Kilohertz QPO 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 cut-off frequency varying between 0.7 and 15 Hz in correlation with the X-ray flux, $f_x$. We observe two non-simultaneous 11–15\% (rms) kHz peaks near 728 and 629 Hz in the power spectra of two of our observations when $f_x \sim 10^{-9}$ erg cm$^{-2}$ s$^{-1}$ (2–10 keV), but find no QPO (<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\pm1.3)\% at 3 to (37\pm12)\% 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\pm0.2) keV and radius (500\pm200) m (other models fit as well), which might indicate the oscillations originate at a small region on the neutron star surface.

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

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1. Introduction

Recently, kilohertz quasi-periodic oscillations (kHz QPOs) have been discovered in eleven 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, suggesting 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. [1995]).

In the X-ray burster (Swank et al. [1978]; Brandt et al. [1992]) and suspected atoll source (Singh & Apparao 1995) 4U 0614+09 twin kHz peaks occur (Ford et al. [1997]). The peaks move between 480 and 800 Hz and 520 and 1150 Hz, respectively. Their separation varies, which is not consistent with a simple beat-frequency interpretation (van der Klis et al. [1997]).

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 February, March, and April 1996 (Table I). We simultaneously collected 2–60 keV data with a time resolution of 8 μs and 8 energy bands, and 16 s in 129 bands. The background and deadtime corrected count rates were 235, 571, and 256 c/s, respectively. A change in PCA gain between March and April affected these values only slightly. In April, only 3 out of the 5 PCA detectors were active; the 5 detector count rate was 426 c/s. 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. [1992]; Zhang [1995]). We obtained background measurements from slew and Earth occultations 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 I. The power-law break frequency varied from 0.7 Hz in February, via 15.4 Hz in March to 6.6 Hz in April.

During March and April strong QPO are 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 our detected peaks are 3 to 14 times weaker than these (Table I). The upper limit on any 328 Hz peak is 3.5% (rms; 95% confidence).

Countrates in March were sufficient to study the photon energy dependence of the QPO. We fitted power spectra in 5 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 Fig. 2a the rms amplitude of the QPO rose from 11% at 3.3 keV via 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.

Fig. 2b shows the energy spectrum of the oscillating flux (QPO rms amplitude in units of c/s/keV vs. photon energy). For reference, we quote the results of a blackbody fit: the best fit (χ^2 = 14.4 with 3 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 ~ 2.5% temperature variation in a ~ 1.1 keV blackbody spectrum with a radius of 10 km, or (χ^2 = 4.9 with 4 dof) by ~ 5% optical depth variations in an unsaturated Comptonization
To convert count rates to fluxes, we fitted the $2–50\ keV$ energy spectra with a blackbody 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 $0.4, 1.0, \text{and } 0.75 \times 10^{-9}\ erg\ cm^{-2}\ s^{-1}$ in February, March, and April, respectively; the $2–50\ keV$ fluxes are $50, 30, \text{and } 40\%$ higher, respectively. As $N_H$ is low absorbed and "unabsorbed" fluxes are the same. We tried various other spectral shapes, with no effect on the derived fluxes. Count rate, flux nor power spectra were affected by the soft color dip.

To compare 4U 0614+09 to confirmed atoll sources (cf. 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 $\sim 800\ s$ dip 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 $\sim 10\%$. Except for the March excursion, this is entirely consistent with atoll-source island-state behavior.

4. Discussion

From color-color diagrams Singh & Apparao 1995, suggested 4U 0614+09 to be an atoll source. Our color-color diagrams and 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 1996), 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 1996; Belloni et al. 1996; Cray 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 photon index 1.6–2.5. Their power spectra show band limited noise with a $\sim 0.1–10\ Hz$ cut-off frequency that is anticorrelated with the level of the flat top (Belloni & Hasinger 1990; Méndez & van der Klis 1997). This anti-correlation 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 (c.f. 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 $\dot{M}$. 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 vs. QPO frequency relations do not clearly identify our peaks as either the higher- or the lower-frequency ones (Fig. 3). 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 c/s, and 0.5–1.5 that at 600–700 c/s. If our peaks are the higher-frequency ones, these ratios are $<0.3$ to $<0.4$ in our data. If they are the lower-frequency ones, these values are $>2.4$ to $>3.5$. As our countrates are 400–600 c/s, 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. 3).

The QPO frequency vs. 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 countrate or frequency (or both) does not track $M$ 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 $M$) shows that even derived bolometric X-ray fluxes do not always track $M$ 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, colours, 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 $M$, but countrate is not. It will be of great interest to see if 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 vs. 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 broad-band 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 time scale intermediate between the QPO time scale (1 ms) and that of the noise (0.1–10 s), can probably be excluded on the basis of the extremely small (20 $\mu$s and $< 50 \mu$s) time lags between the kHz QPO signals at different photon energies recently reported by Vaughan et al. (1997). (Of course, scattering with shorter characteristic time scales 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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### Table 1

**Power- and X-ray spectral parameters**

|                        | 1996 Feb 26 | 1996 Mar 16 (soft color dip) | 1996 Mar 16 (main) | 1996 Apr 13 |
|------------------------|-------------|-------------------------------|-------------------|------------|
| **Start time (UTC)**   | 08:53       | 09:53                         | 08:26             | 09:50      |
| **Exposure time (ks)** | 5.0         | 0.8                           | 4.3               | 5.2        |
| **Power spectra**      |             |                               |                   |            |
| BLN rms [%]            | 30.2 ± 0.9  | 29.4 ± 1.6                    | 28.1 ± 0.7        | 35.3 ± 1.1 |
| ν\text{break} [Hz]     | 0.7 ± 0.1   | 15.4 ± 1.5                    | 15.4 ± 0.8        | 6.6 ± 0.5  |
| P\text{break} rms [%]  | 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 |
| Freq. [Hz]             | 728 ± 8     | 719 ± 5                       | 629 ± 4           |            |
| FWHM [Hz]              | 54 ± 27     | 99 ± 14                       | 98 ± 9            |            |
| 2nd. QPO rms [%]       | < 4         | < 4                           | < 4               |            |
| χ²/dof²                | 284/229     | 270/346                       | 329/346           | 259/242    |
| **Energy Spectra**     |             |                               |                   |            |
| N_H [10⁻²² cm⁻²]       | 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 |
| PL Flux [f]            | 0.36 ± 0.02 | 1.00 ± 0.05                   | 0.89 ± 0.08       | 0.75 ± 0.02 |
| BB Flux [f]            | 0.04 ± 0.01 | <0.08                         | 0.12 ± 0.05       | <0.02      |
| χ²/dof²                | 103/90      | 92/94                         | 80/92             | 95/83      |

- The March observation was divided into 2 parts; see text for details.
- Band limited noise.
- Power of the BLN component at ν\text{break}.
- Number of degrees of freedom.
- 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.
- 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.

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).
Fig. 1.— The power spectra for the 3 observations mentioned 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 $\sim 200$ Hz in the power spectrum from April is less than 3$\sigma$ and was not fitted. We included a QPO at 6.5 Hz in fitting the February spectrum.
Fig. 2.— (a) Fractional rms amplitude vs. photon energy spectrum of the QPO from March 1996. (b) Energy spectrum of the oscillating flux, with black-body fit, for the same data set.
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.
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.