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kHz QUASI-PERIODIC OSCILLATION IN ISLAND STATE OF 4U 1608−52 AS OBSERVED WITH *RXTE*/PCA

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ABSTRACT

We report *RXTE*/PCA observations of 4U 1608−52 on March 15, 18, and 22 immediately after the outburst in early 1996. The persistent count rates ranged from 190 to 450 counts s^{-1} (1–60 keV). During this period of time, 4U 1608−52 was in the island state. We detected quasi-periodic oscillation (QPO) features in the power density spectra (PDS) at 567–800 Hz on March 15 and 22, with source fractional root mean square (rms) amplitude of 13%–17% and widths of 78–180 Hz. The average rms amplitude of these QPO features is positively correlated with the energy. Our results imply that the neutron star spin frequency is possibly between 300 and 365 Hz.

Subject headings: stars: individual (4U 1608−52) — stars: neutron — X-rays: stars

1. INTRODUCTION

4U 1608−52 is a transient low-mass X-ray binary with outbursts that recur on timescales of 80 days to 2 years (Grindlay & Liller 1978; Lewin, van Paradijs, & Taam 1993; Lochner et al. 1994). It was classified to be an atoll source based on the correlated X-ray spectral variability and high-frequency noise (HFN) in the X-ray intensity (Hasinger & van der Klis 1989; Yoshida et al. 1993). 4U 1608−52 has been observed a few times with an energy spectrum consistent with a power law at X-ray luminosities below 10^{37} ergs s^{-1} (Mitsuda et al. 1989; Penninx et al. 1989; Yoshida et al. 1993; S. N. Zhang et al. 1996).

The X-ray monitoring of 4U 1608−52 with *RXTE*/ASM indicated an outburst in early 1996. In response to a high state detection of 4U 1608−52 in *RXTE*/PCA scans (Marshall & Angelini 1996), pointed observations with the *RXTE*/PCA were conducted during the decay phase of this outburst on March 3, 6, 9, and 12 (Berger et al. 1996; M. van der Klis 1997, private communication) and on March 15, 18, and 22 (see Fig. 1). Kilohertz QPOs were discovered in 4U 1608−52 in the March 3, 6, and 9 observations. No X-ray bursts were observed with *RXTE*/PCA in early 1996 March (Berger et al. 1996). Here we report the timing analysis results on *RXTE*/PCA observations of 4U 1608−52 on March 15, 18, and 22.

2. OBSERVATIONS AND ANALYSIS RESULTS

X-ray monitoring by *RXTE*/ASM shows that our observations on March 15, 18 and 22 were taken near the end of the outburst decay, with ASM daily averaged brightness of 44.8 ± 5.2, 13.3 ± 7.2, and 14.5 ± 4.1 mcrab, respectively (see Fig. 1). The persistent X-ray flux (2–20 keV) obtained with the *RXTE*/PCA ranged between 4.6×10^{-10} and 1.1×10^{-9} ergs s^{-1} cm^{-2}. The source count rate in the energy range 1–60 keV varied between 190 and 450 counts s^{-1}. Three X-ray bursts were observed in one orbit on March 22. They show the evidence of a high-energy excess above a Planckian spectrum, but no kHz QPO were detected in the bursts (Yu et al. 1998, in preparation). We thus exclude 50 s data of each burst when estimating the properties of the kHz features in the persistent emission.

The PCA/*RXTE* provides several data modes, which were used in the analysis reported in this paper. The color-color diagrams were constructed from the *standard 2 mode* data. We made use of the *event mode* data (64 energy channels and 122 μs time resolution) to generate the power density spectra (PDS).

2.1. *Color-Color Diagrams*

Background count rates as a function of time were produced with the standard background model supplied by the *RXTE* Guest Observer Facility (Stark & the *XTE*/PCA Team 1997). After subtracting the background in three bands (approximately 2.2–5.1, 5.1–10.1, and 10.1–29.8 keV), color-color diagrams for 4U 1608−52 were generated. Figure 2 is the color-color diagram of 4U 1608−52 plotted with the data obtained on March 15, 18, and 22, as triangles, squares, and circles, respectively. Each data point represents 240 s of observation. The data for about 2000 s, starting from the rise of the first burst to the end of that orbit, were excluded. The uncertainty in the hardness ratios were also estimated for a hypothetical *EXOSAT* observation, as shown in Figure 2.

2.2. *Power Density Spectra* (*PDS*)

We have obtained rebinned PDS in the frequency range of 10^{-3}–100 Hz from background-subtracted light curve of the *event mode* data. The average PDS of individual days on March 15, 18, and 22 are shown in Figure 3. The average level of the white noise caused by counting statistics was subtracted in these spectra. These PDS show similar HFN components with a flat top from 0.01 Hz to about 10 Hz. The low-frequency noise (LFN) can be represented by a power law, and the HFN components can be described as a power law with an exponential cutoff for atoll sources (Hasinger & van der Klis 1989). This model basically agrees with our data as shown in Figure 3. The fractional rms of the HFN for each day is 12.0% ± 1.9%, 13.5% ± 1.6%, and 14.4% ± 0.6%, respectively. The corresponding HFN cutoff frequencies are 25 ± 6, 8 ± 2, and 19 ± 3 Hz. All the above errors represent a 90% confidence level (Press et al. 1992).

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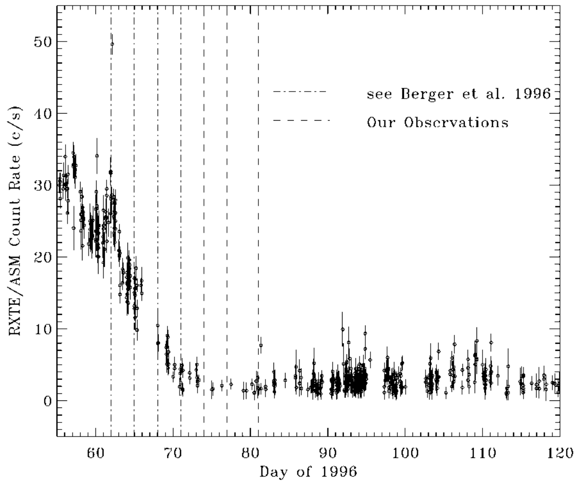

FIG. 1.—Long-term X-ray monitoring of 4U 1608−52 by *RXTE*/ASM. Our observations with *RXTE* were on March 15, 18, and 22.

In the PDS of the first orbit on March 15, a QPO peak at 20 Hz can be seen. A broad excess of power at 10–30 Hz is also visible in the second and third orbits on March 15. Further analysis of the single-bit mode data and the event mode data in each orbit at higher frequencies revealed QPO features in the frequency range of 567–800 Hz in the average PDS. An example of the Leahy-normalized PDS obtained from the event mode data in 1–30 keV in the third orbit on March 15 is shown in Figure 4. There is a broad excess of power between a few tens Hz to about 200 Hz in each of the PDS on March 15 and 22. The results are listed in Table 1. All errors in the table correspond to unreduced $\Delta\chi^2 = 1$. We estimate the rms amplitudes of the kHz QPO peaks by fitting PDS at 200–2000 Hz range with a linear component plus a Lorentzian peak. The rms amplitudes of the QPO peaks were obtained from the Lorentzian component.

We then divided the 2–60 keV energy range into seven bands (2.2–3.5, 3.5–5.4, 5.4–7.9, 7.9–11.1, 11.1–14.6, 14.6–20.4, and above 20.4 keV) and studied the PDS in these bands using the event mode data. The QPO peaks were usually not clearly

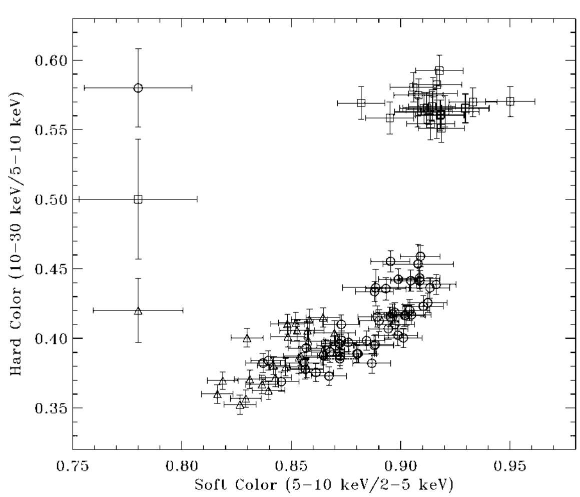

FIG. 2.—Color-color diagram of 4U 1608−52. Data from March 15, 18 and 22 pointings are plotted as triangles, squares, and circles, respectively. Each point represent 240 s of observation. The three data points on the left side of the plot show typical error bars for a hypothetical *EXOSAT* ME observation of 4U 1608−52 on the 3 days with the same energy bands used in the PCA and the computed ratio of the effective areas of the two instruments. On March 18, no significant kHz QPO is detected.

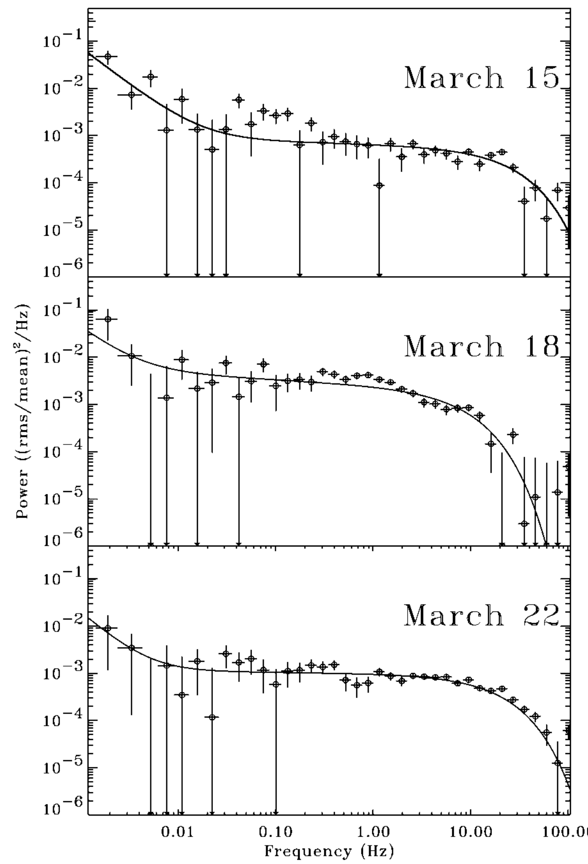

FIG. 3.—Average PDS on March 15, 18, and 22 obtained from the background-subtracted event mode data. The average level of the white noise caused by counting statistics was subtracted. The fits of the PDS with the model described in Hasinger & van der Klis (1989) are also shown in the plot, with reduced χ^2 values (38 d.o.f.) of 1.80, 1.84, and 1.08, respectively. The rms of HFN was about 13% in the above PDS.

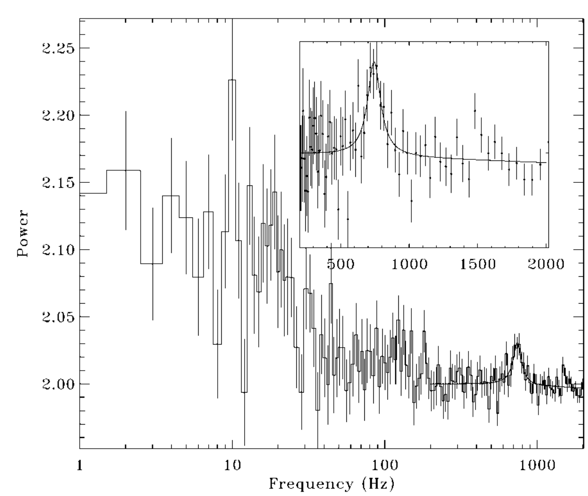

FIG. 4.—Average PDS in the third orbit on March 15 obtained from the 1–30 keV event mode data. High-frequency noise is also visible below 100 Hz. We fit the PDS in 200–2000 Hz range with a model (*solid curve*) composed of a linear component plus a Lorentzian peak at 744 Hz.

TABLE 1
1996 March *RXTE* Observations of 4U 1608−52[a]

Orbit Start Time[b]	Duration (s)	Count Rate[c] (counts s^{-1})	Count Rate[d] (counts s^{-1})	ν_{qpo}[e] (Hz)	FWHM[f] (Hz)	rms[g] (%)
March 3	…	…	2910–3400	830–890	5–15	~6–8
March 6	…	…	1920–2500	830–870	5–15	~14
March 9	…	…	610–730	691 ± 6	131 ± 19	~13.9
March 12	…	…	460–710	…	…	…
March 15 19:28	1800	300–350	150–180	800^{+9}_{-10}	78^{+25}_{-20}	$13.3^{+3.1}_{-3.4}$
March 15 21:39	1200	300–340	155–185	…	…	…
March 15 22:49	2700	280–330	150–175	744 ± 12	116^{+40}_{-30}	$14.4^{+3.3}_{-3.7}$
March 18 19:46	2400	185–225	105–135	…	…	…
March 18 21:10	3000	190–230	105–135	…	…	…
March 22 15:11	1600	415–450	210–250	…	…	…
March 22 16:14[h]	3600	415–450	210–240	638 ± 11	126^{+25}_{-32}	$15.9^{+2.9}_{-3.1}$
March 22 17:50	3600	375–430	200–230	637^{+16}_{-17}	173^{+53}_{-41}	$17.3^{+3.8}_{-3.9}$
March 22 19:35	3000	370–430	190–240	622^{+31}_{-29}	180^{+123}_{-100}	$13.6^{+5.8}_{-8.2}$
March 22 21:22	2400	370–415	190–230	567^{+21}_{-18}	134^{+93}_{-82}	$14.0^{+6.3}_{-9.3}$
March 22 23:04	1400	345–415	184–230	…	…	…

[a] Results before March 15 are from Berger et al. 1996, and the corresponding count rates are from M. van der Klis 1997, private communication.
[b] Start time (UT) of each orbit (date, hour: minute).
[c] The source count rates in our observations were obtained from 1–60 keV light curves with 16 s time resolution. The count rates obtained from 3 PCUs on March 22 have been rescaled to count rates as observed from 5 PCUs.
[d] The source count rates in our observations were obtained from 5–60 keV light curves with 16 s time resolution and rescaled as from 5 PCUs.
[e] The QPO centroid frequencies were obtained by fitting the peak with a Lorentzian.
[f] The FWHM of the Lorentzian peak in PDS.
[g] All has been corrected to fractional rms amplitude of source intensity in 1–30 keV in our observation. Correction of binning effect has been applied.
[h] We exclude 50 s data of each burst to calculate the PDS in the orbit.

visible in the average PDS in each of the seven bands. The individual PDS in the frequency range between 200 and 2000 Hz were fitted with a model composed of a linear component plus a box function. The box functions were centered at the peak frequencies and widths were set to be 2 times the QPO FWHMs (see Table 1). Then we calculated the rms amplitude from the box function integrals. Finally, we averaged the rms amplitudes from each energy-dependent PDS over the six orbits. A positive correlation between the average QPO rms amplitude and the photon energy was observed, as shown in Figure 5.

We also notice that there is no apparent correlation between the QPO rms and the intensity. But the QPO centroid frequencies and the average source intensities show the tendency of a positive correlation within a few hours (see Fig. 6). For example, on March 15, the higher the count rates, the higher the QPO frequencies were. On March 22, a similar trend was also observed.

3. DISCUSSION

Kilohertz QPOs in X-ray flux have been observed from about 12 LMXBs so far (van der Klis 1997, and references therein; Zhang et al. 1998). Nine of them are atoll sources or probable atoll sources. In our observation of 4U 1608−52, its persistent flux in the 2–20 keV band was in the range

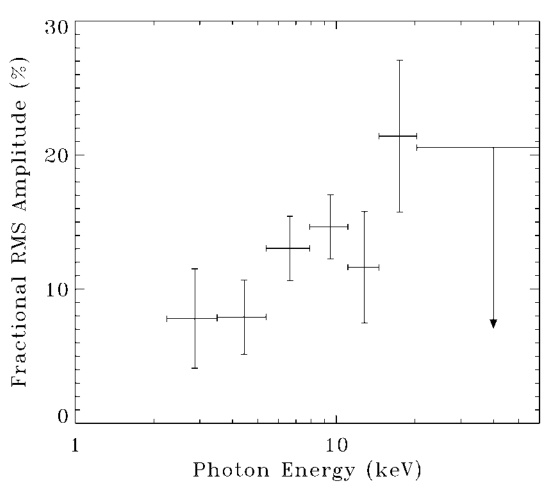

Fig. 5.—Average fractional rms amplitude of QPO as a function of photon energy. We average the results obtained from event mode data analysis of the six orbits.

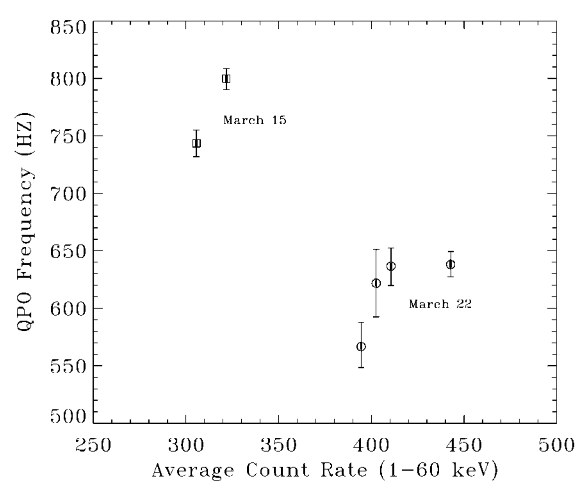

Fig. 6.—Average count rates (1–60 keV) vs. QPO frequency in 4U 1608−52 during the low state observation. Data points on March 15 and 22 were marked as squares and circles. No QPO peaks were observed on March 18.

(4.6–11) $\times$ 10^{-10} ergs s^{-1} cm^{-2}, corresponding to an X-ray luminosity of (0.7–1.7) $\times$ 10^{36} ergs s^{-1} assuming a distance of 3.6 kpc (Nakamura et al. 1989). The luminosity was at or below the lowest luminosity of 4U 1608−52 in its island state ever observed with *EXOSAT* and *Ginga* (Penninx et al. 1989; Yoshida et al. 1993). We detected no large motion in the PCA color-color diagram within a day. Also, the power density spectra were dominated by HFN with rms around 13%. This suggests that 4U 1608−52 was in its island state (Hasinger & van der Klis 1989; van der Klis 1995). It is the second atoll source observed to exhibit kHz QPO in both the banana and the island state (the first is 4U 1636−53, see Wijnands et al. 1997).

The increase in QPO rms amplitude with photon energy in our observations shows that the QPO emission is harder than the average spectrum. A positive correlation between rms amplitude and photon energy in the range from 2 to more than 11 keV has also been observed from kHz QPOs in other sources (e.g., Ford et al. 1997; Zhang et al. 1996). This suggests that all these QPOs are of similar origin.

Our QPO observations can be compared to the observations of 4U 1608−52 made in early March (Berger et al. 1996). In all observations only a single QPO with centroid frequency above 200 Hz has been detected and the QPO rms amplitude increases with photon energy. The rms amplitude versus energy curve for March 15 and 22 is consistent with that presented for March 3 (Berger et al. 1996). However, on March 3 and 6, the QPO was with a FWHM of 5–15 Hz in the PDS averaged over 100 s; while on March 9, 15, and 22, the QPO cannot be tracked as the QPO observed on March 3 and 6. The QPO was with a FWHM of 80–140 Hz, which are derived from the average PDS over a few thousand seconds. On March 3, the X-ray intensity was high and the QPO frequency varied in the range 830–890 Hz with no correlation with X-ray intensity (Berger et al. 1996). Comparing individual orbits on March 15 and 22, when the X-ray intensity is lower, the QPO frequency is lower (570–800 Hz) and appears to be positively correlated with X-ray intensity. This correlation does not hold when data from different days are compared. A similar trend of correlation over 1 day timescales and lack of correlation on longer timescales has been observed for QPO frequency versus X-ray intensity in other X-ray burster sources (Ford et al. 1996; W. Zhang et al. 1998). However, the correlation of QPO frequency with the flux of a blackbody component of the X-ray spectrum was found to be robust over several months in 4U 0614+091 (Ford et al. 1997).

Kaaret, Ford, & Chen (1997) have interpreted the lack of correlation between QPO frequency and X-ray intensity of 4U 1608−52 on March 3 as reported in Berger et al. (1996) as evidence that the accretion disk is terminated near the marginally stable orbit when the source is at high X-ray intensities and high mass accretion rates. The March 15 and 22 observations presented here suggest that the QPO frequency may be correlated with X-ray intensity, at least over 1 day timescales, when 4U 1608−52 is at low X-ray intensities. This is consistent with the interpretation of Kaaret et al. (1997) since, when the mass accretion rate is low, the disk should be disrupted by the neutron star magnetosphere or radiation forces outside the marginally stable orbit and the QPO frequency should then be correlated with mass accretion rate (Alpar & Shaham 1985; Miller, Lamb, & Psaltis 1996). It is important that additional observations of 4U 1608−52 be obtained over a wide range of X-ray intensities.

It is also possible that the QPOs observed on March 15 and 22 may correspond to a pair of QPOs, but only one of the two is detectable in the individual orbit (see Fig. 6). This would imply that the frequency separation is larger than 233 ± 22 Hz (Fig. 6). It is thus reasonable to assume that the neutron spin frequency is larger than 233 Hz, within the framework of the beat frequency model discussed above. In addition, if we interpret the 20 Hz QPO observed on March 15 as caused by the Lense-Thirring precession in the model of Stella & Vietri (1997), the inferred neutron star spin frequency for 4U 1608−52 is between 300 and 365 Hz, depending on the tilt angle off the equatorial plane. However, future simultaneous detection of all three QPOs (the Lense-Thirring precession frequency, the beat frequency, and the Keplerian frequency, as of 20, 435–500, and 800 Hz, respectively, in the case of March 15 observation) in 4U 1608−52 or a detection of QPO in the X-ray bursts from 4U 1608−52 is needed to confirm the above inference.

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