & van der Klis 2002; van Straaten, van der Klis & Wijnands 2004).

Several models have been proposed for these oscillations; these models are based on the identification of the QPO frequencies with various characteristic frequencies in the inner accretion flow (Osherovich & Titarchuk 1999; Stella & Vietri 1999; Lamb & Miller 2003; Zhang 2004). However, there is still no consensus as to the origin of the kHz QPOs.

QPOs in the range 30–450 Hz have been observed in a limited number of black hole candidates; in some of these systems the QPOs seem to move in frequency (see e.g. Homan et al. 2001). However, in the four cases when two QPOs are detected simultaneously in a given black hole candidate, these QPOs appear at frequencies that are consistent with being always the same, with frequency ratios that are consistent with the ratio of two integer numbers, such as 3:2 and 5:3 (see e.g. Miller et al. 2001; Strohmayer 2001a; Strohmayer 2001b). A model for these QPOs based on the resonance of characteristic frequencies at a specific radius in the accretion disc was presented by Abramowicz & KLuznia (2001).

Abramowicz et al. (2003) reported that the ratios of the frequencies in the kHz QPOs from the brightest low-mass X-ray binary (LMXB) in the sky, Sco X-1, tend to cluster around a value of 1.5, which they interpret as evidence for a 3:2 resonance also being responsible for the QPO pairs in neutron star systems.

Belloni, Méndez & Homan (2005, hereafter BMH05), have shown that the frequencies of the lower, $\nu_{\text{low}}$, and upper, $\nu_{\text{high}}$, kHz QPOs are strongly correlated along a line which is inconsistent with $\nu_{\text{high}} = 1.5 \nu_{\text{low}}$, but can be roughly approximated as a straight line not passing through the origin. They also showed that when this correlation is taken into account, the peak in the distribution of ratios in the Sco X-1 data used by Abramowicz et al. (2003) is only marginally significant, since the distribution of the ratio of two correlated quantities is completely determined by the distribution of one of them. BMH05 also found that the frequency distributions of lower kHz QPOs for five systems have statistically significant peaks (some of which did not occur near a 3:2 frequency ratio). However, those peaks are consistent with being caused by a (nearly) random walk of the QPO frequency with time, together with the sampling of the observations.

A mathematical approach to the resonance model was presented by Rebusco (2004) in order to explain the Sco X-1 results; Rebusco (2004) attributed the discrepancies between the data and a pure 3:2
ratio to the action of an additional ad hoc force which moves the frequencies away from their ‘natural’ ratio, along a correlation such as the observed one.

While the correlation analysed in BMH05 treated the sample of sources as a whole, Zhang et al. (2006a, hereafter Z06) analysed the sources separately and showed that there are differences between sources, and deviations from a linear relation. Abramowicz et al. (2005a,b, hereafter A05a and A05b) presented an analysis of the same correlations. Fitting a number of sources separately with a linear function \( \nu_{\text{high}} = a \nu_{\text{low}} + b \), they obtain a set of \( a, b \) pairs (one pair per source). The pairs \( a, b \) themselves follow a linear relation \( b = a \alpha + B \) with intercept \( B \) close to 1.5. A05a and A05b interpret this fact as a property in accordance to the resonance model of Abramowicz & Kluzniak (2001).

Here we show that the analysis of separate sources presented by A05a and A05b does not add new information to that of the global correlation. We also re-examine the frequency correlation with the addition of new data from the literature. In particular, the newly discovered high-frequency oscillations in Cir X-1 (Boutloukos et al. 2006), which extend the correlation to lower frequencies, are important to distinguish between the different classes of models. We show that the frequencies of the kHz QPOs in Cir X-1 are inconsistent with the resonance model of Abramowicz & Kluzniak (2001).

2 ADDITIONAL DATA

Since the analysis by BMH05, new pairs of kHz QPOs frequencies have been published, some of which are particularly important for checking and extending the correlation between the kHz QPO frequencies.

### 2.1 Cir X-1

Recently, twin kHz QPOs have been discovered in the peculiar LMXB Cir X-1 (Boutloukos et al. 2006). At variance with what is observed in Z and atoll sources (see e.g. BMH05), the kHz QPO frequencies observed in this system are substantially lower than in the Z and atoll sources (in the range 56–225 and 230–500 Hz for the lower and upper kHz QPO, respectively) and their difference increases with frequency. Adding the 11 pairs of kHz QPO frequencies from Boutloukos et al. (2006) to the frequency–frequency correlation of BMH05, we find that, compared to the other kHz QPO sources, they follow a very different correlation (see Fig. 1), with linear best-fitting parameters \( a = 2.64 \pm 0.26 \) and \( b = 73 \pm 28 \) (excluding the highest frequency point, which clearly would tilt a linear relation). We note that this relation intersects the 3/2 line at \( \nu_1 = -64 \pm 29 \) Hz. Boutloukos et al. (2006) mention that for Cir X-1 a constant \( \nu_{\text{low}}/\nu_{\text{upp}} = 1:3 \) ratio is possible. A linear relation with \( a = 3 \) and \( b = 0 \) (dotted line in Fig. 1) fits the data statistically worse than the \( b \neq 0 \) one (reduced \( \chi^2 \) of 2.4 and 1.3, respectively); a fit with \( b = 0 \) and \( a \) free, with a reduced \( \chi^2 \) of 1.3, yields \( a = 3.31 \pm 0.10 \), that is, inconsistent with a value of 3.

### 2.2 XTE J1807–294

Another important source to include in the sample is the accreting millisecond pulsar XTE J1807–294, for which pairs of kHz QPOs have been discovered by Linares et al. (2005). It should be noted that some of the peaks found in this source are rather broad. However, in seven cases out of eight, Linares et al. (2005) could firmly identify two peaks as lower and upper kHz QPOs based on correlations with

Figure 1. Plot of the kHz QPO frequency–frequency relation including the points from Cir X-1 (Boutloukos et al. 2006). The XTE J1807–294 data are from Linares et al. (2005) and the SAX J1808.4–3658 point is from Wijnands et al. (2003). The asterisks are pairs of confirmed simultaneous high-frequency QPOs in black hole systems. The thin solid line represents a fixed 3/2 ratio, and the dotted line a 3:1 ratio. The dashed line is a fit to the Cir X-1 points, excluding the highest frequency one. The thick solid line shows the relation between the periastron-precession and the Keplerian frequencies for \( M = 2M_\odot \), in the relativistic precession model (Stella & Vietri 1999) those two frequencies have been identified with the lower and upper kHz QPO, respectively. The dark area represents \( \nu_{\text{low}} > \nu_{\text{high}} \), obviously not allowed by definition.
low-frequency features. We consider only these seven pairs as bona fide kHz QPOs. These points are included in the samples analysed by A05b. Similar values were reported by Zhang et al. (2006b) using the same data.

### 2.3 SAX J1808.4–3658

For this system, the first discovered accreting millisecond pulsar, Wijnands et al. (2003) found a pair of kHz QPOs at \( \sim 500 \) Hz and \( \sim 695 \) Hz, respectively. In addition, van Straaten et al. (2004) reported pairs of broad features at relatively low frequencies that they interpreted as the lower kHz QPO in this system; however, they also mention the possibility that these QPOs are a different component altogether. We do not include these points in our sample. The point corresponding to SAX J1808.4–3658 is shown in Fig. 1 as a six-pointed star.

### 3 PROPERTIES OF THE GLOBAL CORRELATION VERSUS SINGLE-SOURCE CORRELATIONS

In the following we discuss the significance of correlations between linear parameters derived from separate sources. We first show the results of simulations based on the existing data. This more intuitive approach is then followed by its analytical interpretation.

#### 3.1 The BMH05 sample and single sources

As a starting point, we take the sample originally published by BMH05 and partially used also by Z06, A05a and A05b, plus the recent frequencies from the millisecond accreting X-ray pulsar XTE J1807–294 (Linares et al. 2005, see above). Different classes of sources (Atoll and Z) can follow different correlations, as shown by BMH05, A05a and A05b, and the same applies to individual sources (see also Z06). However, the fact that the overall BMH05 sample of points shows a good degree of correlation (we will assume for the remainder of the paper that the correlation is linear, but the precise functional shape is not relevant for this discussion), indicates that the differences between source classes and individual sources cannot be very large.

In Fig. 2, we plot the BMH05 sample together with the best-fitting models found in A05a and A05b for selected sources. Notice that discrepant \( a \) and \( b \) values are quoted in A05a and A05b for the same sources; for the discrepant cases, we use the A05a values. We remark that Fig. 2 contains also points from sources not fitted with the model lines plotted in that figure. Unless there is an unlikely correlation between dynamic range in frequencies and deviation from the average correlation, the moderate spread observed in the data excludes large deviations in correlation parameters for single sources. In other words, in Fig. 2 the spread of the single-source correlations, when extrapolated over the full range of the sample, is larger than the spread of the points. Slopes very different from that of the sample correspond to sources for which a reduced dynamic range of frequencies is observed. This leads to the conclusion that it is likely that these different correlations are the result of points from sources which a reduced dynamic range of frequencies is present. Notice that, at variance with what reported by A05a, the best-fitting models to different sources do not intersect at the same point.

#### 3.2 The sample as a whole

As shown by BMH05, the lower and upper kHz QPO frequencies of a large sample of sources are roughly linearly correlated as \( v_{\text{upper}} = 0.92v_{\text{lower}} + 360 \). The precise values are irrelevant here, as well as the precise functional shape of the correlation (see also Z06). We consider here the BMH05 sample without taking into account the association of points with separate sources. We simulate artificial sources by taking 1000 random subsamples of \( n \) real points where \( n \) is also a random number for each artificial source, chosen between 20 and 80. For each subsample, we fit the \( n \) values with a linear function and thus derive a set of 1000 pairs of \( a \) and \( b \). A plot of these pairs shows a marked anticorrelation \( b = Aa + B \) with slope \( A = (-1.69 \pm 0.01) \times 10^{-3} \) and intercept \( B = 1.51 \pm 0.01 \), consistent with the values quoted by A05b from their source-by-source analysis (see Fig. 3; the range in \( a \) and \( b \) values in our simulation.
is limited because the procedure does not likely produce random subsamples spanning a limited range in frequency, as it appears to happen in reality.) From this simulation we find that any randomly selected subset of points from this data set yields \(a, b\) pairs that are distributed along such a straight line, and have \(B \approx 1.5\). Simulating random straight lines in the plane would of course not lead to any \(a\) versus \(b\) correlation, but in this case we are extracting lines that cross the correlation segment visible in Fig. 2.

The origin of the correlation shown in Fig. 3 can be seen more clearly through a simulation that does not make use of the actual observed frequencies. We simulated an artificial set of pairs of frequencies following a linear correlation \(y = 0.92x + 360\) over the range \(v_1 = 150–900\) Hz and added a Gaussian spread with \(\sigma = 50\) Hz. Then, we repeated 100 times the procedure outlined above (extract 1000 random subsamples, fit them with a linear function, fit linearly the \(a\) values versus the \(b\) values and obtaining the intercept \(B\)), obtaining a set of 100 values for \(B\). The resulting distribution of the 100 \(B\) values is strongly peaked around 1.5; this shows that, while this value could originate from the differences in the frequency–frequency distributions for different sources, as suggested by A05a and A05b, it could also simply be the consequence of the values \(a = 0.92\) and \(b = 360\) of the global correlation and of the ranges spanned by the observed frequencies. We repeated the simulation with the same \(a\) and \(b\) values, but with \(v_1\) in the ranges 600–1000 and 10–500 Hz, and obtained average \(B\) values of 1.36 and 2.0, respectively.

### 3.3 Significance of the anticorrelation between linear parameters

The results of the simulations shown above can be interpreted analytically. The \(a, b\) parameters of a \(y = ax + b\) correlation are covariant. This means that the confidence contours around the best-fitting value are always elongated diagonally in the direction of anticorrelation. The inclination of the confidence ellipse is determined both by the best-fitting parameters and the distribution of the points along the correlation. In particular, the intercept \(A\) of the major axis of the ellipse can be found simply by fitting a linear relation of the form

\[
y = Ax \text{ to the data pairs } x_j, y_j.
\]

Analytically, this can be calculated as

\[
A = \frac{\sum y_j x_j / \sigma_j}{\sum x_j^2 / \sigma_j}.
\]

(1)

If the errors are all the same size, equation (1) reduces to

\[
A = \langle xy \rangle / \langle x^2 \rangle.
\]

(2)

For the typical range of \(x = v_1\) and \(y = v_2\), in the data, this can be approximated as \(A = \langle v_2 \rangle / \langle v_1 \rangle\). Obviously, a fit with zero intercept to data linearly distributed with non-zero intercept will cross the data around the middle of the points, which is roughly centred at \(\langle v_2 \rangle / \langle v_1 \rangle\). This means that, given our data sets, the values of \(A\) will depend also crucially on the distribution of points (see also BMH05).

We selected a clean sample of frequencies from a few sources, fitted with a linear function with zero intercept and computed the \(A\) values from equation (1), which resulted compatible with the fitting parameters (see Table 1, where \(A\) values obtained with equation 1 are shown, as well as \(\langle v_2 \rangle / \langle v_1 \rangle\) values). Notice that for GX 17 + 2 and GX 5–1 we only selected pairs of frequencies where both detections were above 3\(\sigma\) in Homan et al. (2002) and Jonker et al. (2002a).

For GX 340+4, this selection from the data in Jonker et al. (2000) resulted in only three pairs of frequencies: we therefore excluded this source from the sample. It is clear that the \(A\) (excluding Cir X–1) values cluster around the value 1.5. Fig. 4 shows the best-fitting \(A\) and \(B\) values and confidence contours for these sources. The alignment of all ellipses is evident.

As we have shown above, the values of \(A\) cluster around the value 1.5 because the observed linearly correlated frequencies show a ratio of mean values close to 1.5. This was also shown in BMH05. This means that the confidence contours will on average have an inclination pointing at \(B = 0, A = 1.5\).

### 4 DISCUSSION

Aside from precise fitting of separate sources with different models, it is evident from Fig. 2 that the centroid frequencies of kHz QPOs of both atoll and Z sources are roughly distributed, although with some scatter, around a line approximated by \(v_{\text{high}} = 0.92v_{\text{low}} + 360\) (see BMH05). We have shown that this fact alone leads to a

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Table 1. Sample of LMXBs with best-fitting linear parameters, \(A\) values obtained with equation (1), \(\langle v_2 \rangle / \langle v_1 \rangle\) and references.

| Name       | \(a\)        | \(b\)       | \(A\) | \(\langle v_2 \rangle / \langle v_1 \rangle\) | References |
|------------|--------------|-------------|-------|---------------------------------------------|------------|
| GX 5–1     | 0.856 ± 0.022| 374 ± 8     | 1.85  | 1.95                                        | 1          |
| Sco X–1    | 0.791 ± 0.005| 430 ± 3     | 1.41  | 1.42                                        | 2          |
| GX 17+2    | 0.870 ± 0.041| 361 ± 26    | 1.45  | 1.46                                        | 3          |
| 4U 0614+09 | 1.078 ± 0.020| 269 ± 12    | 1.49  | 1.52                                        | 4, 5       |
| 4U 1728–34 | 0.899 ± 0.036| 418 ± 25    | 1.47  | 1.46                                        | 6          |
| 4U 1636–53 | 0.672 ± 0.025| 541 ± 22    | 1.32  | 1.34                                        | 7, 8       |
| 4U 1608–52 | 0.810 ± 0.027| 419 ± 16    | 1.45  | 1.42                                        | 6          |
| 4U 1820–30 | 0.892 ± 0.045| 355 ± 33    | 1.39  | 1.39                                        | 9          |
| 4U 1915–05 | 1.157 ± 0.045| 256 ± 20    | 1.59  | 1.62                                        | 10         |
| XTE J1807–294 | 1.145 ± 0.124| 171 ± 30    | 1.90  | 1.95                                        | 11         |
| Cir X–1    | 2.339 ± 0.474| 104 ± 58    | 3.11  | 3.18                                        | 12         |

References: (1) Jonker et al. (2002a); (2) Méndez & van der Klis (2000); (3) Homan et al. (2002); (4) van Straaten et al. (2000); (5) van Straaten et al. (2002); (6) Méndez, van der Klis & Ford (2001); (7) Di Salvo, Méndez & van der Klis (2003); (8) Jonker, Méndez & van der Klis (2002b); (9) Zhang et al. (1998); (10) Boirin et al. (2000); (11) Linares et al. (2005); (12) Bouloutous et al. (2006).
strong anticorrelation, with intercept very close to the value 1.5 (the exact value of the intercept depends on the range of frequencies spanned by the QPOs), between the parameters \( a \) and \( b \) obtained from linear fits to any subsample of points, or to points generated randomly along the global correlation. This result alone implies that the analysis of separate sources cannot be used in the way proposed by A05a and A05b for testing the resonance model.

The question however remains why the frequencies are distributed along that major correlation and with these frequency boundaries. As shown above, the intercept of 1.5 in the \( a-b \) anticorrelation could be different should the linear parameters of the sample of sources, or the range spanned by the kHz QPO frequencies be different. Moreover, notice that there are different combinations of \( a,b \) and frequency range that yield to \( B \sim 1.5 \). The global correlation visible in Fig. 1, and its frequency range, constitute therefore one of the major observational results that must be directly addressed by theoretical models.

Fig. 1 shows that the frequency points from Cir X-1 pose a more serious problem to the resonance model of Abramowicz et al. (2003). They are distributed along a steeper line than the one followed by the frequencies of the sources in BMH05, A05a and A05b, constituting a low-frequency extension of the correlation defined by those sources. Notice that the linear parameters \( a \) and \( b \) for Cir X-1 are very different from those of the other sources, in a way that is not at all consistent with the correlation shown in Fig. 2 of A05b (see Fig. 3).

It is clear from Fig. 1 that the frequencies of Z and atoll sources do not follow a relation \( v_{\text{high}} = 1.5 v_{\text{low}} \), as already pointed out by BMH05. Rebusco (2004) presented a model where the addition of an ad hoc force on an oscillator responsible for an otherwise fixed pair of frequencies could lead to the observed correlation. The kHz QPOs in Cir X-1 (Boutloukos et al. 2006) follow a correlation which intersects the 3:2 fixed-ratio line at \( \nu \sim -64 \) Hz, that is, the two lines do not intersect in the physical range of interest for the frequencies. This, together with the fact that the kHz QPOs in Cir X-1 show other properties and correlations very similar to the kHz QPOs in other neutron star systems, cast doubt on the model of Rebusco (2004). The possibility of Cir X-1 being a black hole is very unlikely. Eight X-ray bursts were observed with EXOSAT (Tennant, Fabian & Shafer 1986a,b), the high-frequency QPOs are consistent with being neutron star kHz QPOs, and at high luminosities the tracks in the X-ray colour–colour diagrams and the low-frequency variability are very similar to those for the Z sources (Shirey et al. 1998; Shirey, Bradt & Levine 1999). Also, it is suggestive that the Cir X-1 frequencies, while following a much steeper linear relation, join smoothly with the low-frequency end of the Z sources.

One of the most interesting results from Boutloukos et al. (2006) is that the Cir X-1 points are the first kHz QPOs observed with a frequency difference which increases with frequency, in accordance with the prediction of the relativistic precession model (Stella & Vietri 1999) and the Alfvén wave model (Zhang 2004; Zhang et al. 2005; Z06). In Fig. 1, we also plot the line for the relativistic precession model corresponding to a mass of \( 2 M_\odot \) (the line for the Alfvén wave model lies very close to that of the relativistic precession model). The agreement with Cir X-1 and the Z sources at low frequencies is remarkable. At high frequencies, the points lie above the model line; this of course could reflect different masses for the neutron stars, but for some sources additional assumptions are required anyway (see Stella & Vietri 1999). Moreover, above \( v_1 = 150 \) Hz the data follow a rather straight correlation, while the model line is significantly curved at all frequencies.

The points corresponding to the two accreting millisecond pulsars, XTE J1807−294 and SAX J1808.4−3658 (Wijnands et al. 2003; Linares et al. 2005) lie below the global correlation. It is interesting to note that from their analysis of correlations between all timing frequencies of a sample of atoll sources and accreting millisecond pulsars (not including XTE J1807−294), van Straaten, van der Klis & Wijnands (2005) conclude that for two of the millisecond pulsars (including SAX J1808.4−3658) both the lower and upper kHz QPOs appear shifted down by a factor \( \sim 1.5 \) (van Straaten et al. 2005, have to multiply \( v_{\text{low}} \) and \( v_{\text{upp}} \) of these two millisecond pulsars by \( \sim 1.5 \) for them to match the correlation of the other sources in their sample). Applying a 1.5 factor to both kHz QPO frequencies corresponding to the pulsars in our sample, the two sources are indeed moved to the global correlation. Within the relativistic precession model, such a shift could imply a neutron star mass higher by a factor of 1.5, which is unlikely as it would lead to accreting millisecond pulsars containing neutron stars of 3 M\odot, assuming 2 M\odot for the other sources. We note that a similar shift does not move Cir X-1 into the linear correlation defined by the other sources.

On Fig. 1, we also plot the four points corresponding to the pairs of confirmed simultaneous high-frequency QPOs from black hole systems (GRS 1915 + 105: Stroh Mayer 2001a; GRO J1655−40: Stroh Mayer 2001b; XTE J1550−564: Miller et al. 2001; H 1743−322: Homan et al. 2005). Three of these points lie very close to the 3:2 line, while GRS 1915 + 105 is consistent with a 5:3 ratio (it appears close to the 3:2 line due to the low frequencies involved). Clearly, for black hole binaries, a model in which the QPO frequency ratio is the ratio of two integer numbers is consistent with the available data.

5 CONCLUSIONS

We showed that the correlation between parameters obtained from linear fitting to separate sources applied to atoll and Z sources by A05a and A05b is a direct result of the observed general correlation and cannot be used for testing their models. Moreover, the newly discovered kHz QPOs in the peculiar neutron star binary Cir X-1 follow a different correlation than atoll and Z sources. This observed correlation appears to be in contradiction with the predictions of all...
modifications of resonance models, but is in good general agreement with the relativistic precession model (although it is known that the model in its simplest version does not explain all observables, such as the relation between kHz QPOs and spin frequency, and needs correction at high frequencies) and the Alfvén wave model. Our results indicate that the observed high-frequency QPOs in black hole and neutron star low-mass X-ray binaries most likely have a different origin.

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