kHz QUASI-PERIODIC OSCILLATIONS FROM THE 2000 AND 2010 X-RAY TRANSIENTS LOCATED IN THE GLOBULAR CLUSTER TERZAN 5: EXO1745−248 AND IGR J17480−2446

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ABSTRACT

EXO1745−248 is a transient neutron star low-mass X-ray binary located in the globular cluster Terzan 5. It was in outburst in 2000 and displayed during one Rossi X-ray Timing Explorer observation a highly coherent quasi-periodic oscillation (QPO) at frequencies between 670 and 715 Hz. Applying a maximum likelihood method to fit the X-ray power density spectrum, we show that the QPO can be detected on segments as short as $T = 48$ s. We find that its width is consistent with being constant, while previous analysis based on longer segment duration (200 s) found it variable. If the QPO frequency variations in EXO1745−248 follow a random walk (i.e., the contribution of the drift to the measured width increases like $\sqrt{T}$), we derive an intrinsic width of $\sim 2.3$ Hz. This corresponds to an intrinsic quality factor of $Q \sim 297 \pm 50$ at 691 Hz. We also show that $Q$ is consistent with being constant between 2.5 and 25 keV. IGR J17480−2446 is another X-ray transient located in Terzan 5. It is a very interesting object showing accretion-powered pulsations and burst oscillations at 11 Hz. We report on the properties of its kHz QPOs detected between October 18 and October 23, soon after the source had moved from the so-called Atoll state to the Z state. Its QPOs are typical of persistent Z sources; in the sense that they have low $Q$ factors ($\sim 30$) and low rms amplitudes ($\sim 5\%$). The highest frequency (at 870 Hz), if orbital, sets a lower limit on the inner disk radius of $\sim 18.5$ km and an upper limit to the dipole moment of the magnetic field $\mu < 5 \times 10^{26}$ G cm$^3$.

Key words: accretion, accretion disks – globular clusters: general – globular clusters: individual: Terzan 5 – stars: neutron – X-rays: binaries – X-rays: stars

Online-only material: color figure

1. INTRODUCTION

Terzan 5 is a galactic globular cluster, which contains several X-ray sources (Heinke et al. 2003), including EXO1745−248, an X-ray transient that was in outburst in 2000 and 2002 (Markwardt et al. 2000; Wijnands et al. 2002). A strong kHz quasi-periodic oscillation (QPO) from EXO1745−248 was discovered by Mukherjee & Bhattacharyya (2011) from the RXTE data recorded during the 2000 outburst. Mukherjee & Bhattacharyya (2011), using power density spectra (PDS) with an integration time of 10 s, reported that when fitting the QPO on timescales down to 200 s, the quality factor of the QPO was variable and reached a peak value of $264 \pm 38.5$, despite the fact that no correction for the frequency drift was applied, within the 200 s intervals. Mukherjee & Bhattacharyya (2011) thus argued that the shift-and-add procedure (Mendez et al. 1998; Barret et al. 2005), which in its general form involves the average of a large number of PDS, could miss high $Q$ QPOs, appearing in segments of short durations. In their analysis, Mukherjee & Bhattacharyya (2011) suggested also that the quality factor of the QPO could increase with energy. In this paper, we revisit the above observation, by applying a maximum likelihood estimation (MLE) of the QPO parameters, following the method described by Barret & Vaughan (2012). The MLE has been shown more sensitive and much less biased than the more traditionally used min($\chi^2$), especially when the number of PDS fitted is small, as is the case when attempting to track the QPO frequency on short timescales. In Section 2, we present the observation and our analysis, which we complement with simulations to show the level of scattering expected in the fitted $Q$ values, even for a signal of a constant $Q$ factor.

IGR J17480−2446 is another neutron star X-ray transient discovered in 2010 in the globular cluster Terzan 5. It was originally detected by the International Gamma-Ray Astrophysics Laboratory/IBIS imager (Bordas et al. 2010; Ferrigno et al. 2010). Investigation of archival Chandra data revealed that IGR J17480−2446 was distinct from EXO1745−248 (Heinke et al. 2010). IGR J17480−2446 displays very interesting properties: it is an 11 Hz eclipsing bursting X-ray pulsar (Chenevez et al. 2010; Strohmayer & Markwardt 2010; Linares et al. 2010, 2012; Papitto et al. 2011), showing burst oscillations locked to the Z state, around October 16–17 (Altamirano et al. 2010a; Cavecchi et al. 2011). The spectral evolution along its outburst indicated that it made a transition from the so-called Atoll state to the Z state, around October 16–17 (Altamirano et al. 2010a; Chakraborty et al. 2011). Altamirano et al. (2010a) reported a marginal detection of a kHz QPO at about 815 Hz (3.8$\sigma$, single trial significance, 10–50 keV, October 18), but so far no systematic search for high-frequency QPOs from IGR J17480−2446 has been presented. This is the scope of Section 3, where we report on highly significant high-frequency QPOs from IGR J17480−2446. We discuss the results of both sources in Section 4.

2. REVISITING THE QPO FROM EXO1745−248

The 2000 outburst of EXO1745−248 was monitored by RXTE between 2000 July and November. We have extracted the Leahy-normalized PDS, using all events recorded between 3 and 25 keV and an integration time of 8 s (Nyquist frequency at 2048 Hz). Two proposals P50054 and P50138 are considered, amounting to 126 ks of observations. As reported by Mukherjee & Bhattacharyya (2011), in one segment only, a significant kHz QPO was detected (ObsID: 50054-06-11-00, starting on 2000 September 30 at 15$^h$28$^m$53$^s$, and lasting for 3230 s). This observation was taken in the tail of the outburst decay,
Figure 1. Smoothed dynamical PDS for the ObsID 50054-06-11-00 of EXO1745−248. The QPO shows big jumps in frequency on hundreds of second timescales. The 3–25 keV light curve at an 8 s resolution is shown at the top, while the projected PDS is plotted on the right-hand side panel. (A color version of this figure is available in the online journal.)

about 40 days after the peak. The dynamical PDS is shown in Figure 1. The track followed by the QPO can easily be seen, and its frequency varies from $\sim 713$ Hz and $\sim 672$ Hz, and displays relatively large jumps by up to 20–30 Hz on timescales of hundreds of seconds.

2.1. Measuring the QPO Width

In order to reduce the contribution of the frequency drift to the measured QPO width, we minimize the number of 8 s PDS to be averaged ($M$), and yet to have a significant detection of the QPO. The PDS is modeled as the sum of a constant $a$ (to account for the Poisson noise, i.e., equal to 2 for the Leahy-normalized PDS; Leahy et al. 1983), plus a Lorentzian accounting for the QPO, with three parameters: the normalization $R$ (equal to the integrated power of the Lorentzian from 0 to $\infty$), the width $w$ (FWHM), and the centroid frequency $\nu_0$. The rms amplitude is a derived quantity, computed as $\text{rms} = \sqrt{R \times (S + B)/S^2}$ and expressed in percentage, in which $S$ is the net source count rate and $B$ is the background count rate; $B$ is often negligible compared to $S$. We define the minimum $M$ as to have more than 80% of the intervals in which $R/\Delta R \geq 3$, where $\Delta R$ is the 1$\sigma$ error on $R$ (see, e.g., Boutelier et al. 2010). For this observation, we have found a minimum $M$ equal to 6, although $M = 5$ yields a fraction of significant detections of 75%. The QPO parameters can thus be recovered down to a 48 s timescale. The MLEs of the QPO parameters are shown in Figure 2 for $M = 6$. The mean of the MLEs of $w$ ($\langle w_{\text{MLE}} \rangle = 3.8 \pm 0.2$ Hz) is measured for $T = 48$ s (the error is given as the standard error on the mean). The mean value of $R/\Delta R$ is about 4, indicating that the biases on $R$ and $w$ are negligible (the leakage bias at $T = 8$ s is only 0.04 Hz, 50 times less than the error bar on $\langle w_{\text{MLE}} \rangle$; Barret & Vaughan 2012). For a mean QPO frequency of 690 Hz, this width corresponds to a mean quality factor of $Q \sim 182$, or $Q = 177, 189 \pm 8$ at the minimum and maximum frequencies detected. Over 48 s, $Q$ ranges from $82 \pm 29$ to $754 \pm 390$. Fitting of the log $w_{\text{MLE}}$ values (closer to a normal distribution, see Barret & Vaughan 2012) with a constant yields a $\chi^2$ of 53.4 for
57 degrees of freedom. Hence, within the statistical quality of the data, \( w \) is consistent with being constant over the observation, despite the frequency variations, not corrected for within the 48 s of the cumulative PDS integration time. We have reprocessed the data with \( M = 25 \), corresponding to a cumulative integration time of 200 s for the PDS, as in Mukherjee & Bhattacharyya (2011). \( \langle w^{\text{MLE}} \rangle \) becomes 5.9±0.5 Hz, and is not consistent with being constant (due to the fact that not all intervals experience the same frequency drift and the contribution of the drift to the measured width becomes significant). For a mean QPO frequency of 690 Hz, this corresponds to a mean quality factor of \( Q \sim 118 \), or \( Q = 115, 121 \pm 10 \) at the minimum and maximum frequencies detected. Over 200 s, \( Q \) ranges from 64 ± 13 to 281 ± 65; the latter value being consistent with the maximum value reported by Mukherjee & Bhattacharyya (2011).

The effect of increasing \( M \) or the segment duration is obviously to increase \( \langle w^{\text{MLE}} \rangle \) and to increase the scatter due to the variable frequency drift. This is shown in Figure 3 where we show how \( \langle w^{\text{MLE}} \rangle \) increases with \( T = M \times 8 \) s (\( M \) ranges from 5 to 12). As discussed in Barret & Vaughan (2012), if the frequency drift follows a random walk, we expect the broadening of the QPO due to the variable frequency to increase with \( \sqrt{T} \). The power spectrum of the frequency variations using the estimates of the QPO frequency on a timescale of 48 s can be adequately fitted by a simple power-law model of index 2.6 ± 0.6, and is therefore consistent, within error bars, with a random walk (the index should be 2). Assuming that the measured width for a given \( T(w_T) \) includes a contribution from the intrinsic QPO width \( w_{\text{qpo}} \) and a contribution from the drift (\( w_{\text{drift}} \)), such as \( w_T^2 = w_{\text{qpo}}^2 + w_{\text{drift}}^2 \), with \( w_{\text{drift}} \propto \sqrt{T} \), it is possible to recover the intrinsic width of the QPO. As can be seen from Figure 3, the random walk model can fit the data. We found \( w_{\text{qpo}} = 2.3 \pm 0.4 \) Hz or \( Q_{\text{qpo}} = 297 \pm 50 \) at 691 Hz.

### 2.2. Simulations

As shown above, the measured width and its scatter both increase with \( M \) or equivalently the interval duration, but on top of this, it should also be realized that fluctuations around the mean QPO profile will also scatter \( Q \) around its mean value. This is best illustrated with a simulation of a set of synthetic PDS, containing a QPO with fixed frequency, amplitude, and width. Following the method described in Barret & Vaughan (2012), we have simulated 1050 PDS of 8 s duration from segments 256 s long, containing a QPO with the parameters derived from EXO1745−248 \((v_0 = 690 \) Hz, \( \text{rms}_0 = 9.2 \% \), \( w_0 = 2.3 \) Hz, equivalent to \( Q_0 = 300 \)). Fitting the average of the 1050 PDS gave \( w = 2.3 \pm 0.1 \) Hz, an rms amplitude of 9.2% ± 0.1%, and quality factor \( Q = 295 \pm 7 \), consistent with the input parameters. The MLEs of the QPO parameters derived for \( M = 25 \) (equivalent to \( T = 200 \) s) are shown in Figure 4. As can be seen, despite a constant QPO width and frequency (hence fixed \( Q \)), \( Q \) shows some significant scattering, with minimum and maximum values of 217 ± 31 and 470 ± 72. Adding a variable frequency for the QPO would shift down all the \( Q \) estimates by a similar amount on average. The scattering will remain, and for this reason, taking the maximum \( Q \) value found as a measure of the underlying \( Q \) factor of the QPO is not correct. At any given timescales, a better estimate of \( Q \) is obtained as the average of many measurements (as the shift-and-add technique does; Barret et al. 2006, see also Figure 4).

### 2.3. \( Q \) Dependence with Energy

Mukherjee & Bhattacharyya (2011) suggested that the quality factor of the QPO could increase with energy, although within error bars \( Q \) was consistent with being constant. No correction for the frequency drift was applied in their analysis, explaining why the \( Q \) values of their Figure 5 are low (around 30). First we failed to reproduce the smooth trend found in Mukherjee & Bhattacharyya (2011), extracting PDS in the same energy bands and using \( \chi^2 \) fitting (or even maximum likelihood fitting). Second, it should be stressed that to get meaningful \( Q \) values, a correction for the frequency drift must be applied. Using the

![Figure 3](https://example.com/figure3.png)

**Figure 3.** Fitting the increase of the measured QPO width with the number of 8 s PDS averaged or equivalently the segment duration with a random walk model (solid line). The intrinsic QPO width and the quality factor recovered are 2.3 Hz and 296.5, respectively.

![Figure 4](https://example.com/figure4.png)

**Figure 4.** Maximum likelihood estimates of the QPO parameters recovered on 200 s duration from a simulation in which the width, frequency, and amplitude of the QPO are constant \((v_0 = 690 \) Hz, \( \text{rms}_0 = 9.2 \% \), \( w_0 = 2.3 \) Hz, equivalent to \( Q_0 = 300 \)). From top to bottom: the fractional rms amplitude in %, the quality factor, and the QPO width. The error bars are given at 1σ. This simulation illustrates the typical scattering expected from the \( Q \) values measured on this timescale. The mean of the MLEs is given inside the panels and shown with a dashed line.
time history of the QPO frequency as measured on 48 s, we have shifted-and-added all the PDS in four adjacent energy bands. The MLEs of the QPO parameters are shown in Figure 5. As can be seen, within the statistical quality of the data, the quality factor of the QPO is consistent with being constant between 2.5 and 25 keV. The rms amplitude of the QPO increases as it does in similar systems (for 4U1608-525; Berger et al. 1996).

2.4. Q Dependence with Frequency

It is known that the quality factor of the QPO varies with frequency, increasing smoothly with frequency up to a maximum value beyond which a sharp drop is observed (Barret et al. 2006). This effect was observed after averaging large data sets (to reduce the uncertainty in Q), when the QPO spans a large frequency interval (300–400 Hz wide). We have searched for such a variation in the data by grouping 100 8 s PDS of adjacent frequencies, shifting and adding them to the mean frequency. The MLEs of the QPO parameters as derived from the shifted-and-added PDS are presented in Figure 6. Clearly the statistical quality of the data does not allow us to see variations of Q (and the rms amplitude) with frequency, over the 40 Hz interval covered by the observation.

3. kHz QPOs FROM IGR J17480—2446 DURING ITS 2010 OUTBURST

IGR J17480—2446 was monitored during its 2010 outburst between October 13 and November 19. We have processed all the archival data corresponding to proposal P95437 (total observing time of about 284 ks for 46 ObsIDs), and produced 8 s PDS, using all events of energies between 5 and 25 keV (this energy range maximizes the signal-to-noise ratio of the QPOs detected). No screening for X-ray bursts was performed. We split the ObsIDs in time continuous intervals; e.g., switching the Proportional Counter Array from 1 Proportional Counter Unit (PCU) to 2 PCUs defines an interval boundary. We have a total of 102 intervals. A blind search for high-frequency QPOs at frequencies above 500 Hz has been performed on the interval-averaged PDS, using a scanning algorithm (Boirin et al. 2000), and a single trial significance threshold of the excess power of 5σ, below which spurious features are often found (see, e.g., Boutelier et al. 2010).

High-frequency QPOs with significance larger than 5σ (single trial) were detected within four ObsIDs: 95437-01-06-000 (7.6σ), 95437-01-07-00 (7.1σ), 95437-01-09-00 (12.1σ), and 95437-01-10-01 (8.2σ). The ObsID 95437-01-06-00, in which Altamirano et al. (2010) reported a marginal QPO detection, is split into two intervals. No excess is found above 5σ (even 4σ) in either intervals or in their combination. The same conclusion applies to the PDS extracted using events of energy between 10 and 50 keV, as Altamirano et al. (2010) did. The strongest excess reaches 3.5σ (single trial) in the 5–25 keV band (at ~825 Hz), combining the two intervals. Accounting for the number of trials of the scanning routine (~10^3), this excess is clearly not significant. We therefore conclude that no significant QPOs were detected in ObsID 95437-01-06-00.

The high-frequency QPOs we have detected have been fitted with the maximum likelihood on timescales of 1024 s for the three intervals and 512 s for the second interval of the ObsID 95437-01-09-00. The MLEs of the QPO parameters are reported in Table 1. As can be seen, all the detections occurred soon after the source had transited to the Z state. Not surprisingly, its QPOs are relatively broad (few tens of Hz) and of low rms amplitude (3%–6%), which are characteristic properties of QPOs of Z sources (van der Klis 2000). We have shifted-and-added all the PDS containing a high-frequency QPO: at the mean frequency of 839 Hz, the quality factor of the QPO is Q = 32.9 ± 3.7 and the rms amplitude is 4.7% ± 0.2%. No other features were present in the averaged PDS between 500 and 1500 Hz, with an upper limit on the rms amplitude of about 2% for a signal of 20–50 Hz width.

4. DISCUSSION

We now discuss the results obtained above, starting first with EXO1745–248.
Table 1
Maximum Likelihood Estimates of the High-frequency QPOs Detected from IGR J17480−2446

| Time               | T_{PDS} | ν (Hz)       | w (Hz)       | Q      | rms (%) | R/δR |
|--------------------|---------|--------------|--------------|--------|---------|------|
| 2010 Oct 18 at 07:19:28 | 1024    | 803.0 ± 1.7  | 11.5 ± 5.1   | 70.1 ± 31.2 | 3.2 ± 0.5 | 3.1  |
| 2010 Oct 18 at 07:36:40  | 1024    | 828.9 ± 10.1 | 40.3 ± 16.1  | 20.6 ± 8.2  | 4.1 ± 0.8  | 2.6  |
| 2010 Oct 18 at 07:53:52  | 1024    | 808.6 ± 5.2  | 42.7 ± 16.3  | 18.9 ± 7.2  | 4.9 ± 0.8  | 3.1  |

| Time               | T_{PDS} | ν (Hz)       | w (Hz)       | Q      | rms (%) | R/δR |
|--------------------|---------|--------------|--------------|--------|---------|------|
| 2010 Oct 19 at 05:35:54 | 1024    | 829.2 ± 4.3  | 24.3 ± 10.6  | 34.2 ± 14.9 | 3.7 ± 0.7  | 2.8  |
| 2010 Oct 19 at 05:51:06  | 1024    | 814.4 ± 4.8  | 36.1 ± 10.6  | 22.6 ± 6.7  | 4.9 ± 0.7  | 3.8  |

**Notes.** The data are listed by ObsIDs. The starting time of the Fourier PDS, its cumulative integration time, the QPO frequency, width, quality factor, and fractional rms amplitude of the QPO are given, together with a measure of the significance of the detection, which is given as the ratio of the Lorentzian normalization divided by its 1σ error (R/δR ≥ 3 corresponds to a very significant detection).

4.1. EXO1745−248

We have reanalyzed the data from EXO1745−248, in which Mukherjee & Bhattacharyya (2011) discovered a single high-frequency QPO, most likely to be a lower kHz QPO, due to its high-quality factor and amplitude. We have applied the recently developed maximum likelihood method to fit the QPO on the shortest timescales permitted by the data statistics; 48 s in this case. Contrary to Mukherjee & Bhattacharyya (2011), we have found that the QPO width is consistent with being constant within the observation, corresponding to a mean quality factor of ~182 at 690 Hz (on 48 s). We have failed to detect variations of Q with frequency within the 40 Hz frequency interval sampled by the QPO, but this is again likely due to the limited signal-to-noise ratio of the data. It is therefore impossible to tell whether Q from EXO1745−248 could still reach higher values. Within the statistical quality of the data, we have shown that Q, corrected for the frequency drift on a timescale of 48 s, does not depend on energy. Applying a simple random walk model, we have inferred that the intrinsic quality factor of the QPO could be as large as 297 ± 50 at 691 Hz (Figure 3). Despite the relatively large error bar, this puts EXO1745−248 among the QPO sources with the most coherent QPOs, and therefore provides even stronger constraints on QPO models, due to the long inferred lifetime for the underlying oscillator (see the discussion in Barret et al. 2005). We have also shown with simulations that for the QPO parameters recovered for EXO1745−248, the Q values measured on 200 s intervals display some significant scattering. Therefore techniques based on averaging many individual measurements (e.g., as with the shift-and-add technique) are appropriate for deriving meaningful quality factors.

5. IGR J17480−2446

We have reported high-frequency QPOs from IGR J17480−2446: another X-ray transient located in Terzan 5, which was in outburst in late 2010. First, we failed to confirm the marginal QPO detection previously reported by Altamirano et al. (2010a), but we detected highly significant QPOs between October 18 and 23, at frequencies between 800 and 870 Hz. These QPOs were detected soon after the source had moved from the Atoll state to the Z state (around October 16–17). The QPOs are typical of Z sources, in the sense that they are broad and have a relatively low amplitude. They are similar to those detected in the Z phase of the other system, which shows both Atoll and Z states, namely, XTE J1701−462 (Homan et al. 2007;
Sanna et al. 2010). Unlike in the case of XTE J1701−462, no narrower high-frequency QPOs were detected in the Atoll phase of IGR J17480−2446, while the sensitivity of the observations was sufficient (e.g., limiting rms around 3% for a QPO width of 5 Hz on October 14), had the QPO been as strong as the one seen from XTE J1701−462 (rms amplitude between 8% and 10%; see Sanna et al. 2010; Barret et al. 2011). It is hard to tell whether the QPOs detected are lower or upper QPOs, because only a single one was detected in all intervals, and in the combined intervals. The analogy with XTE J1701−462 does not help, as Sanna et al. (2010) have shown that in its Z phase, the upper and lower QPOs had similar Q and rms amplitudes. In general though, in classical Z sources, e.g., Sco X-1, the lower and upper QPOs have comparable Q factors, but the upper QPOs have larger amplitudes and should therefore be easier to detect (Boutelier et al. 2010). Note, however, that in IGR J17480−2446 the spin frequency of the neutron star (νs) is 11 Hz and that in many systems, the frequency separation of the QPOs is either found close to νs or νs/2. (see, however, Méndez & Belloni 2007): detecting two QPOs with such a separation would require very narrow (and comparatively strong) QPOs to start with; this could explain why only one single QPO is seen from IGR J17480−2446 in its Z phase.

The highest frequency at 870 Hz was detected when the source X-ray luminosity was ∼4 × 10^37 erg s^{-1} (Chakraborty et al. 2011), at the distance of 5.5 kpc (Ortolani et al. 2007). Assuming that this frequency is an orbital frequency at the inner disk radius (Rm); this sets a lower limit on Rm as ∼18.5m^{1/3} km (where m is the Neutron Star (NS) mass, given in units of 1.4 M⊙). According to Burderi et al. (2001), the magnetospheric radius Rm is given as Rm ∼ 160 m^{1/4} R_6^{2/7} L_3^{−2/7} μ_28^{−3/7} km, where R_6 is the NS radius in units of 10 km, L_3 is the accretion luminosity in units of 10^{37} erg s^{-1}, and μ_28 is the magnetic dipole moment of the NS in units of 10^{28} G cm^3. Assuming that the disk is truncated at the magnetospheric radius, an upper limit μ ≤ 5 × 10^{26} G cm^3 can be derived on the magnetic dipole moment of the NS (for canonical parameters for the neutron star). Under the simplistic assumption that μ = B_s R^3, the surface magnetic field would be less than 5 × 10^9 G, a value at the lower end of the range derived previously from the detection of pulsations along the outburst and from spectral analysis (2 × 10^8 to 2 × 10^{10} G; Papitto et al. 2011; Miller et al. 2011). In particular, our limit is lower than the magnetic field required (B_s > 10^9 G) to confine the burning material at the polar cap, as invoked by Cavecchi et al. (2011) to explain the burst oscillations and their phase locking with the accretion-powered pulsations.

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