DISCOVERY OF KILOHERTZ QUASI-PERIODIC OSCILLATIONS AND STATE TRANSITIONS IN THE LOW-MASS X-RAY Binary 1E 1724–3045 (TERZAN 2)

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ABSTRACT

We have studied the rapid X-ray time variability in 99 pointed observations with the Rossi X-Ray Timing Explorer (RXTE) Proportional Counter Array of the low-mass X-ray binary 1E 1724–3045, including, for the first time, observations of this source in its island and banana states, confirming the atoll nature of this source. We report the discovery of kilohertz quasi-periodic oscillations (kHz QPOs). Although we have five detections of the lower kHz QPO and one detection of the upper kHz QPO, in none of the observations we detect both QPOs simultaneously. By comparing the dependence of the rms amplitude with energy of kHz QPOs in different atoll sources, we conclude that this information cannot be used to unambiguously identify the kilohertz QPOs as was previously thought. We find that Terzan 2 in its different states shows timing behavior similar to that seen in other neutron-star low-mass X-ray binaries (LMXBs). We studied the flux transitions observed between 2004 February and 2005 October and conclude that they are due to changes in the accretion rate.

Subject headings: accretion, accretion disks — binaries: close — stars: individual (4U 1636–53, 4U 1820–30, 4U 1608–52, 4U 0614+09, 4U 1728–34, Terzan 2, 1E 1724-3045) — stars: neutron — X-rays: stars

Online material: color figure, machine-readable table

1. INTRODUCTION

Low-mass X-ray binaries (LMXBs) can be divided into systems containing a black hole candidate (BHC) and those containing a neutron star (NS). The accretion process onto these compact objects can be studied through the timing properties of the associated X-ray emission (see, e.g., van der Klis 2006 for a review). Hasinger & van der Klis (1989) classified the NS LMXBs based on the correlated variations of the X-ray spectral and rapid X-ray variability properties. They distinguished two subtypes of NS LMXBs, the Z sources and the atoll sources, whose names were inspired by the shapes of the tracks that these sources trace out in an X-ray color-color diagram (CD) on timescales of hours to days. The Z sources are the most luminous, but the atoll sources are more numerous and cover a much wider range in luminosities (e.g., Ford et al. 2000 and references within). For each type of source, several spectral/timing states are identified which are thought to arise from qualitatively different inner flow configurations (van der Klis 2006). In the case of atoll sources, the three main states are the extreme island state (EIS), the island state (IS) and the banana branch, the latter subdivided into lower left banana (LLB), lower banana (LB), and upper banana (UB) states. The EIS and the IS occupy the spectrally harder parts of the color-color diagram and correspond to lower levels of X-ray luminosity (L_X). The associated patterns in the CD are traced out in hours to weeks. The hardest and lowest L_X state is the EIS, which shows strong (up to 50% rms amplitude; see Linares et al. 2007 and references within) low-frequency flat-topped noise also known as band-limited noise (BLN). The IS is spectrally softer and has higher X-ray luminosity than the EIS. Its power spectra are characterized by broad features and a dominant BLN component which becomes weaker and generally higher in characteristic frequency as the flux increases and the >6 keV spectrum gets softer. In order of increasing L_X we then encounter the LLB, where twin kHz QPOs are generally first observed, the LB, where 10 Hz BLN is still dominant and finally, the UB, where the ~1 Hz (power law) very low frequency noise (VLFN) dominates. In the banana states, some of the broad features observed in the EIS and the IS become narrower (peaked) and occur at higher frequency. In particular, the twin kHz QPO can be found in the LB at frequencies higher than 700 Hz (the lower of them with frequencies generally lower than a 1000 Hz, while the upper one up to 1258 Hz; see, e.g., Belloni et al. 2005; Jonker et al. 2007), only one kHz QPO can be generally found in the LB, and neither of them is detected in the UB (see reviews by van der Klis 2000, 2006).

A small number of weak NS LMXBs which do not get brighter than a few times 10^{36} ergs s^{-1} (usually burst sources and often referred to as “weak” or “faint bursters”; see, e.g., Muno et al. 2003 and references within) resemble atoll sources in the EIS, but in the absence of state transitions this identification has been tentative (see, e.g., Barret et al. 2000b; van der Klis 2006). An important clue is provided by the correlations between the component frequencies (and strengths; see, e.g., van Straaten et al. 2002, 2003; Altamirano et al. 2008), which helps to identify components across sources. For example, van Straaten et al. (2002, 2003) compared the timing properties of the atoll sources 4U 0614+09, 4U 1608–52 and 4U 1728–34 (see also Altamirano et al. 2008, for similar results when the atoll source 4U 1636–53 was included in the sample) and conclude that the frequencies of the variability components in these sources follow the same pattern of correlations when plotted versus the frequency of the upper kHz QPO (v_k). Van Straaten et al. (2003) also showed that low-luminosity systems extend the frequency correlations observed for the atoll sources. This last result gave further clues in the link between the atoll and the low-luminosity sources.
Psaltis & Chakrabarty (1999) found an approximate frequency correlation involving a low-frequency QPO, the lower kHz QPO frequency and two broad noise components interpreted as low-frequency versions of these features. This correlation spans nearly three decades in frequency, where the Z and bright atoll sources populate the >100 Hz range and black holes and weak NS systems the <10 Hz range. As already noted by Psaltis & Chakrabarty (1999) because the correlation combines features from different sources which show either peaked or broad components with relatively little overlap, the data are suggestive but not conclusive with respect to the existence of a single correlation covering this wide frequency range (van der Klis 2006).

The low-luminosity neutron star systems can play a crucial role in clearing up this issue. Observations of different source states in such a system could connect the <10 and >100 Hz regions mentioned above by direct observation of a transition in a single source. In the case of the pattern of correlations reported by van Straaten et al. (2003) low-luminosity NS systems extend the frequency correlations observed for ordinary atoll sources down to ~100 Hz. Unfortunately, the low-luminosity NS systems are usually observed in only one state (EIS), which makes it difficult to properly link these sources to the atoll sources. However, some of these objects show rare excursions to higher luminosity levels which might correspond to other states. The occurrence of these excursions are usually unpredictable. Therefore, in practice it was not possible until now to check on the frequency behavior of the different variability components as such a source enters higher luminosity states.

1E 1724−3045 is a classic low-luminosity LMXB; a persistent low-mass X-ray binary located in the globular cluster Terzan 2 (Grindlay et al. 1980), which is a metal-rich globular cluster of the galactic bulge. Its distance is estimated to be between 5.2 and 7.7 kpc (Ortolani et al. 1997). These values are consistent with that derived from a type I X-ray burst that showed photospheric expansion (see Grindlay et al. 1980; but also see Kuulkers et al. 2003; Galloway et al. 2006). The type I X-ray bursts observed from this source also indicate that the compact object is a weakly magnetized neutron star (Swank et al. 1977; Grindlay et al. 1980).

Emelyanov et al. (2002) have shown, using ~30 yr of data from several X-ray satellites, that the luminosity of Terzan 2 increased until reaching a peak in 1997, after which it started to decrease. They suggest that the evolution of the donor star or the influence of a third star could be the cause of this behavior. Olive et al. (1998) and Barret et al. (2000a) have shown that during earlier observations of Terzan 2 its X-ray variability at frequencies ≥0.1 Hz resembled that of black hole candidates. This state was tentatively identified as the extreme island state for atoll sources. Until now, no kilohertz quasi-periodic oscillations have been reported for this source, which was attributed to the fact that the source was always observed in a single intensity state (Barret et al. 2000b).

Monitoring observations by the All Sky Monitor aboard the Rossi X-Ray Timing Explorer showed that the source was weakly variable in X-rays (less than about a factor of 3 on a few day timescale for the first 8 yr of the monitoring). However, recently Markwardt & Swank (2004) reported (using PCA monitoring observations of the galactic bulge; Swank & Markwardt 2001) that during 2004 February, 1E 1724−3045 flared up from its relatively steady ~20 to ~66 mcram (2−10 keV). In this paper we report a complete study of the timing variability of the source. For simplicity, and since only one bright X-ray source is detected in the globular cluster (see § 4.1), in the rest of this report we refer to 1E 1724−3045 as Terzan 2.

2. OBSERVATIONS AND DATA ANALYSIS

2.1. Light Curves and Color Diagrams

We use data from the Rossi X-Ray Timing Explorer (RXTE) Proportional Counter Array (PCA; for instrument information, see Zhang et al. 1993; Jahoda et al. 2006). There were 534 slew observations until 2006 October 30, which are part of the PCA monitoring observations of the galactic bulge (Swank & Markwardt 2001) and which were performed typically every 3 days. These observations were only used to study the long-term LX behavior of the source.

There were also 99 pointed observations in the nine data sets we used (10090-01, 20170-05, 30057-03, 50060-05, 60034-02, 80105-10, 80138-06, 90058-06, and 91050-07), containing ~0.8 to ~26 ks of useful data per observation. We use the 16 s time-resolution Standard 2 mode data to calculate X-ray colors. Hard and soft color are defined as the 9.7−16.0/6.0−9.7 keV and 3.5−6.0/2.0−3.5 keV count rate ratio, respectively, and intensity as the 2.0−16.0 keV count rate. The energy-channel conversion was done using the pca_e2c_e05v02 table provided by the RXTE Team. Channels were linearly interpolated to approximate these precise energy limits. X-ray type I bursts were removed, background was subtracted and dead-time corrections were made. In order to correct for the gain changes as well as the differences in effective area between the PCUs themselves, we normalized our colors by the corresponding Crab Nebula color values (see Kuulkers et al. 1994; van Straaten et al. 2003; see Table 2 in Altamirano et al. 2008 for average colors of the Crab Nebula per PCU) that are closest in time but in the same RXTE gain epoch, i.e., with the same high voltage setting of the PCUs (Jahoda et al. 2006).

2.2. Fourier Timing Analysis and Fitting Models

For the Fourier timing analysis we used either the Event modes E..125us..64M..0..1s or E..16us..64M..0..8s, or the Good Xenon data. Leahy-normalized power spectra were constructed using data segments of 128 and 1/8192 s time bins such that the lowest available frequency is 1/128 ~ 8 × 10−3 Hz and the Nyquist frequency 4096 Hz. No background or dead-time corrections were performed prior to the calculation of the power spectra. We first averaged the power spectra per observation. We inspected the shape of the average power spectra at high frequency (>2000 Hz) for unusual features in addition to the usual Poisson noise. None were found. We then subtracted a Poisson noise spectrum estimated from the power between 3000 and 4000 Hz, using the method developed by Klein-Wolt (2004) based on the analytical function of Zhang et al. (1995). In this frequency range, neither intrinsic noise nor QPOs are expected based on what we observe in other sources. The resulting power spectra were converted to squared fractional rms (van der Klis 1995). In this normalization the power at each Fourier frequency is an estimate of power density such that the square root of the integrated power density equals the fractional rms amplitude of the intrinsic variability in the source count rate in the frequency range integrated over.

In order to study the behavior of the low-frequency components usually found in the power spectra of neutron star LMXBs, we needed to improve the statistics. We therefore averaged observations which were close in time and had both similar colors and power spectra (see, e.g., van Straaten et al. 2002, 2003, 2005; Altamirano et al. 2005; and references within; see also the Appendix in Altamirano et al. 2008 for a discussion on other possible methods).

5 See http://heasarc.gsfc.nasa.gov/docs/xte/pca_news.html.
To fit the power spectra, we used a multi-Lorentzian function: the sum of several Lorentzian components plus, if necessary, a power law to fit the very low frequency noise (VLFN; see van der Klis 2006 for a review). Each Lorentzian component is denoted as $L_i$, where $i$ denotes the type of component. The characteristic frequency ($\nu_{\text{max}}$ as defined below) of $L_i$ is denoted $\nu_{i}$. For example, $L_h$ identifies the upper kHz QPO and $\nu_{h}$ its characteristic frequency. By analogy, other components go by names such as $L_{l}$ (lower kHz), $L_{low}$ (lower Lorentzian), $L_{halo}$ (hectohertz), $L_{b}$ (hump), $L_{b_2}$ (break frequency), $L_{b_2}$ (second break frequency), and their frequencies as $\nu_{l}$, $\nu_{low}$, $\nu_{halo}$, $\nu_{h}$, and $\nu_{b}$, $\nu_{b_2}$, respectively. Using this multi-Lorentzian function makes it straightforward to directly compare the characteristics of the different components observed in Terzan 2 to those in previous works which used the same fit function (e.g., Belloni et al. 2002; van Straaten et al. 2003, 2005; Altamirano et al. 2005, 2008 and references therein).

Unless stated explicitly, we only include those Lorentzians in the fits whose single trial significance exceeds 3 $\sigma$ based on the error in the power integrated from 0 to $\infty$. We give the frequency of the Lorentzians in terms of characteristic frequency $\nu_{\text{max}}$ as introduced by Belloni et al. (2002): $\nu_{\text{max}} = \nu_{0} + (\text{FWHM}/2)^{1/2} = \nu_{0} [1 + (4Q^{2})^{1/2}]$. For the quality factor $Q$ we use the standard definition $Q = \nu_{0}/\text{FWHM}$; $\nu_{0}$ the centroid frequency of the Lorentzian. The quoted errors use $\Delta \chi^2 = 1.0$. The upper limits quoted in this paper correspond to a 95% confidence level ($\Delta \chi^2 = 2.7$).

2.3. Energy Spectra

Since the energy spectra of the quiet state (see § 3.1) of Terzan 2 have already been studied in previous works (see, e.g., Olive et al. 1998; Barret et al., 2000a), in this paper we concentrate on the 14 observations that sample the flaring period (see § 3.1). In all 14 cases, we used data of both the PCA and the HETE instruments.

For the PCA, we only used the Standard 2 data of PCU 2, which was active in all observations. The background was estimated using the PCABACKEST version 6.0 (see FTOOLS). We calculated the PCA 2 response matrix for each observation using the FTOOLS routine PCARSP V10.1. For the HETE instrument, spectra were accumulated for each cluster separately. Dead-time corrections of both source and background spectra were performed using HXTDEAD V6.0. The response matrices were created using HXTRSP V3.1. For both PCA and HETE, we filtered out data recorded during, and up to 30 minutes after passage through the South Atlantic Anomaly (SAA). We only use data when the pointing offset from the source was less than 0.02 degrees and the elevation of the source with respect to the Earth was greater than 10 degrees. We did not perform any energy selection prior to the extraction of the spectra. Finally, we fitted the energy spectra using XSPEC V11.3.2.1.

2.4. Search for Quasi-Periodic Variations over Days and Months

Recently, Wen et al. (2006) have performed a systematic search for periodicities in the light curves of 458 sources using data from the RXTE All Sky Monitor (ASM). Terzan 2 was not included in their analysis, probably due to the fact that the ASM source average count rate is low: 2.05 ± 0.01 counts s$^{-1}$ (the average of the errors $1/n \sum_{\text{err}}^{-1}$ is 0.8 count s$^{-1}$).

Since the PCA galactic bulge monitoring (Swank & Markwardt 2001) has observed the source for more than 8 yr, and the lowest detected source count rate was $170 \pm 5$ counts s$^{-1}$, this new data set provides useful information to search for long term modulations. Lomb-Scargle periodograms (Lomb 1976; Scargle 1982; Press et al. 1992) as well as the phase dispersion minimization technique (PDM; see Stellingwerf 1978) were used. The Lomb-Scargle technique is ideally suited to look for sinusoidal signals in unevenly sampled data. The phase dispersion minimization technique is well suited to the case of nonsinusoidal time variation covered by irregularly spaced observations.

3. RESULTS

3.1. The Light Curve

Figure 1 shows both the PCA monitoring light curve of the source (see top panel and Swank & Markwardt 2001) and the Crab normalized intensity (see bottom panel and § 2.1) of each pointed observation versus time (in units of modified Julian date MJD = Julian Date − 2, 400, 000.5). In the rest of this paper, we will refer as “quiet period” to that between MJD 51214 and 52945, and as “flaring period” between MJD 52945 and 53666.

During the quiet period, 333 monitoring measurements of the source intensity and 85 pointed observations sample the behavior of the source. The count rate slowly decreases from an average of $\sim 300$, to an average of $\sim 190$ counts s$^{-1}$ 5PCU$^{-1}$ at an average rate of $-0.059 \pm 0.002$ count s$^{-1}$ day$^{-1}$. In the flaring period, seven flares sampled with 201 monitoring observations were detected with the galactic bulge scan. Fourteen pointed observations partially sampled parts of four of these flares. In Table 1 we list approximate dates at which the flux transitions occurred, the flare durations and the maximum count rates detected with the PCA. As mentioned in § 2.4, the monitoring is done approximately once every three days; additional gaps in the data are present due to visibility windows. As of course we do not have details of flares that may have occurred during these gaps, the information in Table 1 is only approximate. In Figure 2 we show the intensity of the source during the flaring period. We label the different flares F1, F2, F3, F4, F5, F6, and F7 in order of time of occurrence.

We detected three Type I X-ray bursts. One was during the quiet-state observation 10090-01-01-021 and two during the flaring-state observations 80138-06-06-00 and 90058-06-02-00. A detailed study of these X-ray bursts as well as a comparison to bursts observed in other sources can be found in Galloway et al. (2006).

3.2. Color Diagrams; Identification of States

Figure 3 (top) shows the color-color diagram of the 99 pointed observations. For comparison, we also include the color-color diagram of the atoll source 4U 1608−52, which has been observed in all extreme island, island, and banana states (Fig. 3, bottom). The similarity in shape suggests that Terzan 2 underwent state transitions during observations of the flares. Based on Figure 3 we can identify the probable extreme island, island, and banana state with the hardest, intermediate, and softest colors, respectively. Since partially sampled patterns in the color-color diagrams are not necessarily unambiguous, (see review by van der Klis 2006), power spectral analysis (below) is required to confirm these identifications. The extreme island state is sampled with 85 pointed observations which are clumped in two regions at similar hard colors but at significantly different soft colors. We find three observations in the island state. They sampled the lowest luminosity sections of flares F2, F3, and F5 (see Fig. 2). The banana state is sampled by 11 pointed observations: seven during F1, three during F2 and 1 during F3. The identifications above are strengthened by the similarities in power spectral shapes between Terzan 2 and those reported in other sources (van Straaten et al. 2002, 2003, 2005; Di Salvo et al., 2001, 2003; Linares et al. 2005; Altamirano...
et al. 2005, 2008; Migliari et al. 2005). In the following sections we describe the power spectra in more detail.

3.3. kHz QPOs

We searched each averaged observation’s power spectrum for the presence of significant kHz QPOs at frequencies $\geq$400 Hz. As reported in other works (Barret et al. 1999; Belloni et al. 2002), during the quiet period the power spectra of single averaged observations show significant power up to $\lesssim$300 Hz which is fitted with broad ($Q \approx 0.5$) Lorentzians plus if necessary, one sharp Lorentzian to account for $L_{LF}$. During the flaring period, we found that several observations show power excess above 400 Hz. For each observation we fitted the averaged power spectra between 400 and 2000 Hz with a model consisting of one Lorentzian and a constant to take into account the QPO and Poisson noise, respectively. In five of the 14 observations that sample the flaring period, we detect significant QPOs, with single trial significances up to $6.5 \sigma$. In Table 2 we present the results of our fits and information on these observations. As can be seen, the first three observations were performed during the rise of the first flare while the fourth and fifth observations where done during the decay of the second flare (see Fig. 2). As can be seen in Table 2, there are significant frequency variations. Unfortunately, due to the sparse coverage of the flares and the fact that we cannot detect the QPO on shorter timescales than an observation, no further conclusions are possible.

We do not significantly detect two simultaneous kHz QPOs in any of the five observations. In order to search for a possible second kHz QPO, we used the shift-and-add method as described by Méndez et al. (1998b). We first tried to trace the detected kilohertz QPO using a dynamical power spectrum (e.g., see Fig. 2 in Berger et al. 1996) to visualize the time evolution of the QPO frequency, but the signal was too weak to be detected on timescales shorter than the averaged observation. Therefore, for each observation we used the fitted averaged frequency (see Table 2) to shift each kilohertz QPO to the arbitrary frequency of 770 Hz. Next, the shifted, aligned, power spectra were averaged. The average power spectrum was finally fitted in the range 300–2048 Hz so as to exclude the edges, which are distorted due to the shifting method. To fit the averaged power spectrum, we used a function consisting of a Lorentzian and a constant to fit the QPO and the Poisson noise, respectively. We studied the residuals of the fit, but no
significant power excess was present apart from the 770 Hz feature. In Figure 4 we show the fitted kHz QPO for observation 80138-06-02-00 (no shift and add was applied) and the shifted-and-added kHz QPO detected with the method mentioned above. Since it is known that the kHz QPOs become stronger at higher energies (e.g., Berger et al. 1996; Méndez et al. 1998a; van der Klis 2000 and references within), we repeated the analysis described above (which was performed on the full PCA energy range), using only data at energies higher than \( \text{E}>6\) keV or higher than \( \text{E}>10\) keV. Again, no significant second QPO was present. It is important to note that this method can produce ambiguous results as we cannot be sure we are always shifting the same component (either \( L_u \) or \( L_v \)). We also tried different subgroups, i.e., adding only two to three different observations, but found the same results.

To investigate the energy dependence of the kHz QPOs, we divided each power spectrum into 3, 4, or 5 energy intervals in order to have approximately the same count rate in all the intervals. We then produced the power spectrum as described in § 2 and refitted the data where both frequency and \( Q \) were fixed to the values obtained for the full energy range (see Table 2). In Figure 5 we show the results for the representative kHz QPOs in flares F1 and F2 (observations 80138-06-03-00 and 90058-06-02-00, respectively). Similarly to what is observed in other sources, the fractional rms amplitude of the kHz QPOs increases with energy. The data show that there is no significant difference in the energy dependence of the kHz QPO at \( \text{E}>599\) Hz with that at \( \text{E}>772\) Hz.

### 3.4. Averaged Power Spectrum

As mentioned in § 2.2, in order to study the behavior of the low-frequency components usually found in the power spectra of neutron star LMXBs, we needed to improve the statistics. We therefore averaged observations which were close in time and had both similar colors and power spectra. The resulting data selections are labeled from A to R (ordered mainly in time; see Fig. 6).

### Table 1: Data on the Six Flares Observed until MJD 53,667

| Time Interval (MJD) | Duration (day) | Maximum Count Rate (counts s\(^{-1}\) 5PCU\(^{-1}\)) | Flare Label | No. of Pointed Observations Sampling the Flare |
|---------------------|---------------|---------------------------------|-------------|---------------------------------|
| ~53,038–53,071      | 33            | ~850                            | F1          | 7                               |
| ~53,127–53,155      | 28            | ~950                            | F2          | 4                               |
| ~53,233–53,250      | 17            | ~830                            | F3          | 2                               |
| ~53,493–53,502      | 9             | ~450                            | F4          | 0                               |
| ~53,566–53,620      | 36            | ~1150                           | F5          | 1                               |
| ~53,631–53,651      | 20            | ~650                            | F6          | 0                               |
| ~53,934–53,972      | 38            | ~865                            | F7          | 0                               |

Notes.—See § 3 for details. The modified Julian date is defined as MJD = Julian Date – 2,400,000.5.

![Figure 2](image_url)
components were needed to fit all the power spectra of this

interval and their colors). Their corresponding average power
spectra are displayed in Figure 6 and the fit results are displayed
in Table 4.

Table 3 for details on which observations were used for each
interval and their colors). Their corresponding average power
spectra are displayed in Figure 6 and the fit results are displayed
in Table 4.

3.4.1. The Power Spectra of the Quiet Period

Intervals A–L are all part of the quiet segment. Four to six
components were needed to fit all the power spectra of this
group, where 11 out of the 12 power spectra showed significant
broad components at ~150, ~10, ~1, and ~0.2 Hz. Interval G is
the exception where the broad component at ~150 Hz was not
significantly detected (8.5% rms-amplitude upper limit). A QPO
(Q > 2) at ~0.8 Hz was also significantly detected in 11 out of 12
power spectra, interval B being the exception (1.4% rms-amplitude
upper limit). Finally, an extra component (Lv), where v stands for “very low”) at frequency νv ~ 0.1 Hz was detected only in
interval C.

Similar power spectra have been reported in the extreme island
state of the atoll sources 4U 0614+09, 4U 1728–34 (van
Straaten et al. 2002), XTE J1118+480, SLX 1735–269 (Belloni
et al. 2002), and 4U 1608–52 (van Straaten et al. 2003). Olive
et al. (1998) and Belloni et al. (2002) analyzed an early subset of
the data we present in this work. Our results are consistent with
the frequencies reported in those works. Following van Straaten
et al. (2002), Belloni et al. (2002), and van Straaten et al. (2003),
we identify the components as Lω, Llow, Lh, L LF, and Lh, where νω ~ 150 Hz,νlow ~ 10 Hz, νh ~ 1 Hz, νLF ~ 0.8 Hz and νh ~ 0.1 Hz,
respectively. These identifications are strengthened by the
similarities between both figures suggest that Terzan 2 has been observed
in similar states as 4U 1608–52.

3.4.2. The Power Spectra of the Flaring Period

Intervals M, N, O, P, Q, and R are part of the flaring period.

For intervals M, N and Q, high-frequency (~400 Hz) single
QPOs are seen, which can be identified as either the lower or the
upper kHz QPO.

The kHz QPOs in interval M and N correspond to the averages
of significant QPOs observed in single observations. As seen in
Table 2, the characteristic frequency of the kHz QPOs averaged
in each of the two intervals are within a range of 50 Hz. By our
averaging method we are affecting the

features at lower frequencies (see Appendix in Altamirano
et al. 2008 for a discussion on this issue).

Interval Q is an average of three single observations (see
Table 3) that individually do not show significant QPOs (Q > 2)
at high frequencies, although low-Q power excess can be measured. Lh in interval Q is only 2.6 σ significant (single trial) but
required for a stable fit.

Interval O shows a broad component at 30.5 ± 6.3 Hz and a
3.3% rms low-frequency noise. In this case, the very low
frequency noise was fitted with a broad Lorentzian because a power
law gave an unstable fit. The excess of power at ν ~ 1000 Hz is
less than 3 σ significant. Interval P shows a power spectrum with
a power-law low-frequency noise, and two Lorentzian components
at frequencies 15.5 ± 1.6 and 30.5 ± 6.3 Hz (see Fig. 6). In this
case the high χ²/dof = 218/163 reveals that the Lorentzians do not
satisfactorily fit the data. As can be seen in Figure 6, there is a steep
decay of the power above ν ~ 35 Hz and power excess at ~70 Hz.
A fit with three Lorentzians becomes unstable. To further investig-
tigate this, we refitted the power spectrum using instead two
Gaussians and one power law to fit the power at ν ≤ 40 Hz, and
one Lorentzian to fit the possible extra component at ~70 Hz.
The steeper Gaussian function better fits the steep power decay than
the Lorentzians. In this fit, with three more free parameters, we
obtain a χ²/dof = 188/160, and the Lorentzian at 69.1 ± 2.6 Hz
becomes 3.4 σ single-trial significant. This power spectrum is

Fig. 3.—Top: Hard color vs. soft color normalized to Crab as explained in § 2. Different symbols represent the selections used for averaging the power spectra as explained in § 2 and shown in Fig. 6 (see Fig. 1 for symbols). The arrow marks observation 90058-06-04-00, which was excluded from interval N (see § 3). Bottom: Hard color vs. soft color normalized to Crab for the NS source 4U 1608–52. This source has been observed in all expected atoll states: extreme island state (EIS), island state (IS), lower left banana (LLB), lower banana (LB), and upper banana (UB). The similarity between both figures suggest that Terzan 2 has been observed
in similar states as 4U 1608–52.
very similar to those reported by Migliari et al. (2004, 2005) for the atoll sources 4U 1820−30 and Ser X-1, respectively. Besides the similarity in shape of the power spectrum, it is interesting to note that in both cases these authors found a best fit with components at similar frequencies to the ones we observe in Terzan 2 and which they interpreted as \( v_{\text{Hz}} \), \( v_{\text{Hz}} \), and \( v_{\text{Hz}} \). This coincidence suggests that the sources were in very similar states. To our knowledge, no systematic study of this state has been reported as yet.

Interval R consists of only one observation (90058-06-05-00) of 1.4 ks of data. In addition to a power law with index \( \alpha = 3.1 \pm 0.7 \), we detect one Lorentzian at 68.5 ± 7.2 Hz. Its frequency is rather high if we compare it with the other power spectra presented in this paper and even when compared with results in other sources (see Fig. 8). This result might be due to blending of components due to the low statistics present in this power spectrum.

From the 99 pointed observations, only observation 90058-06-04-00 was not included in any of the averages described above. The averaged colors of this observation are similar to those of interval N (observations 90058-06-01-00, 90058-06-02-00) but the power spectrum does not show a significant QPO at \( v_{\text{Hz}} = 23.6 \pm 3.3 \text{ Hz} \), \( Q = 0.5 \pm 0.2 \), and \( \text{rms} = 13.2\% \pm 0.9\% \). The residuals of the fit

| MJD                  | ObsId     | Used in Interval | \( \nu_0 \) (Hz) | FWHM     | \( Q \) | rms (%) | Significance \( \sigma \) | Counts s\(^{-1}\) (5PCU) |
|----------------------|-----------|------------------|------------------|----------|--------|---------|--------------------------|--------------------------|
| 53,054.94.............| 80138-06-02-00 | M                | 731 ± 3          | 33.2 ± 7.3 | 22.1 ± 4.8 | 10.4 ± 0.8 | 6.5                      | ~665                     |
| 53,055.00.............| 80138-06-02-01 | M                | 764 ± 2          | 14.3 ± 5.2   | 53.4 ± 19.4 | 6.9 ± 0.8  | 4.3                      | ~690                     |
| 53,056.69.............| 80138-06-03-00 | M                | 772 ± 1          | 15.1 ± 4.2   | 51.1 ± 14.2 | 7.1 ± 0.6  | 5.6                      | ~660                     |
| 53,145.57.............| 90058-06-01-00 | N                | 559 ± 2          | 17.3 ± 6.9   | 32.3 ± 12.8 | 6.6 ± 0.7  | 4.7                      | ~765                     |
| 53,147.21.............| 90058-06-02-00 | N                | 599 ± 1          | 20.3 ± 4.8   | 29.5 ± 6.9  | 7.4 ± 0.5  | 6.6                      | ~610                     |

Fig. 4.—Fit to the kHz QPO in observation 80138-06-02-00. In the subplot on the top right of the figure, we show the fit to the data after using the shift-and-add method on all five observations reported in Table 2 where the main peak was set to the arbitrary frequency \( \nu = 770 \text{ Hz} \) (see § 3.3). No significant detections of a second kHz QPO were found.
Fig. 5.—Energy dependence of two representative kHz QPOs of Terzan 2. One in flare F1 (pentagons; ObsID 80138-06-03-00) and another in flare F2 (downward-pointed triangles; ObsID 90058-06-02-00). For comparison we show the energy dependence of both lower (circles and open squares) and upper (squares) peak of the atoll source 4U 1608–52 (Berger et al. 1996; Méndez et al. 1998b) and the upper peak (upward-pointed triangles) of the atoll source 4U 0614+09 (Méndez et al. 1997; van Straaten et al. 2000). [See the electronic edition of the Journal for a color version of this figure.]

### TABLE 3

**Observations Used for the Timing Analysis**

| Observation       | Soft Color (Crab) | Hard Color (Crab) | Intensity (Crab) |
|-------------------|-------------------|-------------------|------------------|
| **Interval A**    |                   |                   |                  |
| 10090-01-01-00    | 1.3615 ± 0.0017   | 1.0760 ± 0.0013   | 0.0389 ± 0.0001  |
| 10090-01-01-001   | 1.3508 ± 0.0019   | 1.0761 ± 0.0014   | 0.0384 ± 0.0001  |
| 10090-01-01-002   | 1.3619 ± 0.0019   | 1.0757 ± 0.0015   | 0.0382 ± 0.0001  |
| 10090-01-01-020   | 1.3783 ± 0.0021   | 1.0781 ± 0.0016   | 0.0386 ± 0.0001  |
| 10090-01-01-021   | 1.4145 ± 0.0019   | 0.9846 ± 0.0013   | 0.0468 ± 0.0001  |
| 10090-01-01-022   | 1.3638 ± 0.0017   | 1.0788 ± 0.0013   | 0.0387 ± 0.0001  |
| 10090-01-01-02   | 1.3723 ± 0.0039   | 1.0801 ± 0.0029   | 0.0389 ± 0.0001  |
| **Interval B**    |                   |                   |                  |
| 20170-05-01-00    | 1.3501 ± 0.0075   | 1.0660 ± 0.0058   | 0.0383 ± 0.0001  |
| 20170-05-02-00    | 1.3440 ± 0.0077   | 1.0492 ± 0.0059   | 0.0384 ± 0.0001  |
| 20170-05-03-00    | 1.3498 ± 0.0076   | 1.0541 ± 0.0058   | 0.0389 ± 0.0001  |
| 20170-05-04-00    | 1.3449 ± 0.0073   | 1.0632 ± 0.0056   | 0.0394 ± 0.0001  |
| 20170-05-05-00    | 1.3492 ± 0.0071   | 1.0703 ± 0.0055   | 0.0398 ± 0.0001  |
| 20170-05-06-00    | 1.3392 ± 0.0072   | 1.0650 ± 0.0056   | 0.0394 ± 0.0001  |
| 20170-05-07-00    | 1.3465 ± 0.0072   | 1.0726 ± 0.0055   | 0.0393 ± 0.0001  |
| 20170-05-08-00    | 1.3295 ± 0.0071   | 1.0605 ± 0.0056   | 0.0382 ± 0.0001  |
| 20170-05-09-00    | 1.3398 ± 0.0070   | 1.0704 ± 0.0054   | 0.0389 ± 0.0001  |
| 20170-05-10-00    | 1.3163 ± 0.0064   | 1.0687 ± 0.0051   | 0.0387 ± 0.0001  |
| 20170-05-11-00    | 1.3601 ± 0.0077   | 1.0714 ± 0.0054   | 0.0400 ± 0.0001  |
| 20170-05-12-00    | 1.3365 ± 0.0074   | 1.0747 ± 0.0058   | 0.0399 ± 0.0001  |
| 20170-05-13-00    | 1.3532 ± 0.0070   | 1.0721 ± 0.0053   | 0.0409 ± 0.0001  |
| 20170-05-14-00    | 1.3215 ± 0.0076   | 1.0768 ± 0.0061   | 0.0407 ± 0.0001  |
| 20170-05-15-00    | 1.3417 ± 0.0070   | 1.0658 ± 0.0054   | 0.0394 ± 0.0001  |
| 20170-05-16-00    | 1.3398 ± 0.0081   | 1.0669 ± 0.0062   | 0.0398 ± 0.0001  |
| 20170-05-17-00    | 1.3290 ± 0.0072   | 1.0832 ± 0.0057   | 0.0386 ± 0.0001  |
| 20170-05-18-00    | 1.3318 ± 0.0086   | 1.0682 ± 0.0067   | 0.0392 ± 0.0001  |
| 20170-05-19-00    | 1.3336 ± 0.0068   | 1.0667 ± 0.0053   | 0.0395 ± 0.0001  |
| 20170-05-20-00    | 1.3309 ± 0.0069   | 1.0599 ± 0.0054   | 0.0397 ± 0.0001  |

**Notes.**—The colors and intensity are corrected by dead time and normalized to the Crab Nebula (see § 2).

Table 3 is published in its entirety in the electronic edition of the Astrophysical Journal. A portion is shown here for guidance regarding its form and content.
Fig. 6.—Power spectra and fit functions in the power spectral density times frequency representation. Each plot corresponds to a different region in the color-color and color-intensity diagrams (see Figs. 3 and 1). The curves mark the individual Lorentzian components of the fit. The rebinning varies between the panels to balance the frequency resolution with the signal-to-noise ratio. For a detailed identification, see Table 4.
| Characteristic Frequency (Hz) | rms (%) | Component ID |
|-------------------------------|---------|--------------|
| **Interval A**                |         |              |
| 156.9 ± 6.6.                  | 0.25 ± 0.06 | 13.9 ± 0.4 \(L_a\) |
| 11.5 ± 0.2.                   | 0.04 ± 0.03 | 17.6 ± 0.3 \(L_{low}\) |
| 1.05 ± 0.01.                  | 0.47 ± 0.02 | 16.3 ± 0.3 \(L_b\) |
| 0.820 ± 0.006.                | 5.76 ± 0.87 | 3.3 ± 0.3 \(L_{LF}\) |
| 0.171 ± 0.005.                | 0.32 ± 0.06 | 12.4 ± 0.6 \(L_b\) |
| **Interval B**                |         |              |
| 200.1 ± 11.6.                 | 0.55 ± 0.09 | 12.6 ± 0.5 \(L_a\) |
| 19.1 ± 1.5.                   | *         | 13.2 ± 0.2 \(L_{low}\) |
| 2.59 ± 0.05.                  | 0.40 ± 0.04 | 13.6 ± 0.4 \(L_b\) |
| 0.40 ± 0.02.                  | *         | 12.2 ± 0.2 \(L_b\) |
| **Interval C**                |         |              |
| 148.4 ± 6.8.                  | 0.27 ± 0.05 | 13.8 ± 0.3 \(L_a\) |
| 9.7 ± 0.1.                    | *         | 18.6 ± 0.1 \(L_{low}\) |
| 0.86 ± 0.01.                  | 0.55 ± 0.02 | 15.1 ± 0.3 \(L_b\) |
| 0.633 ± 0.007.                | 6.2 ± 1.2  | 3.1 ± 0.3 \(L_{LF}\) |
| 0.158 ± 0.006.                | *         | 14.5 ± 0.3 \(L_b\) |
| 0.106 ± 0.006.                | 1.94 ± 1.02 | 3.4 ± 0.03 \(L_{a/1}\) |
| **Interval D**                |         |              |
| 130.8 ± 7.4.                  | 0.21 ± 0.07 | 13.1 ± 0.3 \(L_a\) |
| 8.5 ± 0.20.                   | *         | 18.5 ± 0.1 \(L_{low}\) |
| 0.74 ± 0.01.                  | 0.53 ± 0.03 | 14.5 ± 0.3 \(L_b\) |
| 0.512 ± 0.004.                | 6.5 ± 0.9  | 3.9 ± 0.2 \(L_{LF}\) |
| 0.131 ± 0.005.                | *         | 15.4 ± 0.2 \(L_b\) |
| **Interval E**                |         |              |
| 169.2 ± 8.6.                  | 0.31 ± 0.07 | 13.6 ± 0.4 \(L_a\) |
| 10.8 ± 0.2.                   | 0.01 ± 0.04 | 18.2 ± 0.3 \(L_{low}\) |
| 0.92 ± 0.01.                  | 0.45 ± 0.03 | 16.6 ± 0.3 \(L_b\) |
| 0.750 ± 0.006.                | 7.8 ± 1.8  | 2.8 ± 0.2 \(L_{LF}\) |
| 0.144 ± 0.004.                | 0.34 ± 0.07 | 12.7 ± 0.6 \(L_b\) |
| **Interval F**                |         |              |
| 216.1 ± 2.2.                  | 17.9 ± 8.4 | 3.1 ± 0.5 \(L_{a/1}\) |
| 161.4 ± 17.0.                 | 0.14 ± 0.13 | 14.2 ± 0.8 \(L_a\) |
| 12.1 ± 0.5.                   | 0.10 ± 0.07 | 16.6 ± 0.6 \(L_{low}\) |
| 1.21 ± 0.04.                  | 0.44 ± 0.04 | 15.6 ± 0.5 \(L_b\) |
| 0.93 ± 0.01.                  | 3.5 ± 0.9  | 4.4 ± 0.6 \(L_{LF}\) |
| 0.179 ± 0.009.                | 0.09 ± 0.04 | 13.8 ± 0.3 \(L_b\) |
| **Interval G**                |         |              |
| 17.5 ± 2.4.                   | *         | 19.6 ± 0.5 \(L_{low}\) |
| 1.17 ± 0.07.                  | 0.3 ± 0.1  | 16.4 ± 1.1 \(L_b\) |
| 0.716 ± 0.008.                | 11.28 ± 5 | 4.1 ± 0.6 \(L_{LF}\) |
| 0.152 ± 0.016.                | *         | 16.4 ± 0.7 \(L_b\) |
| **Interval H**                |         |              |
| 131.7 ± 15.8.                 | 0.3 ± 0.1  | 13.2 ± 0.8 \(L_a\) |
| 9.6 ± 0.4.                    | *         | 18.5 ± 0.2 \(L_{low}\) |
| 0.892 ± 0.026.                | 0.47 ± 0.04 | 14.3 ± 0.4 \(L_b\) |
| 0.634 ± 0.006.                | 4.6 ± 0.8  | 4.3 ± 0.4 \(L_{LF}\) |
| 0.133 ± 0.005.                | *         | 16.3 ± 0.2 \(L_b\) |

**Notes.**—The quoted errors use \(\Delta \chi^2 = 1.0\). Where only one error is quoted, it is the straight average between the positive and the negative error. Asterisks indicate broad Lorentzians whose quality factor was fixed to 0.

* This component is not at 3 \(\sigma\) significant. However, without this component the fit becomes unstable (see § 3.4).

b For this component, no clear identification was possible.
show excess power at ±800 Hz but no significant kHz QPO. Although the colors of observation 90058-06-04-00 are similar from Aql X-1 and the two low-luminosity bursters GS 1826−44 (Altamirano et al. 2008), using these correlations to identify the candidates and neutron star systems (see, e.g., Homan et al. 2001). This type of correlation has been already observed in black hole island and banana state correlate with the averaged hard color.

In order to study the rms amplitude dependence on color and intensity, we calculated the average integral power per observation between 0.1 and 1000 Hz. In Figure 9 we show the 0.01−1000 Hz averaged rms amplitude (%), of each of the 99 observations, versus its average hard color. The observations which sample the island and banana state correlate with the averaged hard color. These types of correlation have been already observed in black hole candidates and neutron star systems (see, e.g., Homan et al. 2001). At colors harder than 1.0, there are two clumps (Fig. 9, gray squares), which can also be seen in the color−color diagram (Fig. 3). They both correspond to observations of the extreme island state (quiet state) of the source. As we show in Figure 6, the power spectral shape remains approximately the same with time. However, for a given hard color, the total rms amplitude can change up to ±30%. No correlation with time, intensity or soft color was found and these changes are seen within a small range in intensity (less than 4 mcrab). Similar results are also observed when the rms amplitude is calculated in the 0.01−300 Hz range.

3.5. Integrated Power

In order to study the rms amplitude dependence on color and intensity, we calculated the average integral power per observation between 0.1 and 1000 Hz. In Figure 9 we show the 0.01−1000 Hz averaged rms amplitude (%), of each of the 99 observations, versus its average hard color. The observations which sample the island and banana state correlate with the averaged hard color. These types of correlation have been already observed in black hole candidates and neutron star systems (see, e.g., Homan et al. 2001). At colors harder than 1.0, there are two clumps (Fig. 9, gray squares), which can also be seen in the color−color diagram (Fig. 3). They both correspond to observations of the extreme island state (quiet state) of the source. As we show in Figure 6, the power spectral shape remains approximately the same with time. However, for a given hard color, the total rms amplitude can change up to ±30%. No correlation with time, intensity or soft color was found and these changes are seen within a small range in intensity (less than 4 mcrab). Similar results are also observed when the rms amplitude is calculated in the 0.01−300 Hz range.

3.6. Comparing Terzan 2 with other LMXBs

3.6.1. The Flaring Period

In Figure 10 we plot the frequency correlations between $L_{\text{LF}}$ and $L_h$ reported by Psaltis & Chakrabarty (1999) and updated by Belloni et al. (2002). In Figure 8 we plot the characteristic frequency of all components versus that of $\nu_u$ for the atoll sources 4U 0614+09, 4U 1728−34, 4U 1608−52, 4U 1636−53 and Aql X-1 and the two low-luminosity bursters GS 1826−24 and SLX 1735−269 (van Straaten et al. 2002, 2003; Reig et al. 2004; Altamirano et al. 2008). Using these correlations to identify the highest frequencies we observe (in intervals M, N, and Q) as either $\nu_u$ or $\nu_l$ presents a problem. Both interpretations give consistent results since the correlations observed are complex when $\nu_u \gtrsim 600$ Hz (van Straaten et al. 2005).

In recent work, Barret et al. (2005a, 2005b, 2005c) have systematically studied the variation of the frequency, rms amplitude and the quality factor $Q$ of the lower and upper kHz QPOs in the low-mass X-ray binaries 4U 1636−53, 4U 1608−52, and 4U 1735−44. Although $Q$ depends on the frequency of the component, these authors show that $Q_k$ is always above ~30, while $Q_u$ is generally below ~25. By comparing our results for the kHz QPOs with those of Barret et al. (2005a, 2005b, 2005c) we find that the five QPOs listed in Table 2 (and averaged in intervals M and N) are relatively high-$Q$ and hence consistent with being $L_k$, but also still consistent with being $L_u$. The quality factor of the kHz QPO found in interval Q is low (2.4 ± 0.6) and hence this kHz QPO is probably $L_u$.

In Figure 11 we plot the fractional rms amplitude of all components (except $L_{\text{LF}}$) versus $\nu_u$ for the four atoll sources 4U 0614+09, 4U 1728−34, 4U 1608−52, and 4U 1636−53. With respect to the kHz QPO identification, the interpretation that we found $L_k$ in interval N is strengthened by the rms amplitudes of the two low-frequency components found in the averaged power spectrum. If the QPO we observe is not $L_k$ but $L_u$, then the low-frequency QPO pairs can be identified as either $L_{\text{LF}}-L_h$ or $L_{\text{LF}}-L_Q$. For $\nu_u = 586.1 \pm 6.6$, the pair $L_{\text{LF}}-L_h$ is not consistent with what we observe for other atoll sources (Fig. 11), since $L_h$ is not seen with rms amplitude as low as 3.9 ¿ 0.5%. The pair $L_{\text{LF}}-L_Q$ is not consistent with the data either, since $L_Q$ is always observed at $\nu_u \gtrsim 800$ Hz. If the QPO is $L_k$, then based on what we observe in other well-studied sources (Méndez et al. 1998b; Méndez & van der Klis 1999; Di Salvo et al. 2003; Barret et al. 2005b; van der Klis 2006; Méndez & Belloni 2007) we expect that the frequency difference between kHz QPOs is $\Delta_\nu = \nu_u - \nu_l \approx 300$ and therefore $\nu_u \approx \nu_l + 300 \approx 586 + 300 \approx 886$ Hz. Under this assumption (i.e., $\Delta_\nu \approx 300$) and by using the same reasoning as above, then only the pair $L_{\text{LF}}-L_Q$ is consistent with the data. In the case of interval M, only one component is found at low frequencies with an rms amplitude of 6.4 ± 0.6%. This result is consistent with several interpretations when compared with the data shown in Figure 11. Therefore, for interval M we cannot improve confidence in the identification of the kHz QPO using Figure 11.

In Figures 8, 10, and 11 we have plotted the data for Terzan 2 based on the identifications above. As discussed later in this paper, such identifications need to be confirmed.

3.6.2. The Quiet Period

In Figure 11 we show that the rms amplitude of $L_{\text{LF}}, L_{\text{low}}, L_h,$ and $L_u$ in Terzan 2 approximately follow the trend observed for other sources. Since Psaltis & Chakrabarty (1999) interprets $L_{\text{low}}$ as the same component in different source states, in Figure 11 we plot the data for both components together. Of course, in Figure 11 and Figure 8 as well, there is the well-known gap between these two components. Regarding lower frequency components, the point inside the circle represents our result for $L_{\text{low}}$ in interval C, which is the weakest component found in the EIS of Terzan 2. We plotted our results with those for Di Salvo et al. (2003) and Belloni et al. (2002). The Quiet Period

In Figure 11 we show that the rms amplitude of $L_{\text{low}}, L_{\text{low}}, L_h,$ and $L_u$ in Terzan 2 approximately follow the trend observed for other sources. Since Psaltis & Chakrabarty (1999) interprets $L_{\text{low}}$ as the same component in different source states, in Figure 11 we plot the data for both components together. Of course, in Figure 11 and Figure 8 as well, there is the well-known gap between these two components. Regarding lower frequency components, the point inside the circle represents our result for $L_{\text{low}}$ in interval C, which is the weakest component found in the EIS of Terzan 2. We plotted our results with those for Di Salvo et al. (2003) and Belloni et al. (2002).
Fig. 8.—Characteristic frequencies $v_{\text{max}}$ of the various power spectral components plotted vs. $v_\nu$. The gray symbols mark the atoll sources 4U 0614+09, 4U 1728–34 (van Straaten et al. 2002), 4U 1608–52 (van Straaten et al. 2003), Aql X-1 (Reig et al. 2004), and 4U 1636–53 (Altamirano et al. 2008) and the low-luminosity bursters Terzan 2 (previous results), GS 1826–24 and SLX 1735–269 (but see also Belloni et al. 2002; van Straaten et al. 2005). The black bullets mark our results for Terzan 2. Note that we only plot the results for intervals A–N and O (note that as mentioned in § 3.6.1, the points for intervals M and N ($v_\nu > 800$ Hz) were plotted under the assumption that $v_\nu = v_\nu + 300$ Hz). For intervals O, P, and R no kHz QPOs were detected (see § 3.4).
for the soft component of the spectra and a power law to account for the hard component. In some cases, it was necessary to add a Gaussian to take into account the iron Kα line (6.4 keV; see, e.g., White et al. 1986). We ignore energies below 2.5 and above 20 keV for the HEXTE spectra (see, e.g., Barret et al. 2000a). In most cases, it is not possible to well constrain the interstellar absorption in the energy range 2–20 keV. We therefore opted to fix $n_{\text{H}}$ to the value $n_{\text{H}} = 1.2 \times 10^{22}$ H atoms cm$^{-2}$ (in the Wisconsin cross section model; see Morrison & McCammon 1983) based on previous ASCA/BeppoSAX results (Olive et al. 1998; Barret et al. 1999, 2000a).

Assuming a distance of 6.6 kpc, we found that all 14 observations have luminosities between $\sim 0.4$ and $\sim 1.35 \times 10^{37}$ ergs s$^{-1}$ in the energy range 2–20 keV. We also found that at high energies (20–200 keV) the luminosities of most observations were less than $0.09 \times 10^{37}$ ergs s$^{-1}$. The exceptions are the three observations which sample the island state, which show 20–200 keV luminosities of $\sim 0.16$, $\sim 0.23$, and $\sim 0.29 \times 10^{37}$ ergs s$^{-1}$ (observations 90058-06-03-00, 90058-06-06-00 and 91050-07-01-00, respectively). This may be compared with observations of the brightest interval of the quiet period of Terzan 2, which have averaged luminosities $L_{1-20\text{keV}} = 0.81 \times 10^{37}$ ergs s$^{-1}$ and $L_{20-200\text{keV}} = 0.48 \times 10^{37}$ ergs s$^{-1}$ (Barret et al. 2000a). Clearly, in between the flares the luminosity can drop to similarly low values as in the quiet period. This is consistent with the light curve we show in Figure 1. We note that the observations studied by Barret et al. (2000a) correspond to MJDs 50,391–50,395 (1996 November 4–8) and sample the brightest part of the quiet period of this source observed with RXTE (see Fig. 1).

We are particularly interested in the luminosity at which the kHz QPOs are detected in Terzan 2 compared with other sources. Ford et al. (2000) have measured simultaneously the properties of the energy spectra and the frequencies of the kHz QPOs in 15 low-mass X-ray binaries covering a wide range of X-ray luminosities. The observations of intervals M and N (see Table 1) have average luminosities $L_{2-50\text{keV}}/L_{\text{Edd}}$ between 0.025 and 0.04 (where $L_{\text{Edd}} = 2.5 \times 10^{38}$ ergs s$^{-1}$). The three observations that sample the island state (interval Q) have average luminosity $L_{2-50\text{keV}}/L_{\text{Edd}} \approx 0.02$. This means that during the flares, Terzan 2 shows kHz QPOs at similar luminosities to the atoll sources Aql X-1, 4U 1608–52, 4U 1702–42, and 4U 1728–34 (see Fig. 1 in Ford et al. 2000).

3.8. Lomb Scargle Periodograms

During the quiet period (51214–52945 MJD), we found no significant periodicities using either the Lomb-Scargle or the PDM techniques in the full data set nor in subintervals. As shown in Figure 1, the flares seem to occur every $\sim 60$–100 days. Both Lomb-Scargle and the PDM techniques confirm this with a significant signal of period $P \sim 90.55$ days. In Figure 12 we show the PCA light curve (top) versus a 20 bin 90.55 days period folded light curve (bottom). The folded light curve matches the occurrence of most of the flares. However, it is clear that the flares are not strictly periodic. For example, F3 seems to occur later and F6 occur earlier than expected. Furthermore, it is not possible to say if F7 is an early or late flare, or even a blend of two flares (we observed a small flare which peaked at $\approx 53,926$ MJD, followed by a big one which peaked at $\approx 53,958$ MJD). Although there are gaps in the data, Figure 12 suggests that some flares do not occur at all (see arrow).

4. DISCUSSION

4.1. Contamination by a Second Source in the Same Field of View?

As shown in Figure 1, the luminosity of the source slowly decreases with time during the quiet period 51214–52945 MJD. Although the rms amplitude changes up to 30% (see Fig. 9), the X-ray timing characteristics are very similar (see intervals A–L in Fig. 6). During the 53,000–53,700 MJD period, the source shows flares which show different X-ray timing characteristics consistent with the island and banana states observed in other atoll sources (see, e.g., van Straaten et al. 2003, 2005; Belloni et al. 2002; Altamirano et al. 2005, 2008). A possible mechanism of the observed flux variations in Terzan 2 could be the emergence of a second X-ray source in this globular cluster unresolved by the 1″ (FWHM) field of view of the PCA. If two sources are observed simultaneously with RXTE, then we would expect to see power spectra which are a combination of the intrinsic time variability of both sources.

To further investigate this, we compared the absolute rms amplitude that we observe both in the quiet and flaring states.
Observation 80105-10-01-00 is the last observation performed during the quiet period from which we measured an average source count rate of $\frac{200}{\text{counts s}^{-1}}$. The integrated power between $7.8\text{ to }10$ and $1$ Hz is $\frac{3}{\text{counts s}^{-1}}$, which corresponds to a fractional rms amplitude of $18\%$. If we repeat the analysis using the second RXTE observation during the flaring state (80138-06-02-00), the discrepancy is higher. This observation has an average source countrate of $\frac{405}{\text{counts s}^{-1}}$ and the upper limit for the absolute rms amplitude in the $7.8$ to $10$ Hz frequency range is five counts s$^{-1}$.

Given the characteristics of the power spectra, flares cannot be explained by assuming that another source has emerged, unless Terzan 2 turned off at the same time that the other X-ray source turned on, which is unlikely. Therefore, we conclude that the flux transitions are intrinsic to the only low-mass X-ray binary detected in the globular cluster Terzan 2: 1E 1724–30 (Revnivtsev et al. 2002).

4.2. The kHz QPOs, Different States, and Their Transitions

The results presented in this paper show that the low-luminosity source 1E 1724–3045 in the globular cluster Terzan 2 can be identified as an atoll source. This is the first time a source previously classified as weak burst source (see, e.g., Belloni et al. 2002; van Straaten et al. 2003, and references within) showed other states than those of the extreme island state, confirming previous suggestions that these sources are atoll sources. We have identified the new states as the island and banana states based on comparisons between color-color diagrams of different sources and the characteristics of the power spectra. We have detected at least one of the kHz QPOs, and as explained in §3.4.2 and 3.3, in five cases we may be detecting the lower kHz QPO (intervals M and N; see also Table 2) and in one case the upper one (interval Q). No simultaneous twin kHz QPOs were detected within any of

![Fractional rms amplitude of all components (except $L_{\text{QPO}}$) plotted vs. $v_{\nu}$. The symbols are labeled in the plot. The data for 4U 1728–34, 4U 1608–52 and 4U 0614+09 were taken from van Straaten et al. (2005). The data for 4U 1636–53 were taken from Altamirano et al. (2008). Note that for $L_{\text{QPO}}$ and $L_{\text{QPO}}'$ of 4U 1608–52, the three triangles with vertical error bars which intersect the abscissa represent 95% confidence upper limits (see van Straaten et al. 2003 for a discussion). The points inside the circle represent our results for $L_{\text{M}}$ while the points inside the square represent results for $L_{\text{QPO}}$ (see §4 for a discussion). Note that as mentioned in §3.6.1, the points for intervals M and N ($v_{\nu} > 800$ Hz) were plotted under the assumption that $v_{\nu} = v_{\nu} + 300$ Hz.](image)
the 14 observations that sample the flares. Future observations of flares will allow us to confirm these identifications and might allow us to detect both kHz QPOs simultaneously.

We found that the frequencies of the various components in the power spectra of Terzan 2 followed previously reported relations (Figs. 8 and 10). Terzan 2 is a particularly important source in the context of these frequency correlations because it is one of the few neutron star sources that has been demonstrated to show power spectral features that reach frequencies as low as \( \approx 0.1 \) Hz, which is uncommon for neutron star low-mass X-ray binaries, but not for black holes. Our results demonstrate that in each of the flares, Terzan 2 undergoes flux transitions that, if directly observed, would probably allow us to resolve current ambiguities in the identification of components, such as the case of \( L_{\text{low}} \) component in atoll sources. This component is interpreted by some authors as a broad lower kHz QPO at very low frequencies (see Psaltis & Chakrabarty 1999; Nowak 2000; Belloni et al. 2002) which becomes peaked at higher frequencies, while other authors interpret \( L_{\text{f}} \) and \( L_{\text{low}} \) as different components (see, e.g., discussion in van Straaten et al. 2003). Another example is the identification of the upper kHz QPO at low frequencies. Van Straaten et al. (2003) have suggested that the broad component observed at \( \approx 150 \) Hz in the EIS of atoll sources becomes the peaked upper kHz QPO \( L_{\text{p}} \). These authors based their interpretation on the frequency correlations shown in Figure 8. Nevertheless, as van Straaten et al. (2003) argue, these identifications should be taken as tentative. One way to confirm the link between them would be to observe the gradual transition from one to another one.

During the time between flares, the source shows intensities similar to those measured before the quasi-periodic flares started. Unfortunately, there are no observations during those intervals, but we expect that then Terzan 2 shows X-ray variability similar to that reported in intervals A–L. If this is the case, the state transition between the extreme island state and the island state should be observable in observations at the beginning or at the end of each flare. Given the relatively gradual and predictable transitions, Terzan 2 becomes the best source known up to now to study these important transitions.

4.3. On the \( \sim 90 \) Days Flare Recurrence

The quasi-periodic variations over days and months observed in some LMXBs X-ray light-curves are generally associated with the possible precession period of a tilted accretion disk or alternatively long term periodic variations in the accretion rate or periodic outbursts of X-ray transients. Some examples are the \( \sim 35 \) cycle in Her X-1 which is thought to be caused by a varying obscuration of the neutron star by a tilted-twisted precessing accretion disk; the \( \sim 170 \) days accretion cycle of the atoll source 4U 1820–30, (Priedhorsky & Terrell 1984a; Simon 2003); the 122–125 day cycle in the outbursts of the recurrent transient Aql X-1 (Priedhorsky & Terrell 1984b; Kitamoto et al. 1993). Understanding the mechanisms that trigger the long-term variability associated with variations in the accretion rate of LMXBs can allow us to better predict, within each source, when the state transitions occur. This is useful because these transitions are usually fast and therefore difficult to observe.

The power spectra of our observations of Terzan 2 during the flaring confirm that the source undergoes EIS-IS-LLB-LB-UB state transitions, as observed in other neutron star atoll systems (and not as seen for Z-sources; see reviews by van der Klis 2006 and references within). As the source increased in X-ray luminosity, we found that the components in the power spectra increased in frequency which is consistent with the interpretation that the accretion disk is moving inwards toward the compact object. Therefore, the flaring with average 90 days period is most probably an accretion cycle. We note that the modulation of the light-curve could be related to the orbital period of the system or set by the precession of a tilted disk. However, the mechanisms involved in those interpretations are very unlikely to affect the frequency of the kHz QPOs.

If the flares are explained as an accretion cycle, then it is puzzling why the source underwent a smooth decrease of \( L_X \) for \( \sim 8 \) yr before it started to show the flares. Terzan 2 may not be the only source that shows this kind of behavior. For example, KS 1731–260 is a low-luminosity burster that has shown a high \( L_X \) phase, during which Revnivtsev & Sunyaev (2003) reported a possible \( \sim 38 \) days period, and a low \( L_X \) phase, during which much stronger variability was observed (which was described as red noise). After its low \( L_X \) phase, KS 1731–260 has turned into quiescence (Wijnands et al. 2002a, 2002b. In Figure 13 we show the bulge scan light curve of the source during the low \( L_X \) phase. At MJD \( \sim 51,550 \) the source reached very low intensities, then
flared up again for $\approx 250$ days to finally turn into quiescence. The low luminosities are confirmed by the ASM light curve (not plotted).

Recently, Shih et al. (2005) reported that the persistent atoll source 4U 1636–53 has also shown a period of high $L_X$ followed by a period of low $L_X$. During high $L_X$, no long-term periodicity was found, but a highly significant $\approx 46$ days period was observed after its $L_X$ decline.

These similar patterns of behavior might point toward a common mechanism, which then must be unaffected by the intrinsic differences between these sources.

For example, while Terzan 2 remained with approximately constant luminosity in its extreme island state for $\approx 8$ yr before showing long term periodicities, 4U 1636–53 and KS 1731–260 were observed with variable luminosity and in different states, including the banana state in which the kHz QPOs were found (see, e.g., Wijnands et al. [1997] and Shih et al. [2005] for 4U 1636–53, and Wijnands & van der Klis [1997] and Revnivtsev & Sunyaev [2003] for KS 1731–260). While Terzan 2 reached a maximum luminosity of $L_X/L_{Edd} \approx 0.02$ during one of the flares, 4U 1636–53 shows similar luminosities only at its lowest $L_X$ levels (while it has reached $L_X/L_{Edd} \approx 0.15$; see Altamirano et al. 2008). Further differences may be related to whether these systems are normal or ultracompact binaries. While 4U 1636–53 is not ultracompact (see below), in ‘t Zand et al. (2007) has recently proposed that Terzan 2 may be classified as ultracompact based on measurements of its persistent flux, long burst recurrence times and the hard X-ray spectra. If the luminosity behavior of these sources is related, the differences outlined above suggest that the mechanism that triggers the modulation of the light curve at low $L_X$ may not depend on the accretion history, the luminosity of the source or even whether the system is ultracompact or not. The modulation period may depend on these factors.

Unfortunately, we cannot compare the orbital periods and the companions of the three systems, as these are only known for 4U 1636–53 ($\approx 3.8$ hr and $\approx 0.4$ $M_\odot$; Casares et al. 2006). Nevertheless, with the present data it is already possible to exclude some mechanisms. For example, mass transfer feedback induced by X-ray irradiation (Osaki 1985) is unlikely. In this model, X-ray radiation from the compact object heats the companion star surface, causing enhancement of the mass accretion rate in a runaway instability. However, in Osaki’s (1985) scenario, it is not clear how the system could remember the phase of the cycle if one of the flares is missed or if the size of the flares differs much. Flares F4 and F5 in Terzan 2, independently of the other two sources, may already raise an objection to this model. Although we miss part of F4 due to a gap in the data, Figure 1 shows that F4 was quite short (less than 9 days), while F5 was the longest ($\approx 36$ days) and strongest flare.

Shih et al. (2005) have suggested that the atoll source 4U 1636–53 may turn into quiescence after its low $L_X$ period, as was observed for KS 1731–260. Such an observation for 4U 1636–53 as well as for Terzan 2 would give credibility to the link between these sources. To our knowledge, there is no model which predicts such behavior.

4.4. Energy Dependence as a Tool for kHz QPO Identification

Homan & van der Klis (2000) discovered a single 695 Hz QPO in the low-mass X-ray binary EXO 0748–676 and identified this QPO as the lower kHz QPO. These authors based their identification on the fact that at that time (1) from the 11 kHz QPO pairs found in atoll sources, eight had ranges of lower peak frequencies that include 695 Hz, which was the case for only three of the upper peaks and (2) the upper peaks in atoll sources generally had $Q$ lower than $\approx 14$, while their QPO had $Q \approx 38$, value more common for lower peaks. While from Figure 8 it can be seen that (1) is not valid anymore, since the upper kHz QPOs have been detected down to 300–400 Hz (and possibly down to $\leq 100$ Hz; see § 3.4.1), at these low frequencies $L_u$ is usually much broader than they observed, which confirms their identification (see § 3.6.1 and Barret et al. 2005a, 2005b, 2005c).

Homan & van der Klis (2000) also based their identification on the comparison of the energy dependence of the QPO with that of the two kilohertz peaks in 4U 1608–52, which have rather different energy dependencies (the power-law rms–energy relation for $L_c$ is steeper than that for $L_u$; see Berger et al. 1996; Méndez et al. 1998b, 2001). Similarly, Méndez et al. (2001) use the same method to strengthen the identification of the single kHz QPO observed in the atoll source Aql X–1. To further investigate if this method could be used to identify the sharp kHz QPOs we report in § 3.3, in Figure 5 we compare the energy dependence of the kHz QPOs in 4U 1608–52 (Berger et al. 1996; Méndez et al. 1998b, 2001) and 4U 0614+09 (Méndez et al. 1997) with that of Terzan 2. The data for Terzan 2 seem to fall in between those for $L_c$ and $L_u$ of 4U 1608–52 but shows a completely different behavior than the data of 4U 0614+09. The fact that the rms amplitude of the upper kHz QPO in 4U 0614+09 and 4U 1608–52 are significantly different (by up to a factor of 3) and that the data for Terzan 2 fall in between those of $L_c$ and $L_u$ in 4U 1608–52 show that the method does not lead to unambiguous results. Mean source luminosity, instantaneous luminosity and instantaneous QPO frequency may all affect QPO energy dependence in addition to QPO type.

5. SUMMARY

1. We presented a detailed study of the time variability of the atoll source 1E 1724–3045 (Terzan 2) which includes, for the first time, observations of this source in its island and banana states confirming the atoll nature of this source. We find that the different states of Terzan 2 show timing behavior similar to that seen in other NS-LMXBs. Our results for the extreme island state are consistent with those previously reported in Belloni et al. (2002) and van Straaten et al. (2003).

2. We report the discovery of kilohertz quasi-periodic oscillations (kHz QPOs). Although we do not detect two kHz QPOs simultaneously or significant variability above 800 Hz, the detection of the lower and the upper kHz QPOs at different epochs and the power excess found at high frequencies (such as the case in intervals O or observation 90058-06-04-00) suggest that simultaneous twin kHz phenomena as well as significant variability up to $\approx 1100$ Hz (or more) is probable.

3. By comparing the dependence of the rms amplitude with energy of kHz QPOs in the atoll sources 4U 1608–52, 4U 0614+09, and Terzan 2, we show that this dependence appears to differ between sources and therefore cannot be used to unambiguously identify the kilohertz QPOs in either $L_u$ or $L_c$, as previously thought.

4. We studied the flux transitions or flares observed since 2004 February and from the source state changes observed we conclude that they are due to aperiodic changes in the accretion rate.

5. State transitions between the extreme island state and the island state should be observable in observations at the beginning or at the end of each flare. Given the relatively gradual and predictable transitions, Terzan 2 becomes the best source known up to now to study such transitions.
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