

## DISCOVERY OF KILOHERTZ QUASI-PERIODIC OSCILLATIONS IN THE ATOLL X-RAY BINARY 4U 1705–44

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*Received 1997 December 22; accepted 1998 March 6; published 1998 March 31*

### ABSTRACT

In observations with the *Rossi X-Ray Timing Explorer*, we have discovered quasi-periodic oscillations (QPOs) near 1 kHz from 4U 1705–44, a low-mass X-ray binary with a neutron star classified as an atoll source. In six separate observations, we detect one QPO with a frequency ranging between 770 and 870 Hz and a 4% rms fraction in the full detector energy band. There is evidence for a second QPO at 1073 Hz in one interval. The separation in frequency of the two QPOs is  $298 \pm 11$  Hz. The QPOs are present only in observations where the mass accretion rate is inferred to be at an intermediate level, based on the atoll source phenomenology. At the highest accretion rates, the QPOs are not detected with upper limits to the rms fraction of about 2%. At the lowest accretion rates, the upper limits are about 4%. The QPO frequency increases with inferred mass accretion rate. This is expected in models where the QPO frequency is generated by motion at an inner edge of the accretion disk. An increased mass accretion rate causes the disk edge to move in, increasing the orbital frequency. Five type I X-ray bursts are observed with no detectable oscillations.

*Subject headings:* accretion, accretion disks — stars: individual (4U 1705–44) — stars: neutron — X-rays: stars

### 1. INTRODUCTION

Quasi-periodic oscillations (QPOs) with frequencies near 1 kHz were discovered from X-ray binaries with the *Rossi X-Ray Timing Explorer* (*RXTE*) almost immediately after its launch (for reviews and references, see van der Klis 1997, Kaaret & Ford 1997, and Ford 1997). These QPOs are likely produced very near the accreting neutron star where the dynamical timescale is near  $10^{-3}$  s. Observations of such fast oscillations provide a new opportunity to measure the fundamental properties of neutron stars and the effects of strong field gravity in low-mass X-ray binaries (LMXBs).

Kilohertz QPOs have been discovered in both major subclasses of LMXBs: the Z sources and the atoll sources (see Hasinger & van der Klis 1989). Certain trends are already apparent. For example, the kilohertz QPOs in Z sources are much weaker than those in the lower luminosity atoll sources. In the sources with luminosities intermediate between the majority of Z and atoll sources, QPOs are apparently absent or very weak (Wijnands, van der Klis, & van Paradijs 1998b). To understand the physical mechanisms at work, further observations of a large sample of sources are needed with the unique capabilities of *RXTE*, which are likely to be unequaled in the next decade.

Here we report the discovery of fast QPOs from the low-mass X-ray binary 4U 1705–44 using *RXTE*; 4U 1705–44 has been classified as an atoll source (Hasinger & van der Klis 1989). Its different source states are supposed to reflect changes in its mass accretion rate. We observe a link between the source state and the presence and frequencies of fast QPOs.

In § 2, we summarize the observations and analysis techniques. In §§ 3 and 4, we present the detections of fast QPOs and X-ray burst properties. In § 5, we identify the atoll source states during our observations. Section 6 is a discussion of the relation of the source states to the QPO properties and the physical implications.

### 2. OBSERVATIONS AND ANALYSIS

We have observed 4U 1705–44 with *RXTE* at random times from 1997 February to June. The total usable observing time amounts to 55.3 ks, broken into 18 separate continuous intervals. Here we use data from the Proportional Counter Array (PCA) (Zhang et al. 1993), which has a high time resolution and good sensitivity above the background from about 2 to 30 keV. In these observations, all five detector units of the PCA are on.

The all-sky monitor on *RXTE* shows that during our observations, the flux of 4U 1705–44 is smoothly varying and has a minimum at about 1997 April 1. In our observations, the count rate in the PCA varies from 500 to 2800 counts  $s^{-1}$ , with a flux of  $(0.7\text{--}5.3) \times 10^{-9}$  ergs  $cm^{-2}$   $s^{-1}$  (2–10 keV).

In all observations, we have initiated an “event” mode that provides data in time intervals of 122  $\mu$ s in 64 energy channels ranging from about 1 to 100 keV. From this data, we extract average Fourier power density spectra in 64 s data intervals. The minimum and maximum observable frequencies are thus 0.016 and 4096 Hz.

Since QPO strengths depend on energy, it is important to consider energy subbands in searching for QPOs. We employ three energy bands: 2.4–6.4 keV, 6.4–31 keV, and the full energy range of the PCA. We fitted each QPO feature in the power spectra with a Lorentzian plus a constant. The fitted values determine the centroid frequencies, widths, and rms fractions of the QPOs. We use  $\Delta\chi^2 = 1$  for quoting errors and  $\Delta\chi^2 = 2.71$  for upper limits (95% confidence). Only those QPO features with significance greater than  $3\sigma$  are reported here.

### 3. FAST QPO DETECTIONS

Figure 1 shows an example power spectrum from 3072 s of data beginning 1997 April 3 18:23:56 UTC. The narrow QPO at  $790 \pm 3$  Hz is detected with a significance of  $5.4\sigma$  for a single fitting. Six of our 18 observing intervals exhibit QPOs in the range of 780–870 Hz (Table 1). Most QPOs are detected in both the 6.4–31 keV band and the full energy band but not in the 2.4–6.4 keV band. The rms fraction of the QPOs increases with energy (Fig. 2), similar to other sources.

In addition to the QPO clearly detected at 780–870 Hz, we

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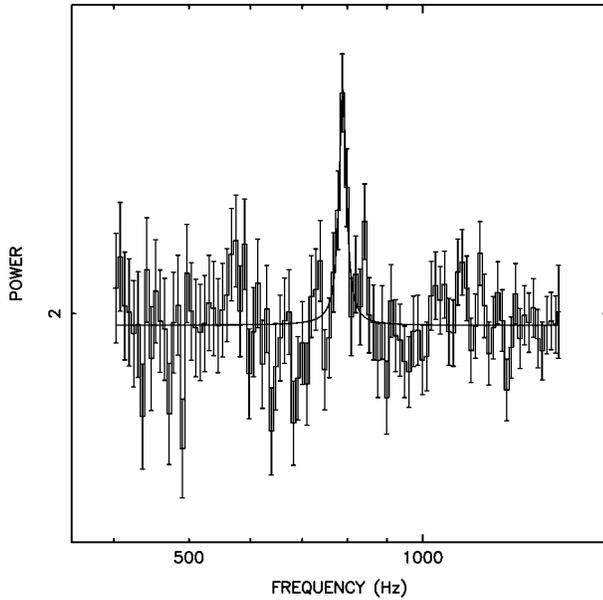


FIG. 1.—Power density spectrum from the 3072 s observing interval beginning 1997 April 3 18:23:56 UTC in the energy range 6.4–31 keV. The fit is a Lorentzian with a centroid frequency of  $792 \pm 3$  Hz and rms fraction  $4.4\% \pm 0.5\%$  plus a constant.

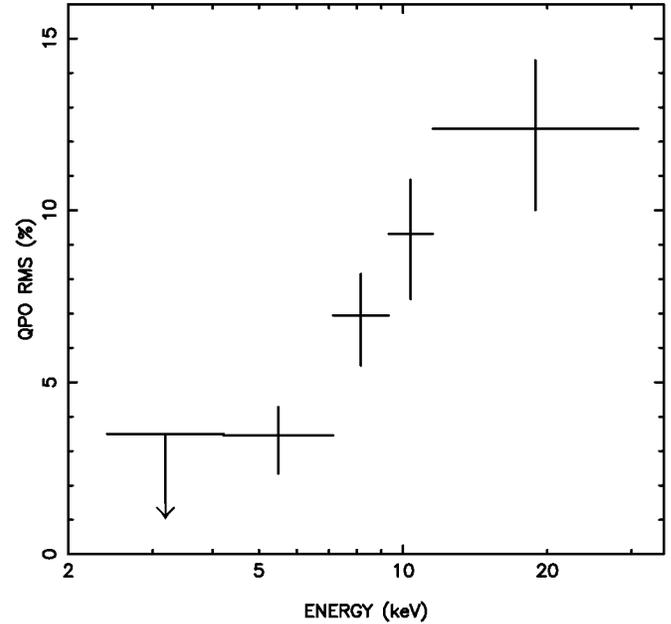


FIG. 2.—Fractional rms vs. energy of the 792 Hz QPO shown in Fig. 1. Error bars use  $\Delta\chi^2 = 1$ . The upper limit is 95% confidence.

have evidence for a second QPO at a higher frequency. This QPO is visible in one observing interval (1997 April 3 16:38:04) at  $1074 \pm 10$  Hz in the 2.4–6.4 keV band with an rms fraction of  $3.1\% \pm 0.5\%$ . The significance is  $5.2 \sigma$ , although this is for a single trial. The quoted error in frequency includes systematic errors due to rebinning the power spectra

in frequency, an important effect for weak features. The two QPOs in this interval are separated by  $298 \pm 11$  Hz.

To help confirm the presence of the second QPO, we have implemented the “shift-and-add” technique of Méndez et al. (1998) with which one can improve sensitivity by adding multiple power spectra. We take all the power spectra where the

TABLE 1  
4U 1705–44 KILOHERTZ QPOs

Observation Start (1997)	$T$ (s)	State	Frequency (Hz)	FWHM (Hz)	rms (%)	$R$ (counts $s^{-1}$ )	$F$
Mar 29 13:22:15	3456	IS1	...	...	$<5.1$	500	0.7
Apr 1 13:25:57 <sup>a</sup>	3280	IS2	...	...	$<3.8$	794	1.3
Apr 1 15:01:25	3648	IS2	...	...	$<3.6$	802	1.3
Apr 1 16:37:25 <sup>a</sup>	3392	IS2	...	...	$<4.3$	817	1.3
Apr 1 18:22:29 <sup>a</sup>	2368	IS2	...	...	$<3.9$	826	1.3
Apr 3 16:38:04	3712	B3	$776.1 \pm 3.9$ $1074.2 \pm 10.4^b$	$21.4 \pm 35.2$ $30.2 \pm 19.2^b$	$3.3 \pm 0.6$ $3.1 \pm 0.5^b$	1215	2.0
Apr 3 18:23:56	3072	B3	$791.5 \pm 3.4$	$28.0 \pm 8.0$	$4.4 \pm 0.5$	1236	2.0
Apr 4 11:49:20 <sup>a</sup>	3584	B4	$867.9 \pm 3.1$	$23.0 \pm 9.9$	$3.8 \pm 0.6$	1223	2.3
Apr 4 13:25:20	3856	B4	$837.2 \pm 4.8$	$23.4 \pm 14.5$	$3.7 \pm 0.5$	1205	2.3
Apr 4 15:01:20	1920	B4	$833.4 \pm 3.4$	$19.9 \pm 10.9$	$3.8 \pm 0.6$	1219	2.3
Apr 4 07:53:13	704	B5	...	...	$<4.5$	1265	2.4
Apr 4 08:37:13	3712	B5	...	...	$<3.1$	1276	2.4
Apr 4 10:13:13	2304	B5	$866.9 \pm 3.6$	$24.1 \pm 10.5$	$4.1 \pm 0.6$	1231	2.4
Feb 16 18:08:06	1856	B6	...	...	$<3.8$	1318	2.3
Feb 16 19:15:58	3584	B6	...	...	$<3.2$	1276	2.4
Feb 16 20:57:02	3712	B6	...	...	$<3.0$	1238	2.4
Feb 16 22:38:22 <sup>a</sup>	320	B6	...	...	$<5.8$	1261	2.3
Jun 9 19:14:33	3136	UB7	...	...	$<1.9$	2883	5.3

NOTE.—The start time of each observation is in UTC (Universal Time coordinated).  $T$  is total amount of data used in generating power spectra. The state of the source is identified in the classification scheme of Hasinger & van der Klis (1989): the island state (IS), the banana state (B), and the upper-banana state (UB). The states are ranked 1–7 according to increasing inferred mass accretion rate, using movement in the color diagrams and properties of the noise below 100 Hz. The QPO frequency, FWHM, and fractional rms power are from Lorentzian fits to the Fourier power spectra with all energy channels (sensitive to 1–30 keV).  $R$  is the mean count rate (in units of counts  $s^{-1}$ ) for each observation after background subtraction summed over all energy channels. All detectors are on.  $F$  is the total observed 2–10 keV flux in units of  $10^{-9}$  ergs  $cm^{-2}$   $s^{-1}$ . Errors use  $\Delta\chi^2 = 1$ . Upper limits are 95% confidence.

<sup>a</sup> Observations with X-ray bursts. Note that the data are excised from before the onset to 300 s after the bursts in generating power spectra and in determining the energy spectra and count rates.

<sup>b</sup> Data are from power spectrum for the energies 2.4–6.4 keV. Error includes effects of rebinning the power spectrum.

lower frequency QPO is detectable, rescale the frequencies so that the lower frequency QPOs all have the same centroid, and then add the power spectra together. With this technique, we also detect the second QPO. The significance and rms fractions are  $3.6 \sigma$ ,  $3.1\% \pm 0.5\%$  (full energy band);  $3.2 \sigma$ ,  $2.6\% \pm 0.5\%$  (2.4–6.4 keV); and  $2.9 \sigma$ ,  $3.1\% \pm 1.7\%$  (6.4–31 keV). The upper limits for a typical single observing interval are 3.1% (full band) and 3.9% (6.4–31 keV). Thus, our nondetection in single intervals is consistent with the rms fractions determined when the data are combined using the shift technique. In all energy bands, the frequency separation of the two QPOs is consistent with the previously quoted value of  $298 \pm 11$  Hz to within  $1.6 \sigma$ .

#### 4. X-RAY BURSTS

There are five X-ray bursts during our observations. We have searched for QPOs in all of the bursts, generating power spectra in 1 s intervals in each of the three energy bands identified above. We detect no QPOs in any of the time intervals or energy subbands. The upper limits to the rms fraction at the peaks of the bursts are approximately 5% in the three weak bursts and 2% in the stronger bursts. These upper limits are much smaller than the amplitudes of the QPOs in the bursts from 4U 1728–34, where the amplitudes reach 20% and perhaps even 40% (Strohmayer, Zhang, & Swank 1997).

Of the five bursts from 4U 1705–44, two occur when the source is in the banana state (February 16 and April 4). These bursts have total durations of about 10 s, rise times of 0.6 s, and average temperatures of about 1.1 keV. Three additional bursts occur when the source is in the island state (April 1). These are about 3 times longer and have peak count rates about 4 times smaller, rise times of 4.5–5.0 s, and average temperatures of about 1.3 keV. The bursts follow the previously established statistical relation of luminosity and burst duration (van Paradijs, Penninx, & Lewin 1998).

The bursts in 4U 1705–44 are cooler compared with those in 4U 1728–34 (roughly 1.2 vs. 2.2 keV for the overall fluence) and have smaller fluences and rise times. The spot sizes may be larger in 4U 1705–44 (6–12 km radii for a distance of 11 kpc), which could account for the absence of QPOs in 4U 1705–44. If the oscillation is due to burning in a hot spot (Strohmayer et al. 1997), a larger emitting area results in a reduced oscillation strength. Oscillations may also be absent if the hot spot is near the rotation axis or if our line of sight is closely aligned with the spin axis of the neutron star.

#### 5. SOURCE STATES

For each observation, we have identified the source state following Hasinger & van der Klis (1989), based on the power at low frequencies (approximately 0.01–100 Hz) and the X-ray colors of the source. At low count rates (March 29 and April 1), the source is in an “island” state of the atoll source; below about 10 Hz, there is strong, band-limited noise, with a fractional rms greater than 20% (Fig. 3a). As the count rate increases, the source moves into a “banana” state, the band-limited noise gets much weaker, and a separate noise component appears in the power spectra below 1 Hz described by a power law (Fig. 3b). The observations on February 16 and April 3 and 4 are in the banana state. On June 9, the source is in the upper banana.

There are 3 days of observations in the lower banana state: February 16 and April 3 and 4. Within the lower banana, the hard color of the source gets softer while the high-frequency

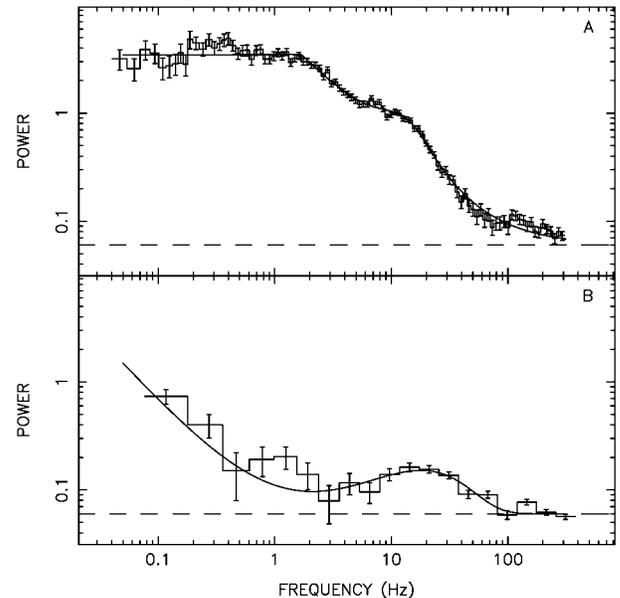


FIG. 3.—Low-frequency power density spectra for the entire PCA energy band in the intervals beginning (a) 1997 April 1 15:01:25 and (b) 1997 April 4 8:37:13 UTC. The spectra are Leahy normalized. A constant has been subtracted, and the Poisson levels are shown by the dashed lines. Observation *a* is an island state with a total rms fraction of the excess noise of 21.4% (0.1–100 Hz). Observation *b* is a banana state with an rms fraction of 6.1%. The fits are standard functions for atoll sources (Hasinger & van der Klis 1989). In (a), a broad Lorentzian is added with a centroid at 10 Hz.

noise component decreases. This behavior is consistent with the motion along the banana branch as observed in 4U 1705–44 with *EXOSAT* (Hasinger & van der Klis 1989), although in this lowest part of the banana branch, the movements in the color diagrams are very small and the changes in the amplitude of the noise components are significant only at the  $1 \sigma$  level. In order of increasing progress along the banana branch, the observations are ordered as April 3, last half of April 4, first half of April 4, and February 16. In Table 1, we assign a numerical ranking of the states from 1 to 7 going from the island state to the upper banana state. The inferred mass accretion rate increases from 1 to 7.

#### 6. DISCUSSION

The 760–870 Hz QPO in 4U 1705–44 is probably a single feature and is likely the lower frequency of two QPO peaks. The second QPO, which we identify at 1074 Hz, then is the higher frequency peak. More observations in the lower banana state are needed to confirm the presence of this second QPO. Such phenomenology is very similar to other atoll sources. A single strong QPO near 800 Hz is present at times in several sources, e.g., 4U 1608–52 (Berger et al. 1996; Méndez et al. 1998), 4U 1820–30 (Smale, Zhang, & White 1997), and 4U 1636–53 (Zhang et al. 1996; Wijnands et al. 1997). In all of these sources, a second QPO is sometimes detectable (see above references). The frequency separation of the two peaks is similar to that in 4U 1705–44. Such double QPOs, and also the QPOs observed in X-ray bursts (e.g., Strohmayer et al. 1997), suggest a beat-frequency mechanism (Alpar & Shaham 1985; Miller, Lamb, & Psaltis 1998). If such an interpretation holds, then the frequency separation of the QPOs in 4U 1705–44 implies that the spin period of the neutron star in this system is  $3.35 \pm 0.12$  ms.

The appearance and frequency of the fast QPOs in 4U 1705–44 are correlated with the states of the source. The states in turn are thought to be related to the mass accretion rate, with the accretion rate increasing from the island to the banana. At the lower end of the banana branch, a QPO appears at about 780 Hz. Farther along the branch, the frequency increases to 835 Hz and then to 865 Hz. This behavior supports models where the QPO modulation is generated at an inner disk edge that shrinks as the mass accretion rate increases (e.g., Miller et al. 1998). We detect the second QPO at 1073 Hz only in the lowest part of the banana where the frequency of the stronger QPO is at its lowest. Farthest along the banana branch, the QPO becomes undetectable with rms fraction upper limits of about 2%. At the highest accretion rates, the reduced QPO amplitude is perhaps due to spreading of the accretion stream; alternatively, a puffed-up inner disk may obscure the central source (Smale et al. 1997).

Similar behavior is observed in other X-ray binaries. Atoll source state identifications have been made simultaneously with fast QPO detection in 4U 1636–53 (Zhang et al. 1996; Wijnands et al. 1997), 4U 1735–44 (Wijnands et al. 1998a), 4U 1820–30 (Smale et al. 1997), and KS 1731–260 (Wijnands & van der Klis 1997). These sources were observed in the banana branch. Consistent with the present data, the QPO in all cases is detected only in the lower part of the banana and disappears as the source moves up along the banana branch. In 4U 0614+091, a similar effect appears as the QPO amplitude decreases as the count rate increases (Ford 1997).

The situation is less clear at low mass accretion rates, i.e., in the island states. Our upper limits of about 4% rms fraction are not very constraining. QPOs have been detected in island

states in both 4U 0614+091 (Méndez et al. 1997) and 4U 1608–52 (Yu et al. 1997). At the lowest count rates in the island state of 4U 0614+091, the QPO is not detected (Méndez et al. 1997). This fits the general trend we observe here.

The QPO frequency shows no correlation with count rate or energy flux in the 2–10 keV band, although we note that the range of count rates is small (1205–1236 counts  $s^{-1}$ ). An effect similar to that seen in 4U 0614+091 may be at work, where there is no unique correlation between rate and frequency in different observations separated by several months (Ford et al. 1997a). The present data indicate that the QPO frequency is better correlated with the atoll state of the source. Changes in the source state are reflected as changes in the X-ray colors, which in turn are simply changes in the energy spectrum of the source. Therefore, the state-frequency correlation also manifests as a spectrum-frequency correlation. From other sources, we know that the changes in QPO frequency are linked to changes in the energy spectrum. The frequencies of the QPOs in 4U 0614+091 are well correlated with the flux of a blackbody component in the energy spectrum (Ford et al. 1997b), and in that source and also in 4U 1608–52, the QPO frequencies are correlated with the spectral index of the power-law component in the energy spectrum (Kaaret et al. 1998).

We thank Mariano Méndez for assistance in implementing the frequency-shifting technique. We thank Rudy Wijnands, Rob Fender, and the referee for helpful discussions and comments. E. C. F. acknowledges support by the Netherlands Foundation for Research in Astronomy, with financial aid from the Netherlands Organization for Scientific Research (NWO) under contracts 782-376-011 and 781-76-017.

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