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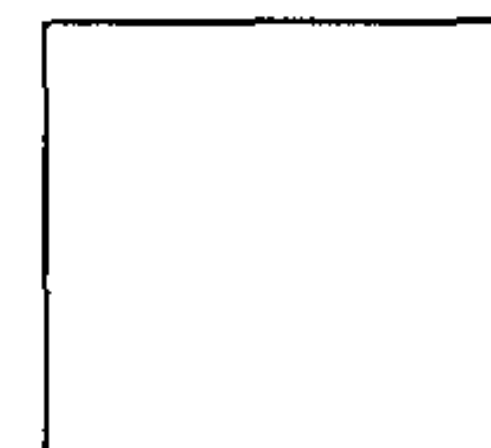
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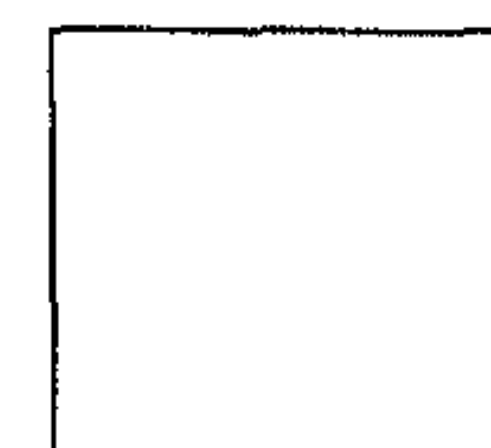
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DISCOVERY OF TWO SIMULTANEOUS KILOHERTZ QUASI-PERIODIC OSCILLATIONS IN KS 1731-260

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ABSTRACT

We have discovered two simultaneous quasi-periodic oscillations (QPOs) at 898.3 ± 3.3 Hz and 1158.6 ± 9.0 Hz in the 1996 August 1 observation of the low-mass X-ray binary KS 1731-260 with the *Rossi X-ray Timing Explorer*. The rms amplitude and FWHM of the lower frequency QPO were $5.3 \pm 0.7\%$ and 22 ± 8 Hz, whereas those of the higher frequency QPO were $5.2 \pm 1.0\%$ and 37 ± 21 Hz. At low inferred mass accretion rate (\dot{M}) both QPOs are visible, at slightly higher \dot{M} the lower frequency QPO disappears and the frequency of the higher frequency QPO increases to ~ 1178 Hz. At the highest inferred \dot{M} this QPO is only marginally detectable (2.1σ) near 1207 Hz, which is the highest frequency so far observed in an X-ray binary. The frequency difference (260.3 ± 9.6 Hz) between the QPOs is equal to half the frequency of the oscillations observed in a type I burst in this source (at 523.92 ± 0.05 Hz; Smith, Morgan, & Bradt 1997). This suggests that the neutron star spin frequency is 261.96 Hz (3.8 ms), and that the lower frequency QPO is the beat between the higher frequency QPO, which could be a preferred orbital frequency around the neutron star, and the neutron star spin. During the 1996 August 31 observation we detected an additional QPO at 26.9 ± 2.3 Hz, with a FWHM and rms amplitude of 11 ± 5 Hz and $3.4 \pm 0.6\%$.

Subject headings: accretion, accretion disks — stars: individual (KS 1731-260) — stars: neutron — X-rays: stars

1. INTRODUCTION

Kilohertz quasi-periodic oscillations (QPOs) have been found so far in the persistent emission of nine low-mass X-ray binaries (LMXBs), three Z sources (Sco X-1, van der Klis et al. 1996a, 1997b; GX 5-1, van der Klis et al. 1996b; GX 17+2, van der Klis et al. 1997a), and six atoll sources (4U 1636-53, Zhang et al. 1996, Wijnands et al. 1997; 4U 1728-34, Strohmayer et al. 1996; 4U 1608-52, Berger et al. 1996; 4U 0614+09, Ford et al. 1996; 4U 1735-44, Wijnands et al. 1996; 4U 1820-30, Smale, Zhang, & White 1996). In the sources Sco X-1, GX 5-1, GX 17+2, 4U 1636-53, 4U 1728-34, 4U 0614+09, and 4U 1820-30, two kilohertz QPOs are seen simultaneously, with a frequency separation between 250 and 360 Hz; in 4U 1608-52 and 4U 1735-44 so far only one QPO has been observed. In the sources 4U 1636-53 and 4U 1728-34 (Zhang et al. 1997; Strohmayer et al. 1996) oscillations were observed during type I bursts whose frequency (or half of it) was consistent with being equal to the frequency separation between the two kilohertz QPOs, which in some beat-frequency models is interpreted as being the neutron star spin frequency. Smith, Morgan, & Bradt (1997) discovered coherent 523.92 ± 0.05 Hz oscillations, which they interpreted as the neutron star spin frequency, during a type I X-ray burst in the low-mass X-ray binary KS 1731-260, and they found no QPOs near 1 kilohertz, with upper limits on the amplitude of 1% rms. We reanalyzed part of the public archive data of KS 1731-260, also used by Smith et al. (1997), and report the discovery of two simultaneous QPOs in the persistent emission near 898 Hz and 1159 Hz, with a frequency separation consistent with being equal to half the frequency of the oscillations in the burst.

2. OBSERVATIONS AND ANALYSIS

We analyzed the public archive data of KS 1731-260 obtained by the *Rossi X-ray Timing Explorer* (*RXTE*; Bradt, Rothschild, & Swank 1993) on 1996 August 1 1646-2044 UT and on 1996 August 31 1738-1941 UT. Due to Earth occultations and South Atlantic Anomaly passages the data were split up in three segments during the August 1 observation, and two segments during the August 31 observation each with a duration of 2000-3000 s. The (2.1-18.9 keV) source count rate varied between 1620 and 1990 counts s^{-1} on August 1 and between 1970 and 2360 counts s^{-1} on August 31. The background was typically 50 counts s^{-1} . Fitting the spectra with a thermal bremsstrahlung model (Sunyaev 1989; Smith et al. 1997), we derive the following 2-10 keV fluxes: 3.2×10^{-9} and 3.8×10^{-9} ergs $cm^{-2} s^{-1}$.

During both observations data were collected with a time resolution of 16 s (129 photon energy channels), and a time resolution of 62 μs (32 channels). Both modes covered the entire 2-60 keV range over which *RXTE*'s proportional counter array is sensitive. X-ray color-color diagrams (CDs) were constructed from the 16 s data, and power spectra were calculated from the 62 μs data using 16 s and 256 s data intervals. The power spectra were fitted using a power law (the very low frequency noise [VLFN], measured between 0.01-1 Hz), Lorentzians (the QPOs, if present), a broken power law (the high frequency noise [HFN], measure between 1-100 Hz), and a constant level (the Poisson noise). We found the QPOs to be strongest at high energy (this is in accordance with all previous results on kHz QPOs), and for that reason the 5.7-24.1 keV band provides the most significant detection. We have used this band throughout our analysis. The results of the

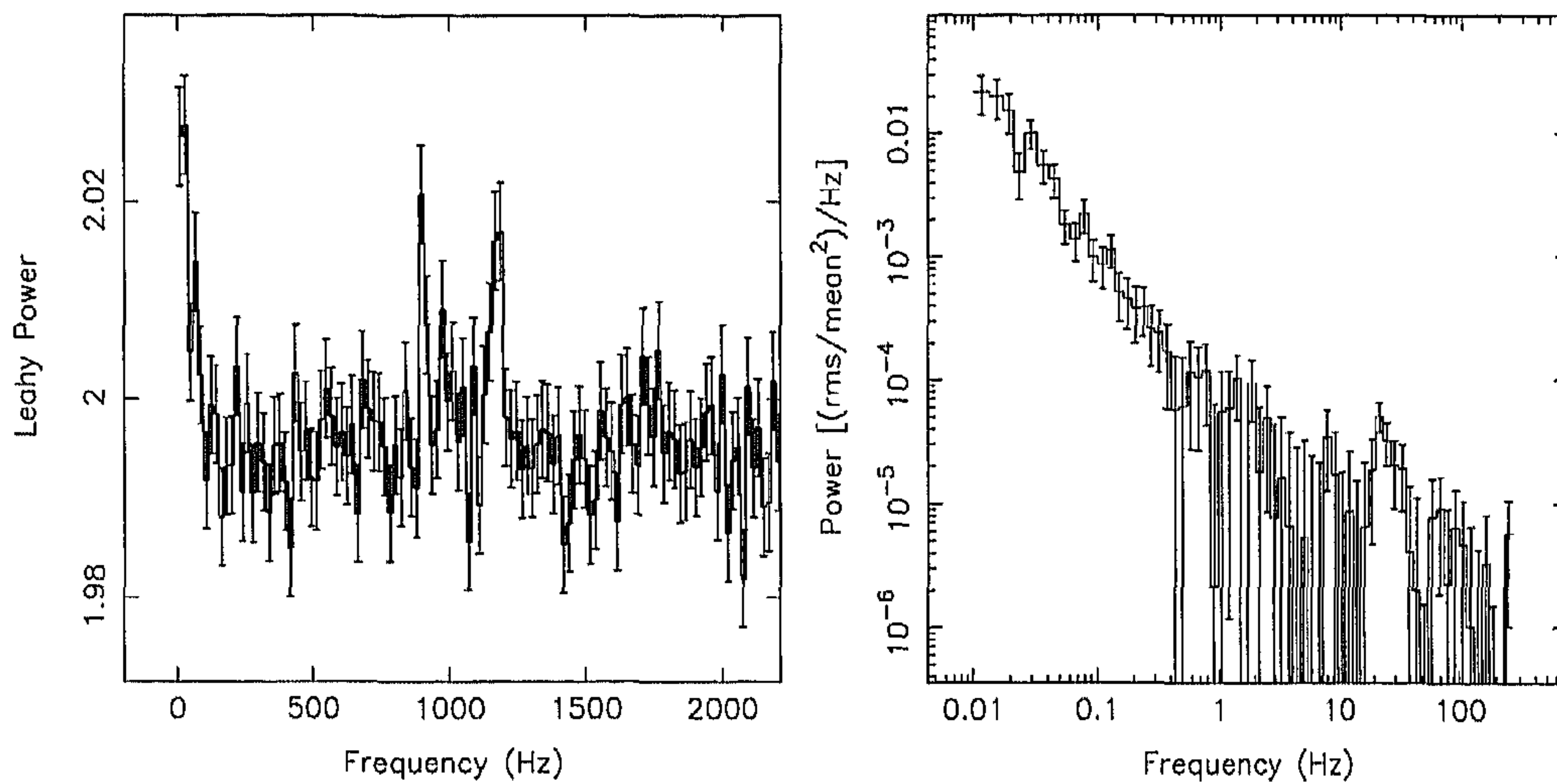


FIG. 1.—Leahy-normalized power spectra (5.7–24.1 keV) of KS 1731–260 during the 1996 August 1 observation (*left*), and the rms normalized power spectra (2.8–24.1 keV) during the 1996 August 31 observation (*right*). The left-hand figure is not corrected for counting statistics or dead time.

fits were corrected for background and differential dead time (see van der Klis 1989). The errors were determined using $\Delta\chi^2 = 1.0$ and the upper limits using $\Delta\chi^2 = 2.71$, which corresponds to the 95% confidence level. The reduced χ^2 -values of the fits were all ~ 1 .

3. RESULTS

Combining all data of the August 1 observation, two simultaneous QPOs are detected at frequencies of 900.1 ± 2.4 Hz and 1176.2 ± 2.9 Hz (Fig. 1, *left*). The rms amplitude (5.7–24.1 keV, see § 2) and FWHM were $3.4 \pm 0.5\%$ and 15 ± 6 Hz, and $4.5 \pm 0.5\%$ and 27 ± 10 Hz, respectively. During the first data segment of this observation we detect only the higher frequency QPO at 1176.2 ± 2.2 Hz, with a FWHM of 16 ± 8 Hz and an amplitude of $4.5 \pm 0.6\%$ rms. The 95% confidence upper limit on the amplitude of a QPO near 900 Hz with a FWHM of 15 Hz is 3.1% rms. During the second segment we find two QPOs at frequencies of 898.3 ± 3.3 Hz and 1158.6 ± 9.0 Hz, and a FWHM and rms amplitude of 22 ± 8 Hz and $5.3 \pm 0.7\%$, and 37 ± 21 Hz and $5.2 \pm 1.0\%$, respectively. During the third and last segment we could only marginally detect the QPOs at 899.8 ± 4.3 Hz (1.7σ) and 1182.9 ± 13.0 Hz (2.6σ). The FWHM and rms amplitude were 13 ± 8 Hz and $3.8 \pm 1.0\%$ for the lower frequency QPO, and 10 ± 9 Hz and $3.7 \pm 0.7\%$ for the higher frequency QPO.

Combining all the data of the August 31 observation only

the higher frequency QPO was detected, although marginally (2.1σ), at 1197 ± 10 Hz, with a FWHM of 38 ± 32 Hz and a rms amplitude of $3.8 \pm 0.9\%$. The lower frequency QPO had an amplitude upper limit of 2.4% rms (FWHM of 25 Hz).

We combined the power spectra of the August 1 and August 31 observations to study the dependence of the kilohertz QPO properties on 5.7–24.1 keV count rate. We selected the power spectra corresponding to count rates below 790 counts s^{-1} (288 spectra), between 790 and 840 counts s^{-1} (208 spectra), and above 840 counts s^{-1} (250 spectra). The selected power spectra, which were mixed in time (in the highest count rate selection power spectra from both observations were combined), were averaged and fitted to determine the kilohertz QPO properties (see Table 1 and Fig. 2). There is a clear correlation between kilohertz QPO frequency and count rate, similar to what was observed in other burst sources.

We made a single combined X-ray color-color diagram (CD) for both observations (Fig. 3) to study the dependence of the kilohertz QPO properties on position of the source in the CD. From Figure 3 it is clear that the kilohertz QPO properties are correlated with the position of the source in the color-color diagram. When the source is at the upper left part in the CD (low soft colors, high hard colors) two kilohertz QPOs are visible in the power spectrum. When the soft color increases and the hard color decreases both QPOs decrease in amplitude (the lower frequency QPO becomes undetectable)

TABLE 1
THE kHz QUASI-PERIODIC OSCILLATIONS VERSUS 5.7–24.1 keV COUNT RATE

Count Rate ^a (counts s^{-1})	LOWER FREQUENCY QPO			HIGHER FREQUENCY QPO			
	rms Amplitude (%)	FWHM (Hz)	Frequency (Hz)	rms Amplitude (%)	FWHM (Hz)	Frequency (Hz)	
758 ± 19	4.3 ± 0.6	20 ± 3	903.3 ± 2.7	...	4.8 ± 0.7	32 ± 14	1169.5 ± 4.6
812 ± 13	$<4.7^b$	...	...	...	4.3 ± 0.6	16 ± 7	1178.0 ± 2.8
929 ± 49	$<2.9^b$	...	...	...	4.0 ± 0.9^c	49 ± 42	1207 ± 11

NOTE.—All errors of the QPO properties correspond to $\Delta\chi^2 = 1$. The upper limits correspond to a 95% confidence level.

^a Errors are the standard deviation of the count rate distribution in the count rate interval, which was selected to calculate the properties of the QPO.

^b The upper limits are for QPOs near 900 Hz, with a FWHM of 50 Hz.

^c At a 2.1σ level.

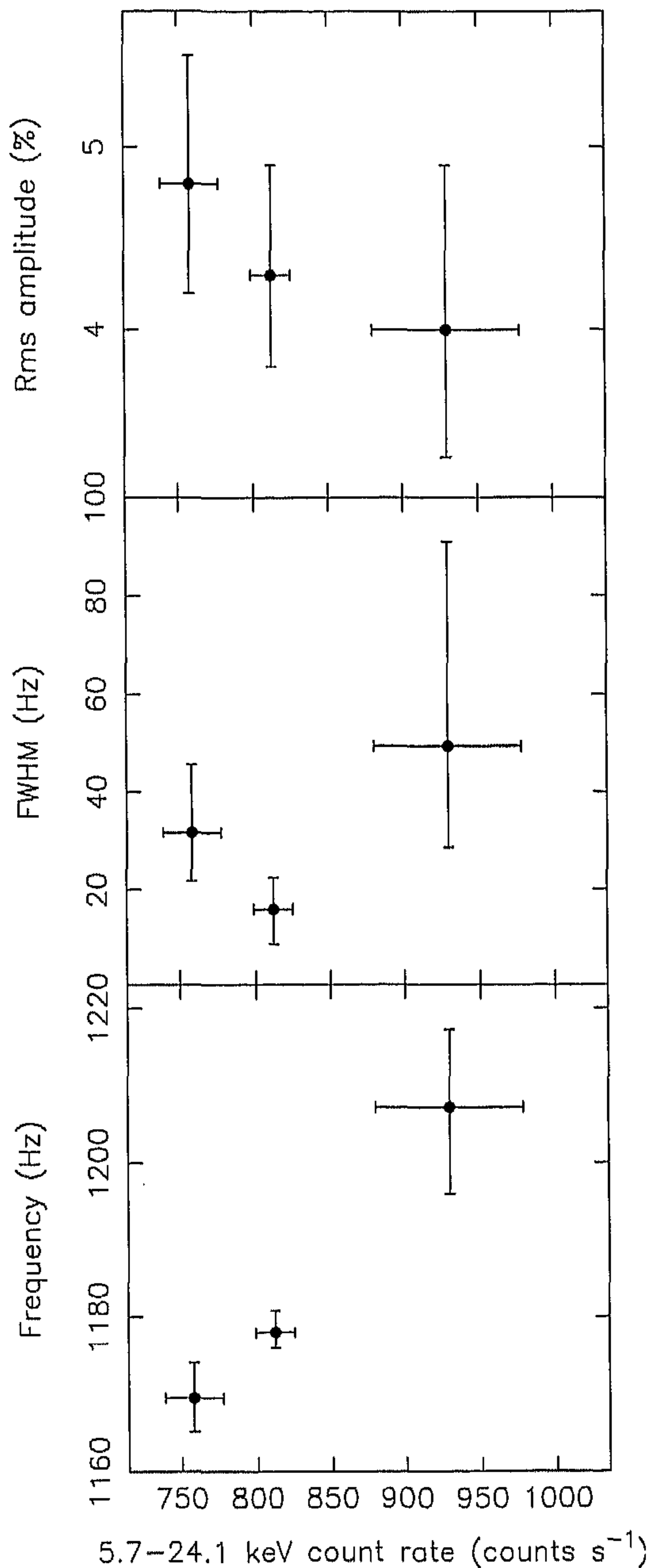


FIG. 2.—rms amplitude (*top*), the full width at half-maximum (*middle*), and the frequency (*bottom*) of the higher frequency kilohertz QPO vs. the 5.7–24.1 keV count rate. The error bars of the count rate represent the standard deviation of the count rate distribution in the count rate interval, which was selected to calculate the properties of the QPO.

and the frequency of the higher frequency QPO increases. The overall count rate of the source also increases in this sense (from upper left to lower right in the CD).

Due to the low signal-to-noise ratio in the individual energy channels the dependence of the rms amplitude of the kilohertz QPOs on photon energy could not be determined in detail. In the energy range 2.8–4.6 keV both QPOs were not detectable, with rms amplitude upper limits of 3.4%. In the energy range

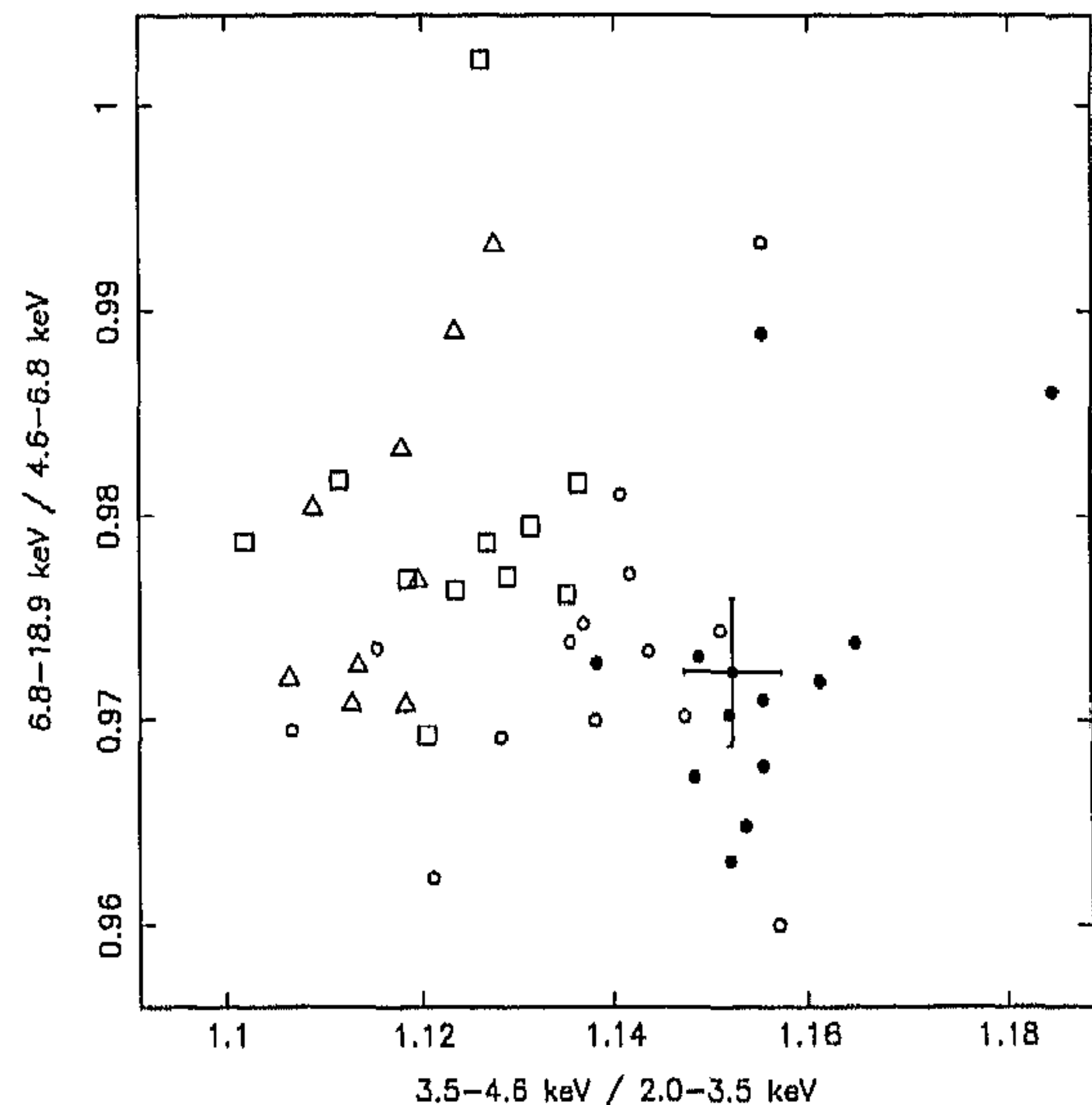


FIG. 3.—X-ray color-color diagram of the 1996 August 1 and August 31 observations. The open circles, the open triangles, and the open squares are data segments one, two, and three, respectively, of the August 1 observation. The filled circles are all data of the August 31 observation. Typical statistical error bars for the colors are shown. All points are 256 s averages. The background was not subtracted; part of the variations in the colors may therefore be due to background fluctuations.

4.6–8.2 keV the rms amplitude of the lower and higher frequency QPO were $4.0 \pm 0.7\%$ and $3.9 \pm 0.6\%$, respectively. In the energy range 8.2–24.1 keV the lower frequency QPO was not detectable (amplitude upper limit of 10% rms); the rms amplitude of the higher frequency QPO was $5.1 \pm 1.1\%$.

The VLFN during the August 1 observation had a rms amplitude of $5.9 \pm 0.6\%$ and a power-law index of 1.61 ± 0.07 . The peaked HFN had a amplitude of $4.6 \pm 0.4\%$ rms, a power-law index of 0.8 ± 0.6 , and a cutoff frequency of 22 ± 13 Hz. The VLFN during the August 31 observation had an rms amplitude of $7.1 \pm 0.6\%$, and a power-law index of 1.51 ± 0.06 . Although no HFN could be detected in that observation, a QPO at the frequency 26.9 ± 2.3 Hz is seen in the power spectrum (Fig. 1, *right*). The FWHM and amplitude of this QPO is 11.1 ± 5.2 Hz and $3.4 \pm 0.6\%$ (5.7–24.1 keV).

4. DISCUSSION

We detected for the first time two simultaneous kilohertz QPOs in KS 1731–260, at frequencies near 898 Hz and 1159 Hz. The amplitudes of these QPOs increase with increasing photon energy. Both QPOs are visible at the lowest count rates. At higher count rates the lower frequency QPO disappears, the amplitude of the higher frequency QPO decreases, and its frequency increases. At the highest count rates the higher frequency QPO is only marginally detected at 1207 ± 11 Hz. If that QPO is real, then its frequency is the highest so far observed in an X-ray binary. When the lower frequency QPO is detected its frequency is consistent with being constant. The minor differences in its frequency between slightly different data sets are within the statistical errors.

When we combine all power spectra from the August 1 observation, the peak separation of the two QPOs (276.1 ± 3.8 Hz) is not consistent with being equal to half the frequency

of the 523.92 ± 0.05 Hz oscillations found by Smith et al. (1997) in a type I burst. However, this inconsistency is artificial. In order to obtain a better signal-to-noise ratio we summed the power spectra of all three data segments obtained during this observation. During the first segment we see only the higher frequency QPO near 1176 Hz, during the second segment we see both QPOs near 898 and 1159 Hz, and during the third segment only the higher frequency peak can be significantly detected near 1183 Hz. Combination of these three data segments gives rise to an artificial increase of the peak separation, due to the different focus in time of the two QPOs. When both kilohertz QPOs are present (segment 2) the peak separation is 260.3 ± 9.6 Hz, which is almost exactly half the oscillation frequency (261.96 Hz) during the type I burst. This result strongly supports models in which the neutron spin frequency is 261.96 Hz (3.8 ms), the higher frequency QPO a preferred orbital frequency around the neutron star, and the lower frequency QPO the beat between these two. Such a model, with the preferred orbital radius the magnetospheric radius, was already suggested for the three QPOs found in 4U 1728-34 (Strohmayer et al. 1996). Miller, Lamb, & Psaltis (1997) proposed a model where the preferred radius is the sonic radius. A problem for these models is the case of Sco X-1, in which the frequency difference is not constant (van der Klis et al. 1997a, 1997b) as would be expected.

The positive correlation between soft color and X-ray count

rate and the negative correlation between hard and soft color (Fig. 3), the properties of the VLFN, and the decrease in the HFN strength with count rate taken together indicate that KS 1731-260 probably is an atoll source, which in our observations was in the lower banana branch, with the inferred accretion rate somewhat higher on August 31 than on August 1. The large scatter in the CD may in part be due to background fluctuations. The 27 Hz QPO is not uncommon in atoll sources (Hasinger & van der Klis 1989; Strohmayer et al. 1996) and seems to be closely related to the HFN ("peaked HFN").

So, the properties of the kilohertz QPOs in KS 1731-260 are consistent with what is known from observations of kilohertz QPOs in other atoll sources. The QPOs decrease in amplitude with mass accretion rate (as inferred from the count rate, the 2-10 keV fluxes, and the position in the CD), and where we can measure it (in the higher frequency QPO) the frequency of the QPO increases with mass accretion rate.

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