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A Study on the Correlations between the Twin kHz QPO Frequencies in Sco X-1

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Abstract For the bright neutron star low-mass X-ray binary Sco X-1, we analyzed all updated frequencies of the twin kilohertz quasi-periodic oscillations (kHz QPOs), their correlations and distributions. We found that the frequency separation of the kHz QPO peaks appears not to be a constant, rather, it decreases with increasing inferred mass accretion rate. We show that the currently available data of Sco X-1 by *Rossi X-ray Timing Explorer* are inconsistent with the proposals of the beat model that the frequency separation is a constant. Our conclusions are consistent with those of some previous researchers and we discuss further implications for the kilohertz QPO models.

Key words: X–rays: accretion disks — stars: neutron — X–rays: stars

1 INTRODUCTION

Quasi-periodic X-ray brightness oscillations at kilohertz frequencies (hereafter kHz QPOs) have been discovered in about 25 neutron-star low-mass X-ray binaries (LMXBs) in their persistent emission by the *Rossi X-ray Timing Explorer* (RXTE; see, e.g., van der Klis et al. 1996; Strohmayer et al. 1996) since its launch in December of 1995. The kHz QPOs often occur in pairs with upper ν_2 and lower frequency ν_1 (see van der Klis 2004, 2000; Swank 2004, for a recent review). The correlation between the high-frequency and low-frequency among the sources can be approximately fitted by a power law function (see, e.g., Stella et al. 1999; Psaltis et al. 1999; Psaltis et al. 1998; Psaltis & Norman 2000; van der Klis 2000, 2004). The peak separation $\Delta\nu = \nu_2 - \nu_1$ between the high and low frequency in a given source is generally inconsistent with a constant value. In some sources $\Delta\nu$ can be either lower or higher than the spin frequency or the frequency of the nearly coherent oscillations observed during type I X-ray bursts that are thought to be the spin frequencies of neutron stars (Mendez et al. 1998; Wijnands et al. 2003; Muno 2004; van der Klis 2004). However, the averaged peak separations across sources are either closely equal to the spin or the half spin (Miller & Lamb 1996; van der Klis 2004; Lamb & Miller 2001; Miller 2004).

The above observations offer strong evidence against the simple beat-frequency model, in which the frequency of the lower kHz QPO is supposed to be the beat frequency between the upper kHz QPO and the neutron star spin frequency ν_s (Strohmayer et al. 1996; Zhang et al. 1997; Miller et al. 1998), i.e., $\nu_1 = \nu_2 - \nu_s$. This model was first proposed in 1985 to interpret the horizontal branch oscillation (HBO, Hasinger & van der Klis 1989) in Sco X-1 (Alpar & Shaham 1985; Lamb et al. 1985). Nonetheless, with the discoveries of pairs of 30–450 Hz QPOs from a few black-hole candidates possessing the frequencies ratios 3:2 (van der Klis 2004; Wang et al. 2005; Petri 2005), Abramowicz et al. (2003) reported that ratios of twin frequencies in the kHz QPOs from the bright LMXB Sco X-1 tend to concentrate around a value of 3:2, and they interpreted it as evidence of ∼3:2 resonance in their model. While the kHz QPO frequency ratio ν_2/ν_1 is certainly not a constant in Sco X-1, Abramowicz et al. (2003) argued that ratios near 3:2 may occur more often than other values and might provide a link with black-hole high-frequency QPOs.

QPO data of Sco X-1 are most fruitful in the known 25 kHz QPO sources. As a very luminous LMXB Z source (Hasinger & van der Klis 1989; Hasinger 1990), its other QPO phenomena and spectrum properties have called much attention in X-ray astronomy (Yu et al. 1997) and led us to find a connection of the kHz QPO frequency to the X-ray spectrum in other LMXB sources (Qu et al. 2000).

In this paper, in order to check the model's predictions, we analyze the recent *RXTE* kHz QPO data of Sco X-1 provided by M. Mendez which includes 88 pairs of kHz QPO frequencies updated in 2005, and newly added data (39 pairs) previously published by Mendez & van der Klis (1999) that were detected in the last 5 years. Thus, the data we analyze here are larger than that used by Psaltis et al. (1998) and Abramowicz et al. (2003). Furthermore, we shall carry out a critical discussion on the kHz QPO correlation and frequency separation required in the simple beat frequency and other models (Section 2). Conclusions and a discussion are given in the last section.

2 THE CORRELATION BETWEEN THE TWIN FREQUENCIES OF SCO X-1

Figure 1 shows the low-frequency ν_1 in Sco X-1 plotted against the high-frequency ν_2. The data points can be adequately fitted by the power-law relation

$$\nu_1 = a\left(\frac{\nu_2}{1000\ \mathrm{Hz}}\right)^b\ \mathrm{Hz}\ , \quad a = 722 \pm 0.7\ \ \mathrm{and}\ \ b = 1.85 \pm 0.01\ , \tag{1}$$

shown in the figure by the solid line. It was found the relation is very similar to that obtained by Psaltis et al. (1998) with $a = 724 \pm 3$ and $b = 1.9 \pm 0.1$ based on fewer data points. However, for the high values of ν_2 (i.e. $\nu_2 > 960$ Hz), we obtain the normalization coefficient $a = 720 \pm 1.3$ and the correlation power law index $b = 1.92 \pm 0.04$; while for the low values of ν_2 (i.e. $\nu_2 < 960$ Hz) we have $a = 712 \pm 1.3$ and $b = 1.60 \pm 0.02$. This fact means that the real correlation between the low-frequency and high-frequency is not a single power law for all the data points over the range of of the kHz QPO frequencies. In fact while the power-law chosen here describes the Sco X-1 data very well, other functional forms could also fit the Sco X-1 data (see, e.g., Belloni et al. 2005). The other $\Delta\nu - \nu_2$ and $\nu_2/\nu_1 - \nu_2$ relations are also shown in Figures 2 and 5 by solid lines.

If Eq. (1) is universally valid for all kHz QPO data of Sco X-1, then it implies a non-monotonic change of the peak separation, with a maximum at an upper kHz QPO frequency of ~ 700 Hz. However, in order to prove this conjecture, we need the QPO frequencies smaller than the lowest kHz QPO frequency detected so far in Sco X-1. Moreover, in Figure 1, as shown by the dashed line, representing $\nu_2 - \nu_1$=300 Hz, and the dotted line, representing $\nu_2 = (3/2)\nu_1$, we find that a non-linear correlation exists between the two frequencies, which is clearly against

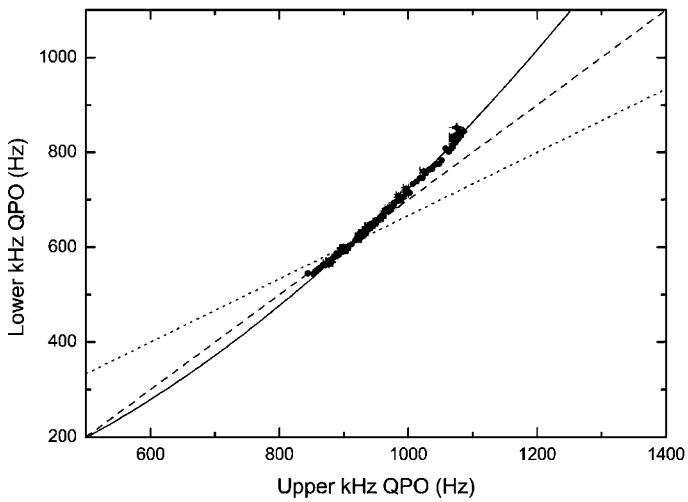

Fig. 1 A plot of the lower frequency versus the higher frequency. The solid line represents the fitted correlation between the pair of frequencies as given by Eq. (1). The dashed line represents $\nu_2 - \nu_1 = 300$ (Hz), and the doted line represents $\nu_2 = (3/2)\nu_1$.

a constant separation and a constant 3:2 ratio. Its details will be thoroughly discussed in the following subsections.

2.1 Testing a Constant Twin Peak Separation

In order to test the hypothesis of a constant peak separation between the twin kHz QPOs predicted by the simple beat model (Miller et al. 1998; Strohmayer et al. 1996), we need to inspect simultaneously detected twin kHz QPOs over a wide range of frequencies in Sco X-1.

Figure 2 shows the frequency separation $\Delta\nu$ plotted against the high-frequency ν_2. The observed peak separation of the kHz QPOs and the curve (solid line) fitted by Eq. (1) are also plotted. We find that the peak separation between the twin kHz QPOs in Sco X-1 decreases as the frequency increases. This property is similar to that the decrease in separation with increasing inferred mass accretion rate (van der Klis et al. 1997; van der Klis 2000, 2004).

Figure 3 shows the number distribution of the detected frequency separation $\Delta\nu$ in Sco X-1. We find that the range of frequency separation of simultaneously detected upper and lower kHz QPOs is wide, i.e., at least 100 Hz. Although about $\sim 55\%$ of the data points are concentrated in the range from 290 Hz to 310 Hz, the other $\sim 45\%$ have a broad distributions. This indicates that the Sco X-1 data are inconsistent with a constant peak separation.

In addition, in Figure 5 we plot the ratio of the twin frequencies against the high-frequency. We also test the constant separation $\nu_2 - \nu_1$=300 Hz hypothesis (dashed line), which can be seen to be far from the observed data. Nonetheless, the kHz QPO frequencies observed in Sco X-1 used in testing the beat-frequency hypothesis in Figure 2 are *also* consistent with a non-constant peak separation, similar to that implied by Eq. (1). Figure 3 has already demonstrated the same result with the number distribution of peak separations.

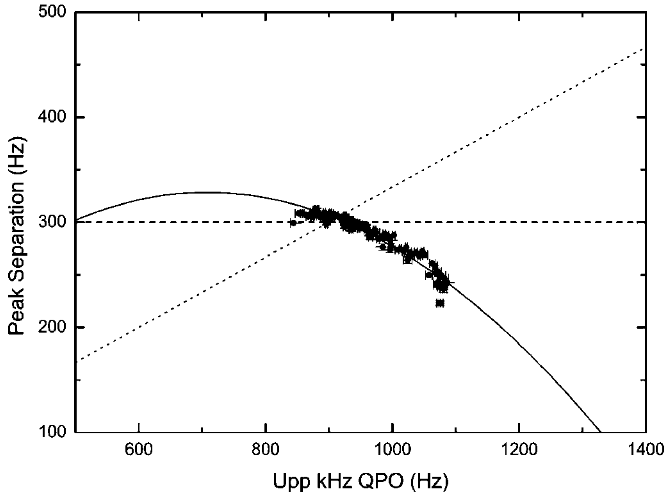

Fig. 2 Peak separation versus higher kHz QPO frequency. The solid line represents the fitted correlation between the pair frequencies as shown in Eq. (1). The dashed line represents $\nu_2 - \nu_1 = 300$ (Hz), and the doted line represents $\nu_2 = (3/2)\nu_1$.

2.2 Testing a Preferred 3:2 Ratio in the Twin kHz QPOs

The effect described above can practically account for the observed peak in Figure 2. However, it is still possible that the points in Figure 1 are intrinsically clustered around the intersection with the 3:2 line, even though there exists a significantly different correlation. As Abramowicz et al. (2003) pointed out, the real distribution in the occurrence of the QPO pairs is masked by typical selection procedures in detecting kHz QPOs. In fact, it can be tested from the published Sco X-1 data selected in an unbiased way (Abramowicz et al. 2003).

Following Abramowicz et al. (2003), we plot the histogram of the ν_2/ν_1 ratio distribution in Figure 4. A clear peak around 1.48, compared to the 1.5 reported by Abramowicz et al. (2003), can be seen in the figure. The ratio distribution centers in the range from 1.45 to 1.55, covering $\sim$ 47% of the total sample, and the other $\sim$ 53% have values from 1.25 to 1.45 and from 1.55 to 1.60. However, the peak distribution at 3:2 ratio should be interpreted with some caution because the occurrence of ratio 3:2 diffuses in a range of about 100 Hz (see Fig. 5). In Figure 5 we see that the constant ratio relation $\nu_2 = (3/2)\nu_1$, shown as the dotted line, does not seem to be such a good fit as the curve of Eq. (1). The same result has also been found in Figures 1 and 2.

3 CONCLUSIONS AND DISCUSSION

We have analyzed all detected kHz QPO twin frequencies in Sco X-1 provided by Mendez (Mendez & van der Klis 1999). The two frequencies are well correlated but, contrary to the suggestions by the beat model (Miller et al. 1998), the frequency-frequency correlation is significantly different from the relation by $\nu_2 - \nu_1$=constant or $\nu_2 = (3/2)\nu_1$. Based on the updated dataset of Sco X-1 we find that there is no sharp concentration around the 3:2 ratio and that, rather, the ratios are broadly distributed over the range 820–1180 Hz. A remarkable correlation between the lower and upper frequencies suggests that the peak separation may be varying across the sources. The results hint that the frequencies of the upper and lower kHz QPOs in

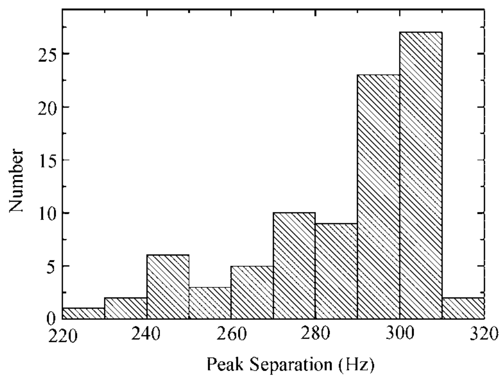

Fig. 3 Distribution of the peak separation.

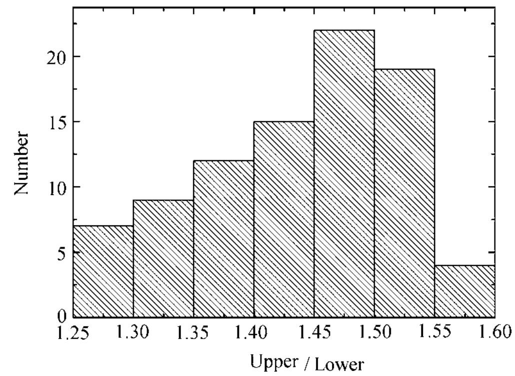

Fig. 4 Distribution of the ratio between the twin kHz QPO frequencies.

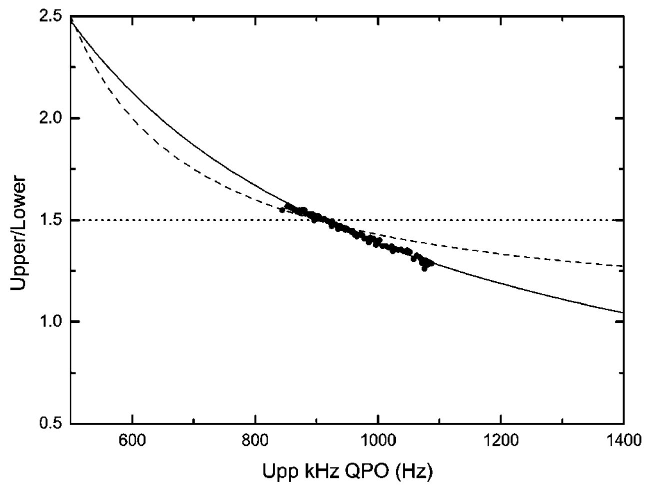

Fig. 5 Ratio of twin kHz QPO frequencies versus lower kHz QPO frequency. The solid line represents the fitted correlation between the pair frequencies as given by Eq. (1). The dashed line represents $\nu_2 - \nu_1 = 300$ (Hz), and the doted line represents $\nu_2 = (3/2)\nu_1$.

Sco X-1 follow a simple power-law relation. This relation would contradict any beat-frequency interpretation of the pairs of kHz QPOs in LMXBs, in which the frequency separation of the QPOs is exactly constant. However, the twin frequency correlation tendency is consistent with the predictions by the model based on the basic general relativistic frequencies around a compact object (Stella & Vietri 1999) and the model based on the Alfven wave oscillation (Zhang 2004; Li & Zhang 2005; Zhang 2005). Both these models have predicted that the peak separation decreases with the frequency increasing, but neither model describes the excitation mechanism responsible for the productions of kHz QPOs.

Significantly, Sco X-1 is the most active source among the known 25 kHz QPO sources, and its QPO properties are very typically shared by the Atoll sources and Z sources, the two classes of neutron star X-ray sources. Moreover, in Sco X-1, variation of the Fourier power spectrum with the mass accretion rate is also explicitly indicated (van der Klis 1997; van der Klis 2000), but its physical mechanism has not yet been uncovered. In addition to the kHz QPO relations described in this paper, we must have some wholly unambiguous impression from all the kHz QPO sources, which will in principle lead us to constructing a theoretical model on kHz QPOs.

In conclusion, the data from Sco X-1 present a varying peak separation between the kHz QPOs. If future data still support this property, they will pose a new constraint on models for explaining kHz QPOs.

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