THE ASTROPHYSICAL JOURNAL, 505:L23–L26, 1998 September 20

KILOHERTZ QUASI-PERIODIC OSCILLATION PEAK SEPARATION IS NOT CONSTANT IN THE ATOLL SOURCE 4U 1608−52

M. MÉNDEZ,[1,2] M. VAN DER KLIS,[1,3] R. WIJNANDS,[1] E. C. FORD,[1] J. VAN PARADIJS,[1,4] AND B. A. VAUGHAN[5]

Received 1998 June 12; accepted 1998 July 27; published 1998 August 24

ABSTRACT

We present new *Rossi X-Ray Timing Explorer* observations of the low-mass X-ray binary 4U 1608−52 during the decay of its 1998 outburst. We detect, by a direct fast Fourier transform method, the existence of a second kilohertz quasi-periodic oscillation (kHz QPO) in its power density spectrum, which was previously only seen by means of the sensitivity-enhancing “shift and add” technique. This result confirms that 4U 1608−52 is a twin kHz QPO source. The frequency separation between these two QPOs decreased significantly, from 325.5 ± 3.4 to 225.3 ± 12.0 Hz, as the frequency of the lower kHz QPO increased from 470 to 865 Hz, in contradiction with a simple beat-frequency interpretation. This change in the peak separation of the kHz QPOs is closely similar to that previously seen in Scorpius X-1 but takes place at a 10 times lower average luminosity. We discuss this result within the framework of models that have been proposed for kHz QPO. Beat-frequency models where the peak separation is identified with the neutron star spin rate, as well as the explanations previously proposed to account for the similar behavior of the QPOs in Sco X-1, are strongly challenged by this result.

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

1. INTRODUCTION

In the past 2 years, the *Rossi X-Ray Timing Explorer* (*RXTE*) has discovered kilohertz quasi-periodic oscillations (kHz QPOs) in 18 low-mass X-ray binaries (LMXBs; see van der Klis 1998 for a review). In almost all cases, the power density spectra of these sources show twin kHz peaks that move up and down in frequency together as a function of the mass accretion rate, keeping a separation consistent with being constant (see, e.g., Strohmayer et al. 1996b; Wijnands et al. 1997; Ford et al. 1997). In some sources, a third QPO peak has been detected during type I X-ray bursts, at a frequency consistent with the frequency separation of the twin peaks (Strohmayer et al. 1996b) or twice that value (Smith, Morgan, & Bradt 1997; Wijnands & van der Klis 1997; Zhang et al. 1996; Wijnands et al. 1997), indicating a beat-frequency interpretation. The third peak, while not strictly constant in frequency but varying by up to 0.4%, has been interpreted as being close to the neutron star spin frequency (Strohmayer et al. 1996b).

Until recently, Scorpius X-1 stood out as the only example where the separation between the two simultaneous kHz QPOs was not constant but varied by 40% (van der Klis et al. 1997) as the mass accretion rate increased, posing a serious challenge to the simple beat-frequency interpretation. Using data of the 1996 outburst, and a new technique to increase the sensitivity to weak QPOs, Méndez et al. (1998) found the second of the twin peaks in 4U 1608−52 and presented evidence for similar variations by 26% of the peak separation in this source, although only significant at the 3.5 σ level.

In this Letter, we report on the results from recent *RXTE* observations obtained during the decay of the 1998 outburst of 4U 1608−52. We again observed two QPOs, and we show conclusively that the peak separation in 4U 1608−52 changes by more than 40%. The changes are remarkably similar to those seen in Sco X-1.

2. OBSERVATIONS

We used the Proportional Counter Array (PCA) on board *RXTE* to observe 4U 1608−52 between 1998 February 6 and April 25. The observations were triggered at the peak of the outburst, as measured by the *RXTE* All-Sky Monitor (ASM) experiment, and were planned to sample the source over the whole decay of the outburst. The data set consists of 40 observations, each of them with exposures between 600 and 19,980 s, and a total observing time of 191 ks. Figure 1 shows the ASM light curve during the outburst, where we indicate the dates when we carried out the pointed PCA observations.

Besides the two standard modes that are available to all *RXTE*-PCA observations, we collected data using additional modes with high-time and moderate-energy resolution, covering the nominal 2–60 keV energy band of the *RXTE*-PCA. We also included a set of burst trigger and catcher modes to record burst data at high-time and high-energy resolution. We recorded three type I X-ray bursts. A timing analysis of these data revealed no burst oscillation, with 95% confidence upper limits to the amplitude of 6% rms at the peak of the bursts and 20% at the beginning or the end.

3. DATA ANALYSIS AND RESULTS

We used the standard 2 data and the standard PCA background model[6] for the spectral analysis. First, we divided the data into four energy bands, 2.0–3.5, 3.5–6.4, 6.4–9.7, and 9.7–16 keV, and constructed a color-color and hardness-intensity diagram. Based on the spectral data, and on the power density spectra (described below) in the range 0.01–128 Hz, we conclude that 4U 1608−52 slowly moved from the upper

---

[1] Astronomical Institute “Anton Pannekoek,” University of Amsterdam, and Center for High-Energy Astrophysics, Kruislaan 403, 1098 SJ Amsterdam, the Netherlands.

[2] Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, Paseo del Bosque S/N, 1900 La Plata, Argentina.

[3] Department of Astronomy, 601 Campbell Hall No. 3411, University of California at Berkeley, Berkeley, CA 94720.

[4] Department of Physics, University of Alabama at Huntsville, Huntsville, AL 35899.

[5] Space Radiation Laboratory, California Institute of Technology, MC 220-47, Pasadena, CA 91125.

[6] The PCA Background Estimator is available at http://heasarc.gsfc.nasa.gov/docs/xte/recipes/pcabackest.html, which is maintained by *RXTE* GOF.

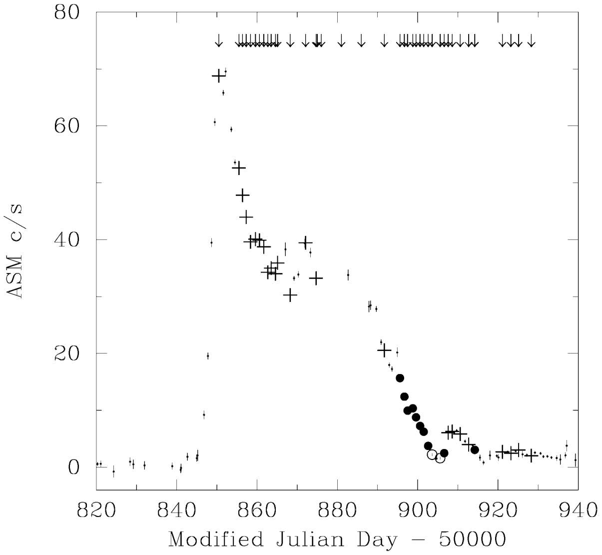

FIG. 1.—ASM light curve of the 1998 outburst of 4U 1608−52. The arrows indicate the dates when we performed the pointed *RXTE* observations. The filled circles indicate the observations where we detect, directly or with shifts, two simultaneous kHz QPOs. The open circles and the crosses indicate the observations where we detect one and no kHz QPOs, respectively.

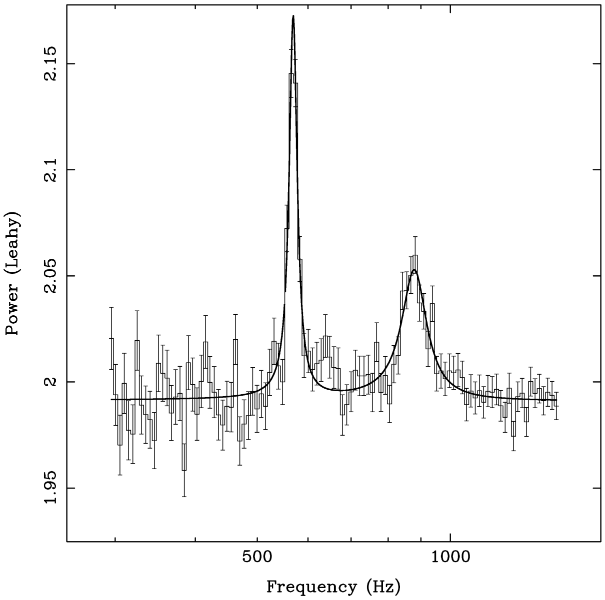

FIG. 2.—Power spectrum of a segment of 4224 s starting on UTC 1998 March 25 16:16, for the full energy band of the PCA. Both kHz QPOs are visible. No shift was applied to this power spectrum (see text). On 64 s timescales, the FWHM of the lower QPO was ~5 Hz, but due to the variation of its central frequency during the observation, it appears broader in the average power spectrum. The upper QPO was broader, and its FWHM on each segment of 64 s was ~100 Hz.

banana through the lower banana to the island state (Hasinger & van der Klis 1989) as the 2–60 keV count rate decayed from ~14,500 to ~260 counts s^{-1}.

We also produced background-subtracted X-ray spectra that were well fitted by means of a model consisting of a blackbody and a power law with a high-energy cutoff. Assuming a distance of 3.6 kpc (Nakamura et al. 1989), during our observations, the 2–20 keV luminosity of 4U 1608−52 decayed from 4.8×10^{37} ergs s^{-1} at the highest count rate to 1.2×10^{36} ergs s^{-1} at the lowest count rate. Details of the spectral fits, color-color diagrams, and the analysis of the low-frequency part of the power spectra will be presented elsewhere.

We divided the high-time resolution data into segments of 64 s and calculated a power spectrum for each segment, preserving the maximum available Nyquist frequency. For each of the 40 observations, we produced an average power spectrum that we used to search for QPOs at frequencies above $\gtrsim$100 Hz. None of the observations obtained before March 23 showed any QPO in this frequency range. The 95% confidence upper limits on the amplitude for a peak with FWHMs of 10, 50, and 100 Hz were 0.8%, 1.2%, and 1.6% rms, respectively, on February 6 and 2.0%, 3.8%, and 4.6% rms, respectively, on March 19. Starting on March 23, when the luminosity of the source (2–20 keV) had dropped to 1×10^{37} ergs s^{-1}, we detected QPO peaks in 12 observations (Fig. 1), at frequencies between 400 and 1000 Hz. In five observations, this straight Fourier analysis revealed two simultaneous QPOs, while in the remaining seven observations, we detected only one QPO peak. In Figure 2, we show an example of an observation where we detected two simultaneous QPOs at ~550 Hz (hereafter the lower QPO) and at ~900 Hz (hereafter the upper QPO).

For those seven observations where we detected only a single peak in the average power spectrum, we applied the same technique that we described in Méndez et al. (1998). We fitted the central frequency of the QPO in each segment of 64 s (or longer when occasionally we had to average some of the 64 s segments to detect the QPO) and then shifted the frequency scale of each spectrum to a frame of reference where the position of the peak was constant in time. Finally, we averaged these shifted power spectra. This procedure revealed a second QPO in five of those seven observations, in three occasions at higher frequencies, and in two observations at lower frequencies than those of the peak originally used to align the individual power spectra. For the two remaining observations (March 31 and April 5), we did not detect a second peak. The 95% confidence upper limits on the amplitude of a second (undetected) QPO with FWHMs of 10, 50, and 100 Hz were 3.5%, 4.7%, and 5.3% rms, respectively, on March 31 and 5.2%, 8.1%, and 10% rms, respectively, on April 5.

For the observation of March 25, when the two QPOs were more or less equally strong, we measured their FWHMs in three energy bands, 3.5–6.8, 6.8–11.2, and 11.2–14.9 keV; the widths of the lower and upper peaks were 8.3 ± 0.4 and 88 ± 12 Hz, respectively, with no significant dependence on energy.

In the rest of this Letter, we present only the results of the analysis of those data where, either directly or with shifts, we detected two simultaneous kHz QPOs in the power spectrum. These are 10 observations of the 1998 outburst (Fig. 1, *filled circles*) plus two observations of the 1996 outburst (March 3 and 6; Méndez et al. 1998), yielding a total of 1336 power spectra, each of them of 64 s of data. During these observations, the 2–60 keV fractional amplitudes of the lower and upper QPOs varied from 5.3% to 9.1% rms and from 3.3% to 8.8% rms, respectively, and the FWHM varied from 4.3 to 9.4 Hz and from 53 to 173 Hz, respectively.

We aligned all the 1336 power spectra using the lower QPO as a reference, and we grouped the data in 13 sets of ~50 to ~150 power spectra, such that the frequency of the QPO did not vary by more than ~10–20 Hz within each set. Finally, we combined these aligned spectra to produce an average power spectrum for each set. We fitted all these 13 power spectra in the range 256–3000 Hz by using a function that consisted of a constant, representing the Poisson noise, and two Lorentzians, representing the QPOs. The fits were good, with reduced $\chi^2 \leq 1.1$, and the significance of both peaks was always greater than 3 σ. In Figure 3, we plot the frequency difference, $\Delta\nu$, between the upper and the lower QPO as a function of the centroid frequency of the lower QPO, $\nu_{\rm low}$: as $\nu_{\rm low}$ increases from ∼475 to ∼865 Hz, the separation gradually changes from 325.5 ± 3.4 to 225.3 ± 12.0 Hz, i.e., by 100.2 ± 12.5 Hz. In Figure 3, we also plotted $\Delta\nu$ versus $\nu_{\rm low}$ as measured for Sco X-1 (van der Klis et al. 1997). Despite the big difference in luminosity, $\sim L_{\rm Edd}$ for Sco X-1 and $\sim 0.1 L_{\rm Edd}$ for 4U 1608−52, both sources behave in the same manner.

In order to get a significant measurement of the properties of the upper QPO as a function of the frequency of the lower QPO, we had to average together power spectra from intervals that were very distant in time. To check whether or not this way of averaging the data affected our results, we selected three contiguous intervals for which the frequency of the lower QPO remained approximately constant, allowing us to measure reasonably well both QPOs simultaneously. During 2624, 2624, and 3264 s of the observations of 1998 March 26 and 27 and 1996 March 3, the lower QPO remained more or less constant at ∼600, ∼770, and ∼870 Hz, respectively. In the worst case (1996 March 3), the significance of the detection of the upper peak was 2.7 σ. These three intervals show exactly the same trend as seen in Figure 3, only the error bars were larger. For these three intervals, $\Delta\nu$ was 298 ± 9, 277 ± 23, and 231 ± 13 Hz, respectively.

4. DISCUSSION

We have confirmed the existence of the second kHz QPO in 4U 1608−52, and we have conclusively shown that $\Delta\nu$, the frequency separation of both peaks, is not constant but changes as a function of the frequency of the lower kHz QPO. This is the first case where this is observed to occur in an atoll source, at a luminosity that is far below the Eddington luminosity. A similar result was obtained previously by van der Klis et al. (1997) for Sco X-1 only, a Z-source at a near-Eddington mass accretion rate.

Three different models have been proposed to explain the kHz QPOs. In the photon bubble oscillations model (Klein et al. 1996a, 1996b), the flow of matter is funneled onto the polar caps of a highly magnetized neutron star that is accreting at high rates, and the radiation pressure becomes locally super-Eddington. The accretion column develops radiation-hydrodynamic turbulence, and energy is transported to the surface of the accretion column by photon bubbles, which produce oscillations in the luminosity. Klein et al. (1996b) applied this model to explain the 20, 40, and 60 Hz QPO and the overall shape of the power spectrum observed in the high-luminosity binary pulsar GRO J1744−28 (Fishman et al. 1995; Kouveliotou et al. 1996), which contains a neutron star with a high magnetic field ($B \sim 2.4 \times 10^{11}$ G; Cui 1997), and the kHz QPO observed in the luminous Z-source Sco X-1 (van der Klis et al. 1996), which is accreting matter at a high rate (Hasinger & van der Klis 1989). It is widely accepted that in the atoll sources, the magnetic field is $\lesssim 10^8$–10^9 G. In 4U 1608−52 during these observations, the X-ray luminosity was less than 10% of the Eddington luminosity for a 1.4 $M_\odot$ neutron star. Combining these numbers, and using standard magnetospheric accretion theory, the area of the pole cap where the matter accreted onto the neutron star was between 20% and 60% of the total stellar surface (see Frank, King, & Raine 1992, eq. [6.14]). It is therefore quite unlikely that the accretion rate was locally super-Eddington. This argues, at least for this source, against the photon bubble interpretation of the kHz QPOs.

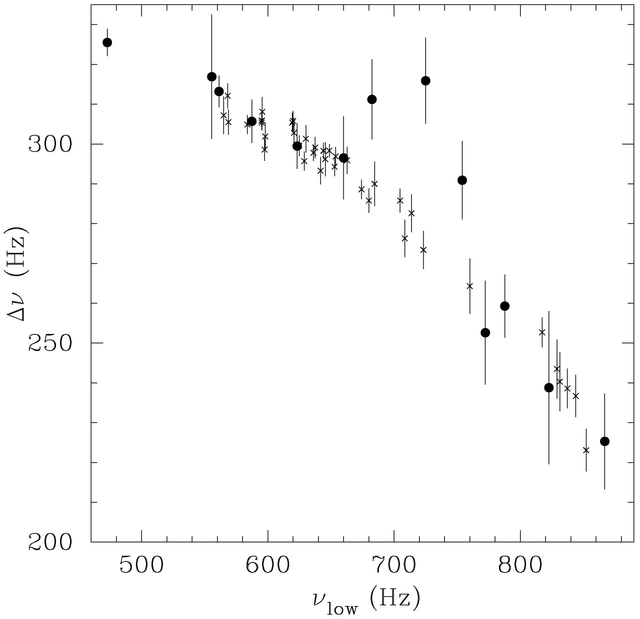

FIG. 3.—The frequency separation between the upper and the lower QPO peak as a function of the frequency of the lower QPO for 4U 1608−52 (*filled circles*). The crosses are the data obtained for Sco X-1 (van der Klis et al. 1997). The rise of $\Delta\nu$ at $\nu_{\rm low} \sim 700$ Hz in 4U 1608−52 is marginally significant.

Titarchuk & Muslimov (1997) and Titarchuk, Lapidus, & Muslimov (1998) proposed that all the QPOs observed in Z-sources and atoll sources might be explained in terms of the rotational splitting of oscillation modes of a nearly Keplerian accretion disk. One of the predictions of this model is that the ratio of the frequency of the upper to the lower kHz QPO, $\nu_{\rm upp}/\nu_{\rm low}$, is only a function of H/R, the ratio of the half-thickness of the disk to the radius of the annulus in the disk at which the oscillations occur. The ratio $\nu_{\rm upp}/\nu_{\rm low}$ (Titarchuk et al. 1998, eq. [A9] for $m = -2$ and $k = 1$) can vary from 5 (for $H \ll R$) to 1.37 (for $H \sim R$). When we detected kHz QPOs, the luminosity of 4U 1608−52 was $\lesssim 10\%$ $L_{\rm Edd}$. For these luminosities, and for any realistic structure of the disk, one expects $H \ll R$. During our observations of 4U 1608−52, $\nu_{\rm upp}/\nu_{\rm low}$ gradually decreased from 1.69 ± 0.01 at $\nu_{\rm low} = 475$ Hz to a value of 1.26 ± 0.01 at $\nu_{\rm low} = 875$ Hz; these values are inconsistent with the predicted value of 5. In Sco X-1, despite the large difference in luminosity, and therefore the large difference of the inferred structure in the inner part of the disk, $\nu_{\rm upp}/\nu_{\rm low}$ changes in the same manner, varying from 1.54 ± 0.01 at 565 Hz to 1.26 ± 0.01 at 852 Hz (van der Klis et al. 1997). Moreover, in both cases, $\nu_{\rm upp}/\nu_{\rm low}$ reaches lower values than those allowed by the model. These results show that the disk oscillation model, as presented, cannot account for the observed kHz QPOs in these two sources.

The most widely accepted models for the kHz QPOs are beat-frequency models where the upper kHz QPO, $\nu_{\rm upp}$, represents the Keplerian frequency of the accreting material in orbit around the neutron star at some preferred radius (van der Klis et al. 1996), while the lower frequency peak, $\nu_{\rm low}$, is produced by the beating of $\nu_{\rm upp}$ with another frequency, ν_S, that is identified as the spin frequency of the neutron star. Strohmayer et al. (1996a) proposed that $\nu_{\rm upp}$ is produced at the magnetospheric radius, while Miller, Lamb, & Psaltis (1998) proposed that it originates at the sonic radius. Since $\nu_S = \nu_{\rm upp} - \nu_{\rm low}$, these models predict that the frequency difference $\Delta\nu$ of the twin kHz peaks should remain constant, although $\nu_{\rm upp}$ and $\nu_{\rm low}$ may vary in time. This kind of model provides a natural explanation for the fact that in most of the sources where two simultaneous kHz QPOs have been observed, $\Delta\nu$ does not change significantly as the frequency of the two QPOs varies, while they are also consistent with the presence of a third kHz peak that is sometimes detected during type I bursts (Strohmayer et al. 1996b; Smith et al. 1997) at a frequency near ν_S or $2\nu_S$.

Two explanations have been put forward to account for the variable peak separation in Sco X-1, both of them related to the inferred near-Eddington mass accretion rate in this source. White & Zhang (1997) proposed that the photosphere of the neutron star might expand by 35% while conserving its angular momentum, and therefore it slows down as $\dot{M}$ increases. Alternatively, at near-Eddington accretion, the height of the inner disk might increase, and the change of $\nu_{\rm upp} - \nu_{\rm low}$ might reflect different values of $\nu_{\rm upp}$ at different heights in the disk (F. K. Lamb 1997, private communication).

However, we know now that in the low-luminosity source 4U 1608−52, $\Delta\nu$ also changes significantly, in contradiction with a beat-frequency interpretation involving the neutron star spin. Neither of the above explanations can account for this result in 4U 1608−52, since it is accreting matter at rates far below the Eddington critical rate. One might argue that 4U 1608−52 and Sco X-1 are different, in some respect, from the rest of the sources that show kHz QPOs. But if this were the case, it would be difficult to explain why the properties of the kHz QPOs observed in all sources (including both 4U 1608−52 and Sco X-1) are so homogeneous. Moreover, Psaltis et al. (1998) recently showed that for nine other sources where the two QPOs have been observed simultaneously, $\Delta\nu$ is consistent both with being constant and with having a similar behavior to that observed in Sco X-1 and 4U 1608−52.

In the beat-frequency model, the lower kHz peak is expected to be at least as broad as the upper peak, since it is generated by a beat between the upper QPO and the (coherent) neutron star spin. This is contrary to what we observe for 4U 1608−52, where the upper peak is intrinsically broader than the lower peak. For instance, during 3840 s on 1998 March 25, when the frequency of the lower peak varied between 550 and 575 Hz, the FWHMs of the lower and upper peak were 9.3 ± 0.8 and 95.4 ± 13.8 Hz (2–60 keV), respectively. A rapidly variable scattering medium around the neutron star could cause the broadening and might even be responsible for the frequency shift, if it has a (quasi-) periodicity of its own (F. K. Lamb 1997, private communication). The QPO at $\nu_{\rm upp}$, which, in the sonic model (Miller et al. 1998), is a beaming oscillation, would be more sensitive to this than the peak at $\nu_{\rm low}$, which is supposed to be produced by oscillations of the luminosity. If this interpretation is correct, it also needs to explain why the width of the upper QPO does not depend on energy.

At this point, none of the modified beat-frequency models proposed can explain the varying peak separation in 4U 1608−52 (and in Sco X-1). In order to maintain a beat-frequency model, the change in $\nu_{\rm upp} - \nu_{\rm low}$ by ~40%, in both 4U 1608−52 and Sco X-1, requires a similar change in ν_S. The spin of the neutron star cannot change by such a large factor on such a short timescale. It might still be possible to rescue the beat-frequency interpretation, although at the expense of its simplicity. Perhaps the idea of a layer at the surface of the neutron star that does not corotate with the body of the star can still be applied to explain these results. The detection of coherent oscillations during a type I burst in 4U 1608−52 might provide a strong clue to the nature of the kHz QPOs in LMXBs, since this would at least make clear at which mass accretion level, if any, the kHz peak separation does approach the inferred spin rate.

We would like to thank Professor Hale Bradt for his comments that helped us to improve the original manuscript. This work was supported in part by the Netherlands Organization for Scientific Research (NWO) under grant PGS 78-277 and by the Netherlands Foundation for research in astronomy (ASTRON) under grant 781-76-017. M. M. is a fellow of the Consejo Nacional de Investigaciones Científicas y Técnicas de la República Argentina. J. v. P. acknowledges support from the National Aeronautics and Space Administration through contracts NAG 5-3269 and 5-4482. M. v. d. K. gratefully acknowledges the Visiting Miller Professor Program of the Miller Institute for Basic Research in Science (UCB).

REFERENCES

Cui, W. 1997, ApJ, 482, L163
Fishman, G. J., Kouveliotou, C., van Paradijs, J., Harmon, B. A., Paciesas, W. S., Briggs, M. S., Kommers, J., & Lewin, W. H. G. 1995, IAU Circ. 6272
Ford, E., et al. 1997, ApJ, 475, L123
Frank, J., King, A., & Raine, D. 1992, Accretion Power in Astrophysics (Cambridge: Cambridge Univ. Press)
Hasinger, G., & van der Klis, M. 1989, A&A, 225, 79
Klein, R. I., Arons, J., Jernigan, G., & Hsu, J.-L. 1996a, ApJ, 457, L85
Klein, R. I., Jernigan, J. G., Arons, J., Morgan, E. H., & Zhang, W. 1996b, ApJ, 469, L119
Kouveliotou, C., van Paradijs, J., Fishman, G. J., Briggs, M. S., Kommers, J., Harmon, B. A., Meegan, C. A., & Lewin, W. H. G. 1996, Nature, 379, 799
Méndez, M., et al. 1998, ApJ, 494, L65
Miller, M. C., Lamb, F. K., & Psaltis, D. 1998, ApJ, in press (astro-ph/9609157)
Nakamura, N., Dotani, T., Inoue, H., Mitsuda, K., Tanaka, Y., & Matsuoka, M. 1989, PASJ, 41, 617
Psaltis, D., et al. 1998, ApJ, 501, L95
Smith, D. A., Morgan, E. H., & Bradt, H. 1997, ApJ, 479, L137
Strohmayer, T. E., Zhang, W., Smale, A., Day, C., Swank, J. H., Titarchuk, L., & Lee, U. 1996a, IAU Circ. 6387
Strohmayer, T. E., Zhang, W., Swank, J. H., Smale, I., Titarchuk, L., Day, C., & Lee, U. 1996b, ApJ, 469, L9
Titarchuk, L., Lapidus, I., & Muslimov, A. 1998, ApJ, 499, 315
Titarchuk, L., & Muslimov, A. 1997, A&A, 323, L5
van der Klis, M. 1998, in Proc. NATO/ASI Conf. Ser. C, The Many Faces of Neutron Stars, ed. R. Buccheri, J. van Paradijs, & M. A. Alpar (Dordrecht: Kluwer), in press (astro-ph/9710016)
van der Klis, M., Swank, J. H., Zhang, W., Jahoda, K., Morgan, E., Lewin, W. H. G., Vaughan, B. A., & van Paradijs, J. 1996, IAU Circ. 6319
van der Klis, M., Wijnands, R. A. D., Horne, K., & Chen, W. 1997, ApJ, 481, L97
White, N. E., & Zhang, W. 1997, ApJ, 490, L87
Wijnands, R. A. D., & van der Klis, M. 1997, ApJ, 482, L65
Wijnands, R. A. D., van der Klis, M., van Paradijs, J., Lewin, W. H. G., Lamb, F. K., Vaughan, B. A., & Kuulkers, E. 1997, ApJ, 479, L141
Zhang, W., Lapidus, I., Swank, J. H., White, N. E., & Titarchuk, L. 1996, IAU Circ. 6541