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Discovery of GRS 1915+105 variability patterns in the Rapid Burster

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ABSTRACT

We report the discovery of two new types of variability in the neutron star low-mass X-ray binary MXB 1730-335 (the ’Rapid Burster’). In one observation in 1999, it exhibits a large-amplitude quasi-periodic oscillation with a period of about 7 min. In another observation in 2008, it exhibits two 4-min long 75 per cent deep dips 44 min apart. These two kinds of variability are very similar to the so-called ρ or ’heartbeat’ variability and the θ variability, respectively, seen in the black hole low-mass X-ray binaries GRS 1915+105 and IGR J17091-3624. This shows that these types of behavior are unrelated to a black hole nature of the accretor. Our findings also show that these kinds of behaviour need not take place at near-Eddington accretion rates. We speculate that they may rather be related to the presence of a relatively wide orbit with an orbital period in excess of a few days and about the relation between these instabilities and the type II bursts.

Key words: stars: neutron – X-rays: binaries – X-rays: bursts – X-rays: individual: MXB 1730-335 – X-rays: individual: GRS 1915+105X-rays: individual: IGR J17091-3624

1 INTRODUCTION

The Rapid Burster (RB, or MXB 1730-335) was discovered by Lewin et al. (1976) as a source of few-seconds long X-ray bursts with recurrence times as small as 6 s, much faster than similar bursts in other sources with recurrence times of an hour or longer. The RB itself was later resolved to exhibit both kinds of X-ray bursts which were from then on called (slow) thermonuclear type I and (rapid) accretion-powered type II X-ray bursts (Hoffman et al. 1978). Up to this date, this dual character of the RB remains unique. The RB is located in the globular cluster Liller 1, which yields an independent distance estimate of 7.9±0.9 kpc (Valenti et al. 2010).

Type I X-ray bursts have so far been seen from about 100 low-mass X-ray binaries in our galaxy. The accretor is a neutron star (NS), on which H and/or He is piled up from the atmosphere of the Roche-lobe overflowing companion star. After a certain time, typically a few hours, ignition conditions are reached at the bottom of the pile and a thermonuclear runaway burns the hydrogen and helium within a fraction of a second. Subsequently, the photosphere heats up to a few tens of MK and cools off, giving rise to a softening X-ray burst of duration ∼1 min (see reviews by Lewin, van Paradijs & Taam 1993 and Strohmayer & Bildsten 2006).

Type II bursts have so far only been identified in two low-mass X-ray binaries: the RB and the Bursting Pulsar (BP). The BP (Kouveliotou et al. 1996) is a transient accretion-powered X-ray pulsar with a period of 0.467 s and a magnetic dipole field strength of a few times 10^{10} G, and a probably low-mass giant companion star in a 11.8 d orbit (Finger et al. 1996; Degenaar et al. 2014).

The RB is less well defined than the BP. Neither the NS spin frequency nor the dipolar magnetic field are known because of the lack of X-ray pulsations. This could either be due to a magnetic field smaller than in the BP (indeed the majority of bursters do not show persistent pulsations), or because of a close alignment of either the observer’s line of sight or the magnetic dipolar component with the rotation axis. The orbital period is also not known. The RB is a transient that goes into outbursts every 100–200 days. The accretion rate increases to quite high values, close to the Eddington limit (Bagnoli et al. 2013), which is rare among LMXBs.

The RB was abundantly observed with the Proportional Counter Array (PCA) on the *Rossi X-ray Timing Explorer* (*RXTE*). A total exposure time of 2.4 Ms was obtained in 17 years of observations, and the RB was active during 1.4 Ms of these (Bagnoli et al. 2015). The large exposure time and large sensitivity of the PCA provide excellent opportunity to detect rare behavior in the RB. In this letter we present the detection of two kinds of peculiar behaviour of the RB, and speculate on their implications.

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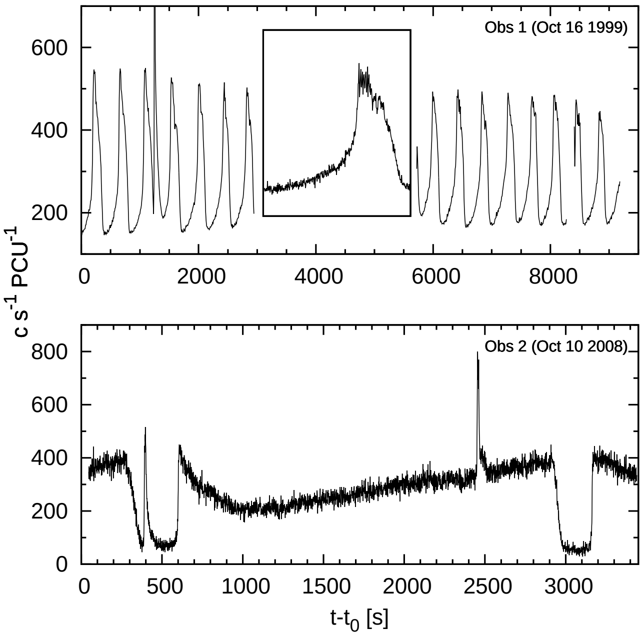

Figure 1. Light curves of the two observations from the full bandpass at 1 s resolution. The intensity was corrected for the background and collimator response to the RB, and for the contamination by 4U 1728-34 during the first part of the first observation (see Fig. 2). The inset in the top panel covers a data gap and shows a complete cycle (450 s) of the instability.

2 OBSERVATIONS

The PCA consists of five proportional counter units (PCUs), each with a photon-collecting area of 1600 cm^2 (Jahoda et al. 2006), between 2–60 keV with a spectral resolution of 20 per cent full-width at half maximum (FWHM) at 6 keV. The two observations that are presented here date to Oct. 16, 1999 (ObsID 40433-01-04-00R and -01R, exposure time 2.8 and 3.4 ks with a data gap of 3.8 ks) and Oct. 10, 2008 (ObsID 92026-01-20-02, exposure time 3.2 ks) The RB was on-axis during the first observation except for the last 0.8 ks when the nearby bright 4U 1728-34 was slewed out of the field of view, thereby putting the RB at an off-axis angle of 0.56 deg and avoiding contaminating signal from 4U 1728-34. The pointing of the second observation was identical to the last 0.8 ks of the first observation, excluding the signal from 4U 1728-34.

Figure 1 (upper panel) shows the light curve of the first observation. A strong quasi-periodic oscillation (QPO) is apparent with a period varying from ~ 350 to ~ 450 s and a peak-to-peak amplitude of roughly 70 per cent (from ≈ 600 to ≈ 200 c s^{-1}PCU^{-1}). We observed 15 such flares. The last two flares occurred during a pointing uncontaminated by 4U 1728-34. This behavior has not been seen from the RB in any other *RXTE* observation or in any other published observation. Near the 1300 s mark, a burst takes place, lasting about 100 s and significantly sub-Eddington. The characteristics of this burst are consistent with being of type I: it shows a decreasing spectral hardness and lacks ringing during the decay so typical of type II bursts of this duration (Bagnoli et al. 2015). The type-I burst is identified to originate from the RB, because its peak flux, duration and lack of photospheric expansion are consistent with other bursts from the RB and inconsistent with all other bursts from 4U 1728-34 (for more details on the burst identification, see Bagnoli et al. 2013). The light curve of the second observation is plotted in Fig. 1 (lower panel). It shows a gradual change in intensity with two dips by about 75 per cent in intensity lasting 260 and 220 s, respectively (from halfway ingress to halfway egress). The ingresses are about 100 and 80 s long, while the egresses last a shorter 40 and 20 s. The persistent emission outside dips peaks at about 400 c s^{-1}PCU^{-1}right after the first dip, falls to 200 c s^{-1}PCU^{-1}in 400 s, and then peaks again at the roughly the same maximum value right before the second one. The entire cycle (ingress, dip, egress, maximum, decreasing and increasing back to maximum) lasts about 2650 s. The second dip is on average about 50 c s^{-1}PCU^{-1}. Judging from the portions of the lightcurve before the first dip and after the second, the behaviour seems to be roughly cyclical. Also, there are two bursts, one of them in a dip. These are also of type I, following the above-mentioned arguments. They must be from the RB because 4U 1728-34 was outside the field of view. Both have a net peak flux of 460 c s^{-1}PCU^{-1}, calculated with respect to the persistent emission flux right before. The type I burst recurrence time is 2.1 ks.

3 DATA ANALYSIS

In Fig. 2, the intensity versus hardness ratio diagram is drawn for both observations. It shows that, in the first observation, the rises and falls of the oscillations follow the same track, without hysteresis.

In general, the spectrum of the RB (including type II bursts, but excluding type I bursts) is satisfactorily modelled by a Comptonized spectrum (Bagnoli et al. 2015). Therefore, we applied this model to the two observations. We only included data for which 4U 1728-34 was outside of the field of view. This pertains to the last 0.8 ks of the first observation and the complete second observation. The results are presented graphically in Fig. 3. Indeed, the model is satisfactory. There is mild spectral variability, with the spectral hardness anti-correlating with the flux. There is no evidence for increased absorption during the dips. The flux change is mostly due to a change in the normalization, which represents projected emission region size. The bolometric flux for the applied model is $(2-5)\times10^{-9}$ erg cm^{-2} s^{-1} during the first observation, and $(1-6)\times10^{-9}$ erg cm^{-2} s^{-1} during the second. Under the same assumptions as in Bagnoli et al. (2015) this corresponds to 7 – 18 and 3.5 – 21 per cent of the Eddington luminosity, respectively.

Contiguous *RXTE* observations span 15 to 3 days before the Oct. 16, 1999 observation and 3 to 12 days after it, and 5 to 2 days before and then again 6 days after the Oct. 10, 2008 observation. In both cases, the source was clearly in the high/soft state in the prior observations, only emitting type I bursts (for the general spectral and outburst behaviour of the source, see Bagnoli et al. 2015), while, afterwards, it had switched to the low/hard state, showing a fainter persistent emission (by a factor of ≈5) and both type I and II bursts. Both types of behaviour are, therefore, coincident with the transitional state of the source, like the ≈ 10 s dips in some type I bursts in the same state (Bagnoli et al. 2014). Prior to the second observation, six long (∼60 s) type I bursts were visible, with a measured recurrence time of 2.2 ks. The observed $t_{\rm rec}$, which we have shown to be a tight function of the accretion rate in the RB (Bagnoli et al. 2013) is compatible with this transitional-state identification.

The type I burst and the flaring activity in the first observation do not seem to affect one another. Likewise, the two type I bursts in the second observation show nearly identical peak fluxes and durations, despite taking place during the dip and well outside it, respectively. The oscillations and the dips are therefore unaffected by thermonuclear burning taking place on the surface, and viceversa.

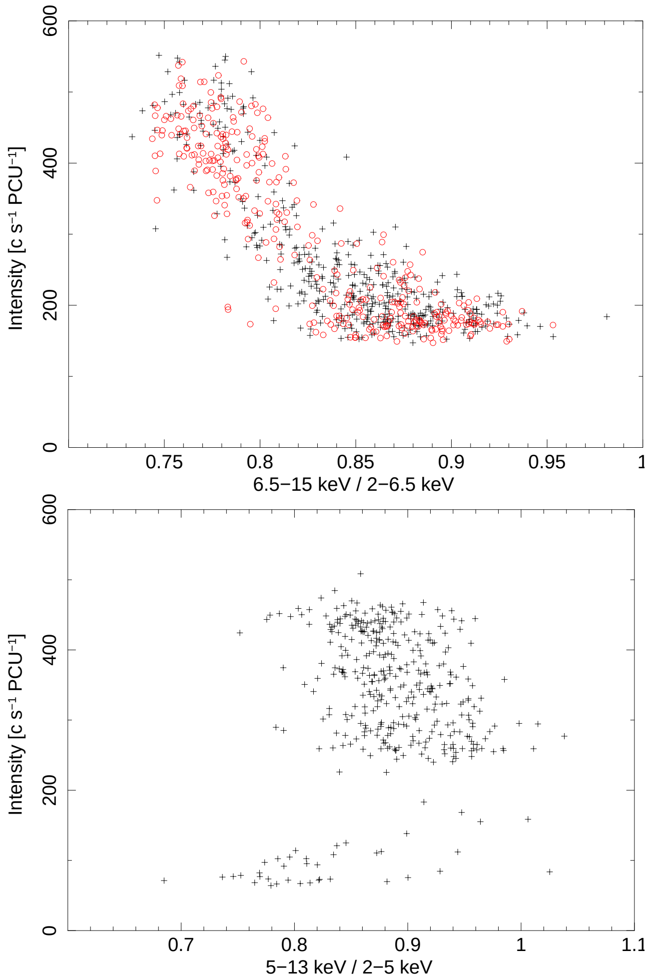

Figure 2. Top panel: color-intensity diagram of the first observation at 8-s resolution. Intensity and color were corrected for the background, a (changing) collimator response and the contribution by 4U 1728-34, assuming that the amplitudes of the last four flares are constant. The (black) crosses and (red) circles refer to the rising and decaying portions of the flares. The color is the same as employed in Altamirano et al. (2011). Bottom panel: color-intensity diagram for the second observation. The same corrections were applied as for the top panel, except for contamination by 4U 1728-34 because that source was outside the field of view for the complete observation. The color is the same as employed in Belloni et al. (2000). We note the trends are identical for the color employed in the top panel.

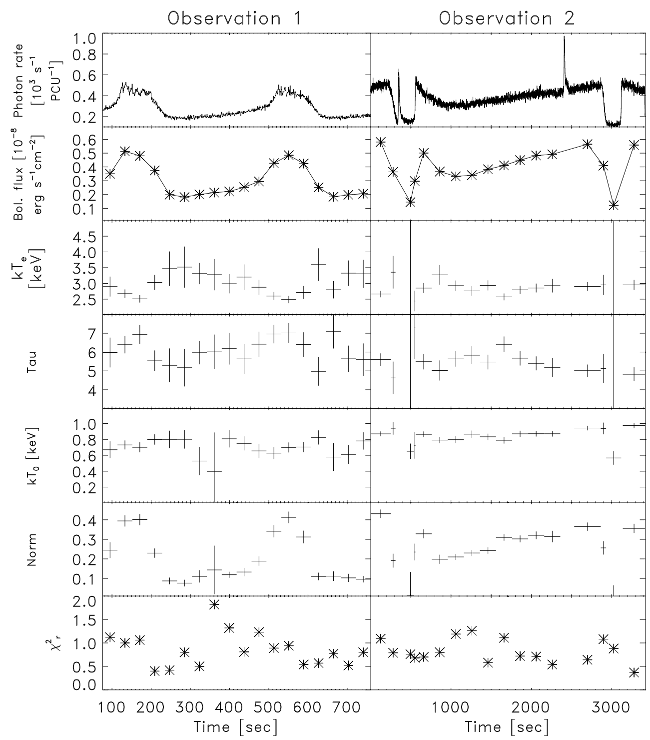

Figure 3. Spectral analysis of the two observations, employing a Comptonization model. For the first observation, only the uncontaminated portion of the data was employed. The entire second observation is unaffected by contamination. The type I bursts were ignored.

4 DISCUSSION

We have discovered two new kinds of behaviour that have never been seen before from the RB, and add to the complexity of this peculiar source. Light curves similar to the ones analyzed here have only been seen in two other LMXBs, GRS 1915+105 and IGR J17091-3624. Both are thought to harbour black holes (BHs), although only the former has a dynamical mass measurement (most recently refined to $12.4^{+2.0}_{-1.8}$ $M_{\odot}$, Reid et al. 2014).

GRS 1915+105 has the largest orbit among LMXBs (orbital period 33.5 days, Greiner et al. 2001), has been active for 20 years (Castro-Tirado et al. 1994) and shows super-Eddington fluxes and superluminal jets with a distance of $\approx$ 12.5 kpc (Mirabel & Rodríguez 1994). It exhibits at least twelve classes of variability (Belloni et al. 2000). In general, the extraordinary behavior is attributed to intermittent ejections from the disk (Klein-Wolt et al. 2002; Fender & Belloni 2004). IGR J17091-3624 is less well characterized. Orbital period, distance and BH mass are unknown.

The first RB observation highly resembles the ρ ('heartbeat') variability state of GRS 1915+105 (Belloni et al. 2000) and IGR J17091-3624 (Altamirano et al. 2011). In all three sources, the heartbeats are asymmetric, decaying faster than they rise. The ρ behavior is the slowest in the RB, with timescales of $\approx 2-100$ s in IGR J17091-3624, and $\approx 40-120$ s for GRS 1915+105 (Neilsen et al. 2011). The relative scatter in the timescale of the RB is similar to that seen in GRS 1915+105, where the period can vary by more than 20 per cent between consecutive flares (Neilsen et al. 2011). Variability near the maxima of the modulation is visible in the RB observation and has also been noticed in GRS 1915+105 (Belloni et al. 2000). The fractional amplitudes are similar, 60–75 per cent.

The largest difference in behaviour is that in GRS 1915+105 the peak flux of the modulation is 80–90 per cent of the Eddington limit (Neilsen et al. 2011). In the RB, this is only 18 per cent. The uncertainty on the luminosity in terms of the Eddington limit (see Bagnoli et al. 2015) cannot bring the two results in agreement. The spectra behave partially similarly. The pattern of the RB in the hardness-intensity diagram (HID, Fig. 2) partly follows the one in GRS 1915+105 when the latter is below about 6000 c/s/PCU (Altamirano et al. 2011), with hard low-flux intervals and soft high-flux ones. However, the highest luminosity points reached by GRS 1915+105 are the hardest, and create a circular hysteresis pattern in the HID that is not seen in the RB. Note that IGR J17091-3624 also shows a hysteresis pattern, although in an opposite sense to GRS 1915+105.

The intrinsic luminosity of IGR J17091-3624 is not known, due to the lack of a distance measurement. Assuming the source emitted at the Eddington limit like GRS 1915+105, this would imply either a distance in excess of 20 kpc, with a galactic latitude suspiciously high above the disk, or an extremely low mass BH ($< 3M_\odot$, Altamirano et al. 2011; Rao & Vadawale 2012). However, hydro-dynamical simulations by Janiuk et al. (2014) found that a thermal-viscous instability led by radiation-pressure domination in the innermost region of disc can occur for luminosities as small as 10 per cent of the Eddington limit, and can reproduce the time scales and amplitudes of the heartbeat light curves. The disc is stable at smaller luminosities, while larger ones produce, in regions of the disc further out, a wind so strong it effectively depletes the inner disc, killing off the instability. Their hypothesis is supported by the detection of strong absorption lines (due to outflows) in the spectrum of IGR J17091-3624, which become undetectable when the luminosity decreases and the instability becomes visible (King et al. 2012). A sub-Eddington luminosity would bring IGR J17091-3624 better into agreement with the radio/X-ray correlation for BH (Rodriguez et al. 2011). Clearly, the appearance of the ρ class in the RB at roughly the same fraction of the Eddington limit supports this scenario.

A possible explanation for the lack of hysteresis in the RB as shown by the BH accretors during the ρ variability could be related to the presence of an additional emission component from the solid surface and/or boundary layer of the former. As shown by Done & Gierliński (2003), NS and BH accretors clearly show different spectral evolutions as a function of luminosity in their bright states, which is due to the presence of a surface in the case of NSs.

In all three sources, the flares in the heartbeat are asymmetric: they decay sharply, to then rise more gradually. This is true for all hard phases in GRS 1915+105 which Belloni et al. (1997a,b) interpreted as the result of a viscous-thermal instability in the accretion disk, with the rise time determined by the speed at which a heating wave moves through the disc, and the faster decay time corresponding to the infall of matter into the BH.

The second observation highly resembles the θ-class variability of GRS 1915+105 (not seen in IGR J17091-3624). This class also presents "M"-shaped light curves separated by 100-200 s long minima. The luminosities are again lower in the RB than in GRS 1915+105 where this variability reaches the Eddington limit (Belloni et al. 2000). The spectral behaviour of the RB is similar to that observed in GRS 1915+105, in which the "M" portions are harder, while the dips are slightly softer. The separation is however not as clear as in GRS 1915+105.

A particularly interesting feature of the θ variability in the RB is the occurrence of an unaffected type I burst during the dip. The burst reveals that the NS emission must be unaffected. Still, the accretion disk flux drops by 75 per cent within a matter of 60 s. This points either to a cylindrically asymmetric disk which is obscured from below or above our line of sight to the NS or to a global change of the emissivity of the disk, for instance by a loss of mass. The latter would be consistent with the ideas about GRS 1915+105.

Just as there are similarities between the RB and GRS 1915+105, there are similarities between the RB the BP: like the RB, the BP shows type II bursts. GRS 1915+105 and the BP are physically better characterized than the RB and it is tempting to search for commonalities and attribute those to the RB as well. Both sources have relativily long orbital periods of 33.5 and 11.8 d, respectively. IGR J17091-3624 may also have a large orbital period (Wijnands et al. 2012; Ghosh & Chakrabarti 2014). A long orbital period points to a relatively large accretion disk, which naturally explains the large accretion rates. It may be smaller for the RB, because its transient outbursts last shorter and recur more frequently, but still longer with respect to the average LMXB. Wu et al. (2010) have shown that a single relation exists between the maximum outburst luminosity as a fraction of Eddington and the orbital period for NS and BH LMXBs. Substituting the maximum observed persistent luminosity $F_{\rm peak} = 0.45 F_{\rm Edd}$ (Bagnoli et al. 2013) yields indeed a relatively large $P_{\rm orb} = 7.8$ days for the RB.

It is striking that similar behaviour is present between the RB, a NS system, and the two BH systems, even more because they are all peculiar sources among their own classes. Also, both the observations analyzed here take place at the transition between a type-II-burst-free state and an active type II bursting phase, which suggests that type II bursts and these variabilities might be connected. With respect to this, we note that apart from variability classes θ and ρ, GRS 1915+105 shows light curves (particularly those of variability classes μ and λ, see Belloni et al. 2000) that resemble the type II burst behavior in the RB.

However, there are important differences. The type II bursts are well known to show very little hardness variations (see e.g., Appendix B in Bagnoli et al. 2015), whereas the intensity variations during variability in GRS 1915+105 always correspond to spectral transitions. Also, while the type II burst rise times are always shorter than the decay time (which is why they can be mistaken for type I bursts and viceversa) and their duration determines the waiting time to the next burst, the opposite is true for the λ variability class in GRS 1915+105, where rises are slower than decays and the duration of a burst correlates with that of the previous quiescent phase, compatibly the thermal instability picture mentioned above (Belloni et al. 1997a). Finally, type II bursts in the RB only appear below a critical persistent luminosity of about $0.1 L_{\rm Edd}$ (Bagnoli et al. 2015), whereas states of GRS 1915+105 with no large amplitude variations (ϕ and χ) are not clearly separated in luminosity from the other ones.

Nonetheless, these differences might be related to the nature of the accretor, for example because NSs possess a strong magnetic dipole field. It would be interesting to perform complete population studies of the X-ray bursts in the BH systems and the BP, to carry out a comparison with the results by Bagnoli et al. (2015) for the RB.

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REFERENCES

Altamirano D., Belloni T., Linares M., van der Klis M., Wijnands R., Curran P. A., Kalamkar M., Stiele H., Motta S., Muñoz-Darias T., Casella P., Krimm H., 2011, ApJ, 742, L17

Bagnoli T., in't Zand J. J. M., D'Angelo C. R., Galloway D. K., 2015, MNRAS, in press

Bagnoli T., in't Zand J. J. M., Galloway D. K., Watts A. L., 2013, MNRAS, 431, 1947

Bagnoli T., in't Zand J. J. M., Patruno A., Watts A. L., 2014, MNRAS, 437, 2790

Belloni T., Klein-Wolt M., Méndez M., van der Klis M., van Paradijs J., 2000, A&A, 355, 271

Belloni T., Méndez M., King A. R., van der Klis M., van Paradijs J., 1997a, ApJ, 488, L109

Belloni T., Méndez M., King A. R., van der Klis M., van Paradijs J., 1997b, ApJ, 479, L145

Castro-Tirado A. J., Brandt S., Lund N., Lapshov I., Sunyaev R. A., Shlyapnikov A. A., Guziy S., Pavlenko E. P., 1994, ApJS, 92, 469
Degenaar N., Miller J. M., Harrison F. A., Kennea J. A., Kouveliotou C., Younes G., 2014, ApJ, 796, L9
Done C., Gierliński M., 2003, MNRAS, 342, 1041
Fender R., Belloni T., 2004, ARA&A, 42, 317
Finger M. H., Koh D. T., Nelson R. W., Prince T. A., Vaughan B. A., Wilson R. B., 1996, Nat, 381, 291
Ghosh A., Chakrabarti S. K., 2014, ArXiv e-prints
Greiner J., Cuby J. G., McCaughrean M. J., 2001, Nat, 414, 522
Hoffman J. A., Marshall H. L., Lewin W. H. G., 1978, Nat, 271, 630
Jahoda K., Markwardt C. B., Radeva Y., Rots A. H., Stark M. J., Swank J. H., Strohmayer T. E., Zhang W., 2006, ApJS, 163, 401
Janiuk A., Grzedzielski M., Capitanio F., Bianchi S., 2014, ArXiv e-prints
King A. L., Miller J. M., Raymond J., Fabian A. C., Reynolds C. S., Kallman T. R., Maitra D., Cackett E. M., Rupen M. P., 2012, ApJ, 746, L20
Klein-Wolt M., Fender R. P., Pooley G. G., Belloni T., Migliari S., Morgan E. H., van der Klis M., 2002, MNRAS, 331, 745
Kouveliotou C., van Paradijs J., Fishman G. J., Briggs M. S., Kommers J., Harmon B. A., Meegan C. A., Lewin W. H. G., 1996, Nat, 379, 799
Lewin W. H. G., Doty J., Clark G. W., Rappaport S. A., Bradt H. V. D., Doxsey R., Hearn D. R., Hoffman J. A., Jernigan J. G., Li F. K., Mayer W., McClintock J., Primini F., Richardson J., 1976, ApJ, 207, L95
Lewin W. H. G., van Paradijs J., Taam R. E., 1993, Space Sci. Rev., 62, 223
Mirabel I. F., Rodríguez L. F., 1994, Nat, 371, 46
Neilsen J., Remillard R. A., Lee J. C., 2011, ApJ, 737, 69
Rao A., Vadawale S. V., 2012, ApJ, 757, L12
Reid M. J., McClintock J. E., Steiner J. F., Steeghs D., Remillard R. A., Dhawan V., Narayan R., 2014, ApJ, 796, 2
Rodriguez J., Corbel S., Caballero I., Tomsick J. A., Tzioumis T., Paizis A., Cadolle Bel M., Kuulkers E., 2011, A&A, 533, L4
Strohmayer T., Bildsten L., 2006, New views of thermonuclear bursts. pp 113–156
Valenti E., Ferraro F. R., Origlia L., 2010, MNRAS, 402, 1729
Wijnands R., Yang Y. J., Altamirano D., 2012, MNRAS, 422, L91
Wu Y. X., Yu W., Li T. P., Maccarone T. J., Li X. D., 2010, ApJ, 718, 620