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CORRELATION BETWEEN FAST QUASI-PERIODIC OSCILLATIONS AND X-RAY SPECTRAL SHAPE IN ATOLL SOURCES

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ABSTRACT

We present correlations between the frequency of the fast quasi-periodic oscillations (QPOs) and the shape of the X-ray spectrum in the atoll sources 4U 1608−52 and 4U 0614+091. We find that the photon index of a power-law component of the energy spectrum is well correlated with the QPO frequency in both sources. The correlation between the photon index and the QPO frequency most likely represents a common dependence on some physical parameter of the system.

Subject headings: accretion, accretion disks — stars: individual (4U 0614+091, 4U 1608−52) — stars: neutron — X-rays: stars

1. INTRODUCTION

The discovery of quasi-periodic oscillations (QPOs) at frequencies near 1000 Hz with the *Rossi X-Ray Timing Explorer* (*RXTE*) has provided a new probe of the dynamics of accretion in neutron star low-mass X-ray binaries (LMXBs). The QPO frequencies correspond to timescales of orbital motion very close to the neutron star surface, and, when the origins of the QPOs are understood, the fast QPOs may lead to constraints on the properties of neutron stars and of strong-field gravity (for a review, see Kaaret & Ford 1997). In attempting to understand the physical origins of the QPOs, it is useful to search for correlations between QPO properties and other properties of the X-ray emission from LMXBs.

The QPO frequency is correlated with the X-ray count rate in several neutron star LMXBs. However, neither the count rate nor the total luminosity is a robust predictor of QPO frequency. The frequency versus count rate, or luminosity, relation is different for different epochs for the atoll source 4U 0614+091 (Ford et al. 1997a, 1997b) and the soft X-ray transients 4U 1608−52 (Yu et al. 1997) and Aql X-1 (Zhang et al. 1998). Recently, Ford et al. (1997b) demonstrated a robust correlation between the QPO frequency and the flux in a soft blackbody component of the X-ray spectrum of 4U 0614+091. Here we present evidence for a correlation between the photon index of a power-law component of the X-ray spectrum and the QPO frequency in both 4U 1608−52 and 4U 0614+091.

2. ANALYSIS

The timing analysis of the observations of 4U 1608−52 was presented in Yu et al. (1997). We recalculated the uncertainties in the QPO frequencies, allowing $\Delta\chi^2 = 4.72$ for 4 degrees of freedom (dof).

We performed spectral analysis on 4U 1608−52 for five of six *RXTE* orbits during which QPOs have been detected (Yu et al. 1997). We exclude one orbit during which X-ray bursts occurred, since the spectrum appears to be affected strongly by the bursts. Two orbits occurred on 1996 March 15 and three on 1996 March 22. The X-ray flux was relatively low, near 10^{-9} ergs cm^{-2} s^{-1} (2–20 keV). Version 1.5 of the *RXTE* proportional counter array (PCA) background estimator and version 2.2.1 of the PCA response matrices were used, and a systematic error of 1% was included. The source was not strong in the High Energy X-Ray Timing Experiment (HEXTE), and the results below are only from the PCA. We used only proportional counter unit (PCU) 0 and PCU 1, which were on during all of the orbits. We did not use PCU 2, since it shows large residuals in fits to the Crab Nebula (R. Remillard 1997, private communication). The separate spectra of the two PCUs were fitted simultaneously, and the relative normalization of the PCUs was left free. We found that the normalizations differed by 2% and included a 2% systematic error on the flux measurements.

Several single-component continuum models were fitted to the data in the 2.5–20 keV energy band for each orbit. None of the single-component continuum models produced an acceptable fit. In most cases, the largest residuals were clustered near 6–7 keV. The inclusion of an emission line with a centroid fixed to 6.4 keV improved the fits significantly. Line emission at this energy has been previously detected with *Ginga* from 4U 1608−52 in a low-intensity state (Yoshida et al. 1993). Line emission from 4U 1608−52 has also been detected at 6.7 keV with *Tenma* (Suzuki et al. 1984). However, the χ^2_ν of the fits to the *RXTE* spectra are increased significantly when the line is shifted from 6.4 to 6.7 keV.

With the addition of an emission line, a Comptonization spectrum (Sunyaev & Titarchuk 1989), an exponentially cut off power law, and a power-law spectrum all gave acceptable fits to the data. The χ^2_ν for the three models were very similar. However, the parameters of the Comptonization spectrum and the cutoff energy in the exponentially cut off power law were not well constrained. For this reason, we have chosen to use the power-law model to characterize the spectral shape. Previous observations have also shown that the spectrum of 4U 1608−52, while in a low-intensity state, is well characterized by a power law (Penninx et al. 1989; Yoshida et al. 1993).

We fitted the spectrum for each of the five orbits with a model consisting of a power law, a Gaussian line fixed at 6.4 keV, and absorption (Table 1). The column density N_H was a free parameter. The column density varied in the range (0.5–1.4) × 10^{22} cm^{-2}. This is reasonably consistent with the range of N_H found in various *EXOSAT* observations of the

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TABLE 1
QPO AND SPECTRAL PARAMETERS OF 4U 1608−52 FOR EACH ORBIT

Start Time	Duration (s)	QPO ν (Hz)	Photon Index	Flux (2–20 keV) (10^{-10} ergs cm^{-2} s^{-1})	χ^2/dof	Photon Index (9–20 keV)
March 15 19:28	1800	799 ± 21	2.496 ± 0.049	8.22 ± 0.16	95.6/103	2.64 ± 0.05
March 15 22:49	2700	743 ± 27	2.377 ± 0.046	7.81 ± 0.16	84.0/103	2.43 ± 0.05
March 22 17:50	3600	642 ± 35	2.303 ± 0.041	10.49 ± 0.21	95.0/93	2.27 ± 0.04
March 22 19:35	3000	622 ± 73	2.242 ± 0.040	10.30 ± 0.21	105.4/93	2.20 ± 0.04
March 22 21:22	2400	567 ± 51	2.198 ± 0.042	10.15 ± 0.20	139.8/93	2.07 ± 0.04

source (Penninx et al. 1989). To allow for the possible effect of an incorrect N_H on the power-law index, we refitted each spectrum with N_H fixed to the two extremal values. This systematic uncertainty was the dominant uncertainty in the photon index.

The Gaussian lines are very strong and broad, although they are not inconsistent with line profiles found previously in X-ray binaries (Gottwald et al. 1995). It is likely that the Gaussian line used in the fit is only an approximation of more complex spectral features in this band (Yoshida et al. 1993). We found that reasonable fits could be obtained with the sum of a power law, a reflection component, and a (forced) narrow Fe line. However, the fits obtained with this more complex model were somewhat worse than those obtained with the simple model with a broad line. In addition, if the width of the Fe line was allowed to vary, a broad line gave the best fit. Since we are mainly interested in the photon index, we chose to retain the simple model consisting of a power law and a Gaussian line. To check that the features in the spectra near 6 keV did not seriously affect the photon index obtained, we fitted the high-energy part of the spectrum (9–20 keV) using a power law alone. The results of these fits are shown in Table 1. The photon indices obtained from the two fitting procedures are consistent.

The results presented here for 4U 0614+091 make use of the timing analysis presented in Ford et al. (1997a). The spectra of 4U 0614+091 were modeled as the sum of a power law, a blackbody, and an Fe emission line (Christian, White, & Swank 1994). Our spectral analysis for 4U 0614+091 is similar to that described in Ford et al. (1997b). However, for consistency, we reanalyzed the data using the same response matrices used for 4U 1608−52, fixing the Fe emission-line energy at 6.4 keV and including a 1% systematic error on each bin. The χ^2_ν values were in the range 0.7–1.8 for 255 degrees of freedom. The statistical uncertainties of the fit results were calculated allowing $\Delta\chi^2 = 7.04$, appropriate for 68.3% confidence bounds for 6 degrees of freedom. The data presented here also include a number of observations that were excluded in Ford et al. (1997b) because the blackbody component was not well constrained.

3. CORRELATION OF SPECTRAL SHAPE AND QPO FREQUENCY

Figure 1 shows the QPO frequency plotted versus the total flux in the 2–20 keV band for 4U 1608−52. There is no apparent correlation. A plot of QPO frequency versus total flux for 4U 0614+091 (see Fig. 2 of Ford et al. 1997b) also shows that there is no unique correlation.

Figure 2 shows the photon index plotted as a function of QPO frequency for 4U 1608−52 and 4U 0614+091. For 4U 0614+091, we have used the higher QPO frequency. For each source, the photon index and the QPO frequency are well correlated. The significance of the correlation is very high for 4U 0614+091. The linear correlation coefficient is 0.95 for 22 data points. For 4U 1608−52, the correlation coefficient is 0.97 for five points, and the formal probability of random occurrence is less than 1%. We find that either a linear or a logarithmic

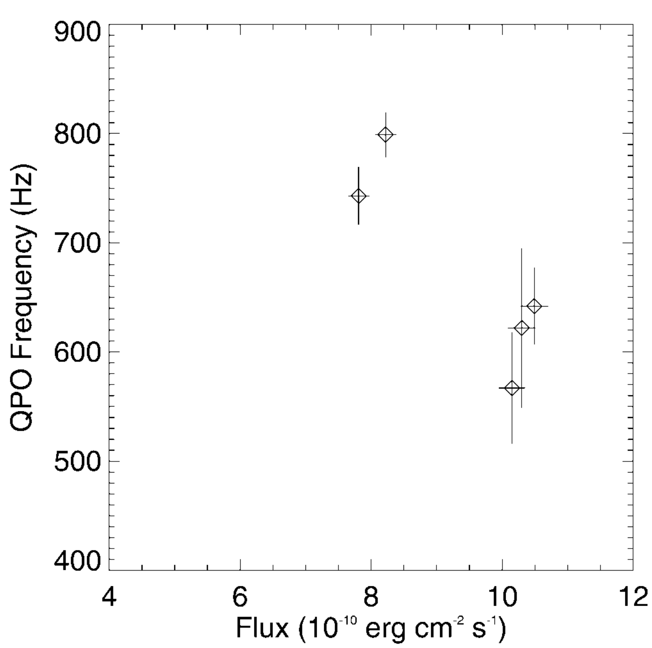

FIG. 1.—QPO frequency vs. total flux in the 2–20 keV band for 4U 1608−52.

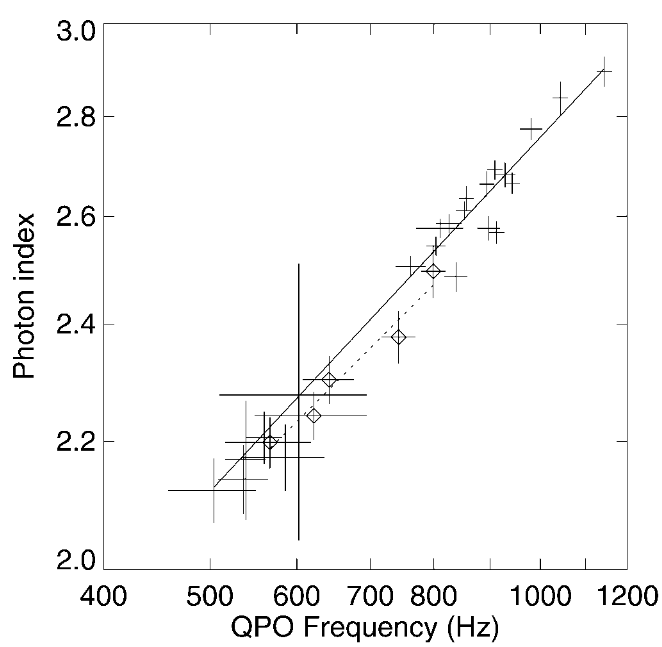

FIG. 2.—Photon index vs. QPO frequency on a log-log plot. The crosses indicate data for 4U 0614+091; the solid line is a power-law fit to the data for 4U 0614+091; the diamonds and the dashed line indicate the data and fit, respectively, for 4U 1608−52.

correlation gives an adequate fit. We choose to parameterize the relation as $\alpha \propto \nu^{\gamma}$. We find $\gamma = 0.38 \pm 0.03$ for 4U 0614+091 and $\gamma = 0.35 \pm 0.07$ for 4U 1608−52 (68.3% confidence errors).

The photon index versus QPO frequency relations appear consistent for the two sources. However, only one QPO is detected from 4U 1608−52 in these observations. It is not certain whether the QPO from 4U 1608−52 should be identified with the higher or the lower frequency QPO from 4U 0614+091. Thus, we cannot determine whether a unique correlation between photon index and QPO frequency holds for both sources. We conclude that 4U 1608−52 and 4U 0614+091, taken individually, show a robust correlation between photon index and QPO frequency.

The relatively steep photon indices suggest that there may be significant X-ray emission below the lower energy cutoff of 2 keV of *RXTE*. We checked whether the correlation of QPO frequency with spectral index represents a correlation of QPO frequency with total luminosity over a broader band by integrating the unabsorbed power-law spectra down to lower energies. We did not find a good correlation for any energy band chosen.

4. DISCUSSION

The correlation between the photon index and the QPO frequency most likely represents a common dependence on some physical parameter of the system.

Ford et al. (1997b) found that the higher QPO frequency, ν, and the blackbody flux, $F_{\rm BB}$, in 4U 0614+091 were well correlated and obeyed a power-law relation, $\nu \propto F_{\rm BB}^{\beta}$, with an exponent in the range $\beta = 0.27$–0.37. The large range in β is due to the uncertainty in the response matrix; for the particular response matrix used here, we find $\beta = 0.34 \pm 0.01$. In Ford (1997), a correlation between the photon index and the blackbody flux is presented (see also Ford et al. 1996). We find that the exponent describing this correlation, $\alpha \propto F_{\rm BB}^{\delta}$, has a value of $\delta = 0.13 \pm 0.02$. These two correlations taken together would naturally lead to a correlation between the photon index and the QPO frequency. We note that the exponents should be related as $\beta = \delta/\gamma$. This relation is satisfied for 4U 0614+091.

We tentatively suggest the following physical picture as one possible mechanism that could produce the correlations observed from 4U 0614+091. Mass accretion onto the neutron star may occur both through the accretion disk and also radially (e.g., Ghosh & Lamb 1979). The mass accretion rate through the disk may determine the inner radius of the disk and, in turn, the QPO frequency (Alpar & Shaham 1985). Mass accretion through the disk may also produce a blackbody flux. Since the blackbody flux from the disk would be related to the mass accretion rate through the disk, this would produce the correlation between the blackbody flux and the QPO frequency observed in 4U 0614+01. We suggest that the power-law component of the X-ray spectrum may be produced from a corona. The flux of photons from the disk blackbody emission would cool the corona via Compton scattering, thus leading to a power-law spectrum that steepens as the blackbody flux increases. This would lead to the relation between the photon index of the power-law component and the QPO frequency that is observed in both 4U 0614+091 and 4U 1608−52.

The lack of correlation between the QPO frequency and the total flux may arise because the total flux is determined by the total mass accretion rate, while the QPO frequency is determined only by the part of mass accretion that occurs through the disk. If the disk accretion rate is not a fixed fraction of the total, then the relation between the QPO frequency and total luminosity may be different for different epochs. This may explain the lack of correlation between the QPO frequency and the total flux in 4U 1608−52, 4U 0614+091 (Ford et al. 1997b), and Aql X-1 (Zhang et al. 1998).

The correlation presented here between the QPO frequency and the power-law photon index may prove particularly useful because it can be applied to a large sample of sources. Many atoll sources do not have soft blackbody components that are detectable with *RXTE*. Even for 4U 0614+091, the soft blackbody component is usually at relatively low temperatures (<0.8 keV) and often cannot be well measured with *RXTE*. The correlation between the photon index and the QPO frequency shown in Figure 2 for 4U 0614+091 extends over a wider frequency range than does the blackbody flux versus QPO frequency correlation presented in Ford et al. (1997b) because the blackbody cannot be measured accurately when the temperature is low, as occurs at low QPO frequencies, but the photon index can be determined accurately over the full range of luminosities.

In the observations of 4U 1608−52 and 4U 0614+091 presented here, the power-law component contributes most of the X-ray flux. Several of the fast QPO atoll sources have spectra that are well characterized by a power-law model in the 2–20 keV band, and it should be possible to search for a similar correlation between the QPO frequency and the power-law photon index in many of the fast QPO atoll sources. However, the correlation found here may not extend to high-luminosity states since the spectra of 4U 1608−52 and other LMXBs in high-luminosity states are not simple power laws. Mitsuda et al. (1989) found that the spectrum of 4U 1608−52 can be accurately represented, over a wide range in luminosity, as the sum of a disk blackbody component and a Comptonized blackbody component. The parameters of this model vary continuously with luminosity. At low luminosities, the degree of Comptonization increases and the spectrum approaches a power law. The correlation of QPO frequency with photon index presented here may reflect a physical correlation of QPO frequency with the temperature and optical depth of the Comptonizing cloud (Vaughan et al. 1997). It would be interesting to search for a correlation between the QPO frequency and the spectral parameters of high-luminosity states, particularly if the same spectral model can be extended over a wide range in luminosity. A comprehensive study of the correlation of fast QPOs and the X-ray spectral properties of LMXBs should provide significant clues to the physical origins of fast QPOs.

REFERENCES

Alpar, M. A., & Shaham, J. 1985, Nature, 316, 239

Christian, D. J., White, N. E., & Swank, J. H. 1994, ApJ, 422, 791

Ford, E. C. 1997, Ph.D. thesis, Columbia Univ.

Ford, E. C., et al. 1996, ApJ, 469, L37

———. 1997a, ApJ, 475, L123

———. 1997b, ApJ, 486, L47

Ghosh, P., & Lamb, F. K. 1979, ApJ, 234, 296

Gottwald, M., Parmar, A. N., Reynolds, A. P., White, N. E., Peacock, A., & Taylor, B. G. 1995, A&AS, 109, 9

Kaaret, P., & Ford, E. C. 1997, Science, 276, 1386

Mitsuda, K., Inoue, H., Nakamura, N., & Tanaka, Y. 1989, PASJ, 41, 97

Penninx, W., Damen, E., Tan, J., Lewin, W. H. G., & van Paradijs, J. 1989, A&A, 208, 146

Sunyaev, R. A., & Titarchuk, L. 1989, in 23rd ESLAB Symp. on Two Topics in X-Ray Astronomy, vol. 1, X-Ray Binaries, ed. J. Hunt & B. Battrick (Paris: ESA), 627

Suzuki, K., Matsuoka, M., Inoue, H., Mitsuda, K., Ohashi, T., & Tanaka, Y. 1984, PASJ, 36, 761

Vaughan, B. A., et al. 1997, ApJ, 483, L115
Yoshida, K., Mitsuda, K., Ebisawa, K., Ueda, Y., Fujimoto, R., & Yaqoob, T. 1993, PASJ, 45, 605
Yu, W., et al. 1997, ApJ, 490, L153
Zhang, W., Jahoda, K., Kelley, R. L., Strohmayer, T. E., Swank, J. H., & Zhang, S. N. 1998, ApJ, 495, L19