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Published in:
Monthly Notices of the Royal Astronomical Society

DOI:
10.1111/j.1365-2966.2007.12306.x

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Document Version
Publisher's PDF, also known as Version of record

Publication date:
2007

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Méndez, M., & Belloni, T. (2007). Is there a link between the neutron-star spin and the frequency of the kilohertz quasi-periodic oscillations? *Monthly Notices of the Royal Astronomical Society*, *381*(2), 790-796. https://doi.org/10.1111/j.1365-2966.2007.12306.x

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Mon. Not. R. Astron. Soc. **381,** 790–796 (2007) doi:10.1111/j.1365-2966.2007.12306.x

Is there a link between the neutron-star spin and the frequency of the kilohertz quasi-periodic oscillations?

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Accepted 2007 July 31. Received 2007 July 27; in original form 2007 June 1

ABSTRACT

There is a general consensus that the frequencies of the kilohertz quasi-periodic oscillations (kHz QPOs) in neutron-star low-mass X-ray binaries are directly linked to the spin of the neutron star. The root of this idea is the apparent clustering of the ratio of the frequency difference of the kHz QPOs, and the neutron-star spin frequency, $\Delta\nu/\nu_s$, at around 0.5 and 1 in 10 systems for which these two quantities have been measured. Here, we re-examine all available data of sources for which there exist measurements of two simultaneous kHz QPOs and spin frequencies, and we advance the possibility that $\Delta\nu$ and ν_s are not related to each other. We discuss ways in which this possibility could be tested with current and future observations.

Key words: stars: neutron – X-rays: binaries.

1 INTRODUCTION

Observations of neutron-star (NS) low-mass X-ray binaries (LMXBs) with the *Rossi X-ray Timing Explorer* (*RXTE*, Bradt, Rothschild & Swank 1993) have led to two important discoveries: strong variability on millisecond time-scales in the X-ray light curves of these systems, the so-called kilohertz quasi-periodic oscillations (kHz QPOs, van der Klis et al. 1996a) and pulsations during X-ray bursts, also known as burst oscillations (Strohmayer et al. 1996a).

The kHz QPOs are relatively narrow peaks in the power density spectrum of NS LMXBs that often appear in pairs, at frequencies ν_1 and $\nu_2 > \nu_1$ that change with time. These QPOs are thought to reflect motion of matter at the inner edge of an accretion disc around the NS.

Burst oscillations are short-lived ($\tau \lesssim 10$s), almost coherent pulsations seen at the rise and tail of X-ray bursts in NS LMXBs. The frequency of these oscillations, ν_b, increases in the tail of the bursts to an asymptotic value that is consistent with being the same in bursts separated by more than a year time (Strohmayer et al. 1998b). This, and the fact that in the accretion-powered millisecond X-ray pulsar (AMP) SAX J1808.4−3658 burst oscillations appear at the same frequency as the pulsations seen during persistent (non-burst) intervals (Wijnands et al. 2003), indicates that the frequency of these burst oscillations is equal to the spin frequency of the NS, ν_s.

It is commonly accepted that the spin of the NS is directly involved in the mechanism that produces the kHz QPOs. This consensus stems from the first detection of kHz QPOs and burst oscillations in the same source, the LMXB 4U 1728−34, very early on in the *RXTE* mission. While in different observations the kHz QPOs appeared at different frequencies, ν_1 in the range ∼600–800 Hz and ν_2 in the range ∼500–1100 Hz, the frequency difference of the QPOs, when both were present simultaneously, was consistent with being constant, $\Delta\nu = \nu_2 - \nu_1 \approx 363$ Hz, and also consistent with the oscillations seen during bursts in this source at $\nu_b = 363$ Hz (Strohmayer et al. 1996b). This fitted with the suggestion (Strohmayer et al. 1996c) that a beat mechanism with the NS spin was responsible for the kHz QPOs. Further results on other sources (e.g. Ford et al. 2007) appeared to confirm this picture. A detailed model, the sonic-point model, proposed by Miller, Lamb & Psaltis (1998) explained the observed relation between the kHz QPOs, and the NS spin in terms of a beat between material orbiting at the inner edge of the disc with the Keplerian frequency at that radius and the spin of the NS.

As soon as kHz QPOs were discovered in 4U 1636–53 (van der Klis et al. 1996b) with a frequency difference of $\Delta\nu = 272 \pm 11$ Hz, and burst oscillations at a frequency $\nu_b = 581$ Hz (Zhang et al. 1996), it became apparent that in this source $\Delta\nu$ was inconsistent with being equal to ν_b, but it was close to $\nu_b/2$. This would have been the end of the sonic-point model, unless in 4U 1636−53 the 581 Hz frequency seen during X-ray bursts was the second harmonic of the NS spin frequency, $\nu_b = 2 \times \nu_s$, with $\nu_s = 290.5$ Hz, for example, if the pulsed radiation came from two antipodal poles on the NS. Although searches for a signal at half the burst oscillations frequency, the putative spin frequency of the NS (Miller 1999), in the power spectrum of the bursts in 4U 1636−53 yielded no positive result (Strohmayer 2001; Strohmayer & Markwardt 2002), this option remained viable.

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When kHz QPOs and burst oscillations were discovered in more sources, it became apparent that there was a systematic trend in how $\Delta\nu$ and $\nu_{\rm b}$ were related: for sources for which $\nu_{\rm b} \lesssim 400$ Hz, $\Delta\nu \simeq \nu_{\rm b}$, whereas for sources for which $\nu_{\rm b} \gtrsim 400$ Hz, $\Delta\nu \simeq \nu_{\rm b}/2$. These two groups of sources were then called 'slow' and 'fast' rotators, respectively (Muno et al. 2001).

Related to this, it is interesting to note that when plotted against each other, the frequencies of the kHz QPOs in 19 different sources all follow approximately the same relation (Belloni, Méndez & Homan 2005; Zhang et al. 2006; Belloni, Méndez & Homan 2007). This is a priori unexpected if in each source the frequency of the upper and the lower kHz QPOs were related to the spin frequency as $\nu_2 = \nu_1 + \nu_{\rm s}$, given that ν_1 and ν_2 span more or less the same frequency range in all sources of kHz QPOs, whereas the NSs in these systems have spins that span a large range of frequencies, $\nu_{\rm s} \approx 200$– 620 Hz (Chakrabarty et al. 2003).

More kHz QPO data, and more precise QPO frequency measurements, showed that at least in some sources $\Delta\nu$ was not constant, but decreased as the QPO frequencies increased (van der Klis et al. 1997; Méndez et al. 1998), and it was always significantly lower than either $\nu_{\rm b}$ (Méndez & van der Klis 1999) or $\nu_{\rm b}/2$ (Méndez, van der Klis & van Paradijs 1998). Modifications of the sonic-point model (Lamb & Miller 2001) could account for this difference, considering that the frequencies of the QPOs drift slightly when the material that produces the QPOs crosses the sonic point and falls on to the NS surface.

Three other results raised more serious issues against the sonic-point beat-frequency model, and eventually rendered it untenable: (i) Jonker, Méndez & van der Klis (2002) found that in 4U 1636−53, when the frequency of the kHz QPOs decreases sufficiently, $\Delta\nu$ is significantly higher than $\nu_{\rm b}/2$, which was difficult (if not impossible) to explain by the sonic-point model, even after the modifications introduced by Lamb & Miller (2001); in the AMP SAX J1808.4−3658, (ii) Chakrabarty et al. (2003) found that the frequency of burst oscillations is equal to the NS spin frequency (see Markwardt & Swank 2003, for a similar result in another AMP, XTE J1814−338), while (iii) Wijnands et al. (2003) detected two simultaneous kHz QPOs with a frequency separation $\Delta\nu \simeq \nu_{\rm s}/2$. If this is extended to other sources in which $\Delta\nu \simeq \nu_{\rm b}/2$, it would also be true that for those $\nu_{\rm b} = \nu_{\rm s}$, and hence $\Delta\nu \simeq \nu_{\rm s}/2$. The sonic-point model could not explain this.

But soon after the SAX J1808.4−3658 results were published, a new model that re-established a relation between the spin frequency of the NS and the kHz QPO, the sonic-point and spin-resonance model (Lamb & Miller 2003), was proposed (see also Lee, Abramowicz & Kluźniak 2004). In this model, there is a resonance in the accretion disc at the radial distance at which the Keplerian orbital frequency is equal to the NS spin frequency minus the vertical epicyclic frequency. This resonance could lead to either $\Delta\nu = \nu_{\rm s}$ or $\Delta\nu = \nu_{\rm s}/2$ depending on whether the disc flow at the resonance radius is smooth or clumped. In fact, the same source may, in principle, show both cases, but this has so far not been observed.

Almost in parallel with some of these explanations, and as a result of some of the difficulties for beat-frequency models mentioned above, a different class of models was proposed, in which the frequencies of the kHz QPOs were associated to two of the three epicyclic frequencies of general relativity, or a combination of those (e.g. Stella & Vietri 1999). In these models, the NS spin frequency plays no role in setting up the frequencies of the kHz QPOs, except for the small corrections it introduces to the epicyclic frequencies. While these models reproduce qualitatively the trends seen in the data, and predicted other trends that were later on observed (Migliari, van der Klis & Fender 2003; Boutloukos et al. 2006), they have problems to fit the data in detail. The main criticism to these models, however, has always been that they do not explain the fact that in several sources $\Delta\nu \simeq \nu_{\rm s}$ or $\Delta\nu \simeq \nu_{\rm s}/2$ (Lamb 2003). In other words, the criticism is that in these models the NS spin plays no role in the mechanism that produces the QPOs.

Recently, Yin et al. (2007) compared the average frequency separation of the kHz QPOs, $\langle\Delta\nu\rangle$, with $\nu_{\rm s}$ in six systems in which these two quantities have been measured. They suggest that despite the low number of sources available for their analysis, $\langle\Delta\nu\rangle$ depends weakly on $\nu_{\rm s}$, $\langle\Delta\nu\rangle \simeq -0.20\nu_{\rm s} + 390$ Hz.

In summary, the history of models of the kHz QPOs is a cycle of attempts to explain the phenomenon in relation to the spin of the NS; each time that a new observation raised an issue against one such model, a modification of that model, or a new model, was proposed that tried to re-establish the role of the NS spin in the mechanism that produces the kHz QPOs.

After more than ten years from the discovery of the kHz QPOs, a critical assessment of the current paradigms is necessary. Here, we review all the values of $\Delta\nu$ and $\nu_{\rm s}$ available in the literature in order to compare the slow/fast rotator paradigm with other possibilities. We suggest that the data may in fact show that there is no relation between NS spin and kHz QPOs. Actually, the data appear to be consistent with a situation in which the average separation in frequency of the kHz QPOs $\langle\Delta\nu\rangle$ is more or less constant, independent of the spin of the NS in the system. The division between 'slow' and 'fast' rotators may be an effect of the low number of sources for which two simultaneous kHz QPOs and burst oscillations and/or pulsations in the persistent emission have been observed, and the fact that $\langle\Delta\nu\rangle$ is independent of $\nu_{\rm s}$.

2 DATA

We use data from the literature. For the rest of the paper, we assume that the frequency $\nu_{\rm b}$ of burst oscillations is equal to the spin frequency of the NS, $\nu_{\rm s}$ (see Section 1). There are 10 sources for which both $\Delta\nu$ and $\nu_{\rm s}$ have been measured. Two of these sources are the AMPs SAX J1808.4−3658 and XTE J1807−294, six of them are the atoll sources 4U 1608−52, 4U 1636−53, 4U 1702−43, 4U 1728−34, KS 1731−260 and 4U 1915−05 (see Hasinger & van der Klis 1989, for a definition of the atoll class) and the other two are IGR J17191−2821 and SAX J1750.8−2900 which most likely are also atoll sources.

For each of these sources, we give in Table 1 the spin frequency and the range of measurements of $\Delta\nu$. Although there are too few sources to draw firm conclusions from this table it is apparent that the average of the $\Delta\nu$ range in the AMPs SAX J1808.4−3568 and XTE J1807−214 is somewhat lower than for the other eight sources.

In Fig. 1, we show in black the distribution of measurements of $\Delta\nu$ for the 10 sources with known spin frequencies in Table 1, and for the other sources of kHz QPOs for which the spin frequency is not known. The data for this figure were taken from the papers in which the kHz QPOs were measured (see van der Klis 2006, for a complete reference list). We note that to measure both kHz QPOs significantly and calculate $\Delta\nu$, in most cases power spectra had to be selected on the basis of some property of the source (e.g. intensity, colours, characteristic frequency of a low- or high-frequency timing feature, etc.; see for instance Jonker et al. 2000) and averaged. In this process, part of the information of the real distribution of $\Delta\nu$ is lost. Therefore, the plots in Fig. 1 do not show the real $\Delta\nu$ distribution, but just the range of values observed and a rough idea

Table 1. Measurements of the frequency separation of the kHz QPOs, $\Delta\nu$, and spin frequencies, ν_s, for the 2 AMP and 6 + 2 atoll sources studied in this paper.

Source	$\Delta\nu$ range (Hz)	ν_s (Hz)	References
AMPs			
XTE J1807−294	180–250	191	1
SAX J1808.4−3658	195	401	2
Atoll sources			
4U 1608−52	225–325	619	3
4U 1636−53	215–330	581	4
4U 1702−43	330	330	5
4U 1728−34	270–360	363	6
4U 1731−260	265	524	7
IGR J17191−2821	330	294	8
SAX J1750.8−2900	317	600	9
4U 1915−05	290–355	270	10

References – (1) Linares et al. (2005); (2) Wijnands et al. (2003); (3) Méndez et al. (1998), Muno et al. (2001); (4) Di Salvo, Méndez & van der Klis (2003), Jonker et al. 2002 and Strohmayer et al. 1998a; (5) Markwardt, Strohmayer & Swank (1999); (6) Méndez & van der Klis (1999) and Strohmayer et al. (1996b); (7) Wijnands & van der Klis (1997) and Smith et al. (1997); (8) Markwardt et al. (2007) and Klein-Wolt et al. (2007); (9) Kaaret et al. (2002); (10) Boirin et al. (2000) and Galloway et al. (2001).

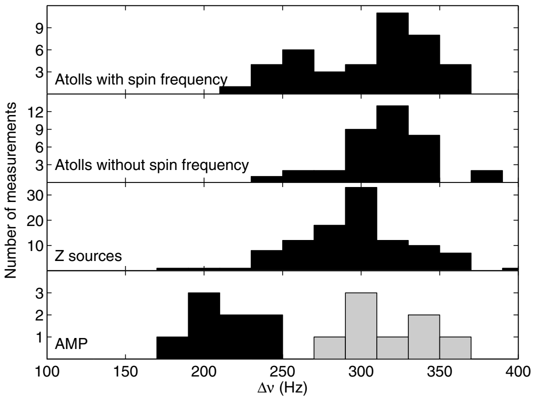

Figure 1. The distribution of measurements of $\Delta\nu$ in different groups of sources. As described in the text, because of the way the measurements were done, the histograms do not necessarily represent the true distribution of $\Delta\nu$ (see the text for details). Upper panel: atoll sources for which the spin frequency of the NS is known from burst oscillations. Second panel: atoll sources for which the spin period of the NS is not known. Third panel: *Z*-sources; spin frequencies are not known in this case. Lower panel: accreting millisecond X-ray pulsars. The black histogram shows the actual $\Delta\nu$ measurements; the grey histogram is the distribution of measurements multiplied by the factors close to 1.5 taken from van Straaten et al. (2005) and Linares et al. (2005).

of how often a certain value of $\Delta\nu$ has been observed. This plot again suggests that the average $\Delta\nu$ of the AMP, $\langle\Delta\nu\rangle \simeq 210$ Hz, is somewhat lower than the average $\Delta\nu$ of the other sources, $\langle\Delta\nu\rangle \simeq 300$ Hz.

Fig. 2 shows the plot of $\Delta\nu/\nu_s$ versus ν_s for the 10 sources in Table 1. For each source, we plot all the individual $\Delta\nu$ measurements, taken from the references listed in Table 1, divided by ν_s (see van der Klis 2005, for a similar plot). The open circles correspond to the two AMPs, and the filled circles are the other eight sources in Table 1. The dashed line in this figure is a step function, $S(\nu_s) = 1$ for $\nu_s \leqslant 400$ Hz, $S(\nu_s) = 0.5$ for $\nu_s > 400$. This figure shows the fact that for ‘slow rotators’, NSs with $\nu_s \lesssim 400$ Hz, the ratio $\Delta\nu/\nu_s \simeq 1$, whereas for ‘fast rotators’, NSs with $\nu_s \gtrsim 400$ Hz, the ratio $\Delta\nu/\nu_s \simeq 0.5$. Note that, as mentioned in Section 1, for some sources $\Delta\nu$ is significantly different from ν_s or $\nu_s/2$, respectively; hence, some of the individual ratios are significantly different from 1 or 0.5, respectively.

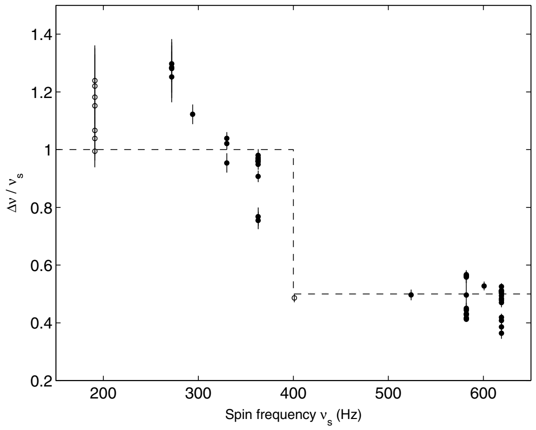

Figure 2. The ratio of individual measurements of $\Delta\nu$ divided by ν_s as a function of ν_s for the sources listed in Table 1. The open circles correspond to the two AMPs and the filled circles are the other eight sources in Table 1. The dashed line is the step function, $S(\nu_s) = 1$ for $\nu_s \leqslant 400$ Hz, $S(\nu_s) = 0.5$ for $\nu_s > 400$.

Psaltis, Belloni & van der Klis (1999), van Straaten et al. (2002), van Straaten, van der Klis & Méndez (2003), Reig, van Straaten & van der Klis (2004), van Straaten, Wijnands & van der Klis (2005) and Altamirano et al. (2007), have shown that there is a correlation between the frequency of the kHz QPOs and that of other low-frequency QPOs. More specifically, all these authors have shown that when plotted versus the frequency of the upper kHz QPO, the frequency of the lower kHz QPO as well as the frequency of all low-frequency QPOs follow individual correlations that are consistent with being the same in five atoll sources, one *Z*-source (see Hasinger & van der Klis 1989, for the definition of the *Z*-class), three low-luminosity bursters and two AMPs (see van Straaten et al. 2005 and Altamirano et al. 2007, for an overview of these correlations).

The AMPs SAX J1808.4−3568 and XTE J1807−214 show relations between the frequencies of the low-frequency QPOs and ν_2 that are similar to those of the low-luminosity bursters and atoll sources. But the relations of SAX J1808.4−3568 and XTE J1807−214 are shifted with respect to those of the other sources (Linares et al. 2005; van Straaten et al. 2005). The shift[1] is between the frequencies of the low-frequency QPOs and ν_2, and is best described as a multiplication of ν_2 by a factor close to 1.5. The exact multiplicative factors are 1.45 for SAX J1808.4−3568 and 1.59 for XTE J1807−214, respectively. While this factor applied to ν_2 works for the low-frequency QPOs versus ν_2 correlations, it does not work for the correlation between ν_1 and ν_2. Interestingly, van Straaten et al. (2005) and Linares et al. (2005) noticed that the ν_1 versus ν_2 correlation in the AMPs and in the other sources could be reconciled if they also multiplied ν_1 by *the same factor* that they used to describe

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[1] This is usually called a shift since van Straaten et al. (2005) and Linares et al. (2005) measure a frequency shift in a log–log plot.

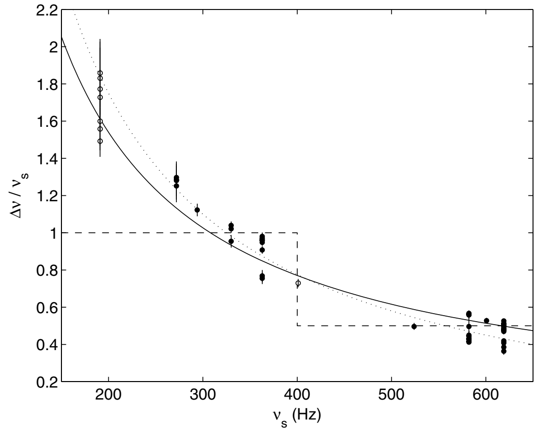

Figure 3. The ratio of individual measurements of $\Delta\nu$ divided by ν_s as a function of ν_s for the sources listed in Table 1, but with $\Delta\nu$ of the AMP multiplied by the factors close to 1.5 from van Straaten et al. (2005) and Linares et al. (2005). The symbols and the dashed line are same as in Fig. 2. The solid line corresponds to a constant $\Delta\nu = 308$ Hz. The dotted line shows the relation $\Delta\nu = -0.20\ \nu_s + 390$ Hz from Yin et al. (2007).

the shift of the ν_2 versus low-frequency QPO correlations. (Notice that ν_1 was not used to derive that factor.)

The nature of this shift is unclear, but taken at face value, a multiplicative factor applied both to ν_1 and ν_2 implies that the frequency difference $\Delta\nu = \nu_2 - \nu_1$ must also be multiplied by this factor. The grey histogram in the lower panel of Fig. 1 shows the distribution of $\Delta\nu$ (apart from the caveat described above in this section) for the two AMPs, XTE J1807−294 and SAX J1808.4−3658 multiplied by the factors (close to 1.5) taken from van Straaten et al. (2005) and Linares et al. (2005). This multiplicative factors appear to bring the values of $\Delta\nu$ in these two AMP into the range of the values measured in all the other sources. The average $\Delta\nu$ of the combined sample (atoll sources with spin frequency and the two AMPs multiplied by the factors close to 1.5) is 308 Hz and the standard deviation is 38 Hz.

We note that the above procedure could imply a circular argument: matching the ν_1 versus ν_2 correlation of the AMPs and the other sources via a multiplicative factor means that also $\Delta\nu$ of the AMPs and of the other sources would match. However, both van Straaten et al. (2005) and Linares et al. (2005) determined the shift factor on ν_2 using only the correlations between the low-frequency QPOs and ν_2, independently of ν_1. They then noted that they could also match the ν_1 versus ν_2 correlations of the AMPs and the other sources if they applied the *same factor* (within errors) also to ν_1 (thence, there would be no freedom in choosing the shift factor on ν_1; see the description in Linares et al. 2005). Withal, the argument would indeed be circular if the shifts on ν_1 and ν_2 turned out not to be the same. This conundrum may eventually be resolved when more shifts in other sources are observed. In the meantime, we caution the reader about the possible caveats in our procedure of multiplying $\Delta\nu$ in the AMPs by the factors found by van Straaten et al. (2005) and Linares et al. (2005).

In Fig. 3, we show the plot of $\Delta\nu/\nu_s$ for the 10 sources in Table 1, but now we have multiplied the $\Delta\nu$ values of the AMPs by the factors taken from van Straaten et al. (2005) and Linares et al. (2005). As in Fig. 2, the dashed line is the step function $S(\nu)$ (see above); the solid line corresponds to a constant $\Delta\nu = 308$ Hz. The dotted line shows the relation $\Delta\nu = -0.20\ \nu_s + 390$ Hz from Yin et al. (2007).

3 DISCUSSION

There is a general (but not universal) tendency to try and include the spin of the NS, ν_s, as a key ingredient in models that explain the kHz QPOs. In this type of models, the spin is related to the difference between the frequencies of the kHz QPOs, $\Delta\nu = \nu_2 - \nu_1$. This tendency persisted, despite the fact that several results seemed to contradict the predictions of these models. Amendments to the original ideas meant that models had to appeal to rather contrived geometries to explain the data, and rather artificial classes of sources had to be introduced to explain the diversity of the results (e.g. the division of sources with a different relation between $\Delta\nu$ and ν_s into 'slow' and 'fast' rotators). Here, we propose that the data are in fact consistent with a simpler picture in which the frequency separation between kHz QPOs, $\Delta\nu$, is independent of ν_s, with $\langle\Delta\nu\rangle$ more or less constant across sources.

In Fig. 4, we compare the distribution of the $\Delta\nu$ measurements in all types of sources for which two simultaneous kHz QPOs have been detected (see Fig. 1), with the distribution of spin frequencies of 23 sources for which pulsations in the persistent emission or burst oscillations have been measured (see Yin et al. 2007, and table 1 for the list of sources and spin frequencies). From this figure it is apparent that the distribution of $\Delta\nu$ measurements is much more concentrated than the distribution of spin frequencies. The distribution of $\Delta\nu$ measurements can be well described ($\chi^2 = 14.3$ for 12 degrees of freedom) by a Gaussian with a mean value $\langle\Delta\nu\rangle = 303.2 \pm 2.9$ Hz and a standard deviation $\sigma_{\Delta\nu} = 36.0 \pm 2.1$ Hz (1σ errors). A Kolmogorov–Smirnov (K–S) test yields a very low probability, $P \approx 7 \times 10^{-7}$, that the two samples are drawn from the same parent population. According to the paradigm of slow and fast rotators (see Section 1), when $\nu_s \gtrsim 400$ Hz (the exact value is not specified) $\Delta\nu$ should be compared to $\nu_s/2$ instead of ν_s. After dividing by two the spin frequencies higher than 400 Hz, a K–S test indicates that the distributions of ν_s and $\Delta\nu$ are marginally consistent with each other, with a K–S probability $P \approx 1 \times 10^{-2}$ that the two are drawn from the same parent population.

Using $\Delta\nu$ and ν_s for six of the atoll sources also included in our sample, Yin et al. (2007) proposed that $\Delta\nu$ may be (weakly) related to ν_s in a way that is different than predicted by beat-frequency

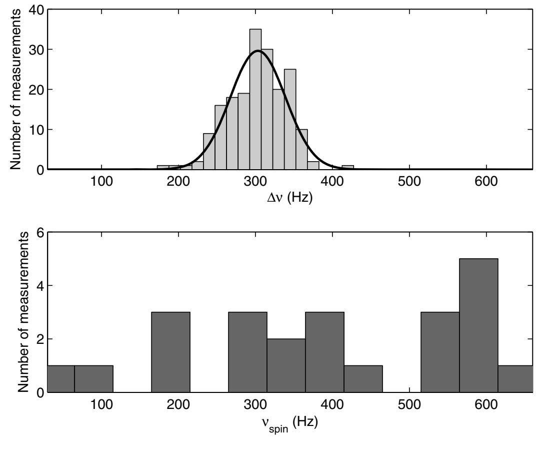

Figure 4. Upper plot: The distribution of measurements of $\Delta\nu$, of all types of sources in Fig.1 combined. The solid line represents the best-fitting Gaussian to this distribution, with a centroid of 303.2 ± 2.9 Hz and a standard deviation of 36.0 ± 2.1 Hz ($\chi^2 = 14.3$ for 12 degrees of freedom; 1σ errors shown). Lower plot: the distribution of ν_s in 23 sources, nine AMPs with pulsations in the persistent emission and 14 sources with burst oscillations (see Yin et al. 2007, and Table 1 for the list of sources and spin frequencies).

models. They found that $\langle \Delta\nu \rangle \simeq -0.20\ \nu_{\rm s} + 390$ Hz[2]. In their analysis, Yin et al. (2007) treat the two AMPs differently, and do not include them in their fit. Following the results of van Straaten et al. (2005) and Linares et al. (2005), here we do include the two AMPs in the analysis. We take a step further than Yin et al. (2007), and we advance the hypothesis that in fact $\Delta\nu$ and $\nu_{\rm s}$ are independent quantities.[3]

Our interpretation that $\Delta\nu$ is independent of $\nu_{\rm s}$ relies on the discovery by van Straaten et al. (2005) and Linares et al. (2005), who found that to reconcile the frequency–frequency correlations of the two AMPs SAX J1808.4−3568 and XTE J1807−214 with similar correlations in other sources, the frequencies of the kHz QPOs in the AMPs have to be multiplied by a factor of ∼1.5 (see Section 2 for a discussion of possible caveats of this). Both van Straaten et al. (2005) and Linares et al. (2005) find that they can also reconcile the frequency–frequency correlations if they apply different multiplicative factors to the frequency of all variability components, except ν_2. (As noted by van Straaten et al. 2005, a single multiplicative factor close to 1.5 applied both to ν_1 and ν_2 without changing the frequency of the other variability components is the simplest option.). In particular, they find that if ν_2 remains unchanged, ν_1 of the AMPs SAX J1808.4−3568 and XTE J1807−214 has to be multiplied by a factor of ∼0.8–0.9 to match the $\nu_1 - \nu_2$ correlation defined by the atoll sources and low-luminosity bursters. The picture presented here does not change significantly if we only apply the ∼0.8–0.9 factors to ν_1 and calculate new $\Delta\nu$ values.

Although it is not the purpose of this paper to explain the nature of these factors, here we provide some ideas about their possible origin. The usual suspect is the magnetic field. A stronger field could prevent the inner edge of the disc from moving inwards and, if the kHz QPOs are produced at that radius, a larger inner disc radius could imply lower kHz QPO frequencies, ν_1 and ν_2. If, on the contrary, the low-frequency variability is produced at larger radii, they would be less affected by the NS magnetic field, which could explain why a shift of the frequency of the low-frequency components is not required to match the frequency–frequency correlations. The problem with this explanation is that other AMPs supposedly having relatively high-magnetic fields, at least comparable to those in SAX J1808.4−3568 and XTE J1807−214, show no or very small shifts (van Straaten et al. 2005). Also, at least one other non-pulsating source shows shifts in the correlation, although smaller than the ones in the AMPs: Altamirano et al. (2005) find a shift of ∼1.15 for the LMXB 4U 1820−30. The other sources showing significant shifts in the frequency–frequency correlations are the AMPs XTE J0929−314, with $\nu_{\rm s} = 185$ Hz (Galloway et al. 2002) and a shift of 1.48 ± 0.11 (van Straaten et al. 2005), and XTE J1814−338 with $\nu_{\rm s} = 314$ Hz (Markwardt & Swank 2003) and a shift of 1.21 ± 0.09 (van Straaten et al. 2005, the shift here is marginally significant).

A NS mass difference could also explain these shifts. For example, in the model of Stella & Vietri (1999), and in other models that explain the frequencies of the kHz QPOs in terms of epicyclic frequencies in general relativity, the relation between ν_1 and ν_2 depends explicitly on the NS mass (see e.g. Stella, Vietri & Morsink 1999; Boutloukos et al. 2006): as noted by Belloni et al. (2007), a multiplicative factor applied to the NS mass translates into the same multiplicative factor applied to both kHz QPOs (see equation 4 in Stella et al. 1999). If this (model-dependent) interpretation is correct, a factor of ∼1.5 in ν_1 and ν_2 for the AMPs implies that the NSs in those systems are ∼1.5 times more massive than in the other atoll and Z-sources and the low-luminosity bursters. It is generally assumed that, due to accretion, the NSs in LMXBs have masses larger than the canonical 1.4 $\mathrm{M}_\odot$ NS. If the ∼1.5 factor is related to a difference in NS mass, this would imply uncomfortably large masses for the NSs in the two AMPs. It is somewhat more difficult to assess the effect of the mass of the NS on the low-frequency components, because it is not clear what frequency in the model represents the frequency of those components. If one of these low-frequency QPOs were due to Lense–Thirring precession (Stella & Vietri 1998), its frequency would be (see equation 1 in Stella & Vietri 1998) $\nu_{\rm LT} \propto IM^{-1}\nu_2^2\nu_{\rm s}$, where I and M are the moment of inertia and the mass of the NS, respectively, and as usual ν_2 is the frequency of the upper kHz QPO and $\nu_{\rm s}$ is the spin frequency of the NS. If this identification is correct, the spin frequencies in Table 1, a shift factor of 1.5 in the mass and in the frequency of the upper kHz QPO, but no shift of the low-frequency QPOs imply that the moment of inertia must be a factor of ∼10 different among some of these sources.

We know that $\Delta\nu$ is not the same in all sources (Zhang et al. 2006) and not even for the same source, when more than one significant detection is available (van der Klis et al. 1997; Méndez et al. 1998). However, it is remarkable that, other than in the two AMPs, in all sources in which two simultaneous kHz QPOs have been detected, $\langle \Delta\nu \rangle$ is approximately the same. After applying the multiplicative factors described in van Straaten et al. (2005) and Linares et al. (2005), the same is true for the two AMPs (see Section 2 for possible caveats). This despite the fact that the measured spin frequencies span a factor of more than 3. In the model of Stella & Vietri (1999), $\Delta\nu$ is equal to the radial epicyclic frequency, ν_r which, for the case of negligible eccentricity and a non-rotating NS is $\nu_r = (1 - 6\,GM/rc^2)^{1/2}\ \nu_\phi$, with $\nu_\phi = 1/(2\pi)(GM/r^3)^{1/2}$ the azimuthal frequency, identified with ν_2 in their model. (For NSs with spins smaller than ∼600 Hz and masses in the range 1.4– 2 $\mathrm{M}_\odot$, taking a typical range of ν_2 frequencies, the radial epicyclic frequency is within ≈15 per cent of the value given by this formula.) One would then expect that on average $\Delta\nu$ would be the same for all NSs if they all have more or less the same mass and their upper kHz QPO spans more or less the same frequency range.

If it is generally true that $\langle \Delta\nu \rangle$ is more or less the same in all sources of kHz QPOs, the idea that there is no link between $\Delta\nu$ and $\nu_{\rm s}$ could be tested in the case of the LMXB EXO 0748−676, which has a spin frequency of 45 Hz (Villarreal & Strohmayer 2004). From the results in Fig. 3, for EXO 0748−676 one expects $\Delta\nu \approx 300$ Hz, whereas models that include a direct link between NS spin frequency and frequencies of the kHz QPOs predict that for this source $\Delta\nu$ should be either 22.5 or 45 Hz. In fact, in the context of 'slow' and 'fast' rotators, for EXO 0748−676 $\Delta\nu$ is expected to be 45 Hz. (We cannot discard that if two simultaneous kHz QPOs are detected in EXO 0748−676 with $\Delta\nu \approx 300$ Hz, there would be attempts to modify existing models, or propose completely new ones, to explain $\Delta\nu/\nu_{\rm s}$ ratios that are an integer larger than 1.) Unfortunately, so far a single kHz QPO has been observed from this source (Homan & van der Klis 2000).

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[2] Notice that to get this result, Yin et al. (2007) used the individual measurements of $\Delta\nu$ for each source to calculate $\langle \Delta\nu \rangle$, and the spread of the $\Delta\nu$ values as a measure of the error. In the case of KS 1731−260 for which there is only one measurement of $\Delta\nu$, they instead used the error of the measurement of $\Delta\nu$. In the case of 4U 1702−43, all $\Delta\nu$ measurements were done over a narrow range of QPO frequencies, which may artificially reduce the spread.

[3] Kendall's τ test (e.g. Press et al. 1992) applied to the data presented here, averaged in the same way as in Yin et al. (2007), yields a very low probability (between 1.7 and 1.9 σ, depending on whether we include the two AMPs are not) that there is correlation between $\langle \Delta\nu \rangle$ and $\nu_{\rm s}$.

An equally interesting test of this idea would be to find a source with a spin frequency in the range $\nu_{\rm s} \approx 350$– 500 Hz for which no (or only a small) shift is required to fit the frequency–frequency correlations of van Straaten et al. (2005). A case of more or less constant $\langle \Delta\nu \rangle$ across different sources implies that $\Delta\nu/\nu_{\rm s}$ would be between 0.6 and 0.8. Actually, there is a source that may be used for this in the near future: the AMP XTE J1751−305 has a spin frequency $\nu_{\rm s} = 435$ Hz (Markwardt et al. 2002), whereas van Straaten et al. (2005) find that a shift of only 1.12 ± 0.03 applied to ν_2 is required to match the frequency–frequency correlations. Unfortunately, so far there has been no detection of two simultaneous kHz QPOs that would allow us to calculate $\Delta\nu$ in this source.

Despite the fact that the data seem to suggest that $\langle \Delta\nu \rangle$ is more or less the same in all sources of kHz QPOs (in the cases of the AMP SAX J1808.4−3658 and XTE J1807−294 after applying a multiplicative factor deduced from the low-frequency QPO versus ν_2 correlations; see above and van Straaten et al. 2005 and Linares et al. 2005 for details and possible caveats), we have no strong reason to discard the possibility that there are sources for which this is not the case (even after applying factors similar to those deduced in SAX J1808.4−3658 and XTE J1807−294). Our conjecture that there is no link between $\Delta\nu$ and $\nu_{\rm s}$ would therefore not be weakened if a source with two simultaneous kHz QPOs is ever discovered, for which $\langle \Delta\nu \rangle$ is not close to ∼300 Hz, as long as in such a source $\langle \Delta\nu \rangle$ (after accounting for any possible shift factor as the ones in SAX J1808.4−3658 and XTE J1807−294; van Straaten et al. 2005; Linares et al. 2005) is different from $\nu_{\rm s}$ and $\nu_{\rm s}/2$.

From Fig. 3 it is apparent that in SAX J1808.4−3658 and XTE J1807−294 the shifts on the frequency of the kHz QPOs (van Straaten et al. 2005; Linares et al. 2005), and the idea that $\Delta\nu$ is either equal to $\nu_{\rm s}$ or $\nu_{\rm s}/2$ are inconsistent with each other. It seems unlikely that this issue can be fully resolved as long as the nature of frequency shifts remains unexplained. While here we propose that the shifts imply that $\Delta\nu$ is not equal to $\nu_{\rm s}$ or $\nu_{\rm s}/2$, we cannot completely discard that the shifts have a different explanation, and that in the two AMPs $\Delta\nu/\nu_{\rm s}$ is indeed close to either 1 or 0.5. We note, however, that even without taking the shifts into account, there is solid evidence that in several sources $\Delta\nu$ is significantly different from $\nu_{\rm s}$ or $\nu_{\rm s}/2$ (see Section 1). The question is how strong the evidence must be before the idea that $\Delta\nu$ and $\nu_{\rm s}$ are directly linked is abandoned.

To conclude, here we put forward the idea that the frequency difference of the kHz QPOs, $\Delta\nu$, in NS LMXBs may not be related at all to the spin frequency, $\nu_{\rm s}$, of the NS. Beat-frequency mechanisms have been proposed not just in the context of the kHz QPOs; they were originally advanced in the 1980s (Alplar & Shaham 1985; Lamb et al. 1985) to explain the low-frequency QPOs in these systems. We cannot rule out completely the hypothesis of a similar type of link between the kHz QPOs and the NS spin, but this idea can, in principle, be tested and, if proven wrong, discarded.

ACKNOWLEDGMENTS

We thank Diego Altamirano, Jeroen Homan, Peter Jonker, Manuel Linares, Cole Miller and Michiel van der Klis for useful comments on earlier versions of this manuscript, and the referee for his/her excellent remarks that helped us improve the paper significantly. We also thanks Alice, Amina, Ilaria, and Manuel for their support. TB acknowledges financial contribution from contract PRIN INAF 2006. The Netherlands Institute for Space Research (SRON) is supported financially by NWO, the Netherlands Organization for Scientific Research. This research has made use of data obtained through the High Energy Astrophysics Science Archive Research Centre Online Service, provided by the NASA/Goddard Space Flight Centre.

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