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Study on the correlations between the twin kilohertz quasi-periodic oscillations in low-mass X-ray binaries

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Abstract

The recently updated data of the twin kilohertz quasi-periodic oscillations (kHz QPOs) in the neutron star low-mass X-ray binaries are analyzed. The power-law fitting $\nu_1 = a(\nu_2/1000)^b$ and linear fitting $\nu_2 = A\nu_1 + B$ are applied, individually, to the data points of four Z sources (GX 17+2, GX 340+0, GX 5−1 and Sco X−1) and four Atoll sources (4U 0614+09, 4U 1608−52, 4U 1636−53 and 4U 1728−34). The χ^2-tests show that the power-law correlation and linear correlation both can fit data well. Moreover, the comparisons between the data and the theoretical models for kHz QPOs are discussed.

Keywords: QPOs; Accretion disks; Neutron stars; X-rays binaries

1. Introduction

The kilohertz quasi-periodic oscillations (kHz QPOs) were firstly discovered in Sco X−1, a luminous Z source in neutron star (NS) low-mass X-ray binaries (LMXBs) (e.g., van der Klis et al., 1996), and now they have been detected in 20 more sources (e.g., van der Klis, 2000, 2006; for reviews). Usually, these kHz QPOs appear in pairs, the upper kHz QPO frequency (ν_2, hereafter the upper-frequency) and the lower kHz QPO frequency (ν_1, hereafter the lower-frequency), which are discovered in three classes of sources, i.e. accretion powered millisecond pulsars, bright Z sources and less luminous Atoll sources (e.g., Hasinger and van der Klis, 1989).

The kHz QPO peak separation, $\Delta\nu = \nu_2 - \nu_1$, in a given source generally decreases with frequency, except the recently detected kHz QPOs in Cir X−1, in which the peak separation increases with frequency (Boutloukos et al., 2006). In addition, the variable peak separations are not equal to the NS spin frequencies. However, the averaged peak separation is found to be either close to the spin frequency or to half of it (e.g., van der Klis, 2006; Linares et al., 2005).

The above observations offer strong evidence against the simple beat-frequency model, in which the lower-frequency is the beat between the upper-frequency ν_2 and the NS spin frequency ν_s (e.g., Strohmayer et al., 1996; Zhang et al., 1997; Miller et al., 1998), i.e. $\nu_1 = \nu_2 - \nu_s$. Furthermore, with the discovery of pairs of 30–450 Hz QPOs from a few black-hole candidates with the frequency ratios 3:2 (e.g., van der Klis, 2006), Abramowicz et al. (2003) reported that the ratios of twin kHz QPOs in Sco X−1 tend to cluster around a value about 3:2, and they argued this fact to be a promising link with the black hole high-frequency QPOs (e.g., van der Klis, 2006).

For the all Z and Atoll sources, the data plots of the upper-frequency vs. the lower-frequency can be fitted by a power-law function (e.g., Zhang et al., 2006a), and also roughly fitted by a linear function (Belloni et al., 2005). However, for the individual kHz QPO source, for instance Sco X−1, its kHz QPOs can be well fitted by a power-law function (e.g., Psaltis et al., 1998; Yin et al., 2005).

In this paper, to investigate the twin kHz QPO correlation for the individual Z or Atoll source, we fitted the data

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with a power-law and a linear function for four typical Z sources and four typical Atoll sources, and a comparison of both fittings by χ^2-tests is discussed in Section 2, where comparisons with the models are discussed. The conclusions and consequences are given in Section 3.

2. Correlations between twin kHz QPOs

Until now, twin kHz QPOs have been detected in 21 LMXBs, including 2 accretion powered millisecond X-ray pulsars, 8 Z sources and 11 Atoll sources, as listed in Table 1. In Figs. 1 and 2, we plotted twin kHz QPO data for the Z sources and Atoll sources, showing the correlations of ν_1 vs. ν_2, $\Delta\nu$ vs. ν_2 and ν_2/ν_1 vs. ν_2, where the power-law and linear fitting lines for the eight Z and Atoll sources are presented. The results of the fittings and χ^2-tests are listed in Table 2.

2.1. A power-law fitting

The power-law function is chosen as

$$\nu_1 = a\left(\frac{\nu_2}{1000\ \text{Hz}}\right)^b \text{Hz} \tag{1}$$

to fit twin kHz QPO data points of all Atoll (Z) sources, as well as 4 individual Atoll (Z) sources, separately. It is noted that a same function was applied to the fitting of kHz QPOs of Sco X−1 by Psaltis et al. (1998) with a smaller set of kHz QPO data points. The fitting results of the normalization coefficient a, the power-law index b and $\chi^2/d.o.f.$ for various cases are listed in Table 2, which correspond to the fitting curves as presented in Fig. 2. We find that the power-law index for the fitting of all Z sources (see Table 2) is 1.87, obviously bigger than that of the fitting for all Atoll sources (1.61). Then, for the individual case, the power-law index for Z source is generally bigger than that in Atoll source, except GX 17+2.

2.2. A linear fitting

For the same data sets, the linear fitting function is chosen as,

$$\nu_2 = A\nu_1 + B\ \text{Hz}, \tag{2}$$

which was exploited by Belloni et al. (2005) to discuss the kHz QPO fitting in Sco X−1, 4U 1608−52, 4U 1636−53, 4U 1728−34 and 4U 1820−30. By means of

Table 1
List of LMXBs with the simultaneously detected twin kHz QPOs

Sources	ν_1[a] (Hz)	ν_2[b] (Hz)	$\Delta\nu$[c] (Hz)	ν_2/ν_1[d]	References
Millisecond pulsar (2)					
XTE J1807−294	127–360	353–587	179–247	1.51–2.78	1, 2
SAX J1808.4−3658	499	694	195	1.39	3
Z source (8)					
Cir X−1	56–226	229–505	173–340	2.23–4.19	4
Sco X−1	544–852	844–1086	223–312	1.26–1.57	B, M, K
GX 340+0	197–565	535–840	275–413	1.49–2.72	B, K, P, 5
XTE J1701−462	620	909	289	1.47	6
GX 349+2	712–715	978–985	266–270	1.37–1.38	B, K, 7
GX 5−1	156–634	478–880	232–363	1.38–3.06	B, K, P, 8
GX 17+2	475–830	759–1078	233–308	1.28–1.60	B, K, P, 9
Cyg X−2	532	856.6	324	1.61	B, K, P
Atoll source (11)					
4U 0614+09	153–823	449–1162	238–382	1.38–2.93	B, K, P, 10, 11
4U 1608−52	476–876	802–1099	224–327	1.26–1.69	M, B, K, 12
4U 1636−53	644–921	971–1192	217–329	1.24–1.51	B, K, P, 13, 14
4U 1702−43	722	1055	333	1.46	K, P, 15
4U 1705−44	776	1074	298	1.38	B, K, P
4U 1728−34	308–894	582–1183	271–359	1.31–1.89	B, K, P, 11, 16
KS 1731−260	903	1169	266	1.29	B, K, P
4U 1735−44	640–728	982–1026	296–341	1.41–1.53	B, K, P
4U 1820−30	790	1064	273	1.35	B, K, P
4U 1915−05	224–707	514–1055	290–353	1.49–2.3	B, K, P
XTEJ2123−058	849–871	1110–1140	261–270	1.31–1.31	B, K, P

K: van der Klis (2000, 2006); M: Méndez et al. (1998a); Méndez et al. (1998b); Méndez and van der Klis (1999, 2000); B: Belloni et al. (2002); Belloni et al. (2005); P: Psaltis et al. (1999a), Psaltis et al. (1999b). 1: Linares et al. (2005); 2: Zhang et al. (2006b); 3: Wijnands et al. (2003); 4: Boutloukos et al. (2006); 5: Jonker et al. (2000); 6: Homan et al. (2002) (personal communication); 7: O'Neill et al. (2002); 8: Jonker et al. (2002a); 9: Homan et al. (2002); 10: van Straaten et al. (2002); 11: van Straaten et al. (2000); 12: van Straaten et al. (2003); 13: Di Salvo et al. (2003); 14: Jonker et al. (2002b);15: Markwardt et al. (1999); 16: Migliari et al. (2003).

[a] The range of ν_1.
[b] The range of ν_2.
[c] The range of $\Delta\nu$.
[d] The range of ν_2/ν_1.