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 they trace in an X-ray color-color diagram (CCD) on timescales of hours to days. The Z sources are the most luminous; the atoll sources cover a much wider range in luminosities (e.g., Ford et al. 2000 and references therein). For each type of source, several spectral/timing states are identified which are thought to arise from qualitatively different inner flow configurations. In the case of atoll sources, the main three 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. Each state is characterized by a unique combination of CCD and timing behavior. The EIS and IS occupy the spectrally harder parts of the CCD corresponding to lower X-ray luminosity ($L_X$). The different patterns they show in the CCD are traced out in days to weeks. The hardest and lowest $L_X$ state is generally the EIS, which shows strong low-frequency flat-topped noise. The IS is spectrally softer than the EIS. Its power spectrum is characterized by broad features and a dominant band-limited noise (BLN) component which becomes stronger and lower in characteristic frequency as the flux decreases and the $>6$ keV spectrum gets harder. In order of increasing $L_X$, we encounter the LLB, where the twin kHz quasi-periodic oscillations (QPOs) are first observed; the LB, where dominant 10 Hz BLN occurs; 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 IS become narrower (peaked) and occur at higher frequency. The twin kHz QPOs can be found in the LLB at frequencies in excess of 1000 Hz; only one is seen in the LB, and no kHz QPOs are detected in the UB (see reviews by Hasinger & van der Klis [1989] and van der Klis [2000, 2006] for detailed descriptions of the different states).

The source 4U 1636−53 is an atoll source (Hasinger & van der Klis 1989) which has an orbital period of $\sim 3.8$ hr (van Paradijs et al. 1990) and a companion star with a mass of $\sim 0.4 M_\odot$ (assuming a NS of $\sim 1.4 M_\odot$; see Giles et al. 2002 for a discussion). It was first observed as a strong continuous X-ray source (Norma X-1) with Copernicus (Willmore et al. 1974) and Uhuru (Giacconi et al. 1974). It is an X-ray burst source (Hoffman et al. 1977) which shows asymptotic burst oscillation frequencies of $\sim 581$ Hz (see, e.g., Zhang et al. 1997; Giles et al. 2002). This is probably the approximate spin frequency; although Miller (1999) presented evidence that these oscillations might actually be the second harmonic of a NS spin frequency of $\sim 290$ Hz, this was not confirmed in further work by Strohmayer (2001a). Prins & van der Klis (1997) studied the aperiodic timing behavior of 4U 1636−53 with the EXOSAT Medium Energy instrument up to frequencies of $\sim 100$ Hz in both the IS and the banana state. Wijnands et al. (1997), using observations with the Rossi X-Ray Timing Explorer (RXTE), discovered two simultaneous QPOs near 900 and 1176 Hz when the source was in the banana state. The frequency difference $\Delta \nu$ between the two kHz QPO peaks is nearly equal to half the burst oscillation frequency, similar to what has been observed in other sources with burst oscillations or pulsation frequencies $>400$ Hz. To the extent that this implies $\Delta \nu \sim \nu_{\text{spin}}/2$, this is inconsistent with spin-orbit beat-frequency models (Wijnands et al. 2003) for the kHz QPOs such as proposed by Miller et al. (1998). Other complications for beat-frequency models include the fact that $\Delta \nu$ is neither constant (e.g., in Sco X-1; van der Klis et al. 1997) nor exactly equal to half the burst oscillation frequency. Generally, $\Delta \nu$ decreases as the kHz QPO frequency increases,
and in 4U 1636–53, observations have shown $\Delta\nu$ at frequencies lower, as well as higher, than half the burst oscillation frequency (Méndez et al. 1998b; Jonker et al. 2002a).

Van Straaten et al. (2002, 2003) compared the timing properties of 4U 0614+09, 4U 1608–52, and 4U 1728–34 and concluded that the frequencies of the variability components in these sources follow the same pattern of correlations. Di Salvo et al. (2003), based on five detections of kHz QPOs in 4U 1636–53 in the banana state, were able to show that, at least in that state, the source might fit in with that same scheme of correlations. The detailed investigation of 4U 1636–53 is important because it is one of the most luminous atoll sources (Ford et al. 2000) that shows the full complement of ISs (this paper) and banana states and also shares other timing features with often less luminous atoll sources. For example, Revnivtsev et al. (2001) found a new class of low-frequency QPOs in the mHz range, which they suggested were associated with nuclear burning in 4U 1636–53 and 4U 1608–52. Méndez (2000) and Méndez et al. (2001) compared the relations between kHz QPOs; inferred mass accretion rates in 4U 1728–34, 4U 1608–52, Aql X-1, and 4U 1636–53; and showed that the dependence of the frequency of one of the kHz QPOs on X-ray intensity is complex but similar among sources. Jonker et al. (2000a) discovered a third kHz QPO in 4U 1608–52, 4U 1728–34, and 4U 1636–53 which is likely an upper sideband to the lower kHz QPO. Recently, Jonker et al. (2005) found in 4U 1636–53 an additional (fourth) kHz QPO, likely the corresponding lower sideband.

In this paper we present new results for low-frequency noise (LFN) with characteristic frequencies of 1–100 Hz and QPOs in the range 100–1260 Hz, for the first time including RXTE observations of the IS of this source. These results better constrain the timing behavior in the various states of 4U 1636–53. We compare our results mainly with those of the atoll sources 4U 0614+09, 4U 1608–52, and 4U 1728–34 and find that the frequency of the hectohertz component may not be constant, as previously stated, but may have a sinusoidal modulation within its range from $\sim 100$ to $\sim 250$ Hz. Our results also suggest that the mechanism that sets the frequency of the hHz QPOs differs from that for the other components, while the amplitude-setting mechanism is common. Finally, we demonstrate that it is not possible to clearly distinguish between two harmonics of the low-frequency QPO $L_{HF}$ across different sources, as was previously thought (van Straaten et al. 2003).

2. OBSERVATIONS AND DATA ANALYSIS

We use data from the RXTE Proportional Counter Array (PCA; for instrument information, see Zhang et al. 1993). There were 149 pointed observations in the five data sets we used (60032-01, 60032-05, 70036-01, 80425-01, and 90409-01), each consisting of a fraction of one to several entire satellite orbits, for $\sim 1$ to $\sim 26$ ks of useful data per observation. We use the 16 s time-resolution Standard 2 mode data to calculate X-ray colors as described in Altamirano et al. (2005). Hard and soft colors 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 ratios, respectively, and intensity as the 2.0–16.0 keV count rate. Type I X-ray 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 Proportional Counter Units (PCUs) themselves, we normalize our colors by the corresponding Crab Nebula color values (see Kuulkers et al. 1994; van Straaten et al. 2003) 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). In Table 1 we show for reference the allEpoch averaged colors for the Crab Nebula. All active PCUs were used to calculate the colors in 4U 1636–53, except in observation 60032-01-01-02, where, due to a PCU3 malfunction, we only used PCUs 0 and 2. Figure 1 shows the CCD of the 149 different observations that we used for this analysis, and Figure 2 shows the corresponding hardness-intensity diagrams (soft and hard color vs. intensity).

For the Fourier timing analysis we used data from the $\sim 125$ $\mu$s (1/8192 s) time-resolution Event mode E_125us_64M_0_1s. First,
we used a 2 s binned light curve in order to detect and remove data
dropouts and X-ray bursts (these data were also excluded from the
rest of the analysis). Leahy normalized power spectra were con-
structed using data segments of 128 and 1/8192 s time bins such
that the lowest available frequency was $1/128 \approx 8 \times 10^{-3}$ Hz and
the Nyquist frequency was 4096 Hz. No background or dead-time
corrections were made prior to the calculation of the power spec-
tra. We first averaged the power spectra per observation. We in-
spected 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,
where neither intrinsic noise nor QPOs are known to be present,
using the method developed by Klein-Wolt (2004) based on the
analytical function of Zhang et al. (1995). The resulting power
spectra were converted to squared fractional rms (van der Klis
1995). In this normalization the square root of the integrated
power density equals the variance of the intrinsic variability in
the source count rate. In order to improve the statistics, observa-
tions were averaged together if they described the same source
state. Since it is known from previous work on similar sources that
the position of the source in the CCD generally is well correlated
to its spectral/timing state (see, e.g., van der Klis 2006 and refer-
ences within), we first grouped observations with similar colors.
Within each group, we then compared the shape of each average
power spectrum with all of the others to create subgroups in which
all power spectra had a dependence of power on frequency that
was identical within the errors. So, narrow features had to be at the
same frequency for average power spectra to be added together.
The resulting data selections are labeled as intervals A to N (see

![Fig. 2.— Soft color vs. intensity (left) and hard color vs. intensity (right) in units of the Crab Nebula, as explained in § 1. Symbols are the same as in Fig. 1. For clarity, the dashed line separates the observations corresponding to the IS (left) from the observations corresponding to the banana state (right).](image)

**TABLE 2**

| Observation     | Soft Color (Crab) | Hard Color (Crab) | Intensity (Crab) |
|-----------------|-------------------|-------------------|------------------|
| Interval A1     |                   |                   |                  |
| 80425-01-04-01... | 1.2306 ± 0.0034   | 1.0493 ± 0.0032   | 0.0557 ± 0.0001  |
| Interval A2     |                   |                   |                  |
| 80425-01-03-00... | 1.2097 ± 0.0056   | 1.0585 ± 0.0053   | 0.0400 ± 0.0001  |
| 90409-01-01-00   | 1.1945 ± 0.0049   | 1.0590 ± 0.0049   | 0.0370 ± 0.0001  |
| 90409-01-01-01   | 1.1954 ± 0.0032   | 1.0403 ± 0.0031   | 0.0418 ± 0.0001  |
| 90409-01-02-00   | 1.2002 ± 0.0040   | 1.0424 ± 0.0042   | 0.0487 ± 0.0001  |

**Notes.**—The colors and intensity are normalized to the Crab (see § 2). Table 2 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.
Table 2 for details on which observations were used for each interval and their colors). A disadvantage of this method is that we can lose information about narrow features moving on time-scales shorter than an observation, such as the lower kHz QPO (see, e.g., Berger et al. 1996; Di Salvo et al. 2003). The “shift-and-add” method (Méndez et al. 1998a) might be able to compensate for this to some extent; we explore this issue in the Appendix. Our method is the best-suited one to study the behavior of the broad features such as typically seen in LMXBs’ power spectra (e.g., van Straaten et al. 2002, 2003, 2005; Altamirano et al. 2005; Linares et al. 2005). For these broad components, which are the main aim of this paper, the gain in signal-to-noise ratio due to this averaging process outweighs a minor additional broadening due to frequency variations.

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 VLFN at ≤1 Hz. Each Lorentzian component is denoted as \( L_i \), where \( i \) determines the type of component. The characteristic frequency (\( \nu_{\text{max}} \), as defined below) of \( L_i \) is denoted \( \nu_i \). For example, \( L_u \) identifies the upper kHz QPO and \( \nu_u \) its characteristic frequency. By analogy, other components have names such as \( L_l \) (lower kHz), \( L_{\text{HF}} \) (hectohertz), \( L_h \) (hump), and \( L_b \) (break frequency), and their frequencies are \( \nu_l \), \( \nu_{\text{HF}} \), \( \nu_h \), and \( \nu_b \), respectively. For reference, in Figure 3 we show two representative power spectra in which we label the different components. Using this multi-Lorentzian function makes it straightforward to directly compare the different components in 4U 1636–53 to those in previous works which used the same fit function (e.g., Belloni et al. 2002; van Straaten et al. 2002, 2003, 2005; Altamirano et al. 2005 and references therein).

We only include those Lorentzians in the fits whose single-trial significance exceeds 3 \( \sigma \) based on the negative error bar in the power integrated from 0 to \( \infty \) (i.e., we include only those Lorentzians whose integral power is at least 3 times higher than zero based on the negative 1 \( \sigma \) error) and whose inclusion gives a >3 \( \sigma \) improvement of the fit according to an \( F \)-test. We give the frequency of the Lorentzians in terms of characteristic frequency \( \nu_{\text{max}} \) as introduced by Belloni et al. (2002), \( \nu_{\text{max}} = \frac{\nu_0^2 + (\text{FWHM}/2)^2}{1/2} = \nu_0 [1 + 1/4Q^2]^{1/2} \). For the quality factor \( Q \) we use the standard definition \( Q = \nu_0 / \text{FWHM} \). FWHM is the full width at half-maximum, and \( \nu_0 \) is the centroid frequency of the Lorentzian. Note that \( Q \)-values in excess of ~3 will generally be affected by smearing in an analysis such as ours. Such values are commonly seen in \( L_{\text{HF}}, L_l, \) and \( L_u \). In \$3 \) we indicate in which cases this could have occurred.

We only report the results for \( \nu_{\text{max}} \geq 1 \) Hz. The source 4U 1636–53 is one of three atoll sources which are known to show millihertz QPOs which affect the power-law behavior of the noise at ≤1 Hz (Revnivtsev et al. 2001). A different kind of analysis is needed to study these QPOs; we report the results in a separate paper (Altamirano et al. 2008).

3. RESULTS

Figures 1 and 2 show that from A to H, the spectrum becomes softer (i.e., hard and soft colors both decrease), and the intensity changes little. From H to L, the soft color remains approximately constant, but above 6 keV the spectrum becomes even steeper (i.e., the hard color decreases further), and, from interval G, the intensity increases. Finally, from L to N, below 6 keV the spectrum becomes flatter, and above 6 keV it remains approximately constant in slope, while the intensity continues increasing. Similar behavior has been observed in other atoll sources which are moving from the IS to the LLB and then to the LB state (see, e.g., van Straaten et al. 2003; Altamirano et al. 2005).

In Figure 4 we show the average power spectra A–N with their fits. Two to five Lorentzian components were needed for a good fit, except in power spectrum I, where an extra component is needed, for a total of six. Table 3 gives the fit results. Power spectra A1 and A2 have the same \( \nu_u \) within the errors and only slightly different colors. We treat these two power spectra separately because A1 could be fitted with five significant components and A2, as well as the combined spectrum A1+A2, only with three. Note that power spectrum A1 is the average of one observation (see Table 2), which was performed between the observations used for power spectrum A2. In Figure 5 we show our measured characteristic frequency correlations (black circles) together with those previously measured in other atoll sources (gray symbols). In intervals H–L, the twin kHz QPOs (\( L_u \) and \( L_l \)) are identified unambiguously. The correlation between the lower and upper kHz QPOs is the same as that found in the other atoll sources studied by...
Fig. 4.—Power spectra and fit functions in the power spectral density times frequency representation. Each plot corresponds to a different region in the CCDs and color-intensity diagrams (see Figs. 1 and 2). The curves mark the individual Lorentzian components of the fit. For detailed identification, see Table 3 and Fig. 5.
Table 3—Continued

| $v_{\text{max}}$ (Hz) | $Q$ (%) | rms (%) | ID |
|-----------------------|---------|---------|----|

Interval A1

| $v_{\text{max}}$ | $Q$ | rms | ID |
|------------------|-----|-----|----|
| 434.8 ± 26.1     | 1.6 ± 0.5 | 12.9 ± 1.4 | $L_a$ |
| 175.9 ± 8.9      | 2.7 ± 1.3 | 8.06 ± 1.23 | $L_{\text{BHz}}$ |
| 15.0 ± 0.6       | 0.7 ± 0.1 | 13.3 ± 0.7 | $L_b$ |
| 5.1 ± 0.1        | -7.3 ± 0.5 | 3.2 ± 0.6 | $L_{\text{LF}}$ |
| 3.2 ± 0.4        | 0.33 ± 0.07 | 11.1 ± 0.7 | $L_b$ |

Interval A2

| $v_{\text{max}}$ | $Q$ | rms | ID |
|------------------|-----|-----|----|
| 436.4 ± 28.2     | 0.92 ± 0.24 | 16.5 ± 1.05 | $L_a$ |
| 12.3 ± 0.8       | 0.27 ± 0.11 | 16.1 ± 1.1 | $L_b$ |
| 2.34 ± 0.52      | 0.14 ± 0.09 | 9.9 ± 1.4 | $L_b$ |

Interval B

| $v_{\text{max}}$ | $Q$ | rms | ID |
|------------------|-----|-----|----|
| 464.9 ± 9.4      | 1.7 ± 0.2 | 13.8 ± 0.9 | $L_a$ |
| 154.7 ± 4.6      | 0.53 ± 0.42 | 7.4 ± 1.8 | $L_{\text{BHz}}$ |
| 18.2 ± 0.3       | 0.75 ± 0.06 | 12.4 ± 0.4 | $L_b$ |
| 6.83 ± 0.11      | 3.07 ± 0.66 | 4.1 ± 0.5 | $L_{\text{LF}}$ |
| 4.03 ± 0.31      | 0.19 ± 0.03 | 11.9 ± 0.4 | $L_b$ |

Interval C

| $v_{\text{max}}$ | $Q$ | rms | ID |
|------------------|-----|-----|----|
| 529.3 ± 15.4     | 1.1 ± 0.1 | 17.1 ± 0.6 | $L_a$ |
| 23.1 ± 1.6       | 0.47 ± 0.15 | 11.9 ± 1.5 | $L_b$ |
| 6.38 ± 1.01      | 0.09 ± 0.05 | 13.1 ± 1.2 | $L_b$ |

Interval D

| $v_{\text{max}}$ | $Q$ | rms | ID |
|------------------|-----|-----|----|
| 524.7 ± 8.0      | 2.2 ± 0.4 | 13.9 ± 1.0 | $L_a$ |
| 201.7 ± 4.3      | 0.58 ± 0.35 | 8.6 ± 1.9 | $L_{\text{BHz}}$ |
| 23.9 ± 0.5       | 0.99 ± 0.13 | 10.5 ± 0.6 | $L_b$ |
| 9.8 ± 0.3        | 2.17 ± 0.63 | 5.2 ± 0.9 | $L_{\text{LF}}$ |
| 5.0 ± 0.7        | 0.15 ± 0.04 | 11.4 ± 0.7 | $L_b$ |

Interval E

| $v_{\text{max}}$ | $Q$ | rms | ID |
|------------------|-----|-----|----|
| 593.1 ± 4.3      | 3.1 ± 0.2 | 12.7 ± 0.4 | $L_a$ |
| 270.3 ± 17.9     | 0.63 ± 0.20 | 8.7 ± 0.8 | $L_{\text{BHz}}$ |
| 31.2 ± 1.3       | 0.85 ± 0.15 | 8.9 ± 0.7 | $L_b$ |
| 15.04 ± 0.41     | 1.6 ± 0.5 | 5.7 ± 1.2 | $L_{\text{LF}}$ |
| 8.5 ± 0.9        | 0.22 ± 0.03 | 11.2 ± 0.6 | $L_b$ |

Interval F

| $v_{\text{max}}$ | $Q$ | rms | ID |
|------------------|-----|-----|----|
| 637.2 ± 7.9      | 3.06 ± 0.32 | 15.9 ± 0.6 | $L_a$ |
| 208.7 ± 30.1     | 1.2 ± 0.6 | 7.2 ± 1.2 | $L_{\text{BHz}}$ |
| 18.7 ± 0.9       | 0.02 ± 0.04 | 16.9 ± 0.2 | $L_b$ |

Interval G

| $v_{\text{max}}$ | $Q$ | rms | ID |
|------------------|-----|-----|----|
| 780.01 ± 1.78    | 4.5 ± 0.1 | 13.6 ± 0.1 | $L_a$ |
| 152.7 ± 10.4     | 0.32 ± 0.11 | 8.7 ± 0.49 | $L_{\text{BHz}}$ |
| 23.4 ± 0.5       | 0.34 ± 0.03 | 11.6 ± 0.3 | $L_b$ |
| 3.8 ± 0.9        | 0.20 ± 0.11 | 2.8 ± 0.5 | $L_{\text{LF}}$ |

Interval H

| $v_{\text{max}}$ | $Q$ | rms | ID |
|------------------|-----|-----|----|
| 862.8 ± 1.8      | 6.2 ± 0.2 | 11.4 ± 0.1 | $L_a$ |
| 568.3 ± 4.6      | 7.06 ± 1.22 | 4.6 ± 0.2 | $L_b$ |
| 120.6 ± 1.6      | 1.34 ± 0.03 | 6.4 ± 0.3 | $L_{\text{LF}}$ |
| 26.6 ± 0.5       | 0.57 ± 0.04 | 9.2 ± 0.2 | $L_b$ |
| 4.3 ± 0.7        | 0.35 ± 0.11 | 2.7 ± 0.3 | $L_{\text{LF}}$ |

Notes.—Characteristic frequencies $v_{\text{max}}$, $Q$-values ($v_{\text{max}} = v_{\text{central}}/\text{FWHM}$), fractional rms (in the full PCA energy band), and component identification (ID) of the Lorentzians fitted for 4U 1636–53. 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 errors. Note that the results for the quality factor of both the $L_f$ and $L_{\text{LF}}$ components are affected by our averaging method (see §§3 and 1 and the Appendix).

van Straaten et al. (2003). For intervals M and N, only $L_a$ is observed.

We separately measured the centroid frequencies $v_{\text{c}}$ of the kHz QPOs (see Table 4). The centroid frequency difference $\Delta \nu$ varied between 274.6 ± 5.7 Hz (in interval K) and 316.4 ± 5.7 Hz (in interval I). These values are between the extremes found by Jonker et al. (2002a; $\Delta \nu = 330 \pm 9$ Hz) and Di Salvo et al. (2003; $\Delta \nu = 242 \pm 4$ Hz). Note that those authors used much shorter time intervals to detect the kHz QPOs and hence were more sensitive to short-lived extreme cases. Our average power spectra contain those data that are necessary to detect the broad components well, and hence our measured $\Delta \nu$ values occur at intermediate values, which is when the kHz QPOs are strongest (see, e.g., Méndez et al. 2001). Thus, our method averages out the extreme cases. In power spectrum N, $L_a$ reaches the highest
centroïd frequency found among the intervals analyzed, \(1259 \pm 10\) Hz. Note that power spectra M and N are the result of averaging large amounts of data with no significant kHz QPOs in individual observations (~2.2 \(\times 10^4\) and ~2.5 \(\times 10^5\) s, respectively), based on the position of 4U 1636–53 in the CCD. Figure 6 displays the upper kHz QPOs in power spectra M and N more clearly.

Between ~100 and ~200 Hz, a Lorentzian with a quality factor \(Q \sim 1\) is often found in atoll sources (see van der Klis 2006 and references therein). This feature is called a “hectohertz QPO.”

Figure 5.—Characteristic frequencies \(v_{\text{max}}\) of the various power spectral components vs. \(v_{\sigma}\). The filled circles mark the results for 4U 1636–53. The other symbols mark the atoll sources 4U 0614+09, 4U 1728–34 (van Straaten et al. 2002), 4U 1608–52 (van Straaten et al. 2003), and Aql X-1 (Reig et al. 2004) and the low-luminosity bursters 1E 1724–3045, GS 1826–24, and SLX 1735–269 (van Straaten et al. 2005; but also see Belloni et al. 2002).

### Table 4: Central Frequencies, FWHM, and Frequency Difference

| Interval | \(v_{\sigma}\) | FWHM\(_{1/2}\)^* | \(v_{10}\) | FWHM\(_{1/10}\)^* | \(\Delta v_{10}\) | Ratio \(v_{10}/v_{1/10}\) |
|----------|---------------|-----------------|-------------|-----------------|----------------|------------------|
| H......... | 860.4 ± 1.7   | 136.2 ± 4.8     | 565.4 ± 5.1 | 90.4 ± 12.3     | 295.0 ± 5.4     | 1.52 ± 0.01      |
| I......... | 896.8 ± 2.6   | 115.8 ± 6.3     | 580.4 ± 5.1 | 77.2 ± 12.5     | 316.4 ± 5.7     | 1.54 ± 0.01      |
| J......... | 972.1 ± 3.5   | 98.0 ± 8.7      | 661.1 ± 1.8 | 73.8 ± 4.1      | 311.0 ± 3.9     | 1.470 ± 0.006    |
| K......... | 992.9 ± 6.6   | 177.4 ± 16.9    | 718.3 ± 2.4 | 121.5 ± 6.3     | 274.6 ± 5.7     | 1.38 ± 0.01      |
| L......... | 1147.2 ± 16.6 | 123.4 ± 27.8    | 836.1 ± 0.7 | 64.1 ± 1.9      | 311.1 ± 16.6    | 1.37 ± 0.02      |

**Notes:**—The table gives the central frequencies, FWHM, and frequency difference \(\Delta v_{10}\) for the kHz QPOs for the five intervals where both kHz QPOs were detected significantly (>3 \(\sigma\)).

* Note that these values might have been affected by smearing (see text).
and, in contrast to the other components, its frequency remains confined to this relatively narrow range as \( \nu_u \) increases. When \( \nu_u \gtrsim 800 \) Hz, the twin kHz QPOs are usually identified unambiguously, as is the hHz QPO. For \( \nu_u \approx 600 \) Hz, the lower kHz QPO could also have frequencies between \( \sim 100 \) and \( \sim 300 \) Hz if it were present, which makes it difficult to classify the QPOs found in that range as either \( L_h \), \( L_{h\text{bl}} \), or a blend without more information.

In our data, this is the case for intervals A to E; in Table 3 and hereafter we identify those Lorentzians as hHz QPOs. This identification is supported by the fact that in intervals F and G, i.e., for \( 600 \) Hz < \( \nu_u < 800 \) Hz, \( L_h \) is undetected; this component seems to appear only at \( \nu_u > 800 \) Hz. Interval I shows an \( \sim 3.1 \sigma \) (singletrial) peak with \( \nu_{\text{max}} = 229 \pm 9 \) Hz, which is a factor of \( \sim 2 \) higher than the usual hHz in that range. This QPO may be the second harmonic of the hHz QPO simultaneously found at a characteristic frequency of \( 113 \pm 4 \) Hz (see Fig. 7; however, note that this feature must be interpreted with care due to its low \( 3.1 \sigma \) singletrial significance). As a result of refitting the power spectrum using centroid frequencies, we find that the second harmonic QPO is at \( \nu_0 = 228 \pm 10 \) Hz, while the first harmonic hHz QPO is at \( \nu_0 = 107 \pm 5 \) Hz for a ratio of \( 2.13 \pm 0.13 \), consistent with 2.

Figure 5 shows that \( L_h \) and \( L_b \) also lie on the correlations previously observed in other sources. However, our results show that \( \nu_u \) may anticorrelate with \( \nu_u \) at \( \nu_u \gtrsim 1100 \) Hz. This result has already been observed in Z sources; however, for atoll sources this behavior has not been observed with certainty (see §4). Here \( L_{b2} \) seems to have lower frequencies than in other atoll sources. To further investigate this, in Figure 8 we plot \( \nu_{b2} \) versus \( \nu_u \) with different symbols for each of the four atoll sources for which this component has been measured. Clearly, the range in which \( L_{b2} \) has been found for similar \( \nu_u \) is rather large (up to nearly a decade), particularly at \( \nu_u < 1000 \) Hz. We also studied the possibility that the rms of \( L_{b2} \) could be related to its frequency, but no relation was found.

Intervals A, B, D, and E show a narrow QPO with a characteristic frequency between \( \nu_u \) and \( \nu_b \) (see Table 3). For other NSs such narrow QPOs were previously reported by Yoshida et al. (1993) in 4U 1608–52; Belloni et al. (2002) in the low-luminosity bursters 1E 1724–3045 and GS 1826–24; van Straaten et al. (2002) in 4U 0614+09 and 4U 1728–34; van Straaten et al. (2003) in 4U 1608–52; Altamirano et al. (2005) in 4U 1820–30; van Straaten et al. (2005) in the accreting millisecond pulsars (AMPs) XTE J0929–314, XTE J1834–338, and SAX J1808.4–3658; and Linares et al. (2005) in XTE J1807–294. Similar features were also seen in the BHs Cyg X–1 (Pottschmidt et al. 2003) and GX 339–4 (Belloni et al. 2002; but also see van Straaten et al. 2003). Following van Straaten et al. (2003), for clarity we have omitted these QPOs (\( L_{b1} \)) from Figure 5. In Figure 9 we plot their characteristic frequencies versus \( \nu_b \). The results for 4U 1636–53 are in the range of, but seem to follow a different relation than, the two relations previously suggested by van Straaten et al. (2003) based on other sources. The \( L_{b2} \) QPOs in 4U 1636–53 cannot be significantly detected on timescales shorter than the duration of an average observation.

For completeness, in Figure 10 we plot both the fractional rms amplitude and the quality factor of the \( L_{b2} \) component versus \( \nu_u \). Although the fractional rms amplitude of 4U 1636–53 increases with \( \nu_u \), no general trend is observed among the seven sources shown in this figure. The quality factor \( Q_{b2} \) (which may have been affected by smearing; see §2) seems to be unrelated to \( \nu_u \) for all the sources shown.

In Figure 11 we plot the fractional rms amplitude of all components (except \( L_{b1} \); see Fig. 10) versus \( \nu_u \) for the atoll sources 4U 0614+09, 4U 1728–34, 4U 1608–52, and 4U 1636–53. The rms of the upper kHz QPO for all sources approximately follows the same trend: it increases up to \( \nu_u \sim 750–800 \) Hz and then starts to decrease. This seems to also be the case for \( L_{b1} \) and \( L_b \). Except for 4U 0614+09, the data suggest that at \( \nu_u \gtrsim 1100 \) Hz the rms of \( L_b \) does not decrease further but remains approximately constant. At \( \nu_u \sim 750–800 \) Hz, the rms amplitudes of \( L_{b1} \) and \( L_b \) start to decrease (see also van Straaten et al. 2003). The rms of \( L_b \) of 4U 1636–53 also seems to follow the general trends observed for the other atoll sources. Some of these results were previously reported by van Straaten et al. (2003), Méndez et al. (2001), and Barret et al. (2005a). The source 4U 1636–53 stands out based on the fact that the rms of \( L_{b2} \) and \( L_{b1} \) at \( \nu_u \lesssim 900 \) Hz is always smaller than in the other sources. Moreover, and again contrary to the other sources, in 4U 1636–53 the rms of \( L_{b2} \) remains approximately constant as \( \nu_u \) increases from \( \sim 800 \) to \( \sim 1200 \) Hz.

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**Figure 7.** Part of the power spectrum of interval I, showing the twin kHz QPOs and the hHz QPO and its possible harmonic. This is a Leahy normalized power spectrum with no Poisson noise subtraction.
In Figure 12 we plot the quality factors $Q_{\nu}$, $Q'_{\nu}$, and $Q_{\text{Hz}}$ versus $\nu_{\text{low}}$ and $\nu_{\nu}$. The symbols are labeled in the plot and represent the frequencies of the QPOs in the atoll sources 4U 1728–34, 4U 0614+09, 4U 1608–52, and 4U 1820–30; the BHC Cyg X-1 and GX 339–4; the low-luminosity bursters 1E 1724–3045 and GS 1826–24, and the AMPs XTE J0929–314, XTE J1814–338, and SAX J1808.4–3658 (van Straaten et al. 2003, 2005; Altamirano et al. 2005). The filled triangles show the results for 4U 1636–53. The solid line indicates a power-law fit to the $Q_{\nu}$ vs. $\nu_{\nu}$ relation of the low-luminosity bursters 1E 1724–3045 and GS 1826–24 and the BHC GX 339–4. The dashed line shows a power law with a normalization half that of the solid line. Bottom: Zoom of the high-frequency region.

In Figure 12 we plot the quality factors $Q_{\nu}$, $Q_{\nu}$, and $Q_{\text{Hz}}$ versus $\nu_{\nu}$. As noted in §2, the $Q$-values of $L_{\nu}$ and, to a lesser extent, $L_{\nu}$ have likely been affected by smearing. The $Q$-values of the other components are not plotted, since they are usually broad. The data on 4U 1636–53 are in general agreement with what was found using similar methods on the other sources (van Straaten et al. 2002). Here $Q_{\nu}$ increases monotonically with $\nu_{\nu}$ until $\nu_{\nu} \sim 900-1000$ Hz. At this frequency, $Q_{\nu}$ seems to decrease for all sources, only to immediately increase again as $\nu_{\nu}$ increases. Here $Q_{\nu}$ shows rather random behavior due to smearing (see Di Salvo et al. [2003] and Barret et al. [2005a, 2005b] for $Q_{\nu}$ measurements less affected by smearing); we display this quantity in Figure 12 for comparison to previous works using the same method.

Here $Q_{\text{Hz}}$ shows complicated behavior. To further investigate this behavior, we first rebinned the $Q_{\text{Hz}}$ data by a factor of 3 and fitted a straight line. The best fit gives $\chi^2/\text{dof} = 93/12 \sim 7.7$. Since the data appear to show two bumps separated by a minimum creating a roughly sinusoidal pattern, we also tried to fit a straight line plus a sine wave. The best fit has $\chi^2/\text{dof} = 16.9/9 \sim 1.8$, which gives a 3.4 $\sigma$ improvement of the fit based on an $F$-test.

In Figure 5 it can be seen that $\nu_{\text{Hz}}$ appears to display a similar pattern. Fitting the relation of $\nu_{\text{Hz}}$ versus $\nu_{\nu}$ with only a straight line gives $\chi^2/\text{dof} = 156/12 = 13$, while a straight line plus a sine gives $\chi^2/\text{dof} = 28.4/9 \sim 3.15$. Once again, we find a 3.4 $\sigma$ improvement of the fit based on an $F$-test. The results of the sinusoidal fits, in which the parameter errors have been rescaled by the reduced ($\chi^2$) $1/2$ value, are given in Table 5.

With the present data it is difficult to distinguish whether this is the behavior of $L_{\text{Hz}}$ alone or is due to blending with other components which are not strong and coherent enough to be observed separately on short timescales and are lost in the averaging of the power spectra. This, as well as other ambiguities (see the discussion about the identification of $L_{\nu}$ in van Straaten et al. 2003), arise because of the gaps between the $L_{\nu}$, $L_{\nu}$, $L_{\nu}$, and $L_{\text{Hz}}$ versus $\nu_{\nu}$ relations (see Fig. 5). Although we are not able to explain those gaps, the interpretation that $L_{\text{Hz}}$ could be affected by the presence of other components is made more likely by the fact that $L_{\nu}$ in Z sources can be unambiguously identified down to frequencies of $\sim 150$ Hz (see, e.g., Jonker et al. 2002b) and that $L_{\nu}$ and $L_{\text{Hz}}$.
have sometimes been observed at frequencies up to $\sim 120$ and $\sim 60$ Hz, respectively, i.e., in both cases reaching the hHz QPO range (van Straaten et al. 2005; Linares et al. 2005). If it would be possible to follow a source in its evolution from the EIS, where $L_{\text{low}}$ is prominent, to the LLB, where $L_t$ is seen, then some of these ambiguities could be resolved.

4. DISCUSSION

In this paper we report a detailed study of the time variability of the atoll source 4U 1636–53 using RXTE that includes, for the first time, observations of this source in the (low-luminosity) IS. We divide the data into 15 intervals, A to N, based on the position of the source in the CCD. Based on the facts that (1) intervals A1, B, D, and E show a narrow QPO with a characteristic frequency between $\nu_b$ and $\nu_h$, which was previously seen in other atoll sources when they were in their IS (e.g., van Straaten et al. 2002; Altamirano et al. 2005); (2) intervals A1, A2, B, D, E, and F do not show either $L_t$ or power-law VLFN at frequencies lower than 0.5 Hz, which would be expected to be present in the banana state (Hasinger & van der Klis 1989; van der Klis 2006); (3) the intensity of the source starts to increase from interval G (see Fig. 2); and (4) intervals A1 to F occupy the hardest loci in the CCD (see Figs. 2 and 5), we conclude that intervals A1 to F show the source in the IS, representing the first RXTE observations of 4U 1636–53 in this state. Interval G may represent the transition between the IS and the LLB, since its power spectrum is very similar to that of the first five intervals, but with the difference that a weak ($\sim 1.2\%$ rms) VLFN is present at a frequency lower than 0.1 Hz (see Fig. 5).

Along the CCD we find all seven power spectral components that were already seen in other sources in previous works (see van der Klis 2006 for a review): $L_u$ is detected in all of our power spectra, $L_{\nu_L}$ is unambiguously detected starting from power spectrum H ($\nu_H \sim 800$ Hz), $L_{\text{blitz}}$ is observed in 11 out of 15 power spectra at frequencies between 100 and 270 Hz, $L_h$ and $L_{\text{LF}}$ are detected mainly in the IS, $L_b$ is always observed, and finally, $L_{\text{QPO}}$ is detected when $L_b$ becomes peaked from interval G.

Previous works have shown that the frequencies of the variability components observed in other atoll sources follow a universal scheme of correlations when plotted versus $\nu_H$ (van Straaten et al. 2003 and references therein). We have found that the noise and QPO frequencies of the time variability of 4U 1636–53 follow similar correlations as well (see § 3), confirming the predictive value of this universal scheme. However, we have also found
some differences between 4U 1636–53 and other atoll sources, which we discuss below. As 4U 1636–53 is one of the most luminous atoll sources showing the full complement of ISs and banana states (full atoll track), the object is of interest in order to investigate the luminosity dependence of the spectral/timing state behavior. This is of particular importance to the ongoing effort to understand the origin of the difference between the atoll sources and the more luminous Z sources (see, e.g., Homan et al. 2007).

4.1. The Broad Components in 4U 1636–53 and Z-Source LFN

As can be clearly seen in Figure 8, where we show $\nu_{b2}$ versus $\nu_u$, the behavior of the $L_{b2}$ component differs significantly between sources. For 4U 1636–53 and 4U 0614+09, $\nu_{b2}$ increases with $\nu_u$, while this is not seen for 4U 1608–52 and 4U 1728–34. This frequency behavior is different from that observed for all other components (see § 3), which is instead very consistent between sources, even for the case of the hHz QPO, which has not been seen to correlate with other components (see van der Klis 2006 for a review). This unusual, somewhat erratic behavior of $L_{b2}$ may be related to the fact that it is usually detected as a relatively weak wing to a much stronger $L_{b1}$, so that small deviations in the time-averaged shape of $L_{b1}$ have a large effect on $L_{b2}$.

In order to investigate the relation of $L_{b2}$ to the well-known LFN, which occurs in the same frequency range in Z sources, in Figure 13 we plot the results for 4U 1636–53 together with those for the LFN in the Z sources (Hasinger & van der Klis 1989) GX 17+2 (Homan et al. 2002), Cyg X-2 (Kuznetsov 2002), GX 340+0 (Jonker et al. 2000a), and GX 5–1 (Jonker et al. 2002b). Note that the broadband noise in these Z sources was not fitted with a zero-centered Lorentzian but with a cutoff power law or a smooth broken power law. We used the results of the conversion from power laws to zero-centered Lorentzians by van Straaten et al. (2003). Previous works (e.g., Psaltis et al. 1999; van Straaten et al. 2003) compared the time variability of Z sources with that of atoll sources and tried to associate variability components among these sources. Based on frequency-frequency plots, only the kHz QPOs and the horizontal-branch oscillations (HBOs) found in the Z sources can be unambiguously identified with atoll source

![FIG. 12.—Quality factor $Q$ of $L_u$, $L_c$, and $L_{hHz}$ vs. $\nu_u$. The symbols are the same as in Fig. 11. Note that the results for the quality factor are probably affected by the averaging method (see § 1 and 3 and the Appendix).](image1)

![FIG. 13.—The $\nu_{b2}$ vs. $\nu_u$ values for the atoll source 4U 1636–53 (this paper) and the characteristic frequencies of the LFN vs. $\nu_u$ for the Z sources GX 17+2 (Homan et al. 2002), Cyg X-2 (Kuznetsov 2002), GX 340+0 (Jonker et al. 2000a), and GX 5–1 (Jonker et al. 2002a); see text and van Straaten et al. (2003) for details. (See also Fig. 8.)](image2)
components, the latter with $L_b$. Van Straaten et al. (2003) suggested that the LFN might be identified with $L_{b2}$ and noted that (as in the case of $L_{b2}$) the characteristic frequency of the LFN, when plotted versus $\nu_u$, does not follow exactly the same relations between Z sources. By comparing the different frequency patterns in Figure 13, we find that the behavior of the LFN component of GX 17+2 and that of $L_{b2}$ of 4U 1636–53 is similar, which might indicate that the physical mechanism involved is the same. Perhaps this is related to the fact that 4U 1636–53 is a relatively luminous atoll source (see Ford et al., 2000), while GX 17+2 may be a relatively low-luminosity Z source (Homan et al. 2003). Hence, 4U 1636–53 might be relatively close in $L_X$ to GX 17+2 and differ more in $L_X$ from the other two sources introduced above. Note that the time variability of GX 17+2 is different from that of the other Z sources plotted in Figure 13. For instance, the characteristic frequency of its LFN is rather low and appears as a peak, it shows a flaring-branch oscillation (FBO), and the harmonic of the HBO is relatively strong, whereas the other Z sources plotted showed a flat LFN, no FBO, and a weak harmonic of the HBO (Jonker et al. 2002b). As previously noted by Kuulkers et al. (1997), these properties set GX 17+2 apart from the “Cyg-like” Z sources GX 5–1, GX 340+0, and Cyg X-2 and associate it with the “Sco-like” Z sources Sco X-1 and GX 349+2, not plotted in Figure 13 because no systematic study of the LFN and QPO behavior of these sources in terms of $\nu_{\text{max}}$ is available as yet.

We further investigated the frequency similarities between 4U 1636–53 and GX 17+2 by plotting our results for the two sources. No clear component associations were found. GX 17+2 is the only Z source that showed an anticorrelation between the frequency of one of its components (HBO) and the kHz QPOs at high $\nu_u \approx 1500$ Hz (Homan et al. 2003). A similar effect was seen in the atoll source 4U 0614+09 between $\nu_b$ and $\nu_Q$ (van Straaten et al. 2003). As can be seen in Figure 5, a similar decrease of $\nu_b$ with $\nu_u$ at high frequency may occur in 4U 1636–53. However, the error bars on $\nu_b$ are rather large in the relevant range, and the data are still consistent with $\nu_b$ being constant at $\nu_u \approx 1100$ Hz, and marginally consistent even with a further increase in frequency. It is interesting to note that while 4U 0614+09 has a much lower $L_X$ than 4U 1636–53, both sources might show this same turnover in $\nu_b$ versus $\nu_u$. Of course, these results need confirmation.

4.2. The Low-Frequency QPO

With respect to the low-frequency QPO $\nu_{\text{LF}}$, van Straaten et al. (2003, 2005) observed that in their data there were two groups of sources, one where the $\nu_{\text{LF}}$ feature was visible and a second one where a QPO was detected, which they suggested was the subharmonic of $\nu_{\text{LF}}$ and, therefore, called $\nu_{\text{LF2}}$. Following van Straaten et al. (2003), the solid line in Figure 9 indicates a power law fitted to the $\nu_{\text{LF}}$ versus $\nu_b$ relation of the low-luminosity bursters 1E 1724–3045 and GS 1826–24 and the BHC GX 339–4. If we reproduce the fit where we take into account the errors in both axes, we find a best-fit power-law index $\alpha = 0.97 \pm 0.01$ and $\chi^2$/dof $= 80/19 \approx 4.2$. If we fix $\alpha = 1$, the fit gives $\chi^2$/dof $= 83/20 \approx 4.1$. According to the F-test for additional terms, there is a $<1\sigma$ improvement of the fit when $\alpha$ is set free, so we conclude that $\nu_{\text{LF}}$ is consistent with being linearly related to $\nu_b$. The dashed line in the figure shows a power law with the same index, $\alpha = 0.97$, but with a normalization half that of the solid line.

As can be seen in Figure 9, in 4U 1636–53 the $\nu_{\text{LF}}$ component does not follow either of the two power-law fits. If we fit the points for 4U 1636–53, we find that the power-law index is $\alpha_{\text{LF}} = 1.40 \pm 0.09$ ($\chi^2$/dof $= 0.14/2$), significantly different from that of the other sources. Given the above, it is probably incorrect to think that the difference in the $\nu_{\text{LF}}$ versus $\nu_b$ relation between GX 339–4, GS 1826–24, and 4U 1724–3045 on one hand and 4U 1608–52, Cyg X-1, and XTE J0929–314 on the other hand is associated with harmonic mode switching (van Straaten et al. 2003). This conclusion is supported by the work of Linhares et al. (2005), who also found a different correlation ($\alpha = 0.58 \pm 0.06$; see also Fig. 9) in XTE 1807–294 over a much wider range of frequencies than we obtained for 4U 1636–53; by the high $\chi^2$/dof for the $\nu_{\text{LF}}$-$\nu_b$ fit to the data of the low-luminosity bursters 1E 1724–3045 and GS 1826–24 and the BHC GX 339–4 (see previous paragraph); by the fact that if we use the centroid frequencies instead of $\nu_{\text{max}}$, the relations worsen (see van Straaten et al. 2003); and by the fact that the points for 4U 1728–38 (van Straaten et al. 2002) fall between the two power laws (Fig. 9, solid and dashed lines). Nevertheless, it is interesting that the data for 4U 0614+09, 4U 1728–34, 4U 1636–53, 4U 1820–30, 4U 1608–52, XTE 1807–294, SAX J1808.4+3658, XTE J1814–338, and XTE J0929–314 all fall on or between the two previously defined power laws; i.e., they do not deviate from a single relation by more than a factor of 2. We note that all the $\nu_{\text{LF}}$ values discussed here could, in principle, have been affected by smearing in the averaging process discussed in §2. However, for smearing to shift a frequency-frequency point away from its proper value, large systematic differences are required between the two components in the dependence of amplitude or $Q$ on frequency, and in the case of $L_{\text{LF}}$ and $L_b$ there is no evidence for this.

From Figure 9 it is apparent that the frequency range in which the $L_{\text{LF}}$ component has been identified is rather large (up to 2.5 decades). Clearly, which frequency ranges $L_{\text{LF}}$ covers is not related to source spin frequency, angular momentum, or luminosity of the object. The sources 4U 1608–52, 4U 1820–30, 4U 1636–53, and 4U 1728–34 all show $L_{\text{LF}}$ when they are in their IS, but with $\nu_{\text{LF}} \approx 0.2$ Hz for 4U 1608–52 and $\approx 0.3$ Hz for the other three sources. The AMP XTE J1807–294 shows $\nu_{\text{LF}} \approx 12$ Hz, while the AMP XTE J0929–314 shows $\nu_{\text{LF}} \approx 1$ Hz; both have very similar spin frequencies ($191$ Hz, Markwardt et al. 2003; and 185 Hz, Remillard et al. 2002, respectively). The sources 4U 1820–30 and 4U 1636–53 are at least 1 order of magnitude more luminous than XTE 1807–294 and SAX J1808.4+3658 at their brightest (see Ford et al. 2000; Wijnands 2005), but all four sources show $\nu_{\text{LF}} > 5$ Hz. The only systematic feature in the LF QPO frequencies is that while frequencies up to 50 Hz are seen in NSs, black holes have not been reported to exceed 3.2 Hz, nor do atoll sources in the EIS exceed 2.6 Hz. So, BHCs and NSs in the EIS are similar in this respect (this may be related to an overall similarity in power spectral shape for such sources in these states that was noted before; see, e.g., Psaltis et al. 1999; Nowak 2000; Belloni et al. 2002; van Straaten et al. 2002).

4.3. The X-Ray Luminosity Dependence of rms

It has been suggested that an anticorrelation may exist between the average X-ray luminosity of different sources and the rms amplitude of their power spectral components (see discussion in Jonker et al. 2001; van Straaten et al. 2002, 2003 and references therein). From Figure 11 we find differences in kHz QPO rms amplitudes of no more than a factor of 2 between sources which differ in average luminosity by a factor of up to 10, except for one point of 4U 0614+09 at $\nu_u \approx 1140$ Hz, where the rms of the upper kHz QPOs is a factor of $\approx 7$ higher than that of the other atoll sources. Méndez et al. (2001), Jonker et al. (2001), and van Straaten et al. (2002) have already noted that the data are inconsistent with a model in which the absolute amplitudes of the kHz QPOs are the same among sources, and the decrease in rms
with luminosity between sources is only caused by an additional source of X-rays unrelated to the kHz QPOs.

From Figure 11 it can also be seen that the largest rms amplitude differences are found in the hHz QPOs (excluding 4U 1608–52, which is a transient source covering a large L_b range). For this component we find (1) 4U 0614+09, which has the strongest rms_{L_b} (15% when ν_u ≤ 800 Hz); (2) 4U 1636–53, which has the weakest rms_{L_b} (<10% when ν_u ≤ 800 Hz); and (3) 4U 1728–34, which has an rms_{L_b} value generally between those of (1) and (2) (between 10% and 15% when ν_u ≤ 800 Hz). At ν_u ≥ 800 Hz, the groups can still be differentiated as the rms amplitude decreases with ν_u. From Figure 1 in Ford et al. (2000) it can be seen that 4U 0614+09 is the faintest X-ray source of our sample, while 4U 1636–53 is the brightest. The source 4U 1728–34 shows luminosities between those of the first two sources. This suggests an X-ray luminosity–rms anticorrelation for L_b that is not as clear in the other components (see also Fig. 10).

The fact that the rms of L_b starts to decrease at the same ν_u as that of L_a and L_b, while ν_b does not correlate with ν_u as all other frequencies do, suggests that the frequency-setting mechanism is different for L_b compared with the other components, while the amplitude-setting mechanism is common. As pointed out in § 3, the drop in rms in L_a, L_{L_b}, and L_b starts at ν_u between 700 and 800 Hz. For the case of 4U 1636–53 shown here, this corresponds to interval G. The power spectrum of this interval may represent the transition between the IS and the banana state, when the geometric configuration of the system is thought to change (e.g., Jonker et al. 2000b; Gierliński & Done 2002). For example, the appearance of a puffed-up disk could smear out the variability coming from the inner region where the oscillations are produced.

4.4. The Nature of the Hectohertz QPOs

While our results indicate that the characteristic frequency of the hHz QPO may oscillate as a function of ν_u, ν_{L_b} remains constrained to a limited range of frequencies (100–250 Hz) for 4U 1636–53 and the other sources used in Figure 5. A similar result has been reported for ν_{L_b} in several other atoll sources, such as MXB 1730–335 (Migliari et al. 2005), 4U 1820–30 (Altamirano et al. 2005), and the AMP SAX J1808.4–3658 (Wijnands & van der Klis 1998; van Straaten et al. 2005). Interestingly, the presence of L_{L_b} has not been confirmed for Z sources (van der Klis 2000b), possibly due to the intrinsic differences between atoll and Z sources such as luminosity.

Van Straaten et al. (2002) have suggested a link between the ≤100 Hz QPOs reported by Nowak (2000) in the black holes Cyg X-1 and GX 339–34 and L_{L_b}. Van Straaten et al. (2002) also suggested that L_{L_b} could be related to the ~67 Hz QPO in the black hole GRS 1915+105 (Morgan et al. 1997) and the ~300 Hz QPO in the BHC GRO J1655–40 (Remillard et al. 1999), which also have stable frequencies. Fragile et al. (2001) made a tentative identification of the ~9 Hz QPO in the BHC GRO J1655–40 (Remillard et al. 1999) with the orbital frequency at the Bardeen-Petterson (B-P) transition radius (Bardeen & Petterson 1975) and suggested the same identification for L_{L_b} in NS systems. In this scenario, the orbital frequency at the radius where a warped disk is forced to the equatorial plane by the B-P effect can produce a quasi-periodic signal (see Fragile et al. 2001 for a schematic illustration of the scenario).

Attempts have been made to theoretically estimate the B-P transition radius from accretion disk models in terms of the angular momentum and the mass of the compact object (e.g., Bardeen & Petterson 1975; Ivanov & Illarionov 1997; Hatchett et al. 1981; Nelson & Papaloizou 2000). Fragile et al. (2001) propose a parameterization involving a scaling parameter A, which according to them lies in the range 10 ≤ A ≤ 300. These authors write the B-P radius as R_{B-P} = A(a^2/c^2)R_{GR}, where a = J/cGM^2 is the dimensionless specific angular momentum (∠ and M are the angular momentum and mass of the compact object, respectively) and R_{GR} = GM/c^2. The Keplerian orbital frequency associated with the B-P transition radius can be written as ν_{Kep,B-P} = c^2/(2πGM)(Ma^2/c^2)^{-1}. If we assume that the atoll sources plotted in Figure 5 all have masses between 1.4 and 2 M⊙, that 0.3 ≤ a ≤ 0.7 (see, e.g., Salgado et al. 1994; Cook et al. 1994 and references within), and that the central frequency of the hHz QPOs is between ~100 and ~250 Hz, we can constrain the scaling factor A for these sources to between ~20 and ~84. If A only depends on the accretion disk (i.e., it does not depend on the central object), this can be used to constrain the frequency range in which we expect to observe ν_{Kep,B-P} in black holes. For example, the black hole BHC GRO J1655–40, whose mass is estimated from optical and infrared investigations as M = 6.3 ± 0.5 M⊙ (Greene et al. 2001) and whose specific angular momentum a, can be estimated to be between 0.5 and 0.95 (Cui et al. 1998; Fragile et al. 2001), would have ν_{Kep,B-P} between ~6.5 and ~127 Hz, which would exclude the 300 Hz QPO observed in GRO J1655–40 but would be consistent with the 9 Hz QPO as proposed by Fragile et al. (2001). If one assumes that the 450 Hz QPO in GRO J1655–40 is associated with orbital motion at the last stable orbit, then a could be as low as ~0.15 (Strohmayer 2001b). In this case, ν_{Kep,B-P} can be as high as ~425 Hz for a black hole mass of 5.7 M⊙.

5. SUMMARY

1. Our observations of 4U 1636–53, including the first RXTE island state data of the source, show timing behavior remarkably similar to that seen in other atoll NS LMXBs. We observe all components previously identified in those sources and find that their frequencies follow relations similar to those previously observed. This is interesting, as the sources compared in this work were observed at intrinsic luminosities different by more than an order of magnitude.

2. The previously proposed interpretation of the QPO frequencies ν_{LF} and ν_{LF/2} in different sources in terms of harmonic mode switching is not supported by our data on 4U 1636–53 or by data previously reported for other sources. However, these frequencies still do not deviate from a single relation by more than a factor of 2 for all sources.

3. The low-frequency QPO L_{LF} is seen in black holes and in accreting millisecond pulsars, as well as in nonpulsing NSs at frequencies between ~0.1 Hz and ~50 Hz. The frequency range that L_{LF} covers in a given source is not related to spin frequency, angular momentum, or luminosity of the object.

4. The rms and frequency behavior of the hHz QPO suggests that the mechanism that sets its frequency differs from that for the other components, while the amplitude-setting mechanism is common.

D. A. wants to thank S. van Straaten for all his help in the analysis of these data. D. A. also wants to thank R. Wijnands and C. Fragile for very helpful comments and discussions and J. Homan for comments on an earlier version of this manuscript. This work was supported by the Nederlandse Onderzoekskool Voor Astronomie (NOVA), i.e., the Netherlands Research School for Astronomy, and it has made use of data obtained through the High Energy Astrophysics Science Archive Research Center Online Service, provided by the NASA/Goddard Space Flight Center.
APPENDIX

ON THE METHOD OF AVERAGING POWER SPECTRA

In this Appendix we further discuss other possible approaches to analyze the characteristics of complex power spectra such as generally found in neutron star low-mass X-ray binaries.

In the ideal case, we would have data with enough statistics to be able to follow the evolution of the parameters of all observable components in the power spectra on sufficiently short timescales to be sensitive to the smallest meaningful variations. Unfortunately, this is not the case for the present data, and meaningful variations are averaged out in our data. These variations can sometimes be recovered by the use of alternative methods. For example, with the "shift-and-add" method introduced by Méndez et al. (1998a), it has been possible to better constrain some of the characteristics of the kHz QPOs in several sources than without this method (e.g., Méndez et al. 1998a; Barret et al. 2005b). A disadvantage of the method is that it distorts the power spectrum at the lowest and highest frequencies covered.

We investigated whether this method could also be used for our purpose. However, in our experiments with this we encountered several complications. From the observational point of view, in order to use this method we require a sharp power spectral feature that can be accurately traced in time. There are two possibilities for such features: the lower kHz QPO $L_f$ and the low-frequency Lorentzian $L_{LF}$. While the lower kHz QPO is usually superimposed on well-modeled Poisson noise, tracing $L_{LF}$ is complicated by the fact that it is superimposed on strong variable broadband noise (see van der Klis 2006 and references within). More importantly, while $L_f$ can be traced on sufficiently short timescales ($\approx 64$ s) for the intrinsic changes in the characteristics of the power spectrum to be minimal, typically an entire observation is required for detecting $L_{LF}$ at sufficient signal-to-noise ratio. In practice this means that we can only use the shift-and-add method with $L_f$, which constrains us to only that relatively limited part of the data where $L_f$ is actually detected (see Fig. 5). We note that $L_{LF}$ and $L_f$ are not simultaneously detected in our data set.

We analyzed all the data sets described in §2 and found that $\sim 15\% (\sim 0.17$ Ms) of our data have traceable lower kHz QPOs. Most of that time the lower kHz QPOs were detected at frequencies between 700 and 850 Hz (the full range was 600–900 Hz).

In order to use the shift-and-add method we must adopt a relation between the frequency of the component we wish to shift on (here the lower kHz QPO) and the frequency of the component we wish to detect (here the low-frequency QPOs/noise). For example, in their original work Méndez et al. (1998a) supposed that the difference between the lower and upper kHz QPO frequency remained constant when both peaks moved. The study of the characteristics of the low-frequency QPOs/noise using the shift-and-add method is complicated by the fact that we have imprecise information about their relation with the lower kHz QPOs; a constant frequency difference certainly does not apply even to narrow ranges in shift frequency. The aim of this paper, as well as the aim of the papers cited below, is to present observational results that help constrain those relations.

As van Straaten et al. (2002, 2003) showed, the frequencies of all components except those of the kHz QPOs are correlated in a similar way between sources (see Fig. 5). However, van Straaten et al. (2005) and Linares et al. (2005) also showed that those correlations are shifted in pulsating sources, and Altamirano et al. (2005) found that even nonpulsating systems might show frequency shifts. In addition, the results of van Straaten et al. (2002, 2003, 2005), Linares et al. (2005), and Altamirano et al. (2005) showed that although the frequency relations between the different components are well fitted with a power law, the index and normalization of the power law are different for each relation and may also depend on frequency range.

In order to quantify the problem described above, we studied observation 60032-01-05-00 using power spectra of 64 s data segments at 2 Hz frequency resolution. This is a very good observation for our purpose, since (1) it has $\sim 27$ ks of uninterrupted data, (2) the lower kHz QPO is strong enough to be significantly detected within 64 s for the entire 27 ks, (3) the lower kHz QPO frequency drifts between $\sim 700$ and $\sim 860$ Hz, and (4) the power spectrum can be fitted with four Lorentzians: two for the kHz QPOs, one for $L_h$ (at 40 $\pm$ 4 Hz), and one for $L_{h2}$ (at 20 $\pm$ 12 Hz; 2.9 $\sigma$).

We first analyzed the power spectrum obtained by aligning the $L_f$ components. We found that $L_h$ and $L_{h2}$ had blended into a broad component at $\sim 100$ Hz. This result was expected, as a drift of 160 Hz in $\nu_f$ does not imply a drift of the same magnitude in the frequencies of the low-$\nu$ components. We then tried to align the power spectra by predicting the position of the low-frequency components from $\nu_f$ using a different power-law relation for each component, as reported by van Straaten et al. (2005) for $L_f$ and $\nu_{h2} = e^{-28 \pm 8} \nu_{h}^{3.8 \pm 1.3}$ for $L_{h2}$ (the relation for $L_{h2}$ is based on our data for 4U 1636–53; given the large errors in our data, the $\chi^2$/dof for the power-law fit was 0.26). The results depended on which power law we used; no significant changes in the resulting power spectrum were found when trying to align $L_{h2}$, while the power of both components was smeared out, producing a blend, when we tried to align $L_h$. This was clearly the effect of the difference in power-law indices and normalizations between components. As the frequency relations we used were between $\nu_f$ and the frequencies of the other components, we had to assume a relation between $\nu_f$ and $\nu_{h}$ in order to predict the frequency variations. We variably assumed $\Delta \nu = \nu_{h} - \nu_{f} = 280, 300, and 350 Hz and obtained similar results in each case. We also predicted $\Delta \nu$ by fitting a line to the $\Delta \nu$ versus $\nu_f$ data reported by Jonker et al. (2002a) in the range 720 Hz $\leq \nu_f \leq 900$ Hz. Again, the results of the power spectral fits were the same within the errors as those of the previous experiments.

We repeated the last exercise (using the power-law relations) for all 0.17 Ms of $\nu_f$ useful data and for $L_{h2}$, $L_h$, and $L_h$ (we use the power-law relation as reported by van Straaten et al. [2005] for $L_h$). We again found that our results were dependent on the power law used and not significantly better defined than the average power spectra obtained when all 0.17 Ms of data were averaged together without shift.

In another experiment we calculated four average power spectra, including all 0.17 Ms of useful data, by selecting only those 64 s segments which had $\nu_f$ in the ranges 650–700, 700–750, 750–800, and 800–850 Hz and averaging these selected power spectra without shifting. In all cases we detected both kHz QPOs, a power-law VLFN, and $L_h$. As expected from the results shown in Figure 5, $\nu_{h}$ is correlated with the frequency of both kHz QPOs. The measured frequencies are all consistent within the errors with those reported in Figure 5 and Table 3. The lack of statistics in each average power spectrum did not allow us to well constrain the power spectral parameters of other components.
Finally, we fitted a line to the relation between $\nu_{LF}$ and $\nu_h$ defined by the four points visible in Figure 9. We used the $\nu_{LF}$ we found in all four power spectra (A1, B, D, and E) to predict $\nu_h$ and shift and add these four power spectra together. Again, we found that the blend of components (this time between $L_h$ and $L_b$) and the distortion of the power spectra at low frequencies prevented us from better estimating the $L_h$ parameters.

So, neither the shift-and-add method nor selecting data on $\nu_h$ in 64 s segments (i.e., much shorter than an observation) in our data provided an advantage in measuring the broad, low-frequency components. Therefore, in this paper we decided to use the straightforward method described in § 2.

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