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THE BEAT-FREQUENCY INTERPRETATION OF KILOHERTZ QUASI-PERIODIC OSCILLATIONS IN NEUTRON STAR LOW-MASS X-RAY BINARIES

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ABSTRACT

Pairs of quasi-periodic oscillations (QPOs) at kilohertz frequencies are a common phenomenon in several neutron-star low-mass X-ray binaries. The frequency separation of the QPO peaks in the pair appears to be constant in many sources and directly related to the neutron star spin frequency. However, in Sco X-1 and possibly in 4U 1608−52, the frequency separation between the QPO peaks decreases with increasing inferred mass accretion rate. We show that the currently available *Rossi X-Ray Timing Explorer* data are consistent with the hypothesis that the peak separations in all sources vary by amounts similar to the variation in Sco X-1. We discuss the implications for models of the kilohertz QPOs.

Subject headings: accretion, accretion disks — stars: neutron — X-rays: stars

1. INTRODUCTION

Quasi-periodic X-ray brightness oscillations at kilohertz frequencies (hereafter kHz QPOs) have recently been discovered in many neutron-star low-mass X-ray binaries (LMXBs) with the *Rossi X-Ray Timing Explorer* (*RXTE*; see, e.g., van der Klis et al. 1996; Strohmayer et al. 1996). These are strong, often relatively coherent ($\nu/\delta\nu$ up to ∼200) oscillations that occur commonly in pairs (see van der Klis 1998 for a recent review).

The frequencies of the kHz QPOs are comparable to the dynamical timescale near the neutron star surface and depend on the mass accretion rate as inferred from the observed count rates and the spectral properties of the sources (van der Klis et al. 1996; Strohmayer et al. 1996; Ford et al. 1997a, 1997b; van der Klis et al. 1997). The peak separation between the lower frequency (hereafter the lower kHz QPO) and the upper frequency kHz QPO (hereafter the upper kHz QPO) in a given source is generally consistent with a constant value, independent of the mass accretion rate (Strohmayer et al. 1996; Ford et al. 1997a, 1997b; Wijnands et al. 1997b, 1998a, 1998b). In 4U 1728−34 and in 4U 1702−43, this peak separation is closely equal to the frequency of the nearly coherent oscillations observed during type I X-ray bursts that are thought to be produced at the spin frequencies of the neutron stars (Strohmayer et al. 1996, 1998; Strohmayer, Zhang, & Swank 1997b); in 4U 1636−536 and in KS 1731−26, the peak separation is closely equal to half the frequency of the nearly coherent oscillations observed during type I X-ray bursts (Smith, Morgan, & Bradt 1997; Wijnands & van der Klis 1997; Strohmayer et al. 1998).

The above observations offer strong evidence in favor of beat-frequency models, in which the frequency of the lower kHz QPO is the beat frequency between the upper kHz QPO and the neutron star spin (Strohmayer et al. 1996; Miller, Lamb, & Psaltis 1998). In Sco X-1, however, which is a luminous LMXB, the peak separation of the kHz QPOs is *not* constant, but decreases with increasing inferred mass accretion rate (van der Klis et al. 1997). In 4U 1608−52, which is a less luminous LMXB, there is also evidence for a peak separation that is not constant (Méndez et al. 1998).

In this Letter, we use previously published *RXTE* data on several low-mass X-ray binaries to discuss critically the evidence in favor of a constant frequency separation between the kHz QPO peaks required in any simple beat-frequency interpretation. We find that the current data on all sources except Sco X-1 are insufficient, when used individually, to distinguish between a constant peak separation and a peak separation that varies by amounts similar to those seen in Sco X-1. When we use the combined data set of all sources, we find a remarkable correlation between the frequencies of the lower and upper kHz QPOs, which suggests that the peak separation may be varying in all sources.

2. IS THE PEAK SEPARATION CONSTANT?

The current data on kHz QPOs include observations of 11 neutron-star LMXBs in which pairs of kHz QPOs have beed detected in their persistent emission. In three of these systems, nearly coherent oscillations have been detected during type I X-ray bursts at frequencies consistent with being equal to the peak separation between the kHz QPOs or their first overtones. In 4U 0614+09, a third QPO has been detected with marginal significance (reported to be ∼2.7 σ; Ford et al. 1997a) at a frequency consistent with being equal to the peak separation between the kHz QPOs. Table 1 summarizes these observations.

Testing the hypothesis of a constant peak separation between the kHz QPOs requires for each individual source the detection of both QPOs over a wide range of frequencies. In the three sources in which both the pair of kHz QPOs in the persistent emission and nearly coherent oscillations during type I X-ray

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TABLE 1
KILOHERTZ QPO OBSERVATIONS

Source	ν_2[a] (Hz)	Range[b] (Hz)	Burst QPO (Hz)	Reference
4U 0614+091	825–1145	320	...	1
GX 17+2	780–1080	300	...	2
GX 5−1	500–780	280	...	3
GX 340+0	560–820	260	...	4
4U 1608−52	650–890[c]	240[c]	...	5
Sco X-1	870–1080	210	...	6
4U 1728−34	990–1100	110	363	7
4U 1636−536	1150–1195	45	581	8
Cyg X-2	856	0	...	9
KS 1731−26	1170	0	524	10
4U 1820−30	1066	0	...	11
Aql X-1	...	...	549	12
Galactic center	...	...	589	13

[a] Frequencies of the upper kHz QPO when a lower kHz QPO was simultaneously detected.
[b] Range of upper kHz QPO frequencies at which a lower kHz QPO has been simultaneously detected.
[c] These frequencies are for the lower kHz QPO. The existence of the upper kHz QPO has been inferred indirectly.
REFERENCES.—(1) Ford et al. 1997a, 1997b, Méndez et al. 1997; (2) Wijnands et al. 1997a; (3) Wijnands et al. 1998b; (4) Jonker et al. 1998; (5) Berger et al. 1996, Méndez et al. 1998; (6) van der Klis et al. 1997; (7) Strohmayer et al. 1996; (8) Zhang et al. 1996, Wijnands et al. 1997b, Yu et al. 1997; (9) Wijnands et al. 1998a; (10) Smith et al. 1997, Wijnands & van der Klis 1997; (11) Smale et al. 1997; (12) Zhang et al. 1998; (13) Strohmayer et al. 1997a.

bursts have been detected, the range of reported frequencies of simultaneously detected kHz QPOs in the persistent emission is *very* narrow (see Table 1). In all sources, besides Sco X-1, in which the range of detected frequencies of the pairs of kHz QPOs is wide ($\gtrsim$200 Hz in GX 17+2, GX 340+0, GX 5−1, and 4U 0614−09), the fractional errors in the measurement of the centroid frequencies of the QPOs are substantial. Figure 1 compares the distribution of fractional (1 σ) errors in the determination of the peak separation between the kHz QPOs in Sco X-1 with the corresponding distribution for GX 17+2, GX 340+0, GX 5−1, and 4U 0614−09. In all sources besides Sco X-1, the average 1 σ error is ~10–50 Hz, comparable to the change in the peak separation observed in Sco X-1.

Figure 2*a* shows the results of testing the simple beat-frequency interpretation of the pairs of kHz QPOs in several sources by means of a χ^2 test. We performed this test for the five sources in our sample for which the range of frequencies of simultaneously detected upper and lower kHz QPOs is wide (i.e., at least 200 Hz; the more limited data on 4U 1728−34 and 4U 1636−536 are consistent with the result presented in Fig. 2, as well) using for each source all the measurements reported in the references listed in Table 1; the uncertainties in the measurements were estimated in the same way for all sources, and hence our observational sample is uniform. Figure 2*a* shows the resulting χ^2-values for these sources, confirming the known result that the Sco X-1 data are inconsistent with a constant peak separation, whereas the data on the remaining sources are consistent with it (see also van der Klis et al. 1997; Wijnands et al. 1997b, 1998a, 1998b; Ford et al. 1997a, 1997b). In GX 5−1, the minimum χ^2-value is ~2, mostly because we included for this source frequencies of kHz QPOs that were marginally detected (at less than 3 σ; see Wijnands et al. 1998b for a discussion). The peak separation in all sources is ~300 Hz.

The peak separation between the kHz QPOs in Sco X-1

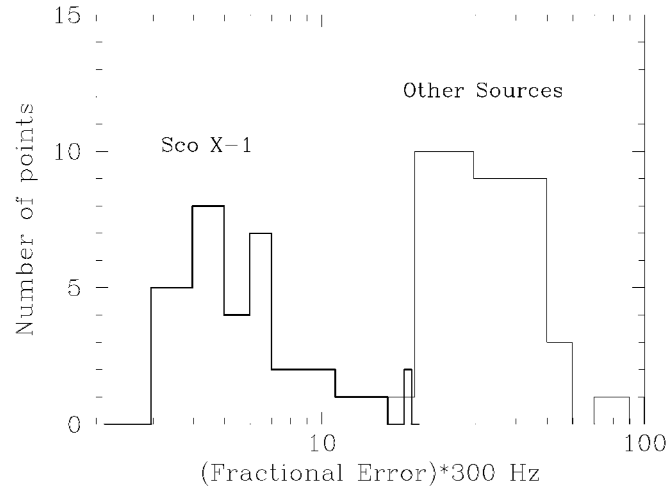

FIG. 1.—Distribution of fractional errors in the determination of the peak separation between the kHz QPOs in Sco X-1 and in GX 17+2, GX 340+0, GX 5−1, and 4U 0614−09.

decreases with increasing inferred mass accretion rate (van der Klis et al. 1997). Figure 3*a* shows the frequency ν_1 of the lower kHz QPO in Sco X-1 plotted against the frequency ν_2 of the upper kHz QPO. The data points can be adequately described

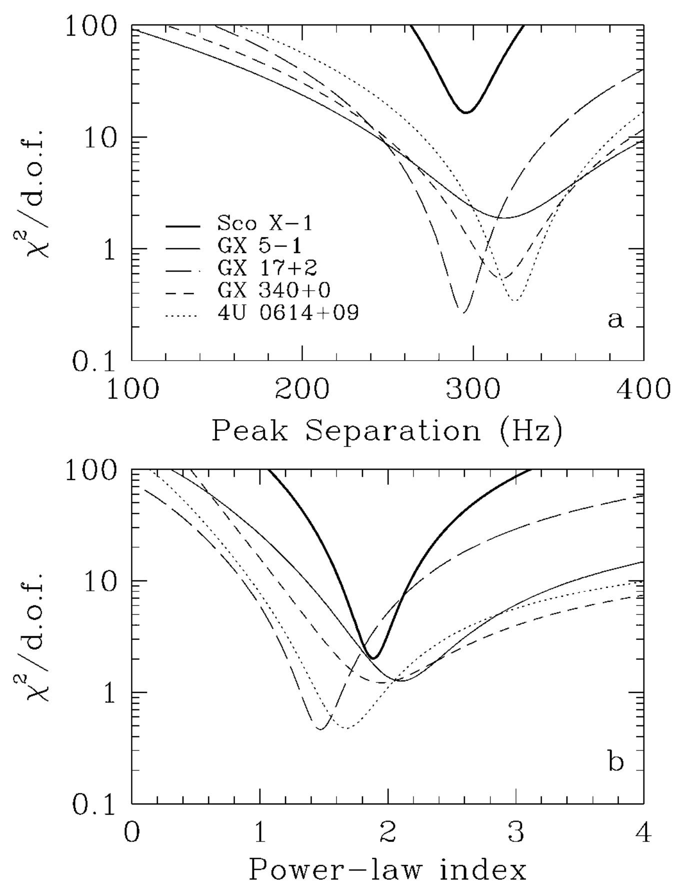

FIG. 2.—Results of testing (*a*) the simple beat-frequency interpretation of the pairs of kHz QPOs and (*b*) the hypothesis of a power-law correlation between the frequencies of kHz QPOs in five LMXBs by means of a χ^2 test.

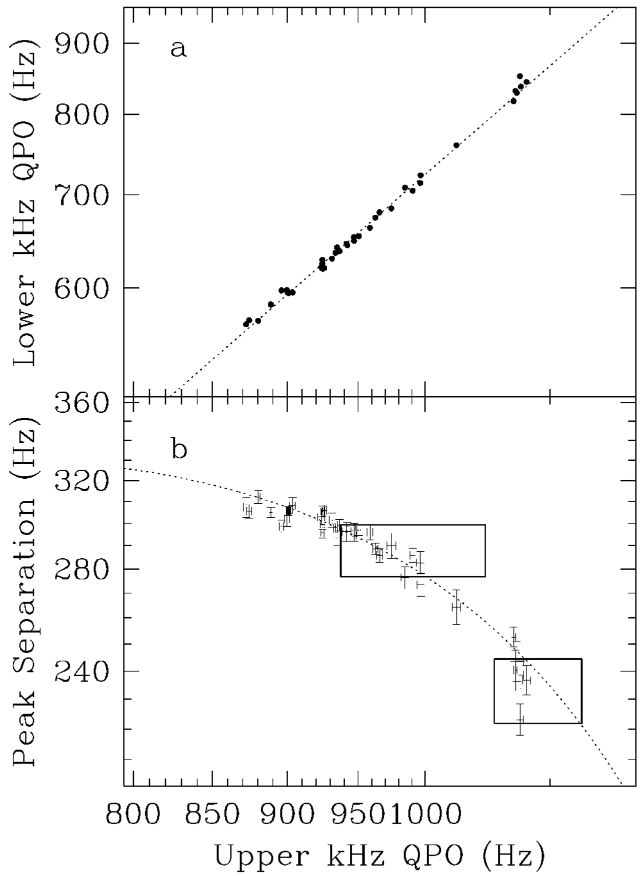

FIG. 3.—(*a*) Observed correlation between the lower and upper kHz QPO frequencies in Sco X-1. (*b*) Observed peak separation between the kHz QPOs in Sco X-1 (*error bars*) and in 4U 1608−52 (*bands*; see text). The error bars in panel (*a*) are smaller than the size of the dots.

by the power-law relation

$$\nu_1 = (724 \pm 3)\left(\frac{\nu_2}{1000\ \mathrm{Hz}}\right)^{1.9\pm0.1}\ \mathrm{Hz}, \qquad (1)$$

which is shown in the figure as a dashed line. The χ^2-value that corresponds to relation (1) is 2.0 (see Fig. 2*b*). This is a relatively high value because, at high (~1100 Hz) frequencies of the upper kHz QPO, the QPO peaks are weak and therefore the measurements are dominated by systematic uncertainties; when we use only the data points with upper kHz QPO frequency ≤1050 Hz, the χ^2-value for relation (1) becomes ≃1.5. It is important to note that the power-law description was arbitrarily chosen here to describe the Sco X-1 data in the following discussion and other functional forms could fit the Sco X-1 data equally well. In particular, relation (1) implies a nonmonotonic change of the peak separation, with a maximum at an upper kHz QPO frequency of ~700 Hz. However, we are proposing here that the peak separation varies nonmonotonically, since this requires extrapolating relation (1) to frequencies smaller than the lowest kHz QPO frequency detected so far in Sco X-1. Figure 3*b* shows the observed peak separation of the kHz QPOs in Sco X-1 together with the curve implied by relation (1).

The atoll source 4U 1608−52 has also shown evidence for a peak separation that decreases with increasing kHz QPO frequency (Méndez et al. 1998). In this source only one kHz QPO has so far been detected in the power spectra (see, e.g., Berger et al. 1996). However, shifting the power spectra so that the kHz QPO peaks are aligned and adding them up reveal the existence of the second, higher frequency kHz QPO peak (Méndez et al. 1998). Because of the shifting of the power spectra and the alignment of the QPO peaks, the information regarding the centroid frequency of the upper kHz QPO is lost. Moreover, the ranges of frequencies of the lower kHz QPOs used originally with the above technique were overlapping. As a result, we cannot directly compare the decrease of the peak separation in Sco X-1 implied by relation (1) to the data of 4U 1608−52.

In the original analysis of Méndez et al. (1998) the frequency of the lower kHz QPO in the observation of 1996 March 3 varied in the range 823–893 Hz. The peak separation was found to be 232.7 ± 11.5 Hz. We have reanalyzed the data of 1996 March 6 using only the part of the data set in which the frequency of the lower kHz QPO was in the range 649–760 Hz to avoid any overlap with the range of frequencies detected on March 3. Even with this restricted part of the data set we detected a second QPO peak (at 4.3 σ) with a peak separation equal to 288.1 ± 11.3 Hz. Figure 3*b* compares the 4U 1608−52 and Sco X-1 data; because of the technique used for 4U 1608−52, the March 3 and 6 observations are represented by bands of constant peak separation. Figure 3*b* suggests that the decreasing peak separation found in 4U 1608−52 is consistent with that of Sco X-1.

The frequencies of the kHz QPOs observed in the sources used to test the beat-frequency hypothesis in Figure 2*a* are *also* consistent with a non-constant peak separation, similar to the one implied by relation (1) for Sco X-1. Figure 2*b* demonstrates this by showing the result of testing the latter hypothesis, i.e., of a power-law correlation between the lower and upper kHz QPO frequencies, by means of a χ^2 test. The minimum χ^2-values for all sources that were found to be consistent also with a constant peak separation (see Fig. 2*a*) are ≲1.0.

As mentioned earlier, for all the sources for which simultaneous kHz QPOs have been detected besides the ones used to plot Figure 2, the range of observed kHz QPO frequencies is narrow. We therefore cannot test directly whether the peak separations between the kHz QPOs in these sources vary by amounts comparable to those seen in Sco X-1 or not. However, Figure 4*a* shows that the frequencies of the lower and upper kHz QPOs observed in all nine sources are remarkably tightly correlated and fairly closely follow relation (1), which describes the data of Sco X-1; Figure 4*b* shows the instantaneous peak separations in all nine sources and compares them with the varying peak separation of Sco X-1. The tight correlation between the kHz QPO frequencies shown in Figure 4*a* together with the large uncertainties in the determination of the peak separation for all sources except Sco X-1 shown in Figure 4*b* strongly suggests that the data on *all* sources are consistent with the varying peak separation of Sco X-1. Note, however, that although all sources are consistent with a peak separation that is varying by amounts similar to those seen in Sco X-1, not all these sources are consistent with a single relation between the lower and upper kHz QPO frequencies. In fact, the lower and upper kHz QPO frequencies for all Z sources, with the possible exception of GX 17+2, are consistent with relation (1) that describes the data of Sco X-1 (see Fig. 2*b*). On the other hand, the data for the atoll sources 4U 0614+09, KS 1731−26, and 4U 1636−53 are consistent with a single power-

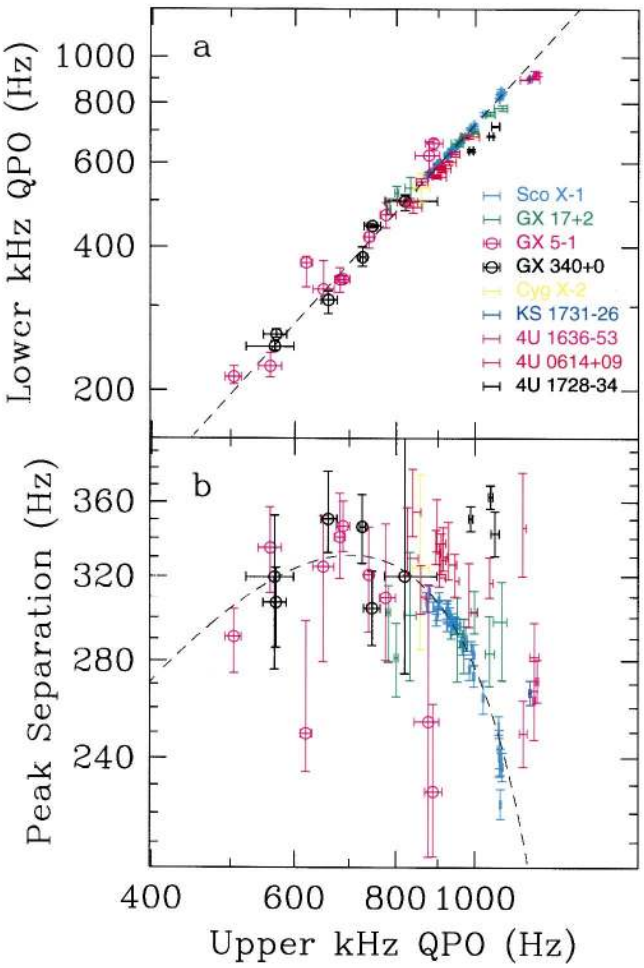

FIG. 4.—(*a*) Observed correlation between the lower and upper kHz QPO frequencies in nine LMXBs. (*b*) The observed peak separation between the kHz QPOs in nine LMXBs.

law relation with the same index as relation (1) but a lower normalization (∼695 Hz; the χ^2-value for testing this relation is $\lesssim 1.5$ in each of the three sources individually).

3. DISCUSSION

In § 2 we showed that, using current kHz QPO data of neutron-star low-mass X-ray binaries, we cannot reject the hypothesis that the frequency separations of the two kHz QPOs in the pair are constant in each source besides Sco X-1, nor the hypothesis that they vary in a way similar to Sco X-1. In Sco X-1, which is the only source with very precisely measured centroid frequencies for the kHz QPOs, the data are inconsistent with a constant peak separation (see also van der Klis et al. 1997). Furthermore, measurements of the peak separation in all other sources in which two simultaneous kHz QPOs have been detected are consistent with change of the kind observed in Sco X-1. This is the case for the Z sources, which are thought to be accreting at near-Eddington mass accretion rates (see, e.g., Hasinger & van der Klis 1989), as well as for the atoll sources, which are thought to be accreting at substantially lower rates.

These results hint that the frequencies of the upper and lower kHz QPOs in all sources considered individually, including Sco X-1, are consistent with following a simple (but not necessarily the same) relation, such as a power-law, which is nevertheless very similar even for sources with very different mass accretion rates. Obeying such a 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 nearly coherent oscillations observed during type I X-ray bursts in two sources with frequencies closely equal to the peak separations of the kHz QPOs and the evolution of their amplitudes during the bursts are very strong evidence that the peak separations in these sources are similar to the spin frequencies of the neutron stars (Strohmayer et al. 1996, 1997b, 1998). Most importantly, in 4U 1728−34 the frequencies of the oscillations in the tails of bursts separated by about 20 months are consistent with being constant, implying a timescale for the frequency change of $\gtrsim 10^3$–10^4 yr (Strohmayer 1997). The only conceivable frequency in these systems that is stable to the degree inferred from the observations of 4U 1728−34 is the spin frequency of the neutron star. Therefore, the frequency separation of the two kHz QPO peaks in this source appears to be *closely equal but perhaps not identical* to the spin frequency of the neutron star. In 4U 1636−536 and in KS 1731−26, the peak separation of the kHz QPOs also appears to be directly related to the neutron star spin frequency.

In current beat-frequency models for the pair of kHz QPOs (see, e.g., Strohmayer et al. 1996; Miller et al. 1998), the upper kHz QPO is produced at the Keplerian orbital frequency at a characteristic radius in the accretion disk; the lower kHz QPO is then produced at the beat frequency of the upper kHz QPO with the neutron star spin. In order for a beat-frequency model to account for the varying peak separation between the kHz QPOs, one of the above assumptions would need to be relaxed. For example, the frequency that is beating with the neutron star spin to produce the lower kHz QPO may not be the frequency of the upper kHz QPO, i.e., the two frequencies could correspond to different radii in (or heights above) the disk plane (see Miller et al. 1998). The fact that the variation in the peak separation of the two kHz QPOs in Sco X-1 is larger than the FWHM of either the lower or upper kHz QPOs implies that the two annuli or regions in the accretion disk responsible for the two kHz QPOs are not overlapping. Alternatively, the frequency that is beating with the upper kHz QPO to produce the lower kHz QPO may be nearly but not strictly equal to the neutron star spin frequency (see, e.g., White & Zhang 1997).

In conclusion, the data from both the Z and atoll sources are consistent with a varying peak separation between the kHz QPOs. If future data support this conjecture, they will pose interesting new constraints on beat-frequency models for these QPOs: the peak separation should correlate more strongly with the frequency of the upper kHz QPO than with the mass accretion rate or the magnetic field strength.

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