Strong-Field Gravity and X-Ray Observations of 4U 1820–30

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STRONG-FIELD GRAVITY AND X-RAY OBSERVATIONS OF 4U 1820−30

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ABSTRACT

The behavior of quasi-periodic oscillations (QPOs) at frequencies near 1 kHz in the X-ray emission from the neutron star X-ray binary 4U 1820−30 has been interpreted as evidence for the existence of the marginally stable orbit, a key prediction of strong-field general relativity. The signature of the marginally stable orbit is a saturation in QPO frequency (assumed to track inner disk radius) versus mass accretion rate. Previous studies of 4U 1820−30 have used X-ray count rate as an indicator of mass accretion rate. However, X-ray count rate is known to not correlate robustly with mass accretion rate or QPO frequency in other sources. Here, we examine the QPO frequency dependence on two other indicators of mass accretion rate: energy flux and X-ray spectral shape. Using either of these indicators, we find that the QPO frequency saturates at high mass accretion rates. We interpret this as strong evidence for the existence of the marginally stable orbit.

Subject headings: accretion, accretion disks — gravitation — relativity — stars: individual (4U 1820−30) — stars: neutron — X-rays: stars

1. INTRODUCTION

For many nuclear equations of state, the surface of a neutron star is expected to lie within the marginally stable orbit—the radius within which no stable circular orbits exist within general relativity (Kluźniak & Wagoner 1985). Thus, under certain conditions, the marginally stable orbit should be dynamically important in determining the accretion flow onto an accreting neutron star. The millisecond quasi-periodic oscillations (kHz QPOs) discovered (Strohmayer et al. 1996; van der Klis et al. 1996) with the *Rossi X-Ray Timing Explorer* (*RXTE*; Bradt, Rothschild, & Swank 1993) in the X-ray emission of neutron star X-ray binaries are likely produced by motion in the inner accretion disk with the QPO frequency related to the inner disk radius. Recently, it has been suggested that the behavior of the kHz QPOs for certain systems provides evidence for the existence of the marginally stable orbit (Kaaret, Ford, & Chen 1997; Zhang, Strohmayer, & Swank 1997). The best evidence has come from the binary 4U 1820−30 (Zhang et al. 1998a).

Two simultaneous kHz QPOs are detected from 4U 1820−30 (Smale, Zhang, & White 1997; Zhang et al. 1998a). Both the upper and lower QPO peak vary in frequency, but maintain an approximately constant frequency separation. Zhang et al. (1998a) found that below a certain count rate, the frequency centroids of both the upper and lower QPO peaks are correlated with count rate, while above that count rate, the QPO frequencies are roughly constant and are independent of count rate. Saturation of QPO frequency at high mass accretion rates had been suggested as a signature of the marginally stable orbit (Miller, Lamb, & Psaltis 1998; Kaaret et al. 1997). A key question is whether the X-ray count rate is a good indicator of the mass accretion rate and whether it is robustly correlated with the QPO frequency. In general, X-ray count rate is not a good indicator of mass accretion rate (Hasinger & van der Klis 1989).

Here, we present new observations of 4U 1820−30 made simultaneously with *RXTE* and *BeppoSAX* and a new analysis of archival *RXTE* observations. The new data show that the QPO frequency is not robustly correlated with X-ray count rate in 4U 1820−30. Thus, a better indicator of mass accretion rate is required. We use energy flux and X-ray spectral shape as indicators of mass accretion rate. Below, we first discuss the observations and analysis. We then present correlations between the QPO frequency and various indicators of mass accretion rate. We conclude with a discussion of the results.

2. OBSERVATIONS AND ANALYSIS

We performed two joint *BeppoSAX/RXTE* observations of 4U 1820−30, on 1998 April 17–18 and 1998 September 19–20, for a total of 100 ks of on-source observing time in each of *BeppoSAX* and *RXTE*. We also reanalyzed the *RXTE* observations described in Smale et al. (1997) and Zhang et al. (1998a).

For the timing analysis, 122 μs time resolution event data from the *RXTE* Proportional Counter Array (PCA) were used. To search for fast QPOs, we performed Fourier transforms on 2 s segments of data with no energy selection and summed the 2 s power spectra within each observation interval. The total power spectrum for each interval was searched for QPO peaks above 200 Hz by fitting a function, which consisted of a Lorentzian plus a constant, for each trial frequency. Only QPO peaks with a chance probability of occurrence of less than 1% as determined from an *F*-test were retained.

For the *RXTE*-only analysis, presented in Figures 1 and 3–5, we divided the data into continuous segments with lengths near 1000 s. In some cases, several 1000 s of data were combined to allow detection of weaker QPOs. For each interval, we calculated PCA count rates in various energy bands using Proportional Counter Units (PCUs) 0, 1, and 2 since these were on in all observations. Since the PCA response changed gradually over the 2 yr span of these observations, we used fixed energy bands and interpolated the count rates within fractional channel boundaries. The X-ray colors in Figures 4 and 5 were calculated from these rates. We also found 129 channel PCA

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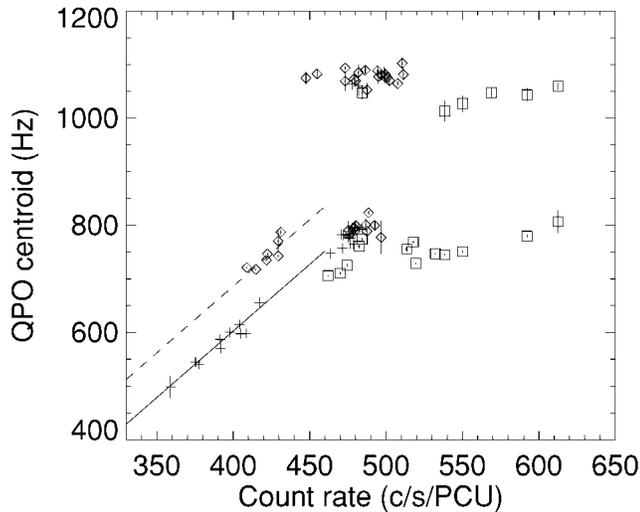[5] NASA/Goddard Space Flight Center, Greenbelt, MD 20771.

Fig. 1.—QPO centroid frequency versus X-ray count rate in the *RXTE* PCA (full band PCA with background subtracted). The diamonds indicate our new data from 1998. The squares are observations from 1997, and the plus signs are from 1996. The solid line is a best fit to the 1996 data in the count rate range 340–440 counts s^{-1} PCU^{-1}. The dashed line is offset by 83.5 Hz. The offset of the 1996 versus 1998 data show that lower QPO frequency is not robustly correlated with X-ray count rate.
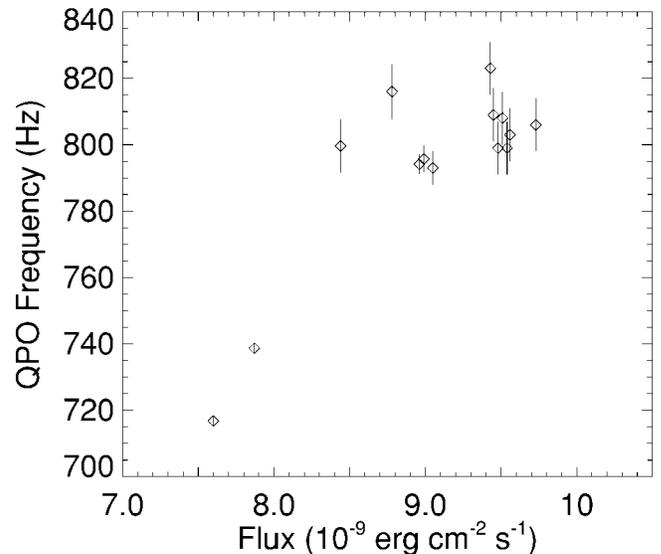

Fig. 2.—Correlation of QPO centroid frequency from *RXTE* observations with the unabsorbed energy flux in the 0.3–40 keV band calculated from simultaneous *BeppoSAX* observations. Only the lower frequency QPO is shown. The QPO frequency appears independent of flux above 8.3×10^{-9} ergs cm^{-2} s^{-1}.

spectra for PCUs 0 and 1, which were used to calculate the unabsorbed energy fluxes for the 2–25 keV band presented in Figures 3 and 5. Detailed analysis of *RXTE* spectral variations and correlations with the QPOs will be given in Bloser et al. (1999).

For the simultaneous *BeppoSAX/RXTE* analysis, we selected the longest continuous segments in order to maximize the statistics in each spectrum. There are 26 simultaneous segments, for a total of 62 ks. We searched for QPOs in the PCA data and performed spectral analysis of the *BeppoSAX* data for each segment. The spectral analysis is described in Piraino et al. (1999). We chose to use a Comptonization model (Sunyaev & Titarchuk 1980) with an added single-temperature standard blackbody component and included interstellar absorption to parameterize the spectra. For this model, the temperature $T_c = 2.83 \pm 0.08$ keV and the optical depth $\tau = 13.7 \pm 0.5$ of the Comptonizing electron cloud, the flux of the blackbody component, and the absorption column density $N_H = (2.8 \pm 0.3) \times 10^{21}$ cm^{-2} are constant within errors for all the joint *BeppoSAX/RXTE* observation intervals (the uncertainties quoted are the typical 90% confidence uncertainty for individual spectra). The values found for τ and T_c are similar to those observed previously (Christian & Swank 1997), and the parameters of the blackbody are similar to those found in an *ASCA* observation of 4U 1820−30 in a low intensity state (Smale et al. 1994). The blackbody temperature T_{bb} and the total flux vary with QPO frequency as reported in Piraino et al. (1999). Using this model, we calculated the unabsorbed energy flux in the 0.3–40 keV band presented in Figure 2.

3. CORRELATION OF SPECTRAL AND TIMING PROPERTIES

Zhang et al. (1998a) showed that the QPO frequency in 4U 1820−30 is correlated with X-ray count rate below a certain critical count rate and that the QPO frequency saturates above that count rate. This has been interpreted as evidence for the existence of the marginally stable orbit. However, a critical question—whether the X-ray count rate is a reliable estimator

of the mass accretion rate through the disk (Kaaret et al. 1998)—needs to be addressed for 4U 1820−30.

Zhang et al. (1998a) includes observations from 1996 and 1997, but the data that show a correlation between X-ray count rate and the lower QPO frequency come from observations that occurred within one 8 hr period in 1996. Since the QPO frequency versus count rate relation is known to change on timescales longer than days (Ford et al. 1997a; Yu et al. 1997; Zhang et al. 1998b; Mendez et al. 1999), it is important to check this relation with additional observations. Figure 1 shows the QPO frequency plotted versus PCA count rate for *RXTE* observations spanning 2 yr. This plot shows both the upper (above 1000 Hz) and lower frequency (below 850 Hz) QPOs. The upper QPO peaks with varying frequency reported in Zhang et al. (1998a) appear in the data, but have *F*-test values in the range 1%–4% and, thus, are not included here. Both the upper and lower QPO frequencies saturate at high count rates. Below a count rate of 440 counts s^{-1} PCU^{-1}, the lower QPO frequency appears correlated with count rate. However, our new data show a shift of the lower QPO frequency versus count rate relation by 83.5 ± 9.0 Hz relative to the 1996 data. This shift indicates that the X-ray count rate versus QPO frequency correlation is not robust in 4U 1820−30. Thus, other indicators of mass accretion rate are required.

Figure 2 shows the relation between the lower QPO frequency and the broadband (0.3–40 keV) unabsorbed energy flux calculated from the *BeppoSAX* data. The QPO frequency appears uncorrelated with the unabsorbed energy flux at high fluxes. The same behavior is seen for the absorbed flux. Since the broadband spectral coverage of *BeppoSAX* allows a reasonably reliable estimate of the total unabsorbed flux, this indicates that the break in the QPO frequency versus count rate relation is not simply due to a spectral change.

We also examined the QPO frequency versus flux relation with the full *RXTE* data set (see Fig. 3). Because of the PCA's lack of spectral coverage below 2 keV, reliable estimates of the broadband energy fluxes are not available, so we chose to
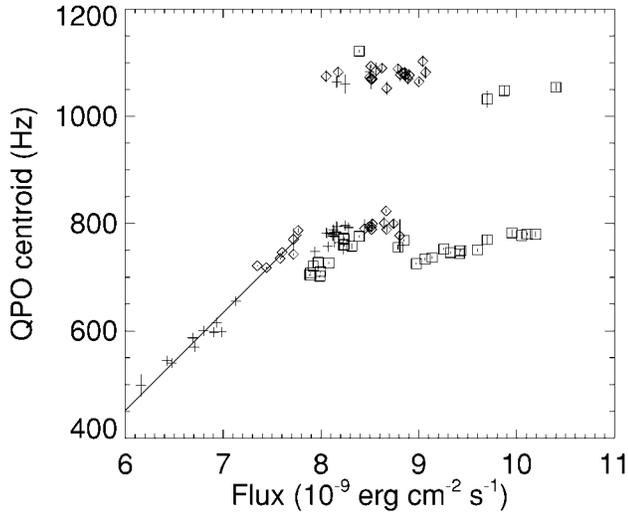
Fig. 3.—QPO centroid frequency versus unabsorbed energy flux in the 2–25 keV band calculated from the PCA spectra. The plot symbols indicate the epoch of the observations as in Fig. 1. The line is a fit to the data in the flux range (6–7.8) × 10^{-9} ergs cm^{-2} s^{-1}. The lower QPO frequency appears robustly correlated with energy flux at low fluxes and saturates at high fluxes.
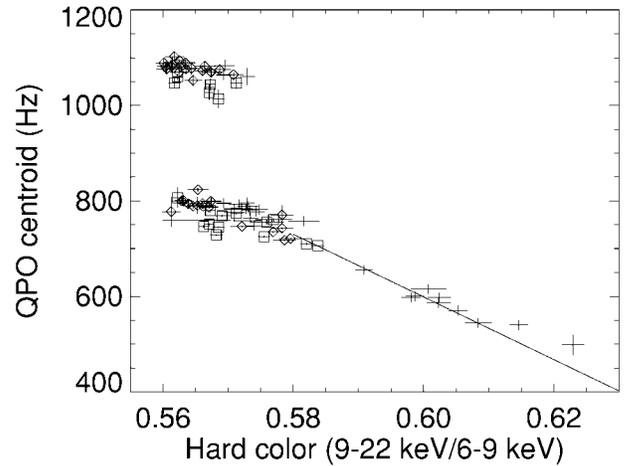
Fig. 4.—QPO centroid frequency versus an X-ray hard color C defined as the ratio of counts in the 9–22 keV band to that in the 6–9 keV band calculated from the PCA data. Lower color values correspond to higher mass accretion rates. The solid lines are linear fits of the lower QPO frequency versus hard color for $C > 0.58$ and $C < 0.575$. The plot symbols indicate the epoch of the observations as in Fig. 1. The lower QPO frequency appears robustly correlated with X-ray color for high color values, and saturates for low color values.

calculate the unabsorbed energy flux in the 2.0–25 keV band from the PCA data. The lower QPO frequency appears correlated with flux in observations spanning 2 yr. This is in contrast to the lack of robust correlation between QPO frequency and flux in other sources (Ford et al. 1997b; Zhang et al. 1998b). In 4U 1820−30, the QPO frequency saturates at high fluxes, consistent with the signature of the marginally stable orbit.

Kaaret et al. (1998) showed that the spectral shape at high energies, above 5 keV, correlates well with QPO frequency for the atoll sources 4U 0614+091 and 4U 1608−52. Spectral shape is also generally accepted as a good indicator of mass accretion rate in neutron star low-mass X-ray binaries based on studies of their spectra and timing noise (e.g., Hasinger & van der Klis 1989; Schulz, Hasinger, & Trumper 1989). The ratio of counts in two energy bands, an X-ray color, can be taken as estimator of spectral shape. In Figure 4, we show the relation between QPO frequency versus a hard X-ray color C, defined as the ratio of counts in the 9–22 keV band to that in the 6–9 keV band and calculated from the PCA data. The lower QPO frequency is well correlated with X-ray color when the spectrum is hard. There appears to be a break to constant QPO frequency when the spectrum becomes softer than a certain critical value.

To test whether the break in the QPO frequency versus hardness relation is significant, we did linear fits of the lower QPO frequency versus hard color for $C > 0.58$ and $C < 0.575$. For $C > 0.58$, the linear correlation coefficient is -0.984, corresponding to a chance probability of occurrence of 1.4×10^{-9}, and the best-fit slope is -6560 ± 350 Hz per color unit, while for $C < 0.575$, the correlation coefficient is -0.012, which implies that an uncorrelated data set would produce a correlation coefficient of this magnitude or larger with a probability of 0.97, and the slope is -97 ± 1310 Hz per color unit. We also fitted the entire data set for the lower frequency peak to two models: a line and a broken line with saturation at a maximum frequency. The χ^2 improved with addition of the extra parameter for the frequency saturation, $\Delta\chi^2/\chi_\nu^2 = 28.74$. The addition of the extra parameter is justified at a confidence level of 2×10^{-6}. Also, the slope found in the broken-line fit

agrees well with the slope found from the linear fit for $C > 0.58$. Thus, the evidence for the saturation in QPO frequency at low C, i.e., high mass accretion rates, is highly significant when evaluated using the linear correlation coefficients, the slopes of the linear fits in the two color ranges, or the decrease in χ^2 with the addition of saturation to the linear model.

In most of the atoll kHz QPO sources studied, QPOs are detected only down to some minimum hard color (e.g., Mendez 1999). The QPOs generally disappear near, or just beyond, a turning point in the color-flux or soft color–hard color diagram, and near the cutoff the QPO frequency varies over a wide range, 200–300 Hz. In 4U 1820−30, the QPOs disappear at a hard color near 0.56 where there is a break in the color-flux relation (see Fig. 5). This is similar to the behavior seen in other sources, although the range of the QPO frequency variation near the QPO disappearance is smaller in 4U 1820−30.

The saturation of QPO frequency in 4U 1820−30 occurs at a hard color near 0.58, significantly higher than the hard color at which the QPOs disappear. The saturation occurs at a position in the color-flux (or color-color) diagram where other kHz QPO sources show a good correlation between QPO frequency and hard color and is thus markedly distinct from the behavior seen in the other kHz QPO sources. The fact that the QPO frequency saturates while the hard color continues to increase suggests that the break in QPO frequency seen in 4U 1820−30 is distinct from the QPO behaviors seen in other sources. Because QPO frequency is well correlated with hard color in most kHz QPO sources and because X-ray color is thought to be a good indicator of mass accretion rate, the break in the QPO frequency versus X-ray hard color relation strengthens the interpretation of the transition to constant QPO frequency in 4U 1820−30 as evidence for the marginally stable orbit.

4. DISCUSSION

Interpretation of the kHz QPO data as evidence for the detection of the marginally stable orbit requires that the mechanism producing the kHz QPOs have a frequency that increases monotonically as the inner disk radius decreases. Keplerian
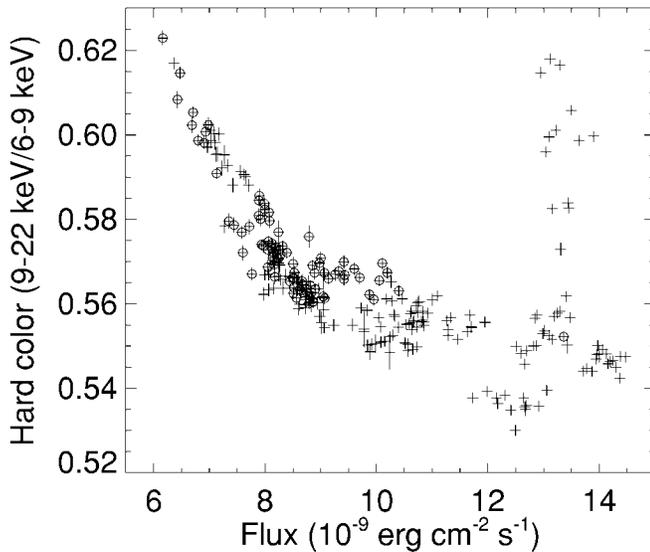
FIG. 5.—X-ray hard color versus energy flux, both calculated from the PCA data. The circles indicate intervals during which kHz QPOs were detected. The hard color versus flux relation has no features at the point where the QPO frequency saturation occurs. The QPO at very high flux has a centroid of 290.7 ± 1.2 Hz and a width of 13 Hz and may indicate a direct detection of the neutron star spin; however, the detection is not of high significance.

orbital motion, sub-Keplerian orbital motion (perhaps due to radiation pressure), or coherent phenomena, such as sound waves or disk oscillation modes, would all give the requisite dependence of QPO frequency on inner disk radius. In any of these cases, the sharp break in the mass accretion rate dependence of the QPO frequency in 4U 1820$-$30 requires a correspondingly sharp break in the dependence of inner disk radius on mass accretion rate.

The transition in QPO behavior versus X-ray hard color shown in Figure 4 occurs over an interval only slightly larger than the typical accuracy of the hard color measurements. Thus, the break must occur over a narrow range in mass accretion rate. A change in disk structure could produce a change in the dependence of QPO frequency on mass accretion rate (Zhang et al. 1998b). However, it is unlikely that a change in disk structure would produce a change to a fixed inner disk radius that then remains constant as the mass accretion rate continues

to increase. It is possible that the break is due to some special orbital radius other than the marginally stable orbit. Ghosh (1998) recently discovered an accretion disk instability that occurs in a fixed annulus covering radii of 14–19 GM/c^2 for a neutron star mass M. However, the instability is important only for gas pressure–dominated disks and is unlikely to be important for 4U 1820$-$30, since the mass accretion rate is of order 0.1 of the Eddington rate and thus the disk is likely radiation pressure dominated.

An alternative explanation—that the accretion disk is terminated at the neutron star surface—is rejected because the high coherence, $\nu/\Delta\nu \sim 30$, of the QPOs requires a lifetime for the phenomena producing the QPOs of at least 30 orbital or rotational cycles. Any spatially localized or coherent phenomena at the inner edge of the disk would be rapidly disrupted by the viscous stress and magnetic fields at the neutron star surface if the disk is terminated at the stellar surface (Miller et al. 1998). Thus, the observed coherence could not be maintained. Another alternative explanation—that the mass accretion rate independent QPO frequency is the spin frequency of the neutron star—is rejected because, based on the persistent emission and X-ray burst QPOs detected from other atoll sources, the spin frequency of 4U 1820$-$30 is most likely within a few 10 Hz of the QPO difference frequency of 270 Hz.

The QPO frequency above the critical mass accretion rate is not constant, but appears to vary over a fractional range (for the upper QPO) of approximately 5%. Analysis of accretion disk flow across the marginally stable orbit (Muchotrzeb 1983; Muchotrzeb-Czerny 1986) shows that if the inner disk radius is driven near the marginally stable orbit, then the inner disk radius varies over a range consistent with the observed QPO frequency variations (Kaaret et al. 1997).

We conclude that the observations of millisecond QPOs in the X-ray emission from 4U 1820$-$30 provide the first strong experimental evidence for the existence of the marginally stable orbit.

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