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The correlations between the spin frequencies and kHz QPOs of neutron stars in LMXBs
(Research Note)

H. X. Yin[1], C. M. Zhang[1], Y. H. Zhao[1], Y. J. Lei[2], J. L. Qu[2], L. M. Song[2], and F. Zhang[2]

[1] 1. National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, PR China
e-mail: `zhangcm@bao.ac.cn`
[2] 2. Astronomical Institute, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100039, PR China

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ABSTRACT

Aims. We studied the correlations between spin frequencies and kilohertz quasi-periodic oscillations (kHz QPOs) in neutron star low-mass X-ray binaries.
Methods. The updated data on kHz QPOs and spin frequencies are statistically analyzed.
Results. We find that when two simultaneous kHz QPOs are present in the power spectrum, the minimum frequency of upper kHz QPO is at least 1.3 times higher than the spin frequency, i.e. $\nu_{\rm s} < \nu_{2\,\rm min}/1.3$. We also find that the average kHz QPO peak separation in 6 Atoll sources anti-correlates with the spin frequency in the form $\langle\Delta\nu\rangle = -(0.19 \pm 0.05)\nu_{\rm s} + (389.40 \pm 21.67)$Hz. If we shift this correlation in the direction of the peak separation by a factor of 1.5, this correlation matches the data points of the two accretion-powered millisecond X-ray pulsars, SAX J1808.4-3658 and XTE J1807-294.

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

1. Introduction

Since the launch of the Rossi X-Ray Timing Explorer (*RXTE*) ten years ago, kilohertz quasi-periodic oscillations (kHz QPOs) have been detected in about thirty neutron star low-mass X-ray binaries (NS/LMXBs; see van der Klis 2006, for a recent review). The kHz QPOs often occur in pairs, the upper-frequency (ν_2) and the lower-frequency (ν_1). These kHz QPOs appear in four categories of NS/LMXBs, i.e. the bright Z sources, the less luminous Atoll sources (see Hasinger & van der Klis 1989, for the definition of Atoll and Z classes), accretion-powered millisecond X-ray pulsars (AMXPs), and other unidentified sources (see e.g., van der Klis 2006, and references therein). The kHz QPOs and other observed characteristic frequencies in these sources follow tight correlations among each other (e.g., Psaltis et al. 1998, 1999a,b; Stella et al. 1999; Belloni et al. 2002, 2005, 2007; Zhang et al. 2006a).

A 401 Hz coherent pulsation and a near 401 Hz X-ray burst oscillation frequency are found in SAX J1808.4-3658 (Chakrabarty et al. 2003; Wijnands et al. 2003), suggesting that the burst frequency is equal to the spin frequency ($\nu_{\rm s}$) in this object (e.g., Strohmayer & Bildsten 2003; Wijnands et al. 2003; Muno 2004). In some sources showing both twin kHz QPOs and spin frequencies, the peak separation ($\Delta\nu = \nu_2 - \nu_1$) is generally inconsistent with being equal to the spin frequency (e.g. Méndez & van der Klis 1999; Jonker et al. 2002a). But the ratio between the peak separation and spin frequency clusters at around ~1 or ~0.5 (e.g., Wijnands et al. 2003; Wijnands 2005; Linares et al. 2005; Zhang et al. 2006b).

In this research note, we study the relation between kHz QPOs and spin frequencies.

2. Correlations between spins and kHz QPOs

From 35 NS/LMXBs with the kHz QPOs and/or spin frequencies, 21(6) sources show twin (single) kHz QPOs, and 22 sources show spin or/and burst frequencies (7 spin and 17 burst sources; see Table 1).

2.1. Distribution of spin frequencies in LMXBs

In Fig. 1 we plot the distribution of the 22 spin frequencies with an average value of 440.8 Hz. For the 8 sources with both twin kHz QPOs and spin frequencies, the ratio between the minimum upper-frequency and the spin frequency is $\nu_{2\,\rm min}/\nu_{\rm s} > 1.3$. If the upper-frequency is interpreted as the Keplerian frequency at the inner edge of the accretion disk (Miller et al. 1998; van der Klis 2000, 2006), this lower limit means that the inner edge of disc penetrates inside the corotation radius where the Keplerian frequency equals the spin frequency. If this applies to the other kHz QPO sources, we can use the relation $\nu_{\rm s} < \nu_{2\,\rm min}/1.3$ to constrain their spin frequencies. For example, we could obtain upper limits of spin frequencies for the 8 Z sources and 5 Atoll sources with simultaneously detected twin kHz QPOs but with unknown spin frequencies (see the inferred upper limits of spin frequencies for these sources in Table 1).

We also notice that, when only a single kHz QPO is detected as in 4U 1608-52 (van Straaten et al. 2003) and 4U 1728-34 (van Straaten et al. 2002), these QPOs do not satisfy the relation $\nu_{\rm s} < \nu_{2\,\rm min}/1.3$. We argue that this relation only holds when two simultaneous kHz QPOs are detected, Our proposal would be ruled out if a pair of kHz QPOs were found and $\nu_{\rm s} > \nu_2/1.3$.

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Table 1. List of LMXBs with the simultaneously detected twin kHz QPOs or spin frequencies.

Sources	$\nu_1{}^{(1)}$ (Hz)	$\nu_2{}^{(2)}$ (Hz)	$\Delta\nu^{(3)}$ (Hz)	$\nu_2/\nu_1{}^{(4)}$	$\nu_{\rm burst}{}^{(5)}$ (Hz)	$\nu_{\rm pulse}{}^{(6)}$ (Hz)	References
Millisecond pulsars (7)							
IGR J00291+5934	–	–	–	–	–	599	1
XTE J0929-314	–	–	–	–	–	185	K
XTE J1751-305	–	–	–	–	–	435	K
XTE J1807-294	127–360	353–587	179–247	1.51–2.78	–	191	2, 3
SAX J1808.4-3658	499	694	195	1.39	401	401	K, 4
XTE J1814-338	–	–	–	–	314	314	K
HETE J1900.1-2455^a	–	–	–	–	–	377	5
Z sources (8)							
Sco X-1	544–852	844–1086	223–312	1.26–1.57	–	649†	M, B, K
GX 340+0	197–565	535–840	275–413	1.49–2.72	–	412†	B, K, P, 6
GX 349+2	712–715	978–985	266–270	1.37–1.38	–	752†	B, K, 7
GX 5-1	156–634	478–880	232–363	1.38–3.06	–	368†	B, K, P, 8
GX 17+2	475–830	759–1078	233–308	1.28–1.60	–	584†	B, K, P, 9
Cyg X-2	532	856	324	1.61	–	658†	B, K, P
Cir X-1	56–226	229–505	173–340	2.23–4.19	–	176†	10
XTE J1701-462	620	909	289	1.47	–	699†	11
Atoll sources (16)							
4U 0614+09	153–823	449–1162	238–382	1.38–2.93	–	345†	B, K, P, 12, 13
XB 1254-690	–	–	–	–	95	–	14
4U 1608-52	476–876	802–1099	224–327	1.26–1.69	619	–	M, B, K, 15
4U 1636-53	644–921	971–1192	217–329	1.24–1.51	581	–	B, K, P, 16, 17
4U 1702-43	722	1055	333	1.46	330	–	K, P, 18
4U 1705-44	776	1074	298	1.38	–	826†	B, K, P
4U 1728-34	308–894	582–1183					
4U 1728-34	3081183	271–359	1.31–1.89	363	–	B, K, P, 13, 19	
KS 1731-260	903	1169	266	1.29	524	–	B, K, P
4U 1735-44	640–728	982–1026	296–341	1.41–1.53	–	755†	B, K, P
XTE J1739-285^a	–	–	–	–	1122	–	20
A 1744-361^a	–	–	–	–	530	–	21
SAX J1750.8-2900^a	–	–	–	–	601	–	K, 22
4U 1820-30	790	1064	273	1.35	–	818†	B, K, P
Aql X-1^a	–	–	–	–	549	–	B, K, P
4U 1915-05	224–707	514–1055	290–353	1.49–2.3	270	–	B, K, P
XTEJ2123-058	849–871	1110–1140	261–270	1.31–1.31	–	854†	B, K, P
Other sources (4)							
EXO 0748-676^a	–	–	–	–	45	–	K, 23
- MXB 1659-298	–	–	–	–	567	–	K, 24
MXB 1743-29	–	–	–	–	589	–	K, 25
SAX J1748.9-2021	–	–	–	–	410	–	K, 26

^{a} Sources with only a single QPO detected. † The inferred upper limit of the spin frequency using the relation $\nu_{\rm s} < \nu_{2\,\rm min}/1.3$ (see text). ^{1} Lower-frequencies; ^{2} upper-frequencies; ^{3} separations of twin kHz QPOs; ^{4} ratios between the upper- and lower-frequencies; ^{5} burst frequency $\nu_{\rm burst}$; ^{6} coherent spin frequency $\nu_{\rm pulse}$. K: van der Klis (2000); M: Méndez et al. (1998), Méndez & van der Klis (1999), (2000); B: Belloni et al. (2002), (2005); P: Psaltis et al. (1999a,b.) 1: Chakrabarty (2004); 2: Linares et al. (2005); 3: Zhang et al. (2006b); 4: Wijnands et al. (2003); 5: Kaaret et al. (2005); 6: Jonker et al. (2000); 7: O'Neill et al. (2002); 8: Jonker et al. (2002b); 9: Homan et al. (2002); 10: Boutloukos et al. (2006); 11: Homan (2006); 12: van Straaten et al. (2002); 13: van Straaten et al. (2000); 14: Bhattacharyya (2006); 15: van Straaten et al. (2003); 16: Di Salvo et al. (2003); 17: Jonker et al. (2002a); 18: Markwardt et al. (1999); 19: Migliari et al. (2003); 20: Kaaret et al. (2007); 21: Bhattacharyya et al. (2006); 22: Kaaret et al. (2002); 23: Homan and van der Klis (2000); 24: Wijnands et al. (2001); 25: Strohmayer et al. (1997); 26: Kaaret et al. (2003).

2.2. Correlations between $\nu_{\rm s}$ and $\Delta\nu$

The sonic-point beat-frequency model (Miller et al. 1998) predicted a constant $\Delta\nu$ equal to the stellar spin frequency, whereas the sonic-point and spin-resonance model by Lamb & Miller (2003) predicts that the kHz QPO peak separation should be approximately equal to one or half the spin frequency considering that the disk flow at the spin-resonant radius is smooth or clumped. To confirm the above conjecture, we average the value of peak separations and plot $\langle\Delta\nu\rangle - \nu_{\rm s}$ diagram for the six Atoll sources and two AMXPs in Fig. 2. We notice that for the sources (XTE J1807-294, 4U 1702-43, 4U 1728-34, and 4U 1915-05) with $\nu_{\rm s} < 400$ Hz $\langle\Delta\nu\rangle/\nu_{\rm s} \sim 1$, whereas for those (SAX J1808.4-3658, 4U 1608-52, 4U 1636-53, and 4U 1731-28) with $\nu_{\rm s} > 400$ Hz $\langle\Delta\nu\rangle/\nu_{\rm s} \sim 0.5$. Alternatively, the relation between the averaged peak separation and spin frequency of the six Atoll sources ($\langle\Delta\nu\rangle$ and $\nu_{\rm s}$) can be fitted by a linear relation $\langle\Delta\nu\rangle = -(0.19 \pm 0.05)\nu_{\rm s} + (389.40 \pm 21.67)\,{\rm Hz}$ (Fig. 2). The relation that crosses the points of the two AMXPs is the same relation as for the Atoll sources divided by 1.5 along the y direction.

If the above anti-correlation between $\langle\Delta\nu\rangle$ and $\nu_{\rm s}$ is real, we can use it to infer the averaged kHz QPO peak separations of sources, such as EXO 0748-676 ($\nu_{\rm s} = 45$ Hz), XB 1254-690

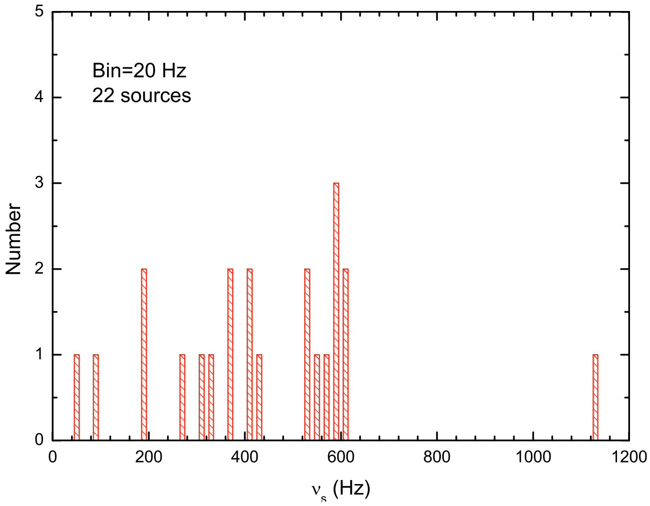

Fig. 1. Distribution of the spin frequencies of the 22 neutron stars in LMXBs.

Table 2. List of the sources with spin frequencies and peak separations.

Sources*	$\langle\Delta\nu\rangle(\sigma)$[1] (Hz)	$\langle\Delta\nu\rangle/\nu_s$[2]	$\nu_{2\,\min}/\nu_s$[3]
Millisecond pulsar			
XTE J1807-294	215(5.9)	1.13	1.8
SAX J1808.4-3658	195(4.0)[a]	0.49	1.7
Atoll source			
4U 1608-52	287(7.2)	0.46	1.3
4U 1636-53	286(9.6)	0.49	1.7
4U 1702-43	333(8.7)	1.01	3.2
4U 1728-34	327(5.8)	0.90	1.6
KS 1731-260	266(8.7)	0.51	2.2
4U 1915-05	338(12.1)	1.25	1.9

* Data are taken from the references listed in Table 1; [1] averaged peak separation and its standard deviation; [2] ratio of averaged peak separation to spin frequency; [3] ratio of the minimum upper-frequency to spin frequency; [a] measured error of the single pair of twin kHz QPOs.

(ν_s = 95 Hz), and XTE J1739-285 (ν_s = 1122 Hz) to be around 380 Hz, 370 Hz, and 160 Hz, respectively. However, this anticorrelation is still a conjecture since it is based on data from only six sources. But if this result were confirmed, it means that the spin frequency would play a role in the mechanism that produces the kHz QPOs, but a different one from the one so far proposed. Further measurements of kHz QPOs in the accretion powered millisecond X-ray pulsars are required to uncover the role of the spin of the neutron star in the mechanism that produces the kHz QPOs.

3. Conclusion

Our main conclusions are the following.

(1) We find that for the 8 sources for which twin kHz QPOs and spins are known, the minimum upper-frequency is at least 1.3 times higher than the spin frequency, i.e. $\nu_{2\,\min}/\nu_s > 1.3$. This relation might be used to estimate the spin frequencies of sources with twin kHz QPOs.

(2) In 6 Atoll sources, the averaged peak separation anticorrelates with the spin frequency as $\langle\Delta\nu\rangle = -(0.19 \pm 0.05)\nu_s + (389.40 \pm 21.67)$ Hz, although their ratios cluster roughly around either 1 or 0.5 as reported (van der Klis 2006). This correlation would also apply to the two AMXPs (SAX J1808.4-3658 and XTE J1807-294) if in this cases the peak separation is divided by a factor of 1.5 (see Fig. 2). It is noted that this kind of shifting of about 1.5 is required to reconcile the frequency-frequency correlation of the AMXPs and the Atoll and Z sources (see van Straaten et al. 2005; Linares et al. 2005). This factor 1.5 remains unexplained, but it could reflect a different stellar magnetic field strength or magnetic angle between the magnetic polar axis and rotational axis between these types of sources.

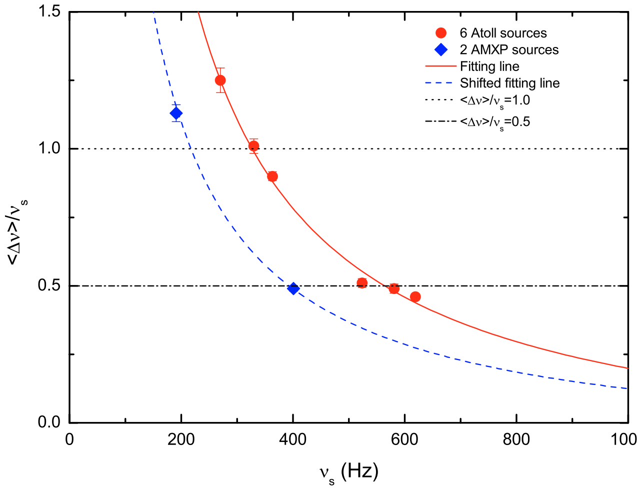

Fig. 2. Plot of $\langle\Delta\nu\rangle/\nu_s$ vs. ν_s. The solid curve stands for $\langle\Delta\nu\rangle = -(0.19 \pm 0.05)\nu_s + (389.40 \pm 21.67)$ Hz, and the dashed curve is the result of shifting the solid curve down by a factor of 1.5 along the direction of the peak separation.

If the above correlations between the spin frequency and kHz QPOs were confirmed in the future, it implies that the kHz QPOs are related to the spin frequencies of neutron stars in some manner. Thus, the spin frequency would play a role in the twin kHz QPO production (indirectly perhaps), and any successful model of kHz QPOs should have to take these relations into account. Usually, we consider the production of kHz QPO to be related to the magnetosphere radius defined by the instantaneous accretion rate, then the spin frequency should be involved with the magnetosphere radius defined by the long-term accretion rate (matched with the different magnetic B-field when considering Atoll and Z), which is almost stable in a short observational time. The instantaneous accretion rate varies around the long-term accretion rate, which accounts for the variation of kHz QPOs, thus the "averaged" QPO variation would be related to the spin frequency. Therefore, in the sense of the average treatment, the kHz QPO has a relation to the spin frequency.

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