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KILOHERTZ QUASI-PERIODIC OSCILLATION AND ATOLL SOURCE STATES IN 4U 0614+09

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ABSTRACT

We report three *RXTE*/PCA observations of the low-mass X-ray binary 4U 0614+09. They show strong (~30% rms) band-limited noise with a cutoff frequency varying between 0.7 and 15 Hz in correlation with the X-ray flux, f_X. We observe two nonsimultaneous 11%–15% (rms) kHz peaks near 728 and 629 Hz in the power spectra of two of our observations when $f_X \sim 10^{-9}$ ergs cm^{-2} s^{-1} (2–10 keV) but find no quasi-periodic oscillations (QPOs; <6% rms) when f_X is half that. We suggest that count rate may not be a good measure for $\dot{M}$ even in sources as intrinsically weak as 4U 0614+09 and that QPO frequency and noise cutoff frequency track $\dot{M}$ more closely than count rate. The QPO increases in rms amplitude from 11% ± 1.3% at 3 keV to 37% ± 12% at 23 keV; the fractional amplitude of the band-limited noise is energy independent. This suggests different sites of origin for these two phenomena. The spectrum of the oscillating flux roughly corresponds to a black body with temperature 1.56 ± 0.2 keV and radius 500 ± 200 m (other models fit as well), which might indicate that the oscillations originate at a small region on the neutron star surface.

Subject headings: accretion, accretion disks — stars: individual (4U 0614+091) — stars: neutron — X-rays: stars

1. INTRODUCTION

Recently, kilohertz quasi-periodic oscillations (kHz QPOs) have been discovered in 11 low-mass X-ray binaries (see van der Klis 1997 for a review). Often, the X-ray power spectra show twin kHz peaks moving up and down in frequency together. Sometimes a third kHz peak is detected near a frequency equal to the separation frequency of the twin peaks, or twice that, which suggests a beat-frequency interpretation, with the third peak near the neutron star spin frequency (or twice that). However, in Sco X-1, the twin peak separation varies, which is not consistent with a simple beat-frequency interpretation (van der Klis et al. 1997).

In the X-ray burster (Swank et al. 1978; Brandt et al. 1992) and suspected atoll source (Singh & Apparao 1994) 4U 0614+09, twin kHz peaks occur (Ford et al. 1997). The peaks move between 480–800 Hz and 520–1150 Hz, respectively. Their separation is consistent with being constant near 323 Hz. There has been one 3.3 σ detection of a third peak near 328 Hz (in the persistent emission, whereas in the three other sources where a third peak occurred, it was seen during X-ray bursts).

It is yet unclear how the properties of the kHz QPO relate to the type and state of the sources in which they have been observed. In this paper we analyze new X-ray timing and spectral data on 4U 0614+09 (preliminary report in van der Klis et al. 1996). We point out a number of correlations between the QPO properties and those of the broadband noise and the X-ray spectra and present for the first time an analysis of the photon energy spectrum of the oscillating flux in kHz QPO.

2. OBSERVATIONS

We observed 4U 0614+09 with the proportional counter array (PCA) on board NASA's *Rossi X-Ray Timing Explorer* (Bradt, Rothschild, & Swank 1993) three times, in 1995 February, March, and April (Table 1). We simultaneously collected 2–60 keV data with a time resolution of 8 μs in eight energy bands and 16 s in 129 bands. The background- and dead-time–corrected count rates were 235, 571, and 256 counts s^{-1}, respectively. A change in PCA gain between March and April affected these values only slightly. In April, only three out of the five PCA detectors were active; the five detector count rate was 426 counts s^{-1}. We observed no X-ray bursts.

We calculated power spectra of the 8 μs data and subtracted the Poisson noise and the very large event window contribution (Zhang et al. 1995; Zhang 1995). We obtained background measurements from slew and Earth occultation data and used them to renormalize all power spectra to fractional rms squared per Hertz (see van der Klis 1995) and to correct the X-ray spectra obtained from the 16 s data.

3. RESULTS

All power spectra (Fig. 1) show strong (~30% rms) band-limited noise, which we fitted with a broken power law. In two cases we observed kHz QPOs. These we fitted with Lorentzian peaks. The fit results are listed in Table 1. The power-law break frequency varied from 0.7 Hz in February, to 15.4 Hz in March, to 6.6 Hz in April.

During March and April, strong QPOs were present near 727 and 629 Hz, respectively. The QPO properties did not vary significantly within each observation. We detect no other kHz QPO peaks. In particular, any peaks 323 Hz above or below

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TABLE 1

POWER AND X-RAY SPECTRAL PARAMETERS

	1996 FEB 26	1996 MAR 16[a] Soft-Color Dip	1996 MAR 16[a] Main	1996 APR 13
		Power Spectra		
Band-limited noise rms (%).....	30.2 ± 0.9	29.4 ± 1.6	28.1 ± 0.7	35.3 ± 1.1
Break frequency (Hz)...........	0.7 ± 0.1	15.4 ± 1.5	15.4 ± 0.8	6.6 ± 0.5
P_{break} rms (%)[b]..................	12.2 ± 1.1	3.0 ± 0.2	3.2 ± 0.2	4.5 ± 0.2
QPO rms (%)..................	<6	11.0 ± 1.8	13.9 ± 0.7	14.6 ± 0.5
Frequency (Hz).................	...	728 ± 8	719 ± 5	629 ± 4
FWHM (Hz)....................	...	54 ± 27	99 ± 14	98 ± 9
Second QPO rms (%)...........	...	<4	<4	<6
χ^2/dof............................	284/229	270/346	329/346	259/242
		Energy Spectra		
N_H (10^{-22} cm^{-2})[c]................	0 (<1.34)	0 (<0.22)	0 (<0.10)	0.14 (<0.39)
kT (keV).........................	0.42 ± 0.05	...	1.10 ± 0.18	...
n (photon index)................	1.97 ± 0.03	2.54 ± 0.03	2.41 ± 0.03	2.30 ± 0.03
Power-law flux[d]..................	0.36 ± 0.02	1.00 ± 0.05	0.89 ± 0.08	0.75 ± 0.02
Blackbody flux[d]..................	0.04 ± 0.01	<0.08	0.12 ± 0.05	<0.02
χ^2/dof............................	103/90	92/94	80/92	95/83

NOTE.—Quoted errors represent 90% confidence intervals for the fits to the X-ray spectra and 1σ confidence intervals for the fits to the power spectra. Quoted upper limits are 95% confidence. A 2% systematic uncertainty was included in the X-ray spectral errors to account for the calibration uncertainties (Cui et al. 1997).

[a] The March observation was divided into two parts; see text for details.

[b] Power of the band-limited noise component at break frequency.

[c] N_H was consistent with zero in all of our fits. The best-fit values are given first, followed by the upper limits in parentheses.

[d] 2–10 keV flux in units of 10^{-9} ergs cm^{-2} s^{-1}. When only an upper limit is given for the blackbody flux, this parameter was kept fixed at zero in the final fit.

our detected peaks are 3–14 times weaker than these (Table 1). The upper limit on any 328 Hz peak is 3.5% (rms, 95% confidence).

Count rates in March were sufficient to study the photon energy dependence of the QPO. We fitted power spectra in

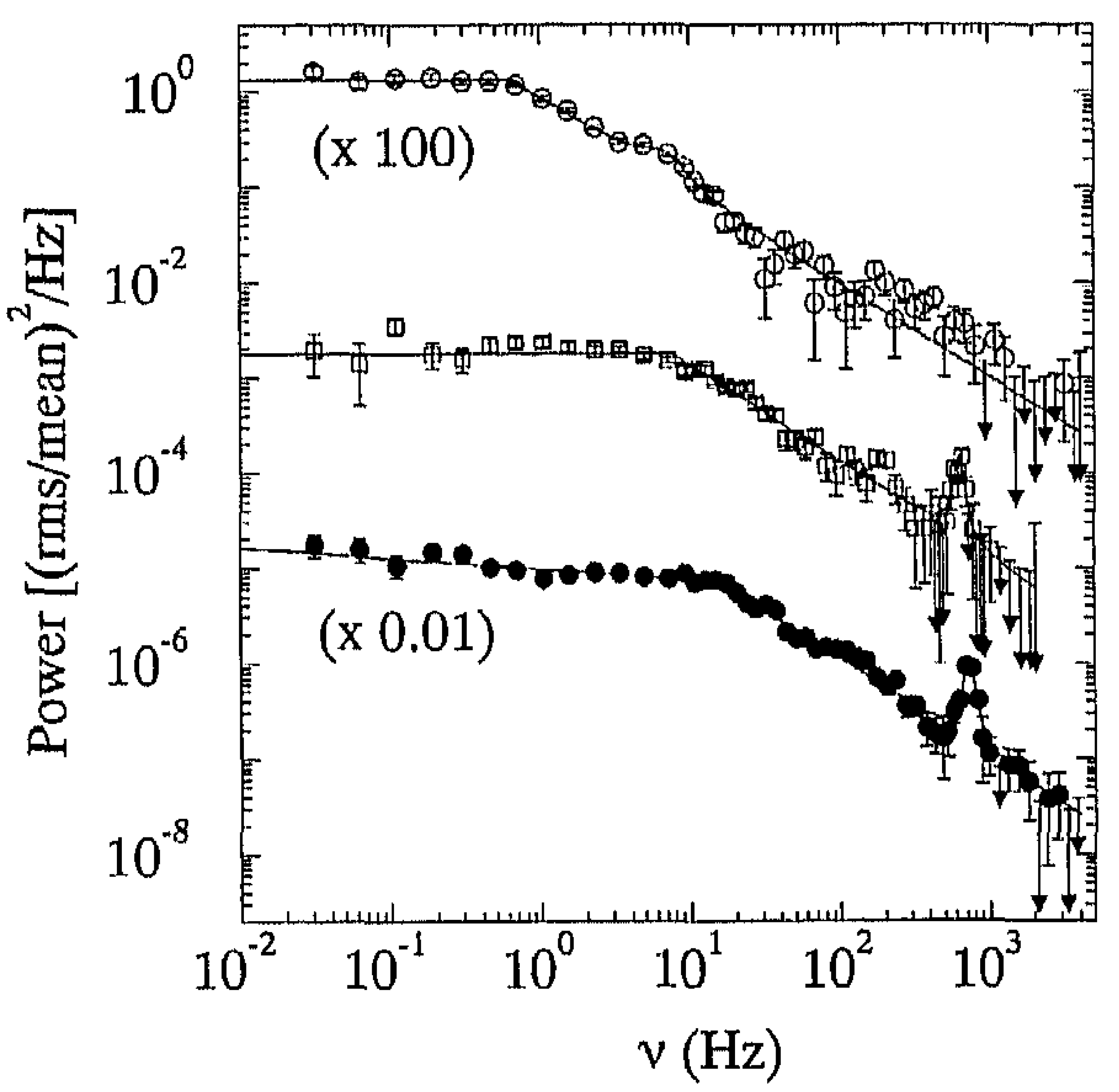

FIG. 1.—Power spectra for the three observations discussed in the paper. The data from February, March, and April are represented by open circles, filled circles, and squares, respectively. The significance of the peak at ~200 Hz in the power spectrum from April is less than 3 σ and was not fitted. We included a QPO at 6.5 Hz in fitting the February spectrum.

five energy bands (1.1–4.3–6.8–8.4–15.5–69.8 keV) with the break frequency, the power-law slopes, and QPO frequency and width fixed to the 2–60 keV values (none of these varied significantly with photon energy). As shown in Figure 2 (*top panel*), the rms amplitude of the QPO rose from 11% at 3.3 keV, to 20% at 11 keV, to 37% ± 12% at 22.8 keV. Similar energy dependencies were seen in other sources. The fractional rms amplitude of the band-limited noise did not vary significantly as a function of photon energy.

The bottom panel of Figure 2 shows the energy spectrum of the oscillating flux (QPO rms amplitude in units of counts s^{-1} keV^{-1} vs. photon energy). For reference, we quote the results of a blackbody fit: the best fit (χ^2 = 14.4 with 3 degrees of freedom [dof]) has a temperature of 1.56 ± 0.2 keV and a radius of 500 ± 200 m (at 3 kpc, Brandt et al. 1992). The resolution of the spectrum is low, and many spectral models are consistent with it. For example, the data can be fitted by a temperature variation of ~2.5% in a blackbody spectrum of ~1.1 keV with a radius of 10 km, or (χ^2 = 4.9 with 4 dof) by optical depth variations of ~5% in an unsaturated Comptonization spectrum. (This latter result was obtained by fitting the fractional rms spectrum.)

To convert count rates to fluxes, we fitted the 2–50 keV energy spectra with a black body plus a power law modified by interstellar absorption (Table 1). In April and during a dip in soft color in March (below), a power law alone could fit the spectrum. The inferred 2–10 keV fluxes were 0.4, 1.0, and 0.75 × 10^{-9} ergs cm^{-2} s^{-1} in February, March, and April, respectively; the 2–50 keV fluxes are 50%, 30%, and 40% higher, respectively. As N_H is low, absorbed and "unabsorbed" fluxes are the same. We tried various other spectral shapes,

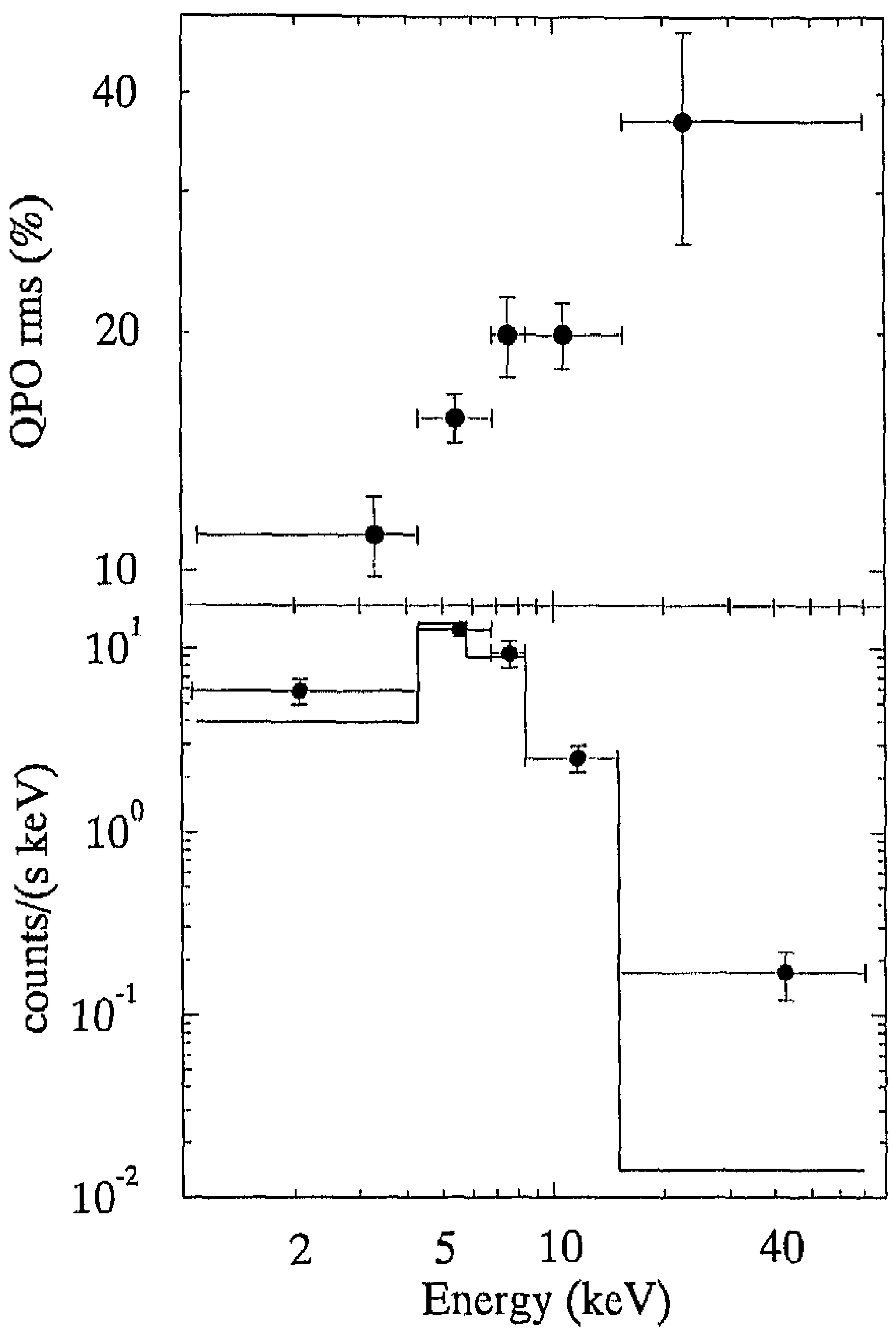

FIG. 2.—*Top,* Fractional rms amplitude vs. photon energy spectrum of the QPO from 1996 March; *bottom,* energy spectrum of the oscillating flux, with blackbody fit, for the same data set.

with no effect on the derived fluxes. Count rate, flux, and power spectra were not affected by the soft-color dip.

To compare 4U 0614+09 with confirmed atoll sources (see Hasinger & van der Klis 1989), we produced an X-ray color-color diagram using the three spectral bands 2–5–10–50 keV (Fig. 3). We corrected for detector gain changes by comparing the count rate ratios with incident flux ratios obtained in the same bands from the spectral fits. Once again we tried different spectral shapes and found negligible effects on the color corrections. There was a dip of ~800 s in soft color starting 5200 s into the March observation. Apart from this, the colors within each observation show no significant changes, with upper limits on any intrinsic color variations of ~10%. Except for the March excursion, this is entirely consistent with atoll-source island-state behavior.

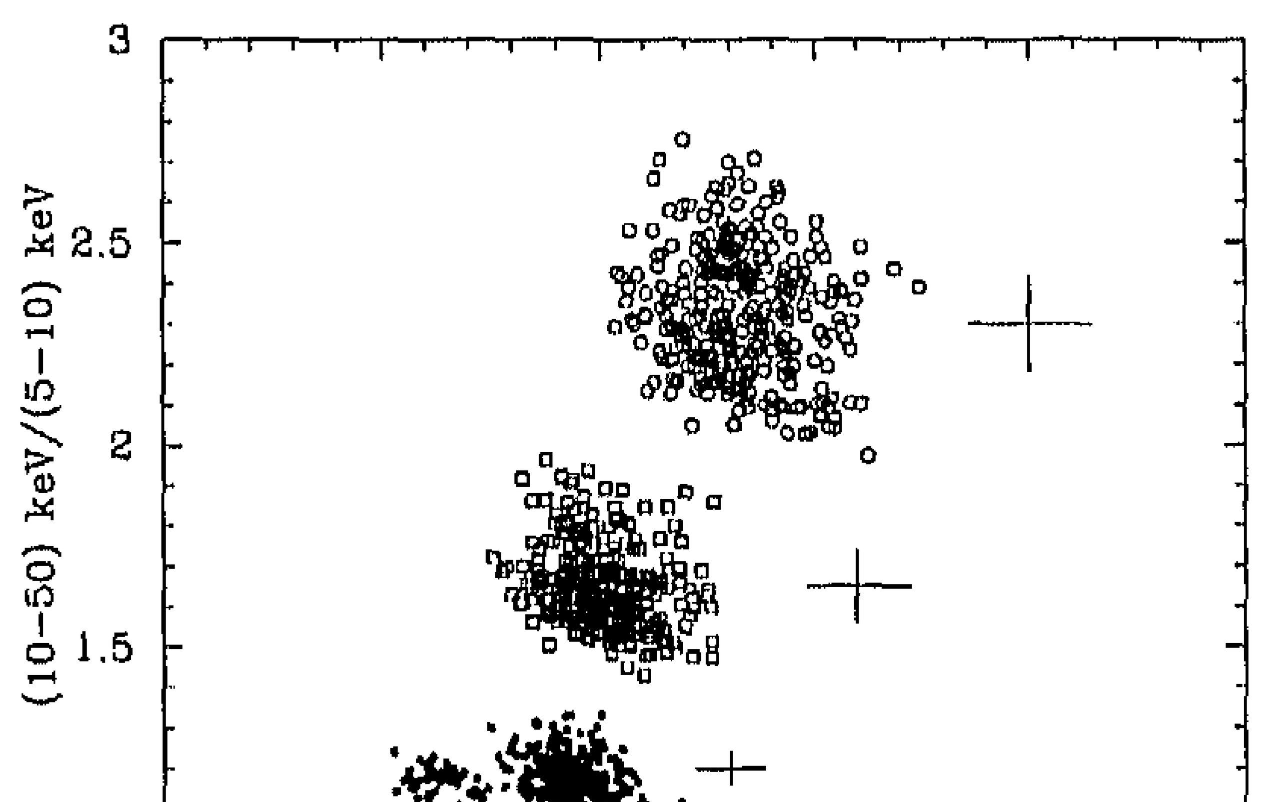

FIG. 3.—Color-color diagram showing all the observations mentioned in the paper. Symbols are the same as in Fig. 1. Each point represents 16 s of data. Typical error bars for each observation are indicated.

4. DISCUSSION

From color-color diagrams, Singh & Apparao (1994) suggested 4U 0614+09 to be an atoll source. Our color-color diagrams, spectral fits, and simultaneous strong band-limited noise with 0.7–15 Hz cutoff frequencies confirm that the correlated X-ray spectral and timing properties of 4U 0614+09 are those of an atoll source, in the island state during our observations. The large fractional amplitude and low cutoff frequency of the band-limited noise and the relatively hard X-ray spectra make the source similar to the atoll sources 4U 1608−52 and 4U 1705−44 in the island state (Hasinger & van der Klis 1989; Langmeier, Hasinger, & Trümper 1989; Yoshida et al. 1993; Berger & van der Klis 1997), which in turn resemble the black hole candidates Cyg X-1 and GX 339−4 in the low and intermediate states (van der Klis 1994a; Berger & van der Klis 1997; Belloni et al. 1996; Crary et al. 1996; Méndez & van der Klis 1997). All these sources are quite hard. Their energy spectra fit a soft component with $kT \sim 1$ keV plus a power law with a photon index of 1.6–2.5. Their power spectra show band-limited noise with a ~0.1–10 Hz cutoff frequency that is anticorrelated with the level of the flat top (Belloni & Hasinger 1990; Méndez & van der Klis 1997). This anticorrelation holds also for our power spectra of 4U 0614+09. Break frequencies and fractional rms at the break are fully consistent with the existing relation between these quantities from other sources (see Fig. 3 of Méndez & van der Klis 1997).

If, as proposed (van der Klis 1994b; Méndez & van der Klis 1997), the break frequency of the band-limited noise component here is an indication for $\dot{M}$, then $\dot{M}$ increased from February to March and then decreased to an intermediate value in April. This is consistent with the variations in X-ray flux among our three observations. Note that this is not always the case in similar sources (e.g., 4U 1608−52; Yoshida et al. 1993).

In this picture, we observe no kHz QPO (<6% rms), when $\dot{M}$ is lowest, and 11%–15% amplitude QPOs at higher inferred $\dot{M}$ values. Although kHz QPOs often get stronger when inferred $\dot{M}$ drops (in 4U 1636−53, Wijnands et al. 1997; KS 1731−260, Wijnands & van der Klis 1997; 4U 1820−30, Smale, Zhang, & White 1997), apparently in 4U 0614+09 there is a value of $\dot{M}$ below which the QPO becomes weaker.

We now turn to the identification of our QPO peaks. In our data, at most one peak is present at each time, whereas for similar count rates, Ford et al. (1997) usually find twin peaks. The count rate–QPO frequency relations do not clearly identify our peaks as either the higher or the lower frequency ones (Fig. 4). The QPOs amplitudes do give a clue. Ford et al. (1997) found the lower frequency peak to have an rms amplitude 0.25–0.75 times that of the higher frequency peak when the count rate was near 400 counts s^{-1} and 0.5–1.5 that at 600–700 counts s^{-1}. If our peaks are the higher frequency ones, these ratios are less than 0.3–0.4 in our data. If they are

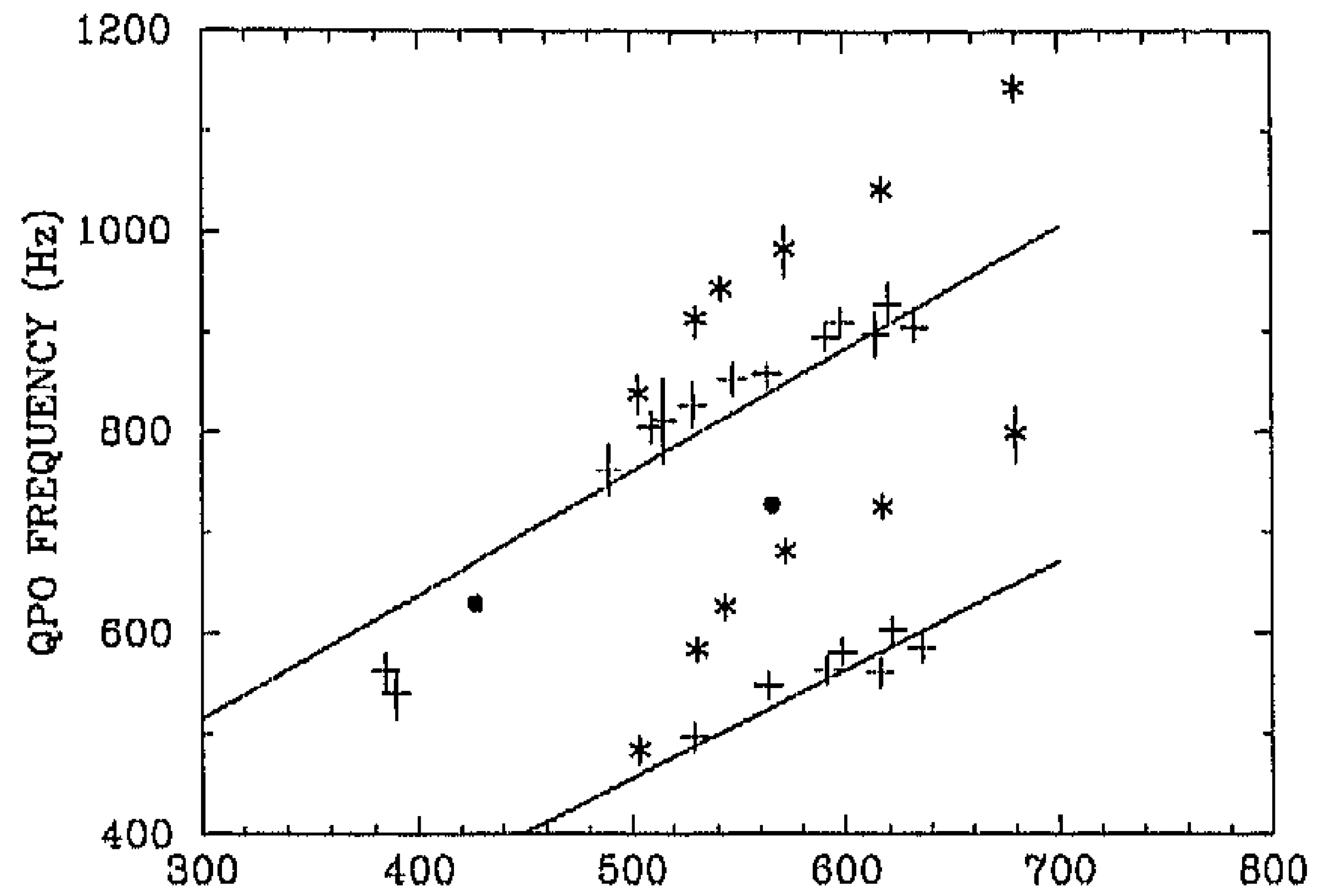

FIG. 4.—The count rate vs. QPO frequency diagram of all 4U 0614+09 data reported to date. Pluses, asterisks, and power-law relations have been taken from Ford et al. (1997); filled circles represent the new data presented in this paper.

the lower frequency ones, these values are greater than 2.4–3.5. As our count rates are 400–600 counts s^{-1}, our peaks are probably the higher frequency ones. Then, in our data we have a positive correlation between QPO frequency and count rate, but one that does not fit either of the relations observed previously (see Fig. 4).

The QPO frequency versus count rate diagram of 4U 0614+09 (Fig. 4) shows that there is no single relation that describes the correlation between those two quantities. This means that either count rate or frequency (or both) does not track $\dot{M}$ well. We suggest that count rate is not a good measure of $\dot{M}$. Both spectral changes and variations in the anisotropy of the emission can destroy the expected correspondence between these two quantities. To the extent that bolometric corrections can be accurately performed, a conversion to energy flux adjusts for the spectral changes. However, the experience from the *Z* sources (at admittedly much higher $\dot{M}$ values) shows that even derived bolometric X-ray fluxes do not always track $\dot{M}$ well. In 4U 1608–52, in a very similar series of island-state observations as the present ones of 4U 0614+09, Yoshida et al. (1993) found that the bolometric flux did not exhibit a one-to-one correspondence to cutoff frequency of the band-limited noise. Whereas there are many processes that can quite easily change the observed X-ray count rates, colors, spectral parameters, and even bolometric fluxes from their original values, the noise cutoff frequency is not so easily affected. The noise cutoff can, in principle, be lowered by scattering delays. The kHz QPO frequency, on the other hand, is very likely a direct diagnostic of the dynamics of the inner flow and is therefore very hard to modify by any propagation effect. It is possible, then, that QPO frequency is well correlated to $\dot{M}$ but that count rate is not. It will be of great interest to see whether the correlation suggested by the joint decrease of the noise cutoff frequency and QPO frequency from March to April (see Table 1) will hold up in future analyses of other data or whether a QPO frequency–flux relation will turn out to be the more reproducible, as this may provide clues to both the best measure of $\dot{M}$ in atoll sources in extreme island states (and perhaps black hole candidates) and to the physical origin of kHz QPO and broadband noise in these systems.

We observed a very strong energy dependence in the kHz QPO but no energy dependence in the band-limited noise. One plausible interpretation of this—namely, that the low-energy photons undergo scattering with a characteristic delay timescale intermediate between the QPO timescale (1 ms) and that of the noise (0.1–10 s)—can probably be excluded on the basis of the extremely small (20 μs and <50 μs) time lags between the kHz QPO signals at different photon energies recently reported by Vaughan et al. (1997). (Of course, scattering with shorter characteristic timescales cannot be excluded and is in fact likely on other grounds.) The kHz QPO spectrum, which resembles a blackbody shape with a characteristic temperature of 1.6 keV and radius of 500 m, might indicate an origin associated with a relatively small area on the neutron star surface, whereas the band-limited noise may have a different site of origin, perhaps in the inner disk. This would be in accordance with the observation that band-limited noise is a common trait among neutron stars and black holes (van der Klis 1994a), whereas correlated twin kHz QPO peaks are so far unique to neutron star systems.

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