Difference Frequency of Kilohertz QPOs Not Equal to Half the Burst Oscillation Frequency in 4U 1636–53

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ABSTRACT

We have analyzed data obtained during two observations with the Rossi X-ray Timing Explorer on January 5 and 8, 1997, of the low-mass X-ray binary (LMXB) and atoll source 4U 1636–53. We measure the frequency separation of the two simultaneous kilohertz quasi-periodic oscillations (kHz QPOs) in this source to be 253.7±4.7 and 246.4±5.4 Hz, respectively. These values are inconsistent with being equal to 0.5 times the frequency of the 581-Hz oscillations that have been detected previously in 4U 1636–53 during type I bursts. The weighted average discrepancy is 39.5±3.5 Hz. This result shows that a simple beat-frequency interpretation of the kHz QPOs, in which the frequency of the oscillations detected during type I bursts equals the separation between the two kHz QPOs (or twice that value), is incorrect.

Subject headings: accretion, accretion disks — stars: neutron — stars: individual (4U 1636–53) — X-rays: stars

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1. Introduction

Observations with the Rossi X-ray Timing Explorer (RXTE) have so far revealed coherent oscillations during type I X-ray bursts in 6 low-mass X-ray binaries (LMXBs): in 4U 1728–34 at 363 Hz (Strohmayer et al. 1996a, 1997b), in 4U 1636–53 at 581 Hz (Zhang et al. 1996, Strohmayer et al. 1998), in KS 1731–26 at 524 Hz (Smith et al. 1997), in 4U 1702–43 at 330 Hz (Strohmayer, Swank and Zhang 1998), in Aql X–1 at 549 Hz (Zhang et al. 1998), and in a source near the Galactic Center (probably MXB 1743–29) at 589 Hz (Strohmayer et al. 1997a). The first four sources have also shown two simultaneous kilohertz quasi-periodic oscillations (kHz QPOs) in their persistent emission (Strohmayer et al. 1996a; Wijnands et al. 1997; Wijnands & van der Klis 1997; Swank 1998). In 4U 1728–34 the separation between the two simultaneous kHz QPOs was 355 ± 5 Hz, consistent with the frequency of the oscillations during the type I bursts. In 4U 1702–43 the kHz QPO separation frequency and the burst oscillation frequency were also similar. In 4U 1636–53 and KS 1731–26 the frequency separation of the kHz peaks was 276 ± 10 Hz and 260 ± 10 Hz, respectively, consistent with half the frequency during the burst oscillations.

These results strongly suggested that the burst oscillations and the twin kHz QPO are connected through a beat frequency relation, in which signals at two of the frequencies are interacting to produce a third one at their difference frequency. There are good arguments that the burst oscillations are due to short-lived thermonuclear-powered hot spots on the neutron star surface that spin around with approximately the star's spin frequency (Strohmayer et al. 1998). In a beat frequency interpretation a natural choice for the two interacting oscillations then is (i) the burst oscillations, occurring at the neutron star spin frequency (or twice that), and the (ii) the higher-frequency kHz QPO, occurring at the Kepler frequency corresponding to some preferred radius in the accretion disk (Strohmayer et al. 1996b; Miller, Lamb, & Psaltis 1998). The lower-frequency kHz QPO is then due to the beat between these two frequencies. In such an interpretation the kHz QPO frequency difference is equal to the neutron star spin frequency and hence predicted to be constant. In most of the sources that showed the simultaneous kHz QPO peaks the frequency difference was indeed consistent with being constant as the twin kHz peaks moved up and down in frequency as a function of, presumably, accretion rate.

In sources for which only the twin kHz QPO, and no burst oscillations, were observed the frequency difference was interpreted in terms of the neutron star spin frequency as well. However, we now know that two of these sources do not fit this interpretation: both in Sco X-1 (van der Klis et al. 1997), and in 4U 1608–52 (Méndez et al. 1998b) the separation between the two simultaneous kHz QPOs varies significantly, by $\sim 40\%$ on time scales of a few days, showing that at least in these sources the separation frequency can not be simply the spin frequency.

In this Letter we present new results that conclusively show that the frequency separation of the kHz QPOs in 4U 1636–53 differs from being equal to half the frequency of the oscillations detected during type I X-ray bursts in this source. In Section 2 we describe the observations and data analysis. In Section 3 we discuss our findings.

2. Observations and Data Analysis

We have analyzed two observations of 4U 1636–53 carried out with the Proportional Counter Array (PCA) on board RXTE during January 1997. The first started on 1997 January 5, 22:05 UTC and lasted for ~ 19.5 ks, and the second one started on January 8, 04:33 UTC and lasted ~ 12.5 ks. In both observations data were collected using an Event mode with 1/8192 s time resolution and 64 energy channels covering the nominal 2–60 keV energy band of the PCA. No type I X-ray bursts were detected.

We divided these high-time resolution 2–60 keV data into segments of 64 s, Fourier transformed these, and for each segment produced a power spectrum extending from 1/64 to 2048 Hz. In both observations a strong kHz QPO peak was visible. The centroid frequency of this peak varied between 830 Hz and 930 Hz on January 5, and between 890 Hz and 1050 Hz on January 8. In both cases, a second, less significant peak was detected at a frequency 200 to 300 Hz higher than that.

We repeated the procedure using data in several different energy bands. While the lower-frequency QPO was significant in all of these bands, the higher-frequency QPO was more significant when we only used data above 5 keV. For this reason, and to reduce the influence of the background at high energies, we decided to use only the data between 5 and

20 keV. Again, we produced a power spectrum every 64 s. As the lower-frequency QPO was well detected in each segment, we fitted its central frequency and then shifted the frequency scale of each spectrum to a frame of reference where the position of the most significant peak was constant in time (see Méndez et al. 1998a). Finally, we averaged these shifted spectra to produce one single 5–20 keV power spectrum per observation.

We fitted the 256–1500 Hz frequency range of each of these two average power spectra using a function consisting of a constant, representing the Poisson noise, and two Lorentzians, representing the QPOs. The fits were good, with reduced $\chi^2 \leq 1.1$. We show in Figure 1 the average power spectrum of the two observations and the model that we used to fit it. The 5–20 keV amplitudes and FWHM of the lower frequency QPO were $8.6 \pm 0.1\,\%$ rms and 13.2 ± 0.4 Hz, respectively on January 5, and $3.5 \pm 0.2\,\%$ rms and 6.2 ± 0.7 Hz, respectively on January 8. The amplitudes and FWHM of the higher frequency QPO were $5.2 \pm 0.4\,\%$ rms and 70 ± 12 Hz, and $4.8 \pm 0.4\,\%$ rms and 64 ± 14 Hz, respectively. The frequency difference between the two simultaneous kHz QPOs was consistent with being constant. The separation between the two peaks was 253.7 ± 4.7 Hz on January 5, and 246.4 ± 5.4 on January 8. The average separation during these two observations as measured from the overall average power spectrum was the same as the weighted average of these two values: 250.6 ± 3.5 Hz.

3. Discussion

Our measured average kHz QPO peak separation, 250.6 ± 3.5 Hz, is inconsistent with being equal to half the burst oscillation frequency at better than 10σ confidence. Although the burst oscillation frequency shows a small (<2 Hz) drift during some bursts, it is statistically very well determined and seems to always be between 579 and 582 Hz (see Strohmayer, Swank and Zhang 1998, and Strohmayer et al. 1998). So, the separation frequency is too small by between 38.9 ± 3.5 and 40.4 ± 3.5 Hz to be equal to half the burst oscillation frequency.

In the beat frequency model for the kHz QPOs (Section 1), the two basic frequencies of the system are the Keplerian frequency of the accreting material in orbit around the neutron star at some preferred radius, identified with the high frequency kHz QPO, at a frequency ν_{upp}, and the spin frequency of the neutron star, ν_{s}. These two frequencies beat with each other to produce the low-frequency kHz QPO at $\nu_{\mathrm{low}} = \nu_{\mathrm{upp}} - \nu_{\mathrm{s}}$. So, the model predicts that $\Delta\nu \equiv \nu_{\mathrm{upp}} - \nu_{\mathrm{low}} = \nu_s$.

As noted in Section 1, this model agrees well with the results obtained in 4U 1728–34 (Strohmayer et al. 1996a) if one assumes that ν_{s} in this source is equal to the frequency ν_{burst} of the oscillations observed during bursts. In 4U 1636–53 and KS 1731–26, $\Delta\nu$ is approximately equal to $\nu_{\mathrm{burst}}/2$ (Wijnands et al. 1997; Wijnands & van der Klis 1997). A beat-frequency model could perhaps account for this if in these two sources $\nu_{\mathrm{s}} = \nu_{\mathrm{burst}}/2$. This could occur if, for example, two hot spots are present during the burst. (This interpretation has been contested by Strohmayer et al. 1998 on the basis of the large observed amplitudes of the oscillations.)

Our results show conclusively that, at least in 4U 1636–53, this simple beat frequency picture is invalid. If we assume that $\nu_{\mathrm{S}} = \nu_{\mathrm{burst}}/2$, then ν_{s} exceeds $\Delta\nu$ by a value near 40 ± 3.5 Hz, a discrepancy of more than 10σ. (Of course, the situation would be worse if $\nu_{\mathrm{s}} = \nu_{\mathrm{burst}} = 581$ Hz).

The beat-frequency model for the twin kHz QPO in LMXBs has been strongly challenged by the measurements of a variable peak separation in Sco X-1 and 4U 1608–52 (van der Klis et al. 1997; Méndez et al. 1998b). Our findings show that the beat frequency model in its current form fails in the case of 4U 1636–53. This is the first time that this is demonstrated in an object where all three of the frequencies involved in the beat-frequency interpretation are measurable. In view of the great similarity of the kHz QPO phenomenology in all LMXBs this conclusion also applies to the phenomenon as observed in other LMXBs.

It may be too early to discard the beat frequency model altogether. It is conceivable that the kHz peak separation frequency, while not being equal to the neutron star spin frequency (or twice that) is still constrained to be relatively near it. This could be the case if it is the spin frequency of accreting matter that is not corotating with the star. It is also possible that the beat frequency is generated by processes occurring at a radius that differs from the radius inferred from the Kepler frequency interpretation of the upper kHz QPO frequency. In view of the complexity apparently involved in a successful beat frequency model for the kHz QPO, in our opinion constraints on physical parameters such as neutron star spin frequency, mass, and radius inferred from the properties

of these QPO, must for the time being be interpreted with great care.

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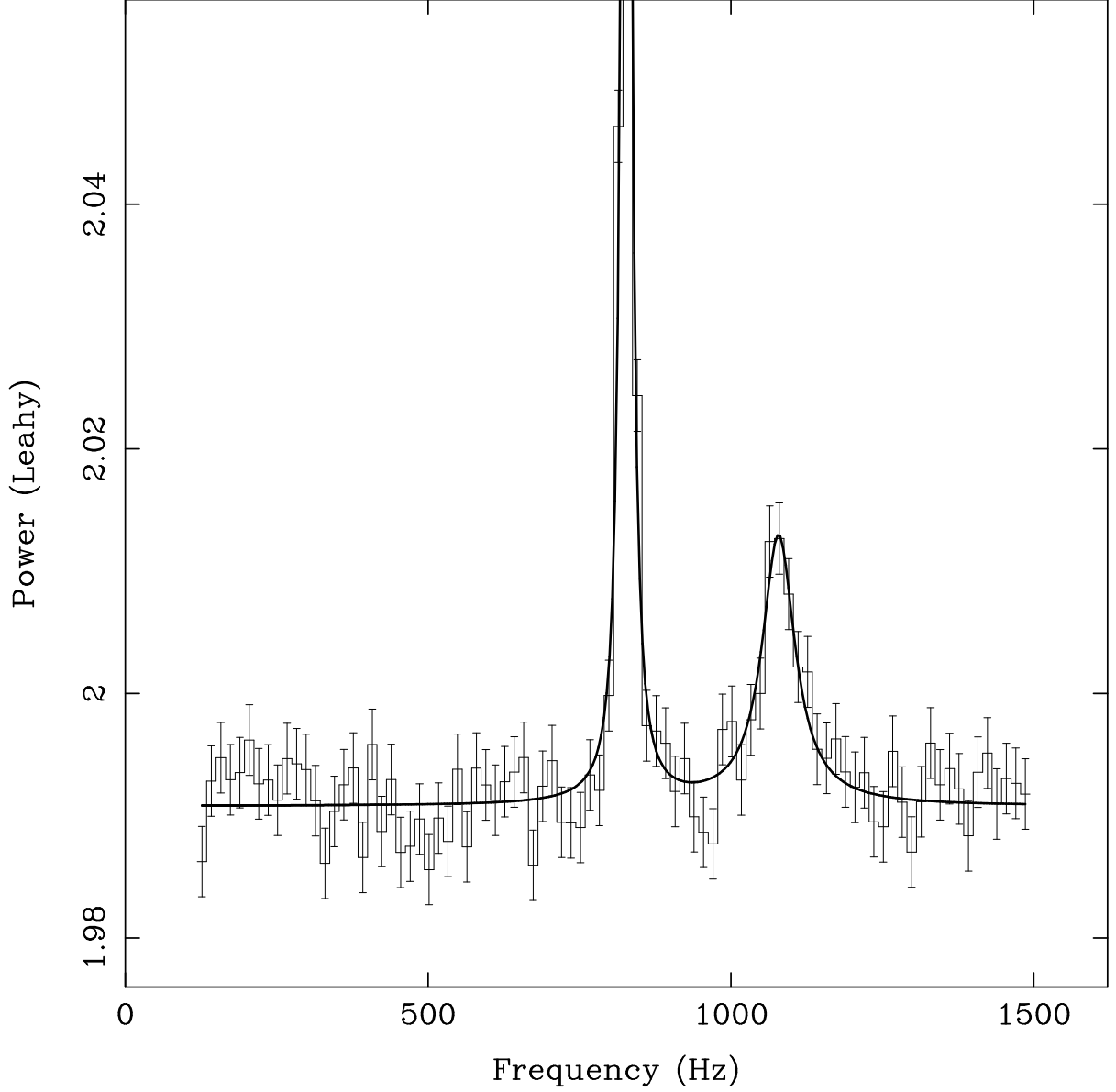
Fig. 1.— Average power spectrum of the two observations presented in this paper, in the 5–20 keV energy range. The frequency of the lower-frequency peak as measured in 64-s data segments was arbitrarily shifted to improve the detection of the QPO at higher frequencies (see Méndez et al. 1998a for details). The solid line represents the best fit model as described in the text. The frequency separation of the two peaks is 250.6 ± 3.5 Hz.