FRACTIONAL AMPLITUDE OF KILOHERTZ QUASI-PERIODIC OSCILLATION FROM 4U 1728–34: EVIDENCE OF DECLINE AT HIGHER ENERGIES

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ABSTRACT

A kilohertz quasi-periodic oscillation (kHz QPO) is an observationally robust high-frequency timing feature detected from neutron star low-mass X-ray binaries (LMXBs). This feature can be very useful to probe the superdense core matter of neutron stars and the strong gravity regime. Although many models exist in the literature, the physical origin of kHz QPO is not known, and hence this feature cannot be used as a tool yet. The energy dependence of kHz QPO fractional rms amplitude is an important piece of the jigsaw puzzle to understand the physical origin of this timing feature. It is known that the fractional rms amplitude increases with energy at lower energies. At higher energies, the amplitude is usually believed to saturate, although this is not established. We combine tens of lower kHz QPOs from a neutron star LMXB 4U 1728–34 in order to improve the signal-to-noise ratio. Consequently, we, for the first time to the best of our knowledge, find a significant and systematic decrease of the fractional rms amplitude with energy at higher photon energies. Assuming an energy spectrum model, blackbody+powerlaw, we explore if the sinusoidal variation of a single spectral parameter can reproduce the above-mentioned fractional rms amplitude behavior. Our analysis suggests that the oscillation of any single blackbody parameter is favored over the oscillation of any single power-law parameter, in order to explain the measured amplitude behavior. We also find that the quality factor of a lower kHz QPO does not plausibly depend on photon energy.

Key words: accretion, accretion disks – methods: data analysis – stars: neutron – X-rays: binaries – X-rays: individual (4U 1728–34) – X-rays: stars

Online-only material: color figures

1. INTRODUCTION

Kilohertz quasi-periodic oscillations (kHz QPOs), discovered in 1996 with Rossi X-ray Timing Explorer (RXTE; van der Klis et al. 1996; Strohmayer et al. 1996), are the fastest variability features known to date in low-mass X-ray binaries (LMXBs). They have been observed for many neutron star LMXBs, although for a given source they are not always detected (Bhattacharyya 2010; van der Klis 2006). These QPOs often occur in pairs, and the twin peaks usually move together in the frequency range of ~400–1200 Hz. The higher frequency QPO is known as the upper kHz QPO (frequency ν_u), and the lower frequency QPO is called the lower kHz QPO (frequency ν_l). The frequency differences of these QPOs (Δν ≡ ν_u − ν_l) tend to cluster around the neutron star spin frequency or half of it (van der Klis 2006 and references therein; but see Méndez & Belloni 2007). The high frequencies of kHz QPOs point toward the dynamical timescale within a few Schwarzschild radii of the neutron star (Barret et al. 2005a, 2005b, 2006; van der Klis 2006; Bhattacharyya 2010). Therefore, this observationally robust timing feature can be useful (1) to measure the neutron star parameters, which, in turn, are essential to understanding the nature of superdense degenerate matter (e.g., Bhattacharyya 2010 and references therein; Périé 2011); and (2) to probe the strong gravitational field regime (Psaltis 2008). However, although many models are available in the literature, the physical origin of kHz QPOs is still not known (e.g., Lin et al. 2011; Török 2009; van der Klis 2006), and hence we cannot yet use this promising feature as a tool. Many proposed models for this timing feature have attempted to explain the frequencies (Miller et al. 1998; Stella & Vietri 1998; Lamb & Miller 2003; Kluźniak & Abramowicz 2001; Abramowicz & Kluźniak 2001; Wijnands et al. 2003; Lee et al. 2004; Zhang 2004; Zhang et al. 2006; Mukhopadhyay 2009; Alpar & Psaltis 2008; Stuchlík et al. 2011). Some of these models involve several general relativistic frequencies at preferred radii and the neutron star spin frequency; in some cases, beating and/or resonances are among these frequencies. Other models include the association of kHz QPOs with accretion through a non-axisymmetric magnetic boundary layer in the unstable regime (Romanova & Kulkarni 2009); attempts to connect the kHz QPOs with the trapped, two-armed nearly vertical oscillations in vertically isothermal disks with toroidal magnetic fields (Kato 2011); attribution of the upper kHz QPO profile to the radial extent of the kHz QPO emission region associated with the transitional layer at the magnetosphere-disk boundary (Wang et al. 2011), etc.

However, modeling only the frequencies gives an incomplete picture; probing radiative transfer and further modulation processes is essential to constrain the existing models for understanding the physical mechanism giving rise to kHz QPOs. For example, the models based on frequencies tentatively suggest some locations of kHz QPO origin. These locations could be at certain radii of the accretion disk, such as the innermost-stable-circular-orbit radius, sonic point radius, etc. (see van der Klis 2006 and references therein). However, one needs to independently verify these proposed locations. Since different energy spectral components originate from different locations, such as disk, boundary layer, corona, etc., a connection found between a kHz QPO property and a spectral component could provide this independent verification. Therefore, it is essential to study the energy dependence of kHz QPO properties.

In this paper, we study the energy dependence of the fractional rms amplitude of kHz QPOs. This property is a measure of QPO strength, and hence studying the energy-dependent kHz QPO property can be useful to probe which spectral
component primarily contributes to this timing feature. This spectral connection of kHz QPO has been discussed by some authors. For example, Méndez (2006) suggested that while the kHz QPO frequencies are plausibly determined at the disk, this feature is modulated at the high-energy spectral component (e.g., corona, boundary layer, etc.). It has been reported by several authors that the kHz QPO fractional rms amplitude increases with photon energy at lower energies, and then plausibly saturates (van der Klis 2006 and references therein; Gilfanov et al. 2003). Several authors have theoretically computed the energy dependence of rms amplitude of Comptonizing component variability (e.g., Cabanac et al. 2010; Lee & Miller 1998; Gierlinski & Zdziarski 2005; Zdziarski et al. 2005). For example, Cabanac et al. (2010) have demonstrated that oscillating hot thermal corona may give rise to an overall increase in rms variability with photon energy. However, the above-mentioned saturation at higher energies is not observationally established for many sources due to the lack of sufficient signal-to-noise ratios (S/Ns) at higher energies. For example, while the higher energy data points of Figure 10 of Gilfanov et al. (2003) are consistent with a flat fractional rms amplitude versus energy behavior, the errors of these data points are quite high.

With this motivation, we try to measure the fractional rms amplitude versus energy behavior of lower kHz QPOs with improved S/N. We combine tens of lower kHz QPOs from the neutron star LMXB 4U 1728–34, in order to improve the S/N (e.g., Ford & van der Klis 1998; Méndez & van der Klis 1999; Di Salvo et al. 2001). We choose lower kHz QPO, because this narrow QPO is more frequent and easier to detect than the relatively broad and weak upper kHz QPO. We find that the fractional rms amplitude systematically decreases with energy at higher energies. In order to understand this new finding, we compare the data with models involving a blackbody+powerlaw energy spectrum. This comparison suggests that the observed behavior of fractional rms amplitude may be reproduced with a fluctuation of the blackbody spectral component. In addition, we find that the quality factor (Q) of lower kHz QPO does not plausibly depend on energy.

In Sections 2 and 3, we describe our data analysis technique in detail and display our results, respectively. In Section 4, we describe the models and discuss which ones are favored. Finally, in Section 5, we summarize our results and give implications.

2. DATA ANALYSIS

In order to study the energy dependence of fractional rms amplitude associated with lower kHz QPOs, we retrieved all RXTE proportional counter array (PCA) pointed observational data of the source 4U 1728–34 for the period of 2000 April 13 to the end of 2009 December (∼272 ks of cleaned exposure time) corresponding to the PCA gain epoch 5. Note that gain, and hence the energy-channel conversion,1 has changed during the entire RXTE lifetime. Therefore, we restrict our analysis to the data of a single epoch in order to make the energy dependence measurement more reliable. Although even within an epoch the energy-channel conversion evolves, such changes would be negligibly small to significantly affect the final conclusion of the analysis. We choose epoch 5 because it has the largest amount of data among all the epochs. We consider only the science event files with time resolution ∼122 μs and having a continuous exposure time of at least 400 s for searching kHz QPOs. We do not apply any filtering based on energies, PCUs, Xenon layers, etc. However, following the usual practice, we filter the data based on time in order to remove thermonuclear X-ray bursts, data gaps, and observed intensity increase/decrease due to instrumental effects (especially due to start or stop of a PCU).

It has been observed that all the lower kHz QPOs (which are strong and narrow) are confined to a small portion, i.e., lower banana, of the color–color diagram (CD) of 4U 1728–34 (Di Salvo et al. 2001). This suggests that they are of the same spectral origin. The strong inter-dependence found between Q-values and frequencies (Barret et al. 2006) of lower kHz QPOs from 4U 1728–34 suggests that all the QPOs considered by us are of the same physical origin. These justify the combination of many kHz QPOs (as mentioned in Section 1).

We follow a few steps to probe the energy dependence of lower kHz QPO amplitudes. In the first step, we collect all the significant kHz QPOs from the event files (with at least 400 s of data) using a blind search. In order to do this, we compute a Leahy-normalized (Leahy et al. 1983) power density spectrum (PDS) using discrete Fourier transform (DFT)2 from each 10 s of data for a given event file (van der Klis 1989). The Nyquist frequency and frequency resolution of each such PDS (from 10 s of data) are 2048 Hz and 0.1 Hz, respectively (van der Klis 1989). Then, all (N) the PDSs from a given event file are averaged and we search for kHz QPOs in the frequency range of 400–1400 Hz in this mean PDS. In order to search effectively, several (W) adjacent frequency bins are combined. The noise powers in this PDS follow a χ² distribution with 2NW degrees of freedom (van der Klis 1989). For a putative peak, we compute the single trial probability (q) of occurrence for a peak greater than or equal to the peak power by chance from the noise power distribution. Note that we consider the peak power and do not fit the peak with a function (e.g., Lorentzian) for significance calculation. The probability q is multiplied by the number of trials (Ntrial) in order to obtain the final probability $\epsilon = q \cdot N_{\text{trial}}$. We use $N_{\text{trial}} = 20480$, i.e., the original total number of frequency bins in a mean PDS. We consider a putative peak as a kHz QPO, if $\epsilon \leq 4.65 \times 10^{-4}$ (i.e., at least 3.5σ significant). We detect tens of kHz QPOs from 4U 1728–34 using the above procedure.

In the second step, described in this paragraph, we identify the lower kHz QPOs from the QPOs detected using the above-mentioned criterion. If twin kHz QPO peaks appear in the mean PDS from an event file, then the identification of the lower kHz QPO requires no further effort. If there is only one peak for an event file, then we consider it as a lower kHz QPO, if its $Q \geq 40$. This is because the Q versus frequency diagram of 4U 1728–34 (Barret et al. 2006) clearly shows that only the lower kHz QPOs can have Q-values greater than 40, and all the upper kHz QPOs have smaller Q-values. In order to estimate the Q-values of kHz QPOs, we first use the shift-and-add technique (e.g., Méndez et al. 1998; Barret et al. 2006) within each event file considering the entire PCA energy range. This technique mostly corrects for the centroid frequency drift. Note that such uncorrected drift makes the measured Q-value smaller than the actual value. After application of shift and add, we fit each PDS containing a detected kHz QPO with a “constant + powerlaw + Lorentzian” model; the constant takes care of the Poissonian white noise, the power law takes care of the low-frequency red noise, and a Lorentzian describes the kHz QPO. We obtain the best-fit centroid frequency ($\nu$) and the best-fit full width at half-maximum (FWHM) from the Lorentzian

1 http://heasarc.gsfc.nasa.gov/docs/xte/e-c_table.html

2 DFT follows the same statistics of Leahy normalization (van der Klis 1989).
component, and compute the $Q$-value ($ν$/FWHM). Then, we identify the lower kHz QPOs using the criterion $Q \geq 40$. From the entire $\approx 272$ ks of data, 40 lower kHz QPOs (each from one event file) are identified spanning 86.32 ks of exposure time and are considered for further analysis.

These 40 lower kHz QPOs are now to be combined in order to study the energy dependence of fractional rms amplitude with improved S/N. However, before doing this, we perform a few preliminary analyses in the third step, described in this paragraph. In this step, we still use the entire PCA energy range. We consider non-overlapping 400 s segments from each of the 40 event files with a lower kHz QPO. Now, we collect only those 400 s segments, in each of which a lower kHz QPO peak with $ϵ \leq 2.7 \times 10^{-3}$ (corresponding to 3σ) exists. To calculate the $ϵ$ for a given 400 s segment, we further divide the segment into 40 segments of 10 s intervals, calculate the PDS for each 10 s interval, average these 40 PDSs, and use $N = 40$ and $N_{\text{trial}} = 10,000/W$. Note that this procedure, as well as the definitions of $ϵ$, $N$, $W$, and $N_{\text{trial}}$, is given in the third paragraph of the current section. We find 173 numbers of 400 s segments with strong lower kHz QPO peaks using the above-mentioned criterion on $ϵ$. The mean of these peaks is $ν_{\text{mean}} = 807.8$ Hz. We also calculate $ν_{\text{diff}}$, which is the separation between $ν_{\text{mean}}$ and the centroid frequency of an individual lower kHz QPO, for each 400 s segment. We use these 173 segments, $ν_{\text{mean}}$, and $ν_{\text{diff}}$ values for further analysis.

In the fourth step, described in this and the next three paragraphs, we compute lower kHz QPO fractional rms amplitudes for several chosen energy ranges after combining the data of 173 numbers of 400 s segments (see the previous paragraph). We consider a set of PCA absolute channel ranges 5–8, 9–11, 12–13, 14–15, 16–17, 18–21, 20–25, 22–25, 22–29, 24–31, 26–33, and 26–49 corresponding to the energy ranges 2.06–3.68, 3.68–4.90, 4.90–5.71, 5.71–6.53, 6.53–7.35, 7.35–8.98, 8.17–10.63, 8.98–10.63, 8.98–12.28, 9.81–13.11, 10.63–13.93, and 10.63–20.62 keV, respectively. In order to study the energy dependence of fractional rms amplitude. We do not use proportional counter unit 0 (PCU0) in this step because the energy-channel conversion for PCU0 is somewhat different from that of the other four PCUs during epoch 5. For each energy range, we compute a mean Leahy-normalized PDS (in the same way as described earlier in this section) for each of the 173 numbers of 400 s segments. Then, we shift each of the 173 lower kHz QPO peaks by $ν_{\text{diff}}$ (the value for the entire PCA energy range; see the previous paragraph) to align them at $ν_{\text{mean}}$ and add them together to obtain a grand average Leahy-normalized PDS for every energy range.

Now, the question is whether the centroid frequencies of the kHz QPOs change with energy. Such a change might affect our grand average Leahy-normalized PDS and further results. We cannot check it directly for individual kHz QPOs because the statistics are not often adequate to detect an individual kHz QPO in a small energy range. So we check it in the following way. If we consider that the centroid frequency of each of the individual kHz QPOs is energy dependent, then there are two extreme possibilities. (1) The centroid frequencies of all these kHz QPOs either increase or decrease at higher energy in a similar way. In this case, the $ν_{\text{mean}}$ value is also expected to either increase or decrease at higher energy, since we do not recalculate $ν_{\text{diff}}$ separately for each energy range. But we find that the $ν_{\text{mean}}$ value remains the same in all the energy bands (Figures 1 and 2).

(2) The centroid frequencies of some kHz QPOs increase, and those of some others decrease with the increase of energy, in such a way that all the $ν_{\text{mean}}$ values at various energy ranges remain the same. In this case, although the centroid frequency would not change, the width of the merged kHz QPOs (i.e., after applying the shift-and-add method) is expected to systematically increase, resulting in a lower and lower $Q$-value at higher and higher energies. But we find that all the measured $Q$-values are quite close to each other (within the errors) and no systematic variation is observed. The fact that both $ν_{\text{mean}}$ values and $Q$-values remain quite similar in all the energy ranges (Figures 1–3) suggests that the centroid frequencies of the kHz QPOs do not change with energy.

The shift-and-add technique to obtain a grand average Leahy-normalized PDS (mentioned above) is a standard method to improve the S/N of kHz QPOs and to correct their $Q$-value (e.g., Barret et al. 2006; Méndez 2006; Méndez et al. 1998, 2001; Méndez & van der Klis 1999; Mukherjee & Bhattacharyya 2011b). The grand average Leahy-normalized PDS for each energy range is then fitted with a “constant + powerlaw + Lorentzian” model (as before), and the fractional rms amplitude and the $Q$-value are computed from the best-fit Lorentzian parameters (see Equation (4.10) of van der Klis 1989 for a general rms amplitude formula).

In the fifth step, we correct the above-mentioned fractional rms amplitudes for the background levels. First, we compute the background count rate in each of the chosen energy ranges using the appropriate channel range of the corresponding standard-2 data files. In order to do this, we use the PCA background model file for bright sources, and the “FTOOLS” command “pcbackest.” Then, we compute the background corrected fractional rms amplitudes ($R_{\nu}$) from the uncorrected fractional rms amplitudes ($R_{\nu_{\text{ac}}}$), the total count rates ($I$), and the background count rates ($B$) using the formula $R_{\nu} = R_{\nu_{\text{ac}}} \times I/(I - B)$ (Muno et al. 2002).

Apart from the energy dependence of fractional rms amplitude, we estimate how the $Q$-value of the lower kHz QPO depends on energy. This is computed from the above-mentioned fitting of the grand average Leahy-normalized PDS for each energy range. The ratio of the best-fit centroid frequency to the best-fit FWHM of the Lorentzian model component gives the $Q$-value. Here, we note that while the shift-and-add technique corrects for a large error in $Q$-value due to the centroid frequency drift, this technique also introduces a small error in $Q$-value, because the centroid frequency is shifted without changing the FWHM.

3. RESULTS

The frequencies of the 173 detected lower kHz QPOs, which are used to study the energy dependence of the fractional rms amplitude (Section 2), span the range of 669.4–912.5 Hz (mean $ν_{\text{mean}} = 807.8$ Hz; median = 810.2 Hz; and standard deviation = 57.8 Hz). In Figures 1 and 2, the grand average Leahy-normalized PDSs (see Section 2) for 12 energy ranges are shown in 12 panels. Each panel is for the same exposure time, we estimate how the fractional rms amplitudes ($R_{\nu}$), the total count rates ($I$), and the background count rates ($B$) using the formula $R_{\nu} = R_{\nu_{\text{ac}}} \times I/(I - B)$ (Muno et al. 2002).

Apart from the energy dependence of fractional rms amplitude, we estimate how the $Q$-value of the lower kHz QPO depends on energy. This is computed from the above-mentioned fitting of the grand average Leahy-normalized PDS for each energy range. The ratio of the best-fit centroid frequency to the best-fit FWHM of the Lorentzian model component gives the $Q$-value. Here, we note that while the shift-and-add technique corrects for a large error in $Q$-value due to the centroid frequency drift, this technique also introduces a small error in $Q$-value, because the centroid frequency is shifted without changing the FWHM.

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In Figure 3, we plot background corrected fractional rms amplitude versus energy. The amplitude increases with energy at lower energies, and systematically decreases (seen from the

3 http://heasarc.gsfc.nasa.gov/docs/xte/e-c_table.html
Figure 1. Leahy-normalized power density spectra (PDSs, with 1σ errors) of 4U 1728–34 after using the shift-and-add technique for each of the energy ranges 2.06–3.68 keV (panel (a)), 3.68–4.90 keV (panel (b)), 4.90–5.71 keV (panel (c)), 5.71–6.53 keV (panel (d)), 6.53–7.35 keV (panel (e)), and 7.35–8.98 keV (panel (f); see Section 2). In each panel, the average total count rate (i.e., without background subtraction) used to compute the PDS is denoted with “total,” the average background count rate is denoted with “bkg,” and the PCA absolute channel range is denoted with “Ch.” Furthermore, the frequency resolution and exposure in each panel are 3.2 Hz and 69.2 ks, respectively. A lower kHz QPO peak is clearly seen in each panel. The best-fit “constant + powerlaw + Lorentzian” model for each energy range is shown with a red curve (Section 2). The fractional rms amplitude and the Q-value of the lower kHz QPO in each energy range are obtained from the Lorentzian model component (Sections 2 and 3).

(A color version of this figure is available in the online journal.)
Figure 2. Same as Figure 1, but for the energy ranges 8.17–10.63 keV (panel (a)), 8.98–10.63 keV (panel (b)), 8.98–12.28 keV (panel (c)), 9.81–13.11 keV (panel (d)), 10.63–13.93 keV (panel (e)), and 10.63–20.62 keV (panel (f); see Section 2). In panels (d)–(f), the lower kHz QPO peak is not clearly seen, and hence the best-fit model curves in these panels are marked with a different color (blue). For each of these three energy ranges, an upper limit to the lower kHz QPO fractional rms amplitude is computed (see Section 3).

(A color version of this figure is available in the online journal.)
not significantly depend on energy (see Sections 2 and 3).

8.98–12.28 keV (Figure 2, panel (c)). This panel shows that the rms amplitude clearly and gradually decreases from 8.98–10.63 keV (Figure 2, panel (b)), 8.98–10.63 keV (Figure 2, panel (d)), 6.53–7.35 keV (Figure 1, panel (e)), 7.35–8.98 keV (Figure 1, panel (f)), 9.81–13.11 keV (Figure 2, panel (d)), and 10.63–20.62 keV (Figure 2, panel (f)). This panel shows that the rms amplitude clearly and gradually decreases at higher energies. Lower panel: Q-value (corrected for frequency drift with shift-and-add technique for 400 s segments; with 1σ error) vs. energy with ranges 2.06–3.68 keV (Figure 1, panel (a)), 3.68–4.90 keV (Figure 1, panel (b)), 4.90–5.71 keV (Figure 1, panel (c)), 5.71–6.53 keV (Figure 1, panel (d)), 6.53–7.35 keV (Figure 1, panel (e)), 7.35–8.98 keV (Figure 1, panel (f)), 8.17–10.63 keV (Figure 2, panel (a)), 8.98–12.28 keV (Figure 2, panel (c)), 9.81–13.11 keV (Figure 2, panel (d)), and 10.63–20.62 keV (Figure 2, panel (f)). This panel shows that the rms amplitude clearly and gradually decreases at higher energies. Lower panel: Q-value (corrected for frequency drift with shift-and-add technique for 400 s segments; with 1σ error) vs. energy with ranges 2.06–3.68 keV (Figure 1, panel (a)), 3.68–4.90 keV (Figure 1, panel (b)), 4.90–5.71 keV (Figure 1, panel (c)), 5.71–6.53 keV (Figure 1, panel (d)), 6.53–7.35 keV (Figure 1, panel (e)), 7.35–8.98 keV (Figure 1, panel (f)), 8.17–10.63 keV (Figure 2, panel (a)), 8.98–10.63 keV (Figure 2, panel (b)), 8.98–12.28 keV (Figure 2, panel (c)), 9.81–13.11 keV (Figure 2, panel (d)), and 10.63–20.62 keV (Figure 2, panel (f)). This panel shows that the rms amplitude clearly and gradually decreases at higher energies. Lower panel: Q-value (corrected for frequency drift with shift-and-add technique for 400 s segments; with 1σ error) vs. energy with ranges 2.06–3.68 keV (Figure 1, panel (a)), 3.68–4.90 keV (Figure 1, panel (b)), 4.90–5.71 keV (Figure 1, panel (c)), 5.71–6.53 keV (Figure 1, panel (d)), 6.53–7.35 keV (Figure 1, panel (e)), 7.35–8.98 keV (Figure 1, panel (f)), 8.17–10.63 keV (Figure 2, panel (a)), 8.98–12.28 keV (Figure 2, panel (c)).

Figure 3. Energy dependence of the background corrected fractional rms amplitude and the Q-value of the lower kHz QPO from 4U 1728–34. In each panel, solid horizontal lines denote a set of energy ranges which are mutually non-overlapping, and energy ranges denoted with dotted horizontal lines overlap with some ranges denoted with solid lines. Upper panel: rms amplitude (with 1σ error or 1σ upper limit) vs. energy with ranges 2.06–3.68 keV (Figure 1, panel (a)), 3.68–4.90 keV (Figure 1, panel (b)), 4.90–5.71 keV (Figure 1, panel (c)), 5.71–6.53 keV (Figure 1, panel (d)), 6.53–7.35 keV (Figure 1, panel (e)), 7.35–8.98 keV (Figure 1, panel (f)), 8.17–10.63 keV (Figure 2, panel (a)), 8.98–10.63 keV (Figure 2, panel (b)), 8.98–12.28 keV (Figure 2, panel (c)), 9.81–13.11 keV (Figure 2, panel (d)), and 10.63–20.62 keV (Figure 2, panel (f)). This panel shows that the rms amplitude clearly and gradually decreases at higher energies. Lower panel: Q-value (corrected for frequency drift with shift-and-add technique for 400 s segments; with 1σ error) vs. energy with ranges 2.06–3.68 keV (Figure 1, panel (a)), 3.68–4.90 keV (Figure 1, panel (b)), 4.90–5.71 keV (Figure 1, panel (c)), 5.71–6.53 keV (Figure 1, panel (d)), 6.53–7.35 keV (Figure 1, panel (e)), 7.35–8.98 keV (Figure 1, panel (f)), 8.17–10.63 keV (Figure 2, panel (a)), 8.98–10.63 keV (Figure 2, panel (b)), 8.98–12.28 keV (Figure 2, panel (c)).

807.8 Hz, this FWHM of this peak remains the same. Given that the standard deviation of the centroid frequency distribution of our detected lower kHz QPOs is 57.8 Hz and ν\_\text{mean} = 807.8 Hz, this error can be estimated to be ∼7% of the typical value of Q = 80. Therefore, this error is small compared to the 1σ error (which is typically ∼25%–45%) from Lorentzian fitting of the QPO peaks. Therefore, the error due to frequency shift does not change our conclusion regarding the energy independence of Q-values, and hence we do not make an attempt to correct it.

4. COMPARISON WITH MODELS

This paper shows a prominent and systematic decrease of the lower kHz QPO fractional rms amplitude at higher energies for the first time to the best of our knowledge. We therefore try to find out if such a decrease is at all theoretically expected. For example, could certain parameter values of the usual energy spectra of neutron star LMXBs explain it qualitatively? Before testing this, let us briefly mention the X-ray components of these sources, as we understand currently. Neutron star LMXBs are believed to have two primary X-ray emitting regions, an accretion disk and a boundary layer. Both these regions are expected to be optically thick, and therefore to emit blackbody radiation. Furthermore, one (or more) of these components may be covered with a corona (coronae). Such a corona may reprocess (Comptonize) the blackbody photons. The amount of reprocessing depends on the optical depth of the corona, as well as the extent of coverage (e.g., full versus partial). As
a result, the observed spectrum either from the disk and/or the boundary layer can be a blackbody, or Comptonized, or a sum of both. Observationally, however, no spectral model usually uniquely describes the data. Moreover, it is not usually clear, where various components of a given model originate from. Therefore, although many works over a few decades (e.g., Mitsuda et al. 1989; Mitsuda & Dotani 1989; White et al. 1988; Church & Balucinska-Church 2001; Christian & Swank 1997; Maccarone & Coppi 2003; Maitra & Bailyn 2004; Gilfanov et al. 2003; Olive et al. 2003; Wijnands 2001; Barret 2001; Lin et al. 2007, 2010; Mukherjee & Bhattacharyya 2011a) support the general understanding mentioned above, the details are still unknown.

In order to have a basic understanding (i.e., as much as possible independent of detailed models) of the lower kHz QPO fractional rms amplitude versus energy behavior we found, we choose the simplest two-component spectral model, which is based on the above-mentioned description of X-ray components. This is a blackbody+powerlaw model in which the power law usually represents the Comptonized component. This is a blackbody+powerlaw model in which we find that not only do both the models give acceptable fits, but the power-law component represents the Comptonization component reasonably well, as verified from the respective fluxes and spectral component curves. This indicates that a blackbody+powerlaw model is appropriate for the 4U 1728–34 spectra.

Before describing our model, here we mention and discuss the assumptions involved in our modeling and interpretation, some of them recapitulated from the data analysis side and some other extra assumptions from the model side. (1) We assume that the spread in energy spectra (e.g., soft colors and hard colors in a CD; van der Klis 2006) and in intensity from our data files containing lower kHz QPOs do not significantly affect the robustness of the energy behavior of the fractional rms amplitude reported by us (Figure 3). This is justified because of the following reasons. (i) All the QPOs (which are strong and narrow) we considered are confined to a small portion, i.e., lower banana, of the CD of 4U 1728–34 (Di Salvo et al. 2001), as mentioned in Section 2. (ii) Given the small fractional rms amplitudes (~5%–14%) of lower kHz QPOs in the 2–16 keV energy range, which is used to compute the CD and hardness-intensity diagram, the entire X-ray energy spectrum does not contribute to these QPOs. Hence, a small spread in CD does not necessarily indicate different physical origins different lower kHz QPOs. (iii) The strong inter-dependence found between $Q$-values and frequencies of lower kHz QPOs from 4U 1728–34 (along with several other atom sources; Barret et al. 2006) suggests that all the QPOs considered by us are of the same physical origin. These support the robustness of our reported rms–energy behavior. (2) We assume that the energy dependence of lower kHz QPOs does not change with frequency. This may be a reasonable assumption, because these QPOs with different frequencies are likely to have originated from the same physical process. (3) Our model considers the sinusoidal fluctuation of a single parameter of the above-mentioned blackbody+powerlaw model. The sinusoidal fluctuation is somewhat justified, because according to some models, the original oscillations are sinusoidal, and the broadening happens because of a decoherence mechanism (say, damping; van der Klis 2006 and references therein). Here, we note that a sinusoidal signal was also assumed by Lee & Miller (1998). We further note that even if the intrinsic oscillations of lower kHz QPOs are a sum of many sinusoids originated separately, our modeling will still be useful to connect a spectral component to these QPOs. (4) Our model does not involve any response matrix. Although application of a response matrix may slightly change the model rms–energy curves quantitatively, the qualitative nature of these curves should not change.

Now, we describe our model. As previously mentioned, the total time-averaged flux (say, $(S(E), t)$; $E$: photon energy, $t$: time) of the source can be well fitted with a combination of blackbody ($S_{BB}$) and power law ($S_{PL}$). Each blackbody and power law has two parameters: normalization ($N_{BB}$) and temperature ($T_{BB}$) for the former, and normalization ($N_{PL}$) and photon index ($\alpha_{PL}$) for the latter. We try to investigate if sinusoidal fluctuation in one of these parameters (while keeping the other three parameters non-fluctuating) can reproduce the observed fractional rms amplitude versus energy behavior. Here, as an example, we consider the case of fluctuating blackbody temperature:

$$N_{BB} \times (S(E), t) = N_{BB} \times [S_{BB}(E, N_{BB}, T_{BB}(t)) + S_{PL}(E, N_{PL}, \alpha_{PL})]$$

where, $T_{BB}(t) = T_{BB0} + T_{BB1}\sin(\omega t)$

$$N_{BB} \times (S(E), t) = N_{BB} \times [S_{BB}(E, N_{BB}, (T_{BB0} + T_{BB1}\sin(\omega t))) + S_{PL}(E, N_{PL}, \alpha_{PL})]$$

$$N_{BB} \times \sigma_{S} = N_{BB} \times \sqrt{(\langle S(E, t)^2 \rangle - \langle S(E, t) \rangle^2)}$$

$$\text{fracRMS} = \frac{\sigma_{S}}{N_{BB} \times \langle S(E, t) \rangle} = \frac{\sqrt{(\langle S(E, t)^2 \rangle - \langle S(E, t) \rangle^2)}}{\langle S(E, t) \rangle}$$

which is independent of $N_{BB}$ (neutral hydrogen column density). Here, fracRMS is our model fractional rms amplitude. Similarly, we compute the model fractional rms amplitude in each case when any one of the other three parameters varies sinusoidally in time.

We note that the blackbody flux and the power-law flux are nonlinear functions of $T_{BB}$ and $\alpha_{PL}$, respectively. Therefore, if $T_{BB}$ (or $\alpha_{PL}$) fluctuates sinusoidally (as we assume), the variation of the blackbody flux (or power-law flux) will not be strictly sinusoidal, and will contain higher harmonics. Here, we show that this flux variation is sinusoidal (which we assume in our modeling) when $T_{BB}$ (or $\alpha_{PL}$) fluctuation is small (e.g., $T_{BB1} \ll T_{BB0}$, for the varying blackbody temperature), and is therefore considered up to the first order:

$$\langle S(E, t) \rangle = \langle S_{BB}(E, N_{BB}, (T_{BB0} + T_{BB1}\sin(\omega t))) \rangle + \langle S_{PL}(E, N_{PL}, \alpha_{PL}) \rangle$$

$$= \langle S_{BB}(E, N_{BB}, T_{BB0}) \rangle + \langle S_{BB1}(E, N_{BB}, T_{BB0}, T_{BB1}\sin(\omega t)) \rangle$$

$$+ O \left[ \frac{T_{BB1}}{T_{BB0}} \right]^2 + \langle S_{PL}(E, N_{PL}, \alpha_{PL}) \rangle$$

$$= S_{BB}(E, N_{BB}, T_{BB0}) + S_{PL}(E, N_{PL}, \alpha_{PL})$$

(which is correct up to the first order in $[T_{BB1}/T_{BB0}]$).

The last step is justified because the observations are several orders of magnitudes longer than the oscillation period $T = 2\pi/\omega$. 

\[7\]
shows that blackbody temperature fluctuation could reproduce the observed energy dependence of the lower kHz QPO fractional rms amplitude (Section 4). (A color version of this figure is available in the online journal.)

The sum of $N$ parameters: the blackbody or normalization of powerlaw varies. The first-order approximation is not required when normalization of $N$ is used to fit the time-averaged spectrum. Finally, note that this parameter values, in order to thoroughly explore if some curves for a given case can reasonably describe the data. We show some examples of these model curves in Figures 5–8. In each figure appears to be the closest to the data among our computed model curves. These figures show that the sinusoidal oscillation of a blackbody parameter describes the data well, and hence the observed energy dependence of the fractional rms amplitude is expected. We note that testing this was the main aim of modeling reported in this paper, as mentioned in the first paragraph of this section. Figures 5–8 also suggest that the blackbody temperature fluctuation could reproduce the observed energy dependence of the lower kHz QPO fractional rms amplitude (Section 4).

5. DISCUSSION

In this paper, we report the decrease of fractional rms amplitude of lower kHz QPOs at higher energies for the first time to the best of our knowledge. As the count rate of neutron star LMXBs decreases at higher energies, it is difficult to reliably measure the fractional rms amplitude with RXTE PCA (the only instrument capable of detecting kHz QPOs) due to the lack of sufficient S/N. Sometimes because of this, the previous studies, to the best of our knowledge, have concluded that the fractional rms amplitude either goes on increasing with energies or first increases and then saturates. In order to improve the S/N, we combine tens of lower kHz QPOs from 4U 1728–34, and also use the standard shift-and-add technique (Section 2). The net count rate of our highest energy range (10.63–20.62 keV) is also larger than that in some other energy ranges. Since the 10.63–20.62 keV range does not have any clear kHz QPO peak, the decrease of fractional rms amplitude at higher energies should be real, and not a result of low S/N (see Figures 1 and 2). Note that the small uncertainties in the channel-energy conversion cannot make the lower kHz QPO disappear at higher energies, and hence cannot produce the decrease. Moreover, the gradual and
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Figure 6. Similar to Figure 5, but the curves are models for sinusoidal fluctuation of the blackbody normalization (see Section 4). The parameter ($N_{\text{PL}}, \alpha_{\text{PL}}, N_{\text{BB}}, T_{\text{BB}},$ and $A$) values for various model curves are as follows in the same sequence (for units see Section 4). 1: [3.69, 2.79, 10.37, 1.42, 0.9]; 2: [0.5, 3.5, 13.8, 1.11, 0.2]; 3: [0.5, 3.5, 13.8, 1.11, 0.5]; 4: [0.5, 3.5, 12.4, 3.0, 0.1]; 5: [0.5, 3.5, 50.0, 3.0, 0.05]; 6: [10.0, 1.5, 10.0, 2.0, 0.1]; 7: [10.0, 3.5, 10.0, 1.0, 0.1]; 8: [0.5, 2.0, 10.0, 1.5, 0.1]; 9: [50.0, 3.5, 50.0, 3.0, 0.25]. The blue dashed curve (curve 1) appears to be the closest to the data among our computed model curves for blackbody normalization fluctuation (see Section 4). This figure shows that blackbody normalization fluctuation could reproduce the observed energy dependence of the lower kHz QPO fractional rms amplitude, although for a high value of $A$ (Section 4).

(A color version of this figure is available in the online journal.)

Figure 7. Similar to Figure 5, but the curves are models for sinusoidal fluctuation of the power-law index (see Section 4). The parameter ($N_{\text{PL}}, \alpha_{\text{PL}}, N_{\text{BB}}, T_{\text{BB}},$ and $A$) values for various model curves are as follows in the same sequence (for units see Section 4). 1: [18.55, 3.5, 2.07, 3.0, 0.027]; 2: [45.0, 3.5, 5.0, 2.5, 0.03]; 3: [45.0, 3.5, 5.0, 2.0, 0.03]; 4: [45.0, 3.5, 5.0, 1.0, 0.03]; 5: [45.0, 3.5, 50.0, 3.0, 0.03]; 6: [45.0, 3.5, 50.0, 2.0, 0.03]; 7: [10.0, 3.5, 5.0, 3.0, 0.03]; 8: [10.0, 2.0, 10.0, 1.5, 0.001]; 9: [10.0, 2.0, 10.0, 1.5, 0.1]. The blue dashed curve (curve 1) appears to be the closest to the data among our computed model curves for power-law index fluctuation (see Section 4). This figure shows that power-law index fluctuation plausibly could not reproduce the observed energy dependence of the lower kHz QPO fractional rms amplitude (see Section 4).

(A color version of this figure is available in the online journal.)

systematic change of fractional rms amplitude at higher energies for overlapping energy ranges (Figures 1–3) strongly supports the decrease of this amplitude of lower kHz QPOs.

The energy dependence of fractional rms amplitude can be very useful to probe the physical origin of kHz QPOs (see Section 1), and hence our finding is important. Therefore, we use a two-component (blackbody+powerlaw) spectral model to gain insights (see Section 4 for details). We explore the shape and fractional rms amplitude values of many model curves, examples of which have been shown in Figures 5–8. These curves suggest that (1) the reported energy behavior of the lower kHz QPO fractional rms amplitude can be explained with simple models and (2) it is likely that the fluctuation in a blackbody-like component primarily causes the lower kHz QPOs. However, we consider the fluctuation of only one model parameter at a time (Section 4), and hence we cannot study
the effects of a simultaneous fluctuation of the two power-law parameters. We also note that the non-dependence of the Q-value on energy (Section 2) may imply that the lifetime of the oscillations is independent of photon energies. This may suggest that the lower kHz QPOs in various energy ranges originate from the same location, and hence from the same spectral component. But we cannot constrain the location of either the blackbody or the power-law component from our study. The blackbody could originate either from the boundary layer or the disk (Tarana et al. 2011). Similarly, the corona, which plausibly gives rise to the powerlaw, could be centrally located near the neutron star or a cover on the accretion disk.

With our new finding, an important question to ask would be whether the fractional rms amplitude of lower kHz QPOs decreases with energy (at higher energies) for other neutron star LMXBs as well. Gilfanov et al. (2003) reported that 4U 1608–52 did not show any decrease in fractional rms amplitudes at energies as high as 20 keV, although at the high-energy end the error in fractional rms amplitude was quite high. A larger (than PCA) area at higher energies may be required (1) to detect a plausible decrease which happens at higher energies than that for 4U 1728–34 and (2) to reduce the errors in fractional rms amplitudes, while increasing the number of data points, in order to perform a better modeling. The upcoming space missions (e.g., ASTROSAT) having sufficient time resolution and much higher (than PCA) area in 20–50 keV will be useful for this purpose.

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Figure 8. Similar to Figure 5, but the curves are models for sinusoidal fluctuation of the power-law normalization (see Section 4). The parameter (N_{PL}, \alpha_{PL}, N_{BB}, T_{BB}, and A) values for various model curves are as follows in the same sequence (for units see Section 4). 1: [0.5, 3.5, 50.0, 0.52, 0.117]; 2: [10.0, 2.0, 10.0, 1.5, 0.02]; 3: [10.0, 3.5, 10.0, 1.5, 0.2]; 4: [10.0, 2.0, 50.0, 1.5, 0.2]; 5: [50.0, 3.5, 50.0, 3.0, 0.2]; 6: [0.5, 3.5, 0.5, 2.0, 0.2]; 7: [0.5, 3.5, 50.0, 1.5, 0.12]; 8: [0.5, 3.5, 50.0, 0.5, 0.3]. The blue dashed curve (curve 1) appears to be the closest to the data among our computed model curves for power-law normalization fluctuation (see Section 4). This figure shows that power-law normalization fluctuation plausibly could not reproduce the observed energy dependence of the lower kHz QPO fractional rms amplitude (see Section 4).

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