Abstract We take the recently published data of twin kHz quasi-period oscillations (QPOs) in neutron star (NS) low-mass X-ray binaries (LMXBs) as the samples, and investigate the morphology of the samples, which focuses on the quality factor, peak frequency of kHz QPOs, and try to infer their physical mechanism. We notice that: (1) The quality factors of upper kHz QPOs are low (2 ∼ 20 in general) and increase with the kHz QPO peak frequencies for both Z and Atoll sources. (2) The distribution of quality factor versus frequency for the lower kHz QPOs are quite different between Z and Atoll sources. For most Z source samples, the quality factors of lower kHz QPOs are low (usually lower than 15) and rise steadily with the peak frequencies except for Sco X-1, which drop abruptly at the frequency of about 750 Hz. While for most Atoll sources, the quality factors of lower kHz QPOs are very high (from 2 to 200) and usually have a rising part, a maximum and an abrupt drop. (3) There are three Atoll sources (4U 1728-34, 4U 1636-53 and 4U 1608-52) of displaying very high quality factors for lower kHz QPOs. These three sources have been detected with the spin frequencies and sidebands, in which the source with higher spin frequency presents higher quality factor of lower kHz QPOs and lower difference between sideband frequency and lower kHz QPO frequency.

Keywords accretion: accretion disks–stars:neutron–binaries: close–X-rays: stars–pulsar

1 Introduction

The kilohertz quasi-periodic oscillations in neutron star X-ray binaries were discovered just two months after the launch of Rossi X-ray Timing Explorer (RXTE) in Sco X-1 (van der Klis et al. 1996a,b,c) and 4U 1728-34 (Strohmayer et al. 1996a,b,c). The former is a bright Z source, while the latter is an Atoll source. In general, Z sources produce the Z-shaped paths in CCDs or hardness-intensity diagram (HID) on timescales of a few hours to days, with three branches, from hard to soft: horizontal branch (HB), normal branch (NB), and flaring branch (FB). Z sources are objects with high luminosity (0.5 ∼ 1.5LEdd)(van der Klis 2006) and mildly high magnetic field (Miller et al. 1998; Campina 2000; Zhang 2007). The Atoll sources, with low luminosity (∼ 0.001 − 0.2LEdd)(van der Klis 2006) and inferred weaker magnetic field (Miller et al. 1998; Campina 2000; Zhang 2007), show a hard, low-luminosity, fuzzy island state (IS) and a soft, high-luminosity "banana" shaped structure on a timescale of weeks (Hasinger et al. 1989; Hasinger 1990; van der Klis 2000, 2006). They trace a U-shaped or a C-shaped track as the sources spectrum evolves between the island and the banana (Gladstone et al. 2007).

These kHz QPOs in LMXBs are peaks with some width in their power density spectra (PDS), and their profiles can be described by the Lorentzian Function

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Most kHz QPO signals usually occur in twins. The centroid frequencies (or peak frequency, i.e. upper $\nu_2$ and lower $\nu_1$ frequency) changes with accretion rate. Each peak has a corresponding quality factor (i.e. upper Q) and the fractional root-mean-squared (rms, which represents a measure of the signal strength and is proportional to the square root of the peak power contribution to the PSD). The quality factor characterizes the coherence of a QPO signal, and its value is related to the lifetime of the signal.

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Therefore, the kHz QPOs can be characterized by three characteristic quantities, i.e., $\nu_0$, quality factor (Q) and the maximum amplitude and coherence of kHz QPOs for a characteristic quantities, i.e., Q $\equiv \frac{\nu_0}{w}$. The implications are discussed in section 3. Section 4 contains the summary.

2 Contrastive Analysis for the Coherence of kHz QPOs

We put the twelve sources together and investigate the relations for kHz QPOs, and the ranges of Q are also different. The Q changes with Q $\nu$ very differently for upper and lower kHz QPOs, and the ranges of Q are also different.

For the upper kHz QPOs (see the left panel of Fig. 1), most data points of $Q_2$ locate in the range with low values, i.e. $Q_2 \sim 2 - 20$ and $\nu_2 \sim 450 - 1200$ Hz. It can be seen that most sources follow the steadily rising track in the $Q_2 - \nu_2$ plot. At the frequency of $\nu_2 \sim 1050 Hz$, a transition presents for 4U 1728-34, i.e. $Q_2$ begins to drop with $\nu_2$. The $Q_2$ of XTE J1701-462 in Z phase present very large errors, clustering in a very narrow range of frequency. As far as the profiles of lower kHz QPOs, It displays two different trajectories in the $Q_1 - \nu_1$ plot (see the right panel of Fig. 1). The data points of Z sources follow the steadily rising tendency with low values of $Q_1$ ($Q_1 \sim 2 - 20$), and $\nu_1$ covers a wide range of frequency ($\nu_1 \sim 150 - 825$ Hz). However, most $Q_1$ for Atoll sources increase with $\nu_1$ to a maximum and abruptly drop. The $Q_1$ can be very high and vary from 2 to 200.

In section 2, we make a contrastive investigation for the quality factor as a function of kHz QPO peak frequency.
The centroid frequencies for these sources cover a relatively narrow range \( \sim 550 - 950 \) Hz. Moreover, despite of the similar tendency, different sources show their own “substructures” in different regions in \( Q_1 - \nu_1 \) diagram, which we will discuss in detail in the following.

On the whole, the Q-factors of lower kHz QPOs for Atoll sources are about 10 times higher than that for Z sources for the same frequency.

2.2 The \( Q - \nu \) Correlations for Z Sources

Two plots in Fig. 2 present the regular and steady tendency, formed by five Z sources and the Z phase of XTE 1701-462. It can be found that the \( Q - \nu \) tracks of Z sources are similar between upper and lower kHz QPOs. For a close inspection, we find that different sources lie in different regions in the \( Q - \nu \) plots, and it can be divided into two regions by the range of frequency for both upper and lower kHz QPOs. One contains GX 5-1 and GX 340+0, with low \( Q \) and \( \nu \). The other includes Sco X-1 and GX 17+2, which presents relatively high \( Q \) and \( \nu \).

The detected \( \nu_1 \) and \( \nu_2 \) for GX 5-1 range from \( 156 \pm 23 \) Hz to \( 627 +23_{-16} \) Hz and from \( 478 \pm 15 \) to \( 866 \pm 23 \) Hz, respectively (Jonker et al. 2002). For GX 340+0, \( \nu_1 \) and \( \nu_2 \) increase from \( 197 \pm 26 \) Hz to \( 565 +9_{-14} \) Hz and from \( 535 \pm 38 \) Hz to \( 840 \pm 21 \) Hz, respectively (Jonker et al. 2000a,b). These two sources form the lower region in both \( Q_1 - \nu_1 \) and \( Q_2 - \nu_2 \) plots. The real maximum may larger than the largest measured value; in fact, the maximum can be at most \( \sim 20\% \) higher than the values we used (Mendez 2006), so it seems that the real maxima are too different from the largest values we used in Fig. 2. The same is true for \( Q_{\text{max}} \) and \( \nu_{\text{max}} \) of other sources. The \( \nu_2 \) and \( \nu_1 \) in the other region (including Sco X-1 and GX 17+2) are \( \nu_2 \sim 850 - 1150 \) Hz and \( \nu_1 \sim 500 - 800 \) Hz (Homan et al. 2002, van der Klis et al. 1997). In addition, Cyg X-2 covers almost the whole range of \( Q_2 \) and \( \nu_2 \) that the others cover, but a very narrow range for both \( Q_1 \) and \( \nu_1 \). Because there are just three measurements of \( Q_1 \) for this source, it is difficult to infer any implication.

XTE J1701-462 presents the link between “Z-track”, “\( \nu \)-track” and Atoll behavior in its CCD and HID (Homan et al. 2006a,b, 2007; Lin et al. 2009; Homan et al. 2010). Both upper and lower QPOs were detected in Z phase (Sanna et al. 2010). The Z phase of XTE J1701-462 presents quite large errors for both \( Q_1 \) and \( Q_2 \), and the frequencies cover the narrow range. The \( Q_2 \) are higher than \( Q_1 \) for this source, which is different with that of the other Z sources. We think the transition between Atoll and Z state of XTE J1701-462 may link to the accretion rate. When the companion is near periastron, the neutron star may have higher accretion rate, its magnetosphere will compress and show a higher magnetic field, then the system shows Z state. On the contrary, when the companion is near apastron, the neutron star may have lower accretion rate, the magnetosphere will expand and show a lower magnetic field, then the system shows Atoll state. But it needs more observational and theoretical investigation.

It is noticed that most data points follow an increasing trend in \( Q_1 - \nu_1 \) diagram (see the right panel of Fig. 2), but an abrupt drop occurs for Sco X-1 at about 750 Hz. Zhang et al. investigated the correlation between upper and lower kHz QPOs in a statistical way (Zhang et al. 2006). They found the power law correlation can fit the data much better than other correlations, e.g. linear relation and constant relation. At the same time, they also found that the power law index shows a turn-over frequency at about \( \nu_2 = 840 \) Hz in \( \nu_2 \) vs. \( \nu_1 \) plot of Z source, which is analogical with the abrupt drop in \( Q_1 \) vs. \( \nu_1 \) plot of Sco X-1. But, we are not sure whether it results from the physical process or from the data itself. If it is a physical reason, it implies that the boundary of the accretion disk and magnetosphere, at where the kHz QPOs are assumed to emit this particular frequency, may occur a physical transition. From the Alfvén wave model for kHz QPOs (Zhang 2004), the disk radius of emitting this particular frequency is about 20 km, or 5 km away from the stellar surface for the star parameters of 15 km and one solar mass (Zhang et al. 2010).

2.3 The \( Q - \nu \) Correlations for Atoll Sources

From the left panel of Fig. 3 it is seen that most \( Q_2 \) increases with \( \nu_2 \) steadily, only the source 4U 1728-34 shows an explicit drop at about \( \nu_2 \sim 1090.4 \) Hz with a maximum of \( Q_2 = 14.4 \pm 3 \). The Kepler orbital radius corresponding to 1090.4 Hz is about \( \sim 17 \) km for a NS of 1.4 solar mass. Thus, the position of turnover frequency is close to the innermost boundary of the accretion disk and it may reflect the corresponding physical process there. The innermost stable circular orbit (ISCO) of a NS with mass of 1.4 solar mass is \( \sim 12.6 \) km, which is the same order as the theoretical radius of NS. We do not know the actual NS mass of 4U 1728-34, so we are not sure whether the ISCO is larger than the star radius. We think that, no matter in which case, the accretion matter may drop because of entering the ISCO boundary or impact onto the surface of the star, and then the system may show an abrupt drop of Q factor. However, the right panel of Fig. 3 presents a very different scenario. Almost all sources display rising, maximum and dropping tendency in the
Fig. 1 Plots for $Q - \nu$ relations of kHz QPOs. The left panel is the $Q - \nu$ relations for upper kHz QPOs, and the right one is that for lower kHz QPOs. The meanings of different symbols are listed in the diagrams.

$Q_1 - \nu_1$ diagram. Five sources (4U 1608-52, 4U 1636-53, 4U 1728-34, 4U 1820-30 and 4U 1735-44) present obvious dropping tendency after the maximum $Q_1$. The maximums are different for each source. 4U 1608-52, 4U 1636-53, 4U 1728-34 present higher $Q_1$. (The detected maxima are 247.0±16.0, 248.0±18.0, and 188.0±18.0, respectively) with wider $\nu_1$ ranges. The narrowest $\nu_1$ range of 4U 1735-44 is from 642 to 821 Hz. There is also a gap of $\nu_1$ (between 613 and 673 Hz) in 4U 1820-30.

The $Q_1$ of Aql X-1 are high and cover a very narrow range (151.1±13.2 – 193.8±22.2), and so does that of the peak frequency (696.1±0.15 – 890.7±0.37 Hz). It seems that the kHz QPO frequencies just are detected at the inflexion of $Q_1 - \nu_1$ track. The $Q_1$ for 4U 0614+09 are relatively low and irregular with large errors, and the maximum is 43.12±16.45 at $\nu_1 = 418.3\pm1.8$ Hz. The points which are higher than $Q_1 = 30$ presents very large error bars, and most of the $Q_1$ are lower than 30. For the Atoll phase of XTE J1701-462, we use the data from the paper by (Sanna et al. 2010) for our plot. It is found that the maximum $Q_1$ is 150.3±20.9 at 811.5±6.6 Hz, and above this frequency the $Q_1$ values begin to drop.

3 Discussions

3.1 Relations between $Q - \nu$ Tracks and CCDs Tracks for Z Sources

In spite of some similar respects (Stella 1986), the tracks in CCDs and HIDs for Z sources, by secular timing inspection, can be divided into two types according to qualitative differences (Kuulkers et al. 1994), i.e. Cyg-like sources (Cyg X-2, GX 5-1 and GX 340+0) and Sco-like sources (Sco X-1 and GX 17+2)(Hasinger et al. 1989, Hasinger 1990). Recently, it is claimed that the Cyg-like sources follow a ”Z-track” in CCDs which have a long horizontal branch and form a ”Z” profile, while the Sco-like sources present a ”$\nu$-track” which have a short horizontal branch and form a ”$\nu$” profile (Homan et al. 2007). According to the recent data obtained with PCA on board RXTE, the five typical sources (Cyg X-2, GX 5-1, GX 340+0, Sco X-1 and GX 17+2) can be divided into two subclasses. Cyg X-2, GX 5-1, and GX 340+0 present ”Z-track” (Jonker et al. 2000a, 2002, Wijnands et al. 1998). Besides, GX 17+2 and Sco X-1 exhibit ”$\nu$-track” with not well defined HB/NB vertex, since the HB is almost a continuation of the NB (Homan et al. 2002). The kHz QPOs are detected on the vertex of HB/NB and the upper NB. It is claimed that the properties of kHz QPOs closely related to the position of the sources on the Z track traced out in CCDs, and the frequencies of kHz QPOs increase from the left of HB to NB/FB vertex (Wijnands et al. 1997).

It seems that the division between Sco-like and Cyg-like sources can be in terms of frequency for kHz QPOs. The Cyg-like sources present much longer HB, and it is found that the kHz QPOs in this class of sources are observed at lower frequencies compared with the other two Z sources (Jonker et al. 2000a, 2002, Wijnands et al. 1998). In addition, a transition from Cyg-like phase to Sco-like phase occurs in Cyg X-2. This property may be consistent with its wide $\nu_2$ range and the kHz QPOs at relatively high frequencies. However, the $Q_1$ and $\nu_1$ lie in a very narrow region, but with large error. The physical reason why the other sources don’t cover the whole range and Cyg X-2 does will be investigated in our future work. Sco X-1 is a very bright Z source, in
Fig. 2  Plots for $Q - \nu$ relations for Z sources. The left panel is for upper kHz QPOs, and the right one is for lower kHz QPOs. The meaning of different symbols are listed in the diagrams.

Fig. 3  The same meaning as Fig. 2 but for Atoll sources.
which the kHz QPOs can be detected all the way onto the FB, corresponding to the high frequencies that are observed. Besides, the high luminosity corresponds to the high accretion rate and it may have some possible reasons: One possibility is that the accretion disk is thickened by the radiation pressure during the Z stage. As a result, the magnetosphere of neutron star expands, while both the inner disk radius and the mass accretion rate increase. The signal may be sucked by the thickened disk and the system shows a drop of Q factor. Another possibility is that the innermost boundary of accretion disk is close to the NS surface. Consequently, the radius of magnetosphere is relatively small, and the frequency of kHz QPO can be up to a high value. The region between innermost disk and the NS surface become narrow. So the $Q_1$ can be up to the relatively high values. When the innermost disk is more close to NS surface, the radiation is sucked by some material accreted by the NS. As a result, the $Q_1$ begins to drop abruptly with $\nu_1$.

3.2 The correlation among $Q - \nu$ track, spin frequency and sideband frequency

The peculiar trends of $Q_1$ as the function of $\nu$ for Atoll sources imply the special physics in the inner disk region of these class of sources. The high values of $Q_1$ indicate the small range of frequency drift for lower kHz QPOs. It is claimed that the drop of $Q_1$ is a hint of the innermost stable boundary of accretion disk (Miller et al. 1998; Barret et al. 2005c). The maximum of $Q_1$ is detected at a mildly higher frequency than that of Z sources which is consistent with the small radius of innermost disk. However, the Atoll sources present low luminosity (van der Klis 2006) and low accretion rate. Accordingly, the magnetic field should be mildly weaker than that of Z sources, allowing for the accretion disk extending to be close to the NS surface.

From the second part of section 2, we know that three sources (4U 1608-52, 4U 1636-53 and 4U 1728-34) exhibit very high $Q_1$ values. Moreover, the spin frequencies have been detected for these sources, i.e., $619 \text{Hz}$ (Hartman et al. 2003), $581 \text{Hz}$ (Strohmayer et al. 1998; Winands et al. 1997; Zhang et al. 1997), $363 \text{Hz}$ (Strohmayer et al. 1996), respectively. In addition, all the three sources display the sideband in their PDS (Jonker et al. 2006a,b). The differences in frequencies between the sidebands and the lower kHz QPOs are, $52.8 \pm 0.9 \text{Hz}$ (4U 1608-52), $58.4 \pm 1.9 \text{Hz}$ (4U 1636-53) and $64 \pm 2 \text{Hz}$ (4U 1728-34) (Jonker et al. 2000a,b). Maybe the high values of $Q_1$ of the three sources allow for the detection of sidebands, while the sidebands may be engulfed by the border peak in other sources.

In order to investigate the relations between spin frequency / sideband frequency and the maximum $Q_1$, we fit the function GCAS to the data of these sources and find out the maximum $Q_1$ for every sources (see Table 1). Then we plot the spin frequency versus $Q_{1\text{max}}$ and the difference between sideband frequency and the lower frequency versus $Q_{1\text{max}}$. We also fit an exponential relation to them (see Fig. 4). The fitting results are listed in Table 2 and Table 3. We notice that the source with higher maximum $Q_1$ present higher spin frequency (see the left panel of Fig. 4), while the difference between $\nu_1$ and the sideband frequency is low (see the right panel of Fig. 4).

The high maximum of $Q_1$ implies that the emission site of lower kHz QPOs is more close to the NS surface. Besides, the high spin frequency is consistent with a small corotation radius (Zhang 2007). With small corotation radius, the drift range of frequency between this radius and the NS surface is narrow, which corresponds to the high value of $Q_1$. Accordingly, this gives us the hint that the lower kHz QPOs may relate to the corotation radius. The source with high spin frequency and high maximum value of $Q_1$ presents the small difference between sideband frequency and $\nu_1$. So we claim that the emissions of lower kHz QPOs and the sideband are spin mediated.

3.3 Revelation for The Nature of kHz QPOs

The upper frequency is the same order as the dynamical time-scales of the innermost region of the accretion flow around the stellar mass compact objects (van der Klis 2006, 2008). It is considered that $\nu_2$ is the innermost orbital frequency of accretion flow both for Z and Atoll sources. Due to some instabilities resulting from the changes of accretion rate, magnetic pressure and others (Romanova et al. 2007; Rastatter & Schindler 1999; Kulkarni & Romanova 2008), the boundary of inner disk is changing during the accretion process. As a consequence, every peak of kHz QPO signal presents drift around the centroid frequency, contributing to the upper quality factor $Q_2$ (Wang et al. 2011).

As far as the nature of lower kHz QPOs, two very different evolutionary scenarios of $Q_1$ as the function of $\nu_1$ (see the right panels of Fig. 2 and Fig. 3 for a detail) imply distinct physics in the inner disk for Z and Atoll sources. High accretion rate leads to strong instabilities which are responsible for the large frequency drift. So the values of $Q_1$ for Z sources are low. For the Atoll sources, the accretion flow with low accretion rate and the relatively stable scenario in the inner region of disk allows for the disk extending all the way to near the NS surface, which accounts for the high values of $Q_1$. 
Table 1  The fitting results for $Q_{1\text{max}}$ of three Atoll sources.

| Source     | $Q_{1\text{max}}$ | error(Q) | $\nu_1$   | error($\nu_1$) |
|------------|-------------------|----------|-----------|----------------|
| 4U 1608-52 | 182.9             | 3.2      | 824.03    | 3.02           |
| 4U 1636-53 | 168.15            | 4.2      | 833.9     | 2.28           |
| 4U 1728-34 | 143.61            | 2.9      | 872.57    | 3.2            |

Table 2  The fitting results for spin frequency versus $Q_{1\text{max}}$.

\[
y = a^{\nu_1 - c} + d \quad 1.0216 \quad 0.98602 \quad 438.85 \quad 146.22
\]

Table 3  The fitting results for the difference between $\nu_1$ and sideband frequency versus $Q_{1\text{max}}$.

\[
y = a^{\nu_1 - c} + d \quad 0.89119 \quad 0.44606 \quad 62.50412 \quad 96.6845
\]

Fig. 4  The fittings for the correlations between spin frequency / frequency difference and $Q_{1\text{max}}$. The left panel is for the spin frequency versus $Q_{1\text{max}}$. The right one is for the difference between $\nu_1$ and sideband frequency versus $Q_{1\text{max}}$. 
We expect to find out the hints for mechanism of lower kHz QPOs from the nature of Z and Atoll sources in our future work.

4 Summary

More and more data about the coherence of kHz QPOs in NS LMXBs are detected, the $Q - \nu$ relations and their implications have been the attractive issues. In this paper, we investigate the recently published data of quality factors for thirteen sources \cite{Mendez2006, Sanna2010}, i.e. seven Atoll sources (4U 1608-52, 4U 1636-53, 4U 1728-34, 4U 0614+09, Aql X-1, 4U 1820-30 and 4U 1735-44), five Z sources (Sco X-1, Cyg X-2, GX 17+2, GX 5-1 and GX 340+0) and XTE 1701-462 which presents both Z and Atoll behaviors. The main conclusions are listed below.

1. The $Q_2$ values are low ($Q_2 \sim 2 - 20$) for both Z and Atoll sources. The $Q_2 - \nu_2$ tracks increase steadily, in general. The values of $Q_1$ are are low ($Q_1 \sim 2 - 20$) for Z sources and increase with frequencies(except for Sco X-1). But the values of $Q_1$ for Atoll sources are very high (up to 200), and increases with frequencies up to a maximum then abruptly drops.

2. Though the $Q - \nu$ distribution of Z sources form a continues relation for both upper and lower kHz QPOs, they can be divided into two regions, according to the ranges of $\nu$. One contains Sco X-1 and GX 17+2, which present high Q-values and high centroid frequencies. The other is formed by GX 5-1 and GX 340+0, with low Q-values and centroid frequencies. However, Cyg X-2 extends almost to the whole range of $Q_2$ and $\nu_2$ that the others cover. The different ranges of frequency may give us useful information about the nature of Z and Atoll source.

3. The $\nu_2$ for Atoll sources cover a boarder range and $Q_2$ values are low $2 - 20$. Almost all $Q_1 - \nu_1$ tracks for Atoll sources present rising part, maximum and then the abrupt drop.

4. The spin period and sidebands were detected in three sources (4U 1608-52, 4U 1636-53 and 4U 1728-34) which present very high $Q_1$. The source with higher spin frequency presents higher $Q_1$ values, and its difference between lower $\nu_1$ and sideband frequency is low.

5. The $Q_1$ values are the same order as $Q_2$ for 4U 0614+09. The lower frequencies for AqI X-1 just were detected in a very narrow range, and the $Q_1$ values are high. XTE 1701-462 presents high errors for $Q_2$ and $Q_1$.

6. The emission of lower kHz QPOs and sideband frequency may be correlated to the NS spin.

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