Strong correlation between noise features at low frequency and the kilohertz quasi-periodic oscillations in the X-ray binary 4U 1728-34

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STRONG CORRELATION BETWEEN NOISE FEATURES AT LOW FREQUENCY AND THE KILOHERTZ QUASI-PERIODIC OSCILLATIONS IN THE X-RAY BINARY 4U 1728−34

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ABSTRACT

We study the timing properties of the low-mass X-ray binary 4U 1728−34 using recently released data from the *Rossi X-Ray Timing Explorer*. This binary, like many others with accreting neutron stars, is known to exhibit strong quasi-periodic oscillations (QPOs) of its X-ray flux near 1 kHz. In addition to the kilohertz QPOs, the Fourier power spectra show a broken power-law noise component, with a break frequency between 1 and 50 Hz, and a Lorentzian between 10 and 50 Hz. We find that the frequencies of the break and the low-frequency Lorentzian are well correlated with the frequencies of the kilohertz QPOs. The correlation between the frequency of the low-frequency Lorentzian and the kilohertz QPO follows a power-law relation with an index of 2.11 ± 0.06. The recent model of Stella & Vietri interprets the Lorentzian feature as an effect of relativistic frame dragging (Lense-Thirring precession) in the inner accretion disk. The predicted scaling index is 2, which is close to the value we measure. This correlation is nearly identical to the one found in *Z*-sources between the well-known QPOs on the horizontal branch and the kilohertz QPOs, suggesting that the low-frequency oscillations are a similar phenomenon in these sources. The frequency of the break in the power spectra is also correlated with the frequencies of the kilohertz QPOs. As previously noted for the similar binaries 4U 1608−50 and 4U 1705−44, this broken power-law component closely resembles that of black hole candidates in the low state, where the break frequency is taken as a indicator of mass accretion rate. The relation between break frequency and kilohertz QPO frequency thus provides additional proof that the frequency of the kilohertz QPOs increases with mass accretion rate.

Subject headings: accretion, accretion disks — black hole physics — stars: individual (4U 1728−34) — stars: neutron — X-rays: stars

1. INTRODUCTION

In most well-observed low-mass X-ray binaries, oscillations of the X-ray flux at frequencies near 1 kHz have been measured with the *Rossi X-Ray Timing Explorer* (*RXTE*) (for reviews and references see van der Klis 1998; Swank 1998). Models describing the production of these quasi-periodic oscillations (QPOs) are not yet definitive, but the fast signals most likely originate in the interesting region of the accretion disk very close to the compact object where the dynamical timescale is short.

The goal of this Letter is to explore the link between the kilohertz QPOs and the broadband timing properties in an X-ray binary. These timing signals may well be related. A common dependence on mass accretion rate is suggested, since the strength of the low-frequency noise decreases with accretion rate, while the frequency of the kilohertz QPOs is expected to increase in current models. The timing features at tens of hertz may also be related to the kilohertz QPOs, as in the Lense-Thirring precession model of Stella & Vietri (1998) or the oscillation mode model of Titarchuk, Lapidus, & Muslimov (1998).

For this analysis, we use *RXTE* observations of 4U 1728−34 (GX 354+0) that have recently become public. Analysis of the kilohertz QPOs in these observations was reported by Strohmayer et al. (1996). Section 2 summarizes the observations and our analysis of the Fourier power spectra. In § 3 we present the correlations between the frequencies of the noise components. Section 4 is a discussion of the results and the physical implications.

2. OBSERVATIONS AND ANALYSIS

The present *RXTE* observations of 4U 1728−34 took place between 1996 February 15 and March 1 and consist of approximately 298 ks of usable data. We use here data from the proportional counter array (PCA) (for more instrument information, see Zhang et al. 1993). We generate Fourier power spectra from the high time resolution data, which consists variously of a "single-bit" or an "event" mode. The time resolutions in these modes range from 1.2 to 122 μs; we use a maximum Nyquist frequency of 4096 Hz. We employ all of the channels of the PCA, most sensitive in the 2–30 keV band. There are 12 X-ray bursts (Strohmayer, Zhang, & Swank 1997). We exclude these from our analysis, excising 300 s of data after each burst.

Four representative power spectra are shown in Figure 1. We have arrived at a simple function that describes all of the power spectra well. The components are (1) a broken power law with a break frequency whose best-fit value ranges between 1 and 50 Hz, (2) the kilohertz QPOs, described by Lorentzians with best-fit centroid values from 325 to 1127 Hz, and (3) a low-frequency Lorentzian with a best-fit frequency from 10 to 50 Hz and FWHM between 3 and 30 Hz. In addition to these three components, we find excess power near 100 Hz. We include this in the fit as (4) another Lorentzian, with a best-fit frequency of about 150 Hz (FWHM: 10–300 Hz). Including the fourth component does not significantly change the best-fit values of the other components. All of the parameters are allowed to vary independently, and the reduced χ^2 for the fits are typically 1.0 to 1.3 with about 200 degrees of freedom (dof). Table 1 shows the parameters for the fits to the power spectra in Figure 1. Other atoll sources also show these same components in their power spectra, as seen with *Ginga* obser-

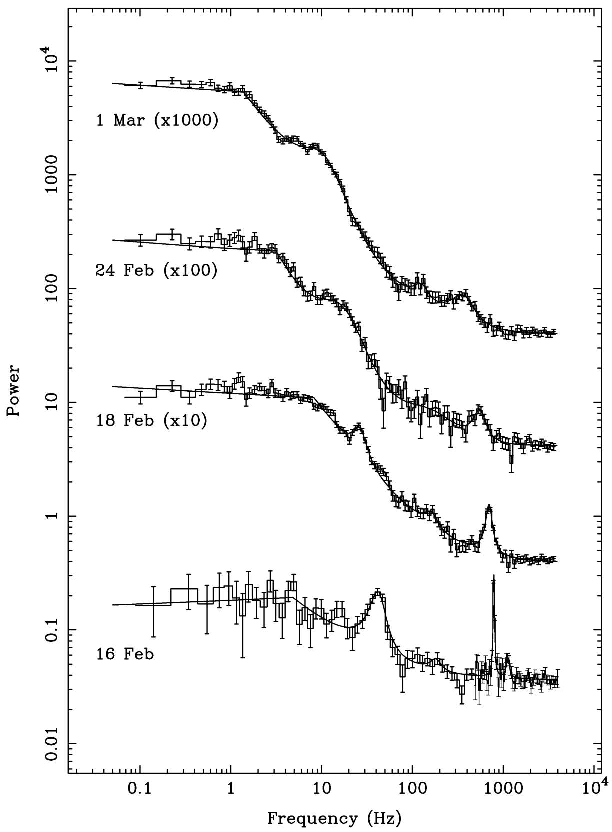

FIG. 1.—Representative power density spectra for four observations. The fit parameters are listed in Table 1. The power is Leahy normalized. We subtract a constant value of 1.95, somewhat less than the Poisson level, and multiply each spectrum by a constant as indicated. Fit functions are shown that consist of a broken power law, a low frequency Lorentzian, a Lorentzian near 100 Hz, and kilohertz QPO(s).

vations of 4U 1608−52 (Yoshida et al. 1993) and *RXTE* observations of 4U 1705−44 (Ford, van der Klis, & Kaaret 1998), 1E 1724−3045 (Olive et al. 1998), 4U 0614+091 (Ford 1997; Mendez et al. 1997; van Straaten et al. 1998), and 4U 1608−52 (Mendez et al. 1998). In the following, we discuss in turn the properties of each of the components of the fits.

The broken power-law component is similar to previous measurements of other atoll sources. The parameters of the broken power law indicate that 4U 1728−34 is in the “island” state in all these observations, i.e., at relatively low inferred mass accretion rate (Hasinger & van der Klis 1989). The measurement of the break frequency is very robust and usually independent of the Lorentzian components that we add to the fit.

The low-frequency Lorentzian feature at 10–50 Hz is a necessary addition to the fits. Taking the February 18 interval shown in Figure 1 as an example, we find that removing the low-frequency Lorentzian increases the χ^2/dof from 275/223 to 439/226. The probability for random variations to exceed the corresponding F-value is 4×10^{-4}, indicating that the inclusion of this Lorentzian is strongly favored. In the March 1 and February 22–24 observations, this feature is quite wide. With a value for Q (= FWHM/ν) of 1.0 ± 0.2, it does not constitute a QPO in the usual sense.

The final component in the spectral fits are the kilohertz QPOs, which have properties similar to those in other low-mass X-ray binaries (van der Klis 1998). Only one QPO is visible in all intervals except the February 16 observations. In the cases in which there is only one QPO, we treat it as the higher frequency QPO. The main justification for this is that then all of the data follow one correlation of frequency versus spectral shape (Kaaret et al. 1998). Also, if this is done, then the February 16 data, in which the rms fraction of the broken power law is lowest, have the highest frequency QPO. This fits with a general trend of an increasing QPO frequency with

TABLE 1
4U 1728−34 POWER SPECTRA FITS

Observation (1996)	March 1 (1:43:13)	February 24[a] (5:15:19)	February 18 (22:18:25)	February 16 (22:14:25)
Rate (counts s^{-1})	1111	908	1269	2021
Kilohertz QPO:				
Frequency (Hz)	355 ± 11	551 ± 13	699 ± 2	1122 ± 13[b]
FWHM (Hz)	260 ± 35	195 ± 48	123 ± 3.5	99 ± 36
rms (%)	12.3 ± 0.7	12.1 ± 1.4	11.2 ± 0.3	4.2 ± 0.7
LF Lorentzian:				
Frequency	9.0 ± 0.2	14.1 ± 0.8	26.5 ± 0.1	41.5 ± 0.8
FWHM	12.6 ± 0.7	22.8 ± 1.5	9.3 ± 0.4	17.7 ± 2.1
rms	14.0 ± 0.6	15.5 ± 1.6	11.2 ± 0.3	4.8 ± 0.3
100 Hz Lorentzian:				
Frequency	124 ± 6	120 ± 46	160 ± 5	182 ± 7
FWHM	58 ± 17	301 ± 144	65 ± 26	17 ± 34
rms	5.3 ± 1.4	15.2 ± 4.3	4.9 ± 0.4	1.9 ± 1.3
Broken PL:				
Break Frequency	1.37 ± 0.04	3.16 ± 0.20	8.26 ± 0.44	4.83 ± 0.69
rms (0.01–100 Hz)	16.1 ± 0.6	12.6 ± 2.3	15.2 ± 0.3	4.3 ± 0.3

NOTE.—The start time of each observation is in UTC (Universal Time, Coordinated). “Rate” is the mean count rate (2.2–15.9 keV) for each observation after background subtraction. The fits to the Fourier power spectra include four components: one or two QPOs with frequency at high frequency (Kilohertz QPO), a Lorentzian at low frequency (LF Lorentzian), a Lorentzian at roughly 100 Hz (100 Hz Lorentzian), and a broken power law (Broken PL). Listed are the frequencies, FWHM, and the fractional rms power, rms. The fits are to power spectra made with all energy channels. Errors are statistical only, calculated using $\Delta\chi^2 = 1$.

[a] Observations with X-ray bursts. Note: data is excised from before the onset to 300 s after the bursts in generating power spectra and in determining the count rates.

[b] This is the higher frequency of two QPOs in this interval. The other has a centroid frequency of 788.0 ± 0.9 Hz.

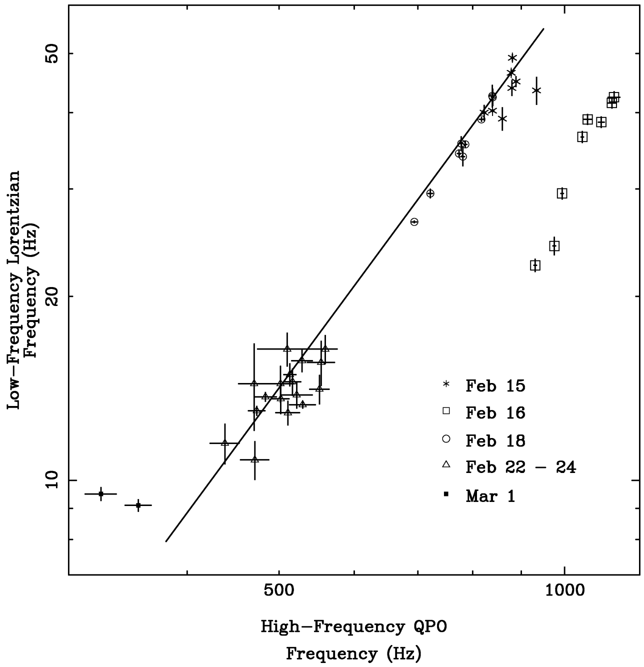

FIG. 2.—Frequency of the Lorentzian at low frequencies versus the frequency of the kilohertz QPOs. The function shown is a power law with index 2.11. This is a fit to all of the data except February 16 (see text).

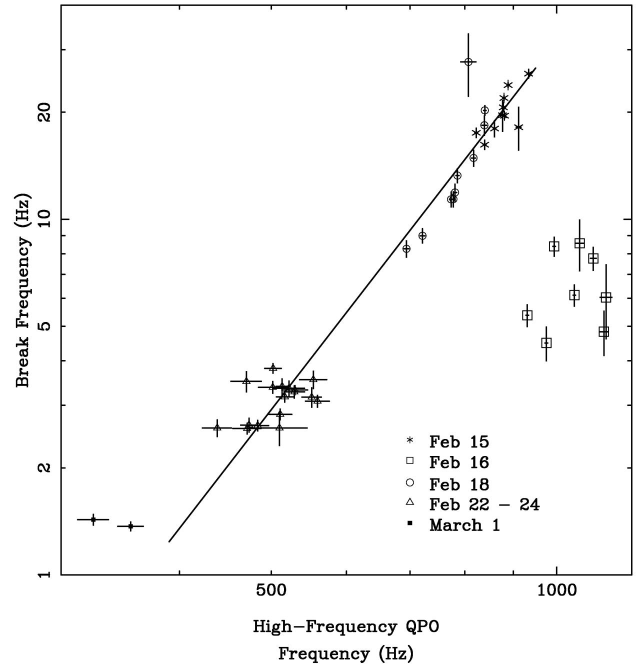

FIG. 3.—Break frequency of the broken power-law function vs. the frequency of the kilohertz QPOs. The function shown is a power law with index 3.44, the best-fit to the data excluding February 16.

a decreasing rms fraction of the broken power-law noise. The QPOs are quite wide on March 1, with a Q of about 1.

We note that there are indications of additional features in the power spectra, for example two possible peaks on top of the low-frequency Lorentzian in March 1 or February 24. In these cases, our adopted four-component fit function is not entirely descriptive, but the extra features are not well constrained by the data.

3. RESULTS

Figure 2 shows the relation between the low-frequency Lorentzian and the kilohertz QPO. The relation between the two frequencies can be described by a power law scaling of the form $\nu_{\rm LFLor} = A\nu_{\rm kHz}^{\alpha}$, where $\nu_{\rm LFLor}$ is the frequency of the low-frequency Lorentzian and $\nu_{\rm kHz}$ is the centroid frequency of the kilohertz QPO. We find $\alpha = 2.11 \pm 0.06$ and $A = 2.9$ $(\pm 1.1) \times 10^{-5}$, excluding the February 16 intervals (see below). The χ^2/dof this fit is large (4.7), which probably is a result of not including systematic errors to take into account the small inadequacies in the power spectral fit function as discussed above. The error on the power-law fit is not accurate due to the large χ^2. To arrive at a more realistic value, we multiply all data errors by a factor of 2, making $\chi^2/\text{dof} = 1.2$. The quoted errors (also above) use this procedure and $\Delta\chi^2 = 1$.

The second notable correlation is between the kilohertz QPOs and the break frequency of the broken power law, as shown in Figure 3. We describe the correlation by a function of the form $\nu_{\rm break} = B\nu_{\rm kHz}^{\beta}$, where $\nu_{\rm break}$ is the break frequency. Using the same procedure outlined above, and again excluding the February 16 intervals, we find $\beta = 3.44 \pm 0.09$ and $B = 1.5\ (\pm 0.9) \times 10^{-9}$.

As the frequency of the break increases, other parameters change as well. The level of the noise at low frequency decreases and the count rate increases. The relation between the rms fraction and the break frequency is consistent with that found for the black hole candidates (Mendez & van der Klis 1997).

The only exceptions to the above correlations are in the February 16 data set. This observation is at the highest count rate, with presumably the highest accretion rate and highest break frequency. However, the best-fit values for both the break frequency and the low-frequency Lorentzian are lower than would be expected. Perhaps these two components are not well separated in the fits, or perhaps the Lorentzian is another component different than any of the four components that we use in fitting the other data (e.g., a harmonic?). Based on the present data, it is not clear if the February 16 observations represent fundamentally different spectra. We fit them in the same way but treat the results on somewhat different footing. We note that the February 16 points follow the correlation if we identify the single kilohertz QPO in all of the other data as the lower frequency of the two QPOs. For the independent reasons outlined above, however, we think that this would not be a correct identification.

4. DISCUSSION

The previous section demonstrates a strong correlation between the frequencies of the kilohertz QPOs and the frequencies of both the break and the low-frequency Lorentzian, even though these features are independently determined in the power spectra.

The low-frequency Lorentzian in this atoll source appears to be very similar to the horizontal branch oscillation (HBO) in Z-sources. In particular, the correlation with the kilohertz QPOs is nearly identical in GX 17+2 (Wijnands et al. 1997), GX 5−1 (Wijnands et al. 1998), and Sco X-1 (van der Klis et al. 1997). This suggests that these signals have a similar origin in both atoll and Z-sources and calls into question the magnetospheric beat-frequency model long used to explain the HBOs (Alpar & Shaham 1985). If this model is to account for the low-frequency signals in atoll sources, where the mass accretion rate is roughly 100 times lower, the magnetic field must be 10 times smaller. This is probably not consistent with the low fields inferred for the accreting X-ray pulsar SAX J1808.4−3658 (Wijnands & van der Klis 1998a), which is similar to atoll sources in other respects (Wijnands & van der Klis 1998b).

Stella & Vietri (1998) have proposed that the low-frequency Lorentzian feature is a result of relativistic frame dragging in the inner accretion disk (Lense-Thirring precession). The frequency of the slower signal correlates with the frequency of the kilohertz QPO, assumed to be fixed by the Keplerian frequency at the inner edge of the disk. We find a scaling index of 2.11 ± 0.06, remarkably close to the predicted value of 2. The free parameters in this model are the spin frequency of the neutron star and the ratio I_{45}/M, where I_{45} is the moment of inertia in units of 10^{45} g cm^2 and M is the mass of the neutron star in units of solar mass. We assume a spin frequency of 363 Hz, based on the frequency of the oscillations observed in X-ray bursts (Strohmayer et al. 1996). We find a value for I_{45}/M of 3–4. This is large for proposed equations of state. We note that Stella & Vietri (1998) found a large value of I_{45}/M for the *Z*-sources but not for atoll sources. This is because they used relatively low frequencies for the low-frequency Lorentzian in the atoll sources, like those on February 16 in the present data set.

Alternatively, the low-frequency signal may be one of the oscillation modes in a boundary layer in the inner disk suggested by Titarchuk et al. (1998). The modes in the vertical direction are responsible for the kilohertz QPOs by Comptonization of incoming photons. The low-frequency signals are probably not connected to modes of rotational splitting. To get the proper scaling with the frequency of the kilohertz QPO, the “s” parameter (Titarchuk et al. 1998) would have to change by a factor of about 5. The low-frequency oscillation, however, may correspond to modes in the radial direction. The predicted scaling is similar to the one reported here (L. Titarchuk 1998, private communication).

The correlation of break frequency and kilohertz QPO frequency may be the result of a mutual dependence on another parameter. The obvious candidate is the mass accretion rate. Models explaining the kilohertz QPOs predict, for different reasons, that the QPO frequency increases with mass accretion rate (Miller, Lamb, & Psaltis 1998; Titarchuk et al. 1998). It is a reasonable conjecture that the break frequency is also correlated with the mass accretion rate, since the power spectra are very similar to the black hole candidates where indeed the break frequency is believed to increase with accretion rate (van der Klis 1994a, 1994b). This similarity is underlined by the fact that the relation between the rms level of the power law and break frequency in 4U 1728−34 fits on the relation established for black holes (Mendez & van der Klis 1997; Belloni & Hasinger 1990).

The question remains as to what causes the low-frequency noise and what determines the frequency of the break. The noise at low frequency may result from a superposition of shots (e.g., Belloni & Hasinger 1990) with the break corresponding to the shots with the longest durations. The timescale of the shots may be set by the lifetime of clumps (van der Klis 1994b). The clumps could be destroyed by shearing in the inner disk. The decreasing shearing timescale at smaller radii (Pringle 1981) could account for the correlation of the break frequency, mass accretion rate, and kilohertz QPO frequency if the inner disk radius decreases when the mass accretion rate increases. Alternatively, the lifetime of a shot may be determined by a diffusion timescale in the boundary layer described in Titarchuk et al. (1998). The predicted correlation of the frequencies is similar to the one measured (L. Titarchuk 1998, private communication).

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