Supporting evidence for the signature of the innermost stable circular orbit in Rossi X-ray data from 4U 1636–536

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ABSTRACT

Analysis of archival Rossi X-ray Timing Explorer (RXTE) data on neutron star low-mass X-ray binaries has shown that for several sources the quality factor \(Q\) of the lower kilohertz Quasi-Periodic Oscillations (QPO) drops sharply beyond a certain frequency. This is one possible signature of the approach to the general relativistic innermost stable circular orbit (ISCO), but the implications of such an interpretation for strong gravity and dense matter are important enough that it is essential to explore alternate explanations. In this spirit, Méndez has recently proposed that \(Q\) depends fundamentally on mass accretion rate (as measured by spectral hardness) rather than the frequency of the QPO. Specifically, he has suggested that analysis of multiple sources shows trends in \(Q\) similar to those previously reported in individual sources, and he surmises that the ISCO therefore does not play a role in the observed sharp drop in \(Q\) in any source. We test this hypothesis for 4U 1636–536 by measuring precisely spectral colors simultaneously with the lower QPO frequency and \(Q\) after correction for the frequency drift, over a data set spanning eight years of RXTE observations. We find that in this source there is no correlation between \(Q\) and spectral hardness. In particular, no apparent changes in hardness are observed when \(Q\) reaches its maximum before dropping off. We perform a similar analysis on 4U 1608–522; another source showing a sharp drop in the quality factor of its lower kHz QPO. We find that for this source, positive and negative correlations are observed between spectral hardness, frequency and \(Q\). Consequently, if we are to search for a common explanation for the sharp drop in the quality factor seen in both sources, the spectral hardness is not a good candidate for the independent variable whereas the frequency remains. Therefore, we conclude that the ISCO explanation is viable for 4U 1636–536, and thus possibly for others.

Key words: Accretion - Accretion disk, stars: neutron, stars: X-rays

1 INTRODUCTION

Kilohertz quasi-periodic brightness oscillations (kHz QPOs) have been observed with the Rossi X-ray Timing Explorer (RXTE, Bradt, Swank and Rothschild, 1993) from some 25 neutron star low-mass X-ray binary systems (NS LMXBs). These QPOs are strong (fractional rms amplitudes are often >10% in the 2-60 keV band), sharp (quality factors up to \(Q \equiv \nu/\text{FWHM} \sim 200\)), high frequency (commonly 700–1000 Hz, with the highest claimed detection at 1330 Hz for 4U 0614+091; van Straaten et al. 2000), and substantially variable (QPO frequencies in a given source can change by hundreds of Hertz). They also commonly come in a pair, with the separation between the upper and lower kHz QPO staying close to the spin frequency \(\nu_{\text{spin}}\) or half the spin frequency despite variations in both QPOs (van der Klis 2006).

There is as yet not a complete consensus about the physical processes that generate these QPOs, let alone their high quality factors which pose severe constraints on all existing models (Barret et al. 2005). Suggestions include beat-frequency mechanisms (Miller, Lamb & Psaltis 1998), some manifestation of geodesic frequencies (Stella & Vietri 1999), and resonant interactions (Abramowicz et al. 2003, Abramowicz et al. 2005). There is, however, broad agreement that the upper kHz QPO frequency is close to the orbital frequency at some special radius (or the vertical epicyclic frequency in some resonance models, but this is...
within a few Hertz of the orbital frequency for the relevant stellar spin parameters). By itself, this implies that there must be an upper limit to the QPO frequency. For very hard high-density equations of state or very low-mass stars the limiting frequency could in principle be set by the innermost stable circular orbit (ISCO). If observational signatures of the approach to the ISCO were observed, this would confirm the strong-gravity prediction of unstable orbits, which has no parallel in Newtonian gravity. It would also allow us direct measurement of the mass of the neutron star (see discussion in Miller, Lamb, & Psaltis 1998), hence the search for such signatures is of great importance for fundamental physics and astrophysics.

It was proposed theoretically (Miller, Lamb, & Psaltis 1998, see also Kluzniak, Michelson, & Wagoner 1990) that as the radius that determines the upper kHz QPO frequency approaches the ISCO (and thus as the lower peak approaches the ISCO frequency minus $\nu_{\text{spin}}$ or $\nu_{\text{spin}}/2$), this will lead to (1) asymptoting of the frequency to a limiting value, (2) decrease in the amplitude of the oscillation, and (3) sharp decrease in the quality factor $Q \equiv \nu$/FWHM of the oscillation. Zhang et al. (1998) suggested that the first of these signatures is apparent in the data from 4U 1820–30, but complications in the relation between count rate and frequency (Méndez et al. 1999) have made the interpretation of this result uncertain (see however, e.g. Bloser et al. 2000). More recently, analysis of archival RXTE data from multiple sources has revealed a sharp drop in $Q$ for the lower QPO with increasing frequency, and this drop is qualitatively and quantitatively consistent with what is expected for the approach to the ISCO (Barret, Olive & Miller 2005a,b 2006).

If confirmed, this result is of great fundamental importance. It is thus essential to examine alternate explanations. In particular, as discussed in Barret, Olive, & Miller (2006), there are many factors that collectively determine $Q$ for an oscillation. Theoretical arguments (Miller, Lamb, & Psaltis 1998) as well as recent observational results (Gilfanov & Revnivtsev 2005) suggest that although the high observed amplitudes require that the energy we see in the QPO is liberated at the stellar surface, the frequency and sharpness of the QPO is determined in the accretion disk. In such a picture, in which the frequencies are generated in some special annulus of the disk, $Q$ depends on the width of the annulus, the inward radial drift speed, and the number of cycles a given oscillation lasts. As discussed in Barret, Olive, & Miller (2006), approach to the ISCO can affect the first two of these factors in a way that agrees with the data.

However, it is also possible that other, non-spacetime-related, effects play a role, e.g., plasma processes in the disk, corona, or stellar surface, or interaction with the stellar magnetic field. Without a detailed model of this type one cannot rule definitively for or against such ideas. Generically, though, one expects that such factors in $Q$ will depend fundamentally on the mass accretion rate, whereas the ISCO-related effects depend fundamentally on the spacetime. Therefore, a strong correlation between $Q$ and a proxy for the mass accretion rate would suggest plasma or magnetic field interactions, whereas the lack of such a correlation combined with the observed dependence of $Q$ on frequency would argue in favor of an ISCO interpretation.

Recently, Méndez (2006) compiled data from multiple sources and suggested that it is in fact the spectral hardness (his measure for the mass accretion rate) that is the primary factor in determining $Q$. Here we test this suggestion with RXTE data on 4U 1636–536. In § 2 we discuss our selection of data and processing algorithms. We also present our results, and specifically show that there is no apparent correlation between the quality factor of the lower kHz QPO and the spectral hardness. Therefore, for this source and perhaps others, there is no evidence that the accretion rate is the primary determinant of $Q$. We discuss the implications in § 3.

2 DATA ANALYSIS AND RESULTS

We used the data presented in Barret, Olive & Miller (2005a,b, 2006). The same analysis scheme applies for the data selection. We consider all data recorded up to September 2004. All PCA Science Event files were retrieved from the HEASARC archive. A file represents a temporally contiguous collection of data from a single pointing. 571 files are considered here. They have been filtered for X-ray bursts and data gaps. Leaky normalized Fourier power density spectra were computed between 1 and 2048 Hz, over 8 second intervals with a 1 Hz resolution.

In parallel, we have analyzed the PCA Standard 2 data (a collection of 129-channel spectra accumulated every 16 seconds), following standard recipes, using REX 0.4.1. We filtered the data using standard criteria: Earth elevation angle greater than 10 degrees, pointing offset less than 0.02 degrees, time since the peak of the last SAA passage greater than 30 minutes, electron contamination less than 0.1. The background of the PCA has been estimated using pbackest 3.0, and the latest bright background model as recommended for sources brighter than 40 counts/s/PCU. To avoid any possible discontinuity near the loss of its propane layer (in May 2000), we exclude PCU 0 in our analysis. PCU units 2 and 3 provide a good overlap between the Standard 2 and Science Event data (they both provide twice as much data as PCU unit 1 for instance). For each ObsID, for the 2 PCU units, considering only the the top layer (layer 1), we have first generated a response matrix using the latest version of pcarsp 10.1. For comparison with previous works, we intend to compute the colors from data recorded in 4 adjacent energy bands: 3.0–4.5 keV, 4.5–6.4 keV, 6.4–9.7 keV, 9.7–16 keV. For each ObsID, we read out from the response matrix the relative channel values corresponding to these energy boundaries, and we use the FTOOLS chantrans to convert the latter into their absolute channel values, as needed for saxextract, called by REX. Since the energy boundaries are not exactly equal to the above exact values defined above and change in time with the detector gains, a correction must applied. Following Barret & Olive (2002), for each ObsID, we have extracted for each PCU unit a PHA count spectrum. By fitting the count spectrum with a polynomial function, one can compute the exact number of counts within the exact energy bounds. This gives us an average correction factor, which corresponds to the difference

1 http://heasarc.gsfc.nasa.gov/docs/xte/recipes/rex.html
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Figure 1. The Leahy normalized Power Density Spectrum averaged over the Science Event file is shown at the top. In the middle panel, a dynamical PDS is shown. The image has been smoothed to make the QPO appear more clearly. The bottom two panels represent the simultaneous evolution of the soft and hard colors (HR1 and HR2, respectively) as computed from Standard 2 data. The non complete overlap between the two data sets is because the Standard 2 data (only PCU 3 data are considered) are filtered with more stringent criteria than the Science Event data. Note that while the QPO frequency varies from 730 Hz to 850 Hz, there are no apparent changes in both the soft and hard colors.

between the counts extracted with saextract and the corresponding counts in the exact energy bands. Finally, another smaller correction is applied to account for the fact that when the energy boundaries move, the corresponding effective areas also change. The light curves in the four energy bands are normalized to the same effective area, which is, for each ObsID, estimated directly from the response matrix generated for each PCU. After these two corrections, the light curves become all comparable. These corrections are especially important because the observations span from 1996 to 2004.

We have computed two spectral colors: the soft color (HR1) defined as the ratio between the 4.5 and 6.4 keV counts and 3.0 and 4.5 keV counts, and the hard color (HR2) as the ratio between the 9.7 and 16.0 keV counts and 6.4 and 9.7 keV counts. For a given Science Event file, the end-product of our analysis at this first stage can be summarized in Figure 1 where the averaged PDS over the file is shown, together with the dynamical power density spectrum and the soft and hard colors as derived from the Standard 2 data.

2.1 Quality factor and spectral colors against frequency in 4U 1636–536

For the sake of clarity, our analysis here is focussed on the lower kilo-Hz QPO, for which we have argued that the drop of coherence at some critical frequency may be related to an approach of the ISCO of the region from which the oscillation originates. We wish to study the dependency of the quality factor versus the soft and hard colors. One would expect that if the drop is indeed related to a spacetime effect, it is not primarily dependent on the energy spectrum. This idea can be tested with spectral colors, which allow us to search for subtle spectral variations.

In order to estimate the quality factor of the QPOs, one must first correct for the frequency drifts. Here we use a sliding window based technique. Namely, we group as many consecutive 8 second PDS (N ≤ 64) as needed to detect a QPO with a significance above a threshold of 3σ. The maximum integration time is then 64 × 8 = 512 seconds. In case of no detection within such an interval starting at T0, a new search starts at T0 + 32 sec. The QPO frequency in each 8 second PDS is then estimated using a linear interpolation between all detected QPO frequencies within a continuous segment. We identify those files containing a lower kilo-Hz QPO in the quality factor-frequency plane (see Barret et al. 2005a for details). We keep those files in which the quality factor recovered after correction for the frequency drift is larger than 30, corresponding to a mean QPO frequency larger than 650 and smaller than 950 Hz. We then divide the data into segments of 1024 seconds, and shift-and-add all 8 second PDS within each segments to a reference frequency which is set to the mean QPO frequency assigned after inter-
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Figure 3. The color-color diagram of all the archival RXTE data analyzed for 4U 1636–536. The color is averaged over segments of 1024 second duration (red filled circles). Bursts and gaps have been filtered out. In blue, the colors corresponding to the QPO detections is shown. Only data from PCU 3 are shown, but the same results is obtained with PCU 2 data.

Figure 4. The variation of the quality factor and hard color with frequency, grouping the data of Figure 2 with a frequency bin of 20 Hz. The hard color is consistent with remaining constant over the frequency range sampled by our analysis (a fit yields $\chi^2$ of 15.2 for 14 d.o.f.).

Figure 5. Quality factor versus hard color for 4U 1636–536 using grouped data of Figure 2. The 1σ error on the mean hard color is represented by the hashed region.

Interpolation to the 8 second PDS over the continuous segment. Some segments are not complete and we have removed all those in which the total number of 8 second PDS shifted is less than 64 (i.e. 512 seconds). Within each segment, when there is an overlap of at least 50% with the Standard 2 data, we compute the corresponding colors HR1 and HR2. In Figure 2, we plot the resulting quality factor and spectral colors. No dramatic changes in either the soft and hard colors is observed when the quality factor of the lower kilo-Hz QPO shows a clear drop. In particular, over the frequency range spanned by the lower kilo-Hz QPO, the hard color is consistent with being constant (a fit by a straight line yields a $\chi^2$ of 295 and 230 for 260 and 256 degrees of freedom (d.o.f.) for PCU 2 and PCU 3 data). Over a narrower frequency range (780-930 Hz), Di Salvo et al. (2004) obtained very similar results. There is a negative smooth anticorrelation between soft color and lower QPO frequency, but nothing notable around the frequency where the quality factor of the QPO drops off, around 850 Hz.

In Figure 3, we show the color-color diagram for all the data considered and overlay the region over which the lower QPO was studied with the present technique. The lower QPO is detected only over a very delimited region of the color-color diagram, even though that it samples a relatively wide range of frequency and quality factor. This by itself shows that even if subtle correlations are masked by the statistics (but see Fig. 4), the drop of the quality factor is not associated with a dramatic spectral change in this source. It is interesting to note that with the procedure described in this paper, lower kilo-Hz QPOs are detected at the intersection between the bottom and diagonal branches of the color-color diagram. The count rate varies from 130 counts/s to 340 counts/s in PCU 3.

Next, we have grouped the data of Figure 2 using weighted averages (and the 1σ errors) in the frequency space, with a bin of 20 Hz to get sufficient statistics and still enough points to keep a good description of the overall behavior of the quality fact and hard color with frequency. The results are shown in Figure 4. The size of the error bars on hard colors has been decreased on average by a factor of 2.7 compared to the data of Figure 2; the mean error on the hard color is reduced to 0.0016. A fit with a constant yields a $\chi^2$ of 15.2 for 14 d.o.f. for PCU 2 data (15.5 for 13 d.o.f for PCU 3 data).

In Figure 5, we plot the quality factor against the logarithm of the hard color to enable a comparison with the data presented for 4U 1608–522 in Mendez (2006).
2.2 Comparison with 4U 1608–522

Using the same technique as described above, we have reproduced the data of 4U 1608–522 presented in Barret, Olive & Miller (2006) focusing on the lower kilo-Hz QPOs. This enables a direct comparison of two homogenous data sets obtained through the same processing scheme. The data set used includes data presented in Mendez et al. (1999), as well as observations performed in September 2002, March 2003 and 2004 (proposal numbers 70059, 80406, 90408). As for 4U 1636–536, we identify segments containing a lower kilo-Hz QPO in the quality-factor-frequency plane. For 4U 1608–522, as shown in Barret, Olive & Miller (2006), the lower QPO so identified spans a frequency range going from \( \sim 570 \) to \( \sim 900 \) Hz. PCU 2 provides the best overlap between the Science Event and the standard 2 data for this source. In Fig. we show the quality factor, soft and hard colors against frequency. Due to the larger count rate of 4U 1608–522 (varying from 150 counts/s up to 480 counts/s in PCU 2), in order to get similar errors on the hard color as the one of 4U 1636–536, one can use shorter integration time for estimating the QPO parameters. We have used \( 8 \times 96 = 768 \) seconds for 4U 1608–522, instead of 1024 seconds for 4U 1636–536. For 4U 1608–522, the hard color is clearly not consistent with being constant: a fit by a constant yields a \( \chi^2 \) of 371 for 103 d.o.f. Negative and positive correlations between hard color and frequency are observed (the same behavior is seen in other PCA units).

We then grouped the data shown on Fig. also with a bin of 20 Hz to produce Fig. and . The mean error on hard colors for 4U 1608–522 is reduced to 0.0020, i.e. slightly larger than those of Fig. Fitting the hard color with a constant results in a \( \chi^2 \) of 263 for 16 d.o.f. Restricting the frequency range to above 650 Hz (the minimum frequency in 4U 1636–536), yields a \( \chi^2 \) of 147 for 13 d.o.f. Since we are interested in the region where \( Q \) reaches its maximum before dropping off, one can consider only those points from, say, 100 Hz before the peak (around 840 Hz) up to the last point, at \( \sim 930 \) Hz in 4U 1636–536 and \( \sim 900 \) Hz in 4U 1608–522, respectively. We obtain a \( \chi^2 \) of 9 for 8 d.o.f. and 95 for 7 d.o.f. for 4U 1636–536 and 4U 1608–522. Clearly for the latter, the hard color is not consistent with being constant over the frequency range spanned by the lower QPO, including the interesting part which encompasses the Q drop-off. We have verified that the same conclusion is reached, independently of the integration time used to estimate the QPO parameters. For instance, using 64 seconds for 4U 1608–522 as in Mendez et al. (1999), the mean error on the hard color after binning is 0.0025 (20% larger than with 768 seconds), and the \( \chi^2 \) is 164 for 15 d.o.f. Looking at Fig. it is worth noting that the relationship between the hard color and frequency is revealed to be more complex than, and certainly not as smooth as, previously thought, based on measurements obtained with lower statistics (e.g. Mendez et al. (1999)).

Comparing Fig. and Fig. requires some comments. First, given that the size of the error bars are fully comparable, it shows that if a similar trend as seen for 4U 1608–522 were to be present in 4U 1636–536, we would have observed it. Second, we note that in 4U 1608–522, significant variations of the hard color (still limited at the \( \sim 5 \% \) level) are observed around the peak of the quality factor-frequency curve. These variations may reflect some changes in the source behavior (e.g. accretion rate, Mendez 2006), but Fig. shows that the effect produced is by no means universal, as we failed to detect it in a similar way in 4U 1636–536. It could be that the drop of the quality factor and change in hard color are simply concomitant in 4U 1608–522.

From this comparison, one can therefore conclude that if we are to search for a common explanation for the sharp drop in the quality factor seen in both sources, the hard color is not a good candidate for the independent variable whereas the frequency remains.

3 DISCUSSION

The results presented in this paper demonstrate that the drop of the quality factor of the lower kilo-Hz QPO in 4U 1636–536 is not accompanied by a significant change in the energy spectrum of the source, as measured by the spectral colors. Therefore, in this source, if the quality factor depends fundamentally on mass accretion rate, it must somehow do so in a way that leaves no detectable correlation between quality factor and either spectral measures or countrate (see Barret, Olive, & Miller 2005a,b, 2006). This seems difficult and contrived. In contrast, the strong correlation of \( Q \) with frequency in the lower peak is as expected if it is largely driven by approach to the ISCO. Together with the observed steady drop in rms amplitude, saturation of the QPO frequency with increasing count rate, and the quantitative consistency of ISCO models with the \( Q \) versus frequency curve (Barret, Olive, & Miller 2005a,b, 2006), 4U 1636–536 behaves as expected if the phenomenology is...
linked to the spacetime and not to the mass accretion rate. Other sources need to be analyzed similarly, but the ISCO hypothesis and its attendant implications for strong gravity are still entirely viable.

What, then, could be the explanation for the results of Méndez (2006), in which he found a correlation between hardness (or average luminosity) and maximum reported $Q$ over sources spanning a range of two orders of magnitude in luminosity? The left panel of his Figure 3 shows that the maximum reported quality factor is low for the lowest-luminosity source (4U 0614+091, at $L/L_{\text{Edd}} \approx 6 \times 10^{-3}$ and $Q_{\text{max}} \sim 30$ [Barret, Olive, & Miller 2006 obtained $Q_{\text{max}} \sim 50$ for this source]), high ($Q_{\text{max}} \approx 100 - 200$) for sources with $L/L_{\text{Edd}} \sim 0.02 - 0.2$, and low ($Q_{\text{max}} \sim 10 - 20$) for sources with $L \sim L_{\text{Edd}}$. A similar pattern, although less monotonic, is shown in his Figure 4, of $Q$ versus hard color. Because this pattern with luminosity or hard color is similar to the behavior in individual sources with frequency ($Q$ is low at low frequency, rises to a peak, then drops sharply), Méndez concludes that it is unlikely that the ISCO plays a role in any of these systems.

We believe that there is another interpretation. At the low luminosity end of Méndez’s correlation there is a single key source: 4U 0614+091. Figure 1 of Barret, Olive, & Miller (2006) shows that there is no apparent drop in the quality factor of the lower QPO up to $\sim 700$ Hz. On the other hand, lower QPOs at frequencies above $700$ Hz have been reported with low $Q$ values (van Straaten et al. 2000), yet without correction for the frequency drift. The status of 4U 0614+091 is thus different than the status of sources such as 4U 1636–536 for which, thanks to the necessary frequency drift correction applied, a clear maximum has been observed. This is an issue because if the 1330 Hz detection of the upper QPO is real, one would not expect, for any plausible spin frequency of the neutron star, that the frequency at which $Q$ starts decreasing to be $\sim 700$ Hz or so. A careful re-examination of the 4U 0614+091 data is thus underway.

At the high luminosity end, the sources all have very high luminosity indeed, comparable to Eddington. Standard disk accretion theory (e.g., Shakura & Sunyaev 1973) then suggests that the disk thickness will be comparable to the orbital radius, and that as a consequence the inward radial drift speed (which scales as $(h/r)^2$, where $h$ is the disk half-thickness) will be large as well. As discussed in Barret, Olive, & Miller (2006), a large inward speed will necessarily decrease $Q$ regardless of other factors. We note that this effect can also be important in reducing the maximum $Q$ from $\sim 200$ to $\sim 100$ around a luminosity $L \sim 0.1 - 0.2 L_{\text{Edd}}$, as seen by Méndez (2006). It is therefore not surprising that high luminosity sources have low $Q$, but it is also not relevant to the evaluation of the behavior of $Q$ with frequency in much lower luminosity sources.

As a final remark, as we have discussed previously (e.g. Barret, Olive, & Miller 2005a,b, 2006), if the ISCO interpretation is correct for our data, then one can infer a mass of the order of 2 $M_\odot$ for the neutron star. This is consistent with phase-resolved spectroscopy of 4U 1636–536 at the VLT by Casares et al. (2006), who assume plausible binary parameters (inclination, disk flaring angle, mass of the donor star) and infer a mass 1.6 – 1.9 $M_\odot$ for the neutron star. In addition, a variety of modern models for neutron star matter, involving hyperons, quarks or normal matter, predict maximum neutron star masses as large as $\sim 2 M_\odot$ (Jha et al. 2006, Klahn et al. 2006). Our results thus add to the growing evidence for heavy neutron stars in accreting systems.

4 CONCLUSIONS

The case for the ISCO is still promising. Analysis of the type that we perform in this paper will be needed for other sources, to determine the strength of evidence in those cases. In addition, focused observations or re-analysis of specific objects will be useful, starting with 4U 0614+091.
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REFERENCES

Abramowicz M. A., Karas V., Kluźniak W., Lee W. H., Rebusco P., 2003, PASJ, 55, 467
Abramowicz, M. A., Barret, D., Bursa, M., Horák, J., Kluźniak, W., Rebusco, P., Torökö, G. 2005, Astronomische Nachrichten, 326, 864
Barret, D., & Olive, J.-F. 2002, ApJ, 576, 391
Barret, D., Kluźniak, W., Olive, J. F., Paltani, S., & Skinner, G. K. 2005, MNRAS, 357, 1288
Barret, D., Olive, J.-F., & Miller, M. C. 2005a, MNRAS, 361, 855
Barret, D., Olive, J.-F., & Miller, M. C. 2005b, Astronomische Nachrichten, 326, 808
Barret, D., Olive, J.-F., & Miller, M. C. 2006, MNRAS, 370, 1140
Boirin L., Barret D., Olive J. F., Bloser P. F., Grindlay J. E., 2000, A&A, 361, 121
Bloser P. F., Grindlay J. E., Kaaret P., Zhang W., Smale A. P., Barret D., 2000, ApJ, 542, 1000
Bradt H. V., Rothschild R. E., Swank J. H., 1993, A&A, 97, 355
Casares, J., Cornelisse, R., Steeghs, D., Charles, P. A., Hynes, R. I., O’Brien, K., & Strohmayer, T. E. 2006, MNRAS, in press (ArXiv Astrophysics e-prints, [arXiv:astro-ph/0610086])
Di Salvo, T., Méndez, M., & van der Klis, M. 2003, A&A, 406, 177
Gilfanov, M., & Revnivtsev, M. 2005, Astronomische Nachrichten, 326, 812
Jha, T. K., Raina, P. K., Panda, P. K., & Patra, S. K. 2006, ArXiv Nuclear Theory e-prints, [arXiv:nucl-th/0608013]
Klähn, T., et al. 2006, Phys. Rev, 74, 035802
van der Klis, M. 2006, Compact stellar X-ray sources. Edited by Walter Lewin & Michiel van der Klis. Cambridge Astrophysics Series, No. 39. Cambridge, UK: Cambridge University Press, p. 39 - 112, 39 (astro-ph/0410551)
Kluźniak W., Michelson P., Wagoner R. V., 1990, ApJ, 358, 538
Méndez M., van der Klis M., Ford E. C., Wijnands R., van Paradijs J., 1999, ApJ, 511, L49
Méndez, M. 2006, MNRAS, 371, 1925
Miller M. C., Lamb F. K., Psaltis D. 1998, ApJ, 508, 791
Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337
van Straaten, S., Ford, E. C., van der Klis, M., Méndez, M., & Kaaret, P. 2000, ApJ, 540, 1049

Zhang W., Smale A. P., Strohmayer T. E., Swank J. H., 1998, ApJ, 500, L171