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The evolution of Rapid Burster outbursts

R. Guerriero,¹ D. W. Fox,¹ J. Kommers,¹ W. H. G. Lewin,¹ R. Rutledge,² C. B. Moore,³ E. Morgan,¹ J. Van Paradijs,^{4,5} M. Van der Klis,^{5,6} L. Bildsten⁶ and T. Dotani⁷

¹MIT Center for Space Research, 77 Massachusetts Ave #37-627, Cambridge, MA 02139-4307, USA

²Department of Astronomy, Caltech MC 220-47, Pasadena, CA 91125, USA

³Kapteyn Astronomical Institute, Postbus 800, 9700 AV Groningen, The Netherlands

⁴University of Alabama in Huntsville, Huntsville, AL 35812, USA

⁵Astronomical Institute ‘Anton Pannekoek’ and Center for High-Energy Physics, Kruislaan 403, 1098 SJ Amsterdam, the Netherlands

⁶Departments of Physics and Astronomy, University of California, Berkeley, Berkeley, CA 94720, USA

⁷Institute of Space and Astronautical Science, Sagamihara, Japan

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ABSTRACT

We describe the evolutionary progression of an outburst of the Rapid Burster. Four outbursts have been observed with the *Rossi X-Ray Timing Explorer* between 1996 February and 1998 May, and our observations are consistent with a standard evolution over the course of each. An outburst can be divided into two distinct phases. Phase I is dominated by type I bursts, with a strong persistent emission component; it lasts for 15–20 d. Phase II is characterized by type II bursts, which occur in a variety of patterns. The light curves of time-averaged luminosity for the outbursts show some evidence for reflares, similar to those seen in soft X-ray transients. The average recurrence time for Rapid Burster outbursts during this period was 218 d, in contrast to an average ~ 180 -d recurrence period observed during 1976–1983.

Key words: stars: individual: Rapid Burster – stars: variables: other – X-rays: bursts – X-rays: stars.

1 INTRODUCTION

The Rapid Burster (MXB 1730–335, or RB hereafter; Lewin et al. 1976), discovered in 1976, is a unique recurrent transient low-mass X-ray binary (LMXB). It is located at a distance of approximately 8 kpc (Ortolani, Bica & Barbuy 1996) in the highly reddened globular cluster Liller 1 (Liller 1977). The RB is the only known LMXB to produce both type I and type II X-ray bursts (Hoffman, Marshall & Lewin 1978a).

Although the RB has been studied for over 20 years, it is still not clear why the RB, and only the RB, emits both type I and type II X-ray bursts. Type I bursts are due to a thermonuclear flash of accreted material on the surface of a neutron star, and are characterized by a distinct spectral softening during burst decay. Of the ~ 125 LMXBs known, at least 43 are type I burst sources (Van Paradijs 1995). Type II bursts are due to spasmodic accretion – the release of gravitational potential energy – presumably resulting from an accretion disc instability; the spectrum of these bursts shows little evolution during the burst. The duration of type II bursts can range from 680 s (the longest type II burst observed to date) down to 4 s. The behaviour of type II bursts is like that of a relaxation oscillator: the type II burst fluence E is roughly proportional to the time interval, Δt , to the following burst (the ‘ E – Δt ’ relation; Lewin et al. 1976). The type II burst

luminosities at burst maximum range from $\sim 4 \times 10^{37}$ to $\sim 3 \times 10^{38}$ erg s^{–1} (Lewin, Van Paradijs & Taam 1993, hereafter LVT93). GRO J1744–28 is the only other LMXB known to emit repetitive type II bursts (Kouveliotou et al. 1996; Lewin et al. 1996a; Kommers et al. 1997). LVT93 provide a comprehensive review of type I and type II X-ray bursts and the Rapid Burster.

The pattern of type I and type II bursts, and the shape of the type II bursts themselves, have been observed to vary widely during a single outburst. At times, the RB emits only type I bursts with strong persistent emission (PE), behaving like a ‘normal’ LMXB. At other times, type II bursts, occurring in a wide variety of forms and patterns, with or without substantial PE, are observed. When the RB is in a rapid bursting mode, it can emit thousands of rapid type II bursts per day, with little or no PE present. Short type II bursts typically exhibit a time-scale-invariant profile, with multiple peaks (‘ringing’) during burst decay (Tawara et al. 1985). Bursts longer than about 35 s, on the other hand, are ‘flat-topped’ in shape (Lewin et al. 1976; Kunieda et al. 1984a; Stella et al. 1988a; Tan et al. 1991). An evolution from type I to type II bursting behaviour was observed previously during the 1983 August outburst (Kunieda et al. 1984a; Barr et al. 1987).

Quasi-periodic oscillations (QPOs) in the 2–8 Hz frequency range are regularly seen in type II bursts from the RB, and

occasionally in the PE (Tawara et al. 1982; Stella et al. 1988a,b; Dotani et al. 1990; Lubin et al. 1991; Rutledge et al. 1995). QPOs are also present in many RB type II bursts in the form of the ringing observed during burst decay (LVT93). QPOs have not been observed in any type I bursts from the RB. There are strong 0.04-Hz QPOs present in the PE after some long type II bursts (Lubin et al. 1992).

The outbursts of the Rapid Burster have long been known to recur every 6–8 months, based on observed outbursts (LVT93). Years at a time have passed without any positive detections; however, monitoring of the source has historically been sporadic (Fig. 1). This changed in 1996 February, when daily coverage of the RB (for 11 months of the year) began with the *Ross X-ray Timing Explorer* (*RXTE*) All-Sky Monitor (ASM) (Levine et al. 1996).

Since then, we have observed four complete outbursts with *RXTE*. These outbursts have recurred at intervals of 200, 217 and 238 d. These outbursts show a nearly identical global evolutionary pattern: all four outbursts evolved, on the same time-scale, from an initial phase dominated by type I bursts to a type II burst-dominated phase. This evolutionary progression may provide some insight into the unique behaviour of the RB.

Rutledge et al. (1998) have observed a radio source at 4.5/8.4 GHz, whose strength is correlated with the X-ray emission

from the RB as measured by the *RXTE* ASM. They have proposed that this radio emission comes from the RB, even though the ~ 1 -arcsec position of the radio source lies well outside the 2σ error circle for the RB obtained with *Einstein* in 1984 (Grindlay et al. 1984; Moore et al., 1999).

We report here on our analysis of data taken with *RXTE* during the 1996 May, 1996 November, 1997 June and 1998 January outbursts of the Rapid Burster (Lewin et al. 1996b,c; Guerriero, Lewin & Kommers 1997; Guerriero et al. 1998). In Section 2 we summarize our observations; in Section 3 we present the general evolution of a RB outburst; in Section 4 we compare our results to past observations of the RB with other satellites, and in Section 5 we give some possible interpretations of our findings.

2 OBSERVATIONS AND ANALYSIS

The RB was observed with *RXTE* on 31 separate occasions from 1996 May 3–13, 1996 November 6–17, 1997 June 26–July 30, and 1998 January 30–February 19 (Table 1). The total observing time during these periods was 7.5, 12.6, 35.0 and 44.8 ks, respectively. Timing and spectral analyses were conducted with data collected with the Proportional Counter Array (PCA). The PCA consists of five identical xenon/methane proportional counters with a total effective area of approximately 6500 cm^2 ; it is sensitive to X-rays in the range 2–60 keV, and is capable of tagging relative event arrivals down to $1 \mu\text{s}$ (Zhang et al. 1993). Our observations used individually described, event-encoded data with a time resolution of $122 \mu\text{s}$ and 64 energy channels. The two standard data modes, providing $\frac{1}{8}$ s timing data and 16 s/129 energy channel data, were also available throughout.

The RB has been monitored almost continuously (except for ~ 1 month per year when the source lies too close to the Sun) by the *RXTE* ASM since 1996 February. The ASM consists of three identical Scanning Shadow Cameras (SSCs) mounted on a rotating assembly. Each SSC contains a position-sensitive proportional counter, which views the sky through a coded mask. The ASM is sensitive to X-rays in the range 2–10 keV. ASM data are taken in a series of 90-s ‘dwells’ with any randomly selected source being scanned typically 5–10 times per day (Levine et al. 1996).

During the 1996 May outburst, the RB was observed with the PCA on three occasions near the end of the outburst (days 21–31 of the outburst) (Lewin et al. 1996b). On May 3 and May 7, 23 type II bursts of duration 8–17 s were observed. Bursts occurred every 80–100 s on May 3, and every 300–600 s on May 7. On May 13, no bursts were observed.

The RB was again observed with the PCA in 1996 November, on days 8–19 of the outburst (Lewin et al. 1996c). One type I burst was observed during each of the observations on November 6, 9 and 11. The RB had an average PE level on those three occasions of 2270, 1840 and $1590 \text{ counts s}^{-1}$, respectively. No bursts were observed on November 10 and 17. No PCA observations were possible after November 17, due to the *RXTE* Sun-angle constraint.

In June and July of 1997, the RB was observed at regular intervals throughout an entire outburst for the first time (Guerriero, Lewin & Kommers 1997). Type I bursts were observed on days 2–17 of the outburst. On July 13, two ‘flat-topped’ type II bursts of long duration (120 and >420 s, respectively) were observed. Rapid type II bursts were then observed until day 36 of

Figure 1. Record of observations of the Rapid Burster (1971–1998). Filled boxes indicate observations that occurred when the RB was active (a filled top half corresponds to Phase I, a filled bottom half to Phase II, and a completely filled box indicates that the phase could not be determined; see text). Open boxes indicate observations in which the RB was inactive. Single lines indicate observations of less than one day in which the RB was inactive. The observations marked with ‘*’ indicate periods in which the source may have been active, but this is uncertain (White et al. 1978). Since 1996 February, the RB has been monitored for 11 months of the year with the *RXTE* ASM (slashed boxes). This figure is an extension of similar figures from Lewin & Joss (1983) and LVT93.

Table 1. *RXTE* observations of the Rapid Burster from 1996 to 1998. Day of outburst is calculated by considering the first $>3\sigma$ detection in the ASM to begin ‘day 1’. Counts refer to the *RXTE* PCA (1 count $\text{s}^{-1} \approx 3 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$; 2–20 keV). Type I burst durations were calculated by considering the end of the burst to be the point at which the excess burst flux returned to 10 per cent of its peak value. The count rates for all bursts and persistent emission during offset pointings have been corrected for aspect (factor of 2.5 for the RB).

Obs Start (UT)		Day of Outburst	Obs Duration (ks)	Bursts		Duration (s)	Average RB PE Level (count s^{-1})
				Type I	Type II		
1996 May	03 15:25	21	1.5	0	+	15	400
	07 15:37	25	3.0	0	+	8	250
	13 12:19	31	3.0	0	+	0	180
1996 Nov	06 19:39	8	2.6	1	+	0	2270
	09 00:31	11	2.7	1	+	0	1840
	10 16:34	12	3.0	0	+	0	1370
	11 21:23	13	1.8	1	+	0	1590
	17 00:41	19	2.5	0	+	0	1090
1997 Jun	26 04:36	2	1.6	3	+	0	4630
	26 08:01	2	2.1	4	+	0	4630
	27 17:45	3	3.0	2*	+	0	4750
	29 06:26	5	2.0	1	+	0	3320
	29 17:53	5	2.6	2	+	0	3320
Jul	02 02:59	8	1.4	0	+	0	2400 [†]
	03 02:59	9	1.3	0	+	0	2400 [†]
	07 13:00	13	2.5	1	+	0	1200 [†]
	10 12:58	16	3.2	1*	+	0	1100 [†]
	13 11:09	19	3.6	1	+	2	700
						Type I: 120	
						Type II: 180–420+	
	17 04:46	23	3.6	0	+	37	450
	20 06:30	26	3.8	0	+	71	220
	24 01:52	30	3.8	0	+	7	220
	29 06:53	35	2.8	0	+	1	230
	30 03:43	36	1.5	0	+	0	230
1998 Jan	30 17:12	3	6.5	5*	+	0	4000
	31 22:57	4	3.5	2	+	0	2820
Feb	02 16:27	6	6.1	2	+	0	2370
	04 19:48	8	3.5	1	+	0	2100
	07 18:22	11	6.2	2	+	0	1030
	10 21:26	14	6.6	1	+	0	1040
	16 13:59	20	6.2	2	+	234	240
						Type I: 40–50	
						Type II: 8–40	
	19 11:53	23	8.1	1	+	91	250
						Type I: 50	
						Type II: 10–30	

* One of these bursts was observed during a slew.

† Count rates are estimated; no offset pointing performed during these observations.

the outburst, when the outburst ended (July 30). The PE level declined steadily throughout the outburst.

A second complete outburst was observed in 1998 January and February (Guerriero et al. 1998). Observations with the PCA began on day 3 of the outburst, and type I bursts were seen exclusively through day 14. On February 16, day 20 of the outburst, the RB was in a mode characterized by many rapid type II bursts, followed by a larger type II burst. This mode is identical to the mode in which the RB was discovered (Lewin et al. 1976). Rapid, regular type II bursting continued on February 19, the final observation of the outburst.

We have performed a spectral analysis to determine the conversion from count rates to fluxes and to draw some rudimentary conclusions about the X-ray-emitting regions. We emphasize that the model we present is probably not uniquely indicated by the data. No single-component models provided acceptable fits to the data (minimum reduced chi-squared values, for 51 degrees of freedom, are $\chi^2_\nu \sim 3$ for type I bursts, 10 for type II bursts, and 170 for the PE). Two- and three-component models that we considered incorporated blackbody, disc blackbody,

thermal bremsstrahlung, Comptonization, and power-law spectral components. The best-fitting models combined a power law with two blackbody components, resulting in $\chi^2_\nu = 0.8\text{--}1.4$. A simple two-component blackbody model, without a power-law component, also provided statistically acceptable fits to most of the type I bursts, but for many type II bursts and the PE this model was not acceptable ($\chi^2_\nu = 6.8$ in some cases). The addition of a power-law component improved the fits in these cases. None of the other models that we investigated provided statistically acceptable fits to the data.

Best-fitting temperatures of the two blackbody components were 1.1–1.5 keV and 0.25–0.40 keV, respectively. Although the temperature of the hotter component in the type I bursts varied from burst to burst, it cooled by ~ 0.2 keV over the course of the type I burst in nearly every case (see Section 3.1). The temperature of the cooler component remained relatively constant during type I bursts. The luminosity of the hotter component was ~ 15 per cent that of the cooler component (2.5–20 keV), in the bursts and in the PE. When it was necessary to include a power-law component in the model, the values for the photon index of the power law ranged

from 1.9 to 4.0, and luminosities ranged from 1 to 2 per cent of the cooler component (2.5–20 keV). Most of the type II bursts and PE required a power-law component in the spectral model to obtain an acceptable fit to the data. The neutral hydrogen column density for our models was fixed at $2 \times 10^{22} \text{ cm}^{-2}$, as determined from *EXOSAT* observations (Tan et al. 1991); we did not find the low-energy spectral response of the PCA sufficient, in these observations, to constrain the column density independent of the other spectral parameters.

One possible physical picture suggested by this model is of a system with three X-ray-emitting regions: the neutron star surface (~ 1 -keV blackbody), the accretion disc (~ 0.3 -keV blackbody), and a Comptonizing cloud of hot electrons (responsible for the power-law component, when present). The cooling of the hotter blackbody component during type I bursts is consistent with a cooling neutron star surface (LVT93). In contrast, the roughly constant temperatures of the two blackbody components throughout the type II bursts suggest emitting regions that vary in size during the burst (normalizations of both components vary with the X-ray flux). We derive blackbody radii for the hotter component during the type I bursts of 9 ± 2 to $14 \pm 2 d_8 \text{ km}$, depending on the burst, where d_8 is defined as $D/8 \text{ kpc}$, and D is the distance to the RB. During type I bursts the cooler component has a blackbody emitting area of 0.7 ± 0.3 to $2.3 \pm 1.0 \times 10^6 d_8^2 \text{ km}^2$.

For the type II bursts, we derive blackbody radii at the peak of the bursts of 5.0 ± 1.0 to $10 \pm 1.5 d_8 \text{ km}$, depending on the burst, for the hotter component, and blackbody emitting areas of 0.5 ± 0.3 to $2.1 \pm 0.9 \times 10^6 d_8^2 \text{ km}^2$ for the cooler component. The normalizations of both components vary with total X-ray flux during the bursts.

For the PE spectra, we derive blackbody radii for the hotter component of 10 ± 2 to $13 \pm 2 d_8 \text{ km}$ and blackbody emitting areas of 0.9 ± 0.4 to $2.5 \pm 0.8 \times 10^6 d_8^2 \text{ km}^2$ for the cooler component. The normalizations of both components decrease over the course of the outburst as the total X-ray flux decreases.

There are known problems with interpreting blackbody X-ray spectral fits in such a literal fashion (LVT93). One problem discussed in LVT93 is that the observed X-ray colour temperature and the effective temperature (that is, the temperature if the source were a true Planckian emitter) can differ by as much as a factor of ~ 1.5 . In the present case, this could lead to blackbody radii $1.5^2 \sim 2$ times larger than the values we have quoted.

Bursts were classified as type I or type II, in part, by performing spectral fits on the ‘excess’ (PE-subtracted) burst counts. This is not a perfectly straightforward procedure (Van Paradijs & Lewin 1986); however, while both type I and type II bursts can show some spectral evolution during the burst, the spectral softening during the decay is much more pronounced in a type I burst (cf. Fig. 4). The burst profile of a type I burst, with a sharp rise and a roughly exponential decay, is also substantially different from that of a type II burst (except when the PE is near its peak level, when burst profiles alone are not sufficient to distinguish the two types). Together with the spectral fits, then, the burst profiles were used to classify bursts as either type I or type II.

The bright LMXB 4U 1728–34 lies only 0.5° from the RB, and is in the field of view of the PCA when the RB is in the centre of the field of view. To determine the contribution of this source, the satellite pointing was offset by 0.5° away from 4U 1728–34 for the last third of each observation. This procedure allowed us to estimate the number of counts arriving from each source, but reduced our count rate from the RB by about a factor of 2.5 for the

offset phase of each observation. Additionally, an occasional type I burst from 4U 1728–34 was observed while the PCA was pointed directly at the RB. These bursts were easily distinguished from RB bursts by their peak flux ($\sim 15\,000 \text{ PCA count s}^{-1}$) and characteristic light curves, both of which differ markedly from bursts emitted by the RB. We also detected the well-known 363-Hz oscillations (Strohmayer et al. 1996) from several of the 4U 1728–34 type I bursts.

3 OUTBURST EVOLUTION

With the *RXTE* ASM we can detect the onset of a RB outburst to within less than one day. The four outbursts observed with *RXTE* began on 1996 13 April, 1996 30 October, 1997 25 June, and 1998 28 January. The intervals between the start of these outbursts are 200, 238 and 217 d, respectively. Using these three values, we find the current average recurrence time for RB outbursts to be 218 d.

The four most recent outbursts have all followed a nearly identical evolution in the ASM (Fig. 2). The time-averaged X-ray flux (PE and bursts) observed with the ASM rises linearly at the beginning of an outburst and peaks within ~ 1 –3 d. The average

Figure 2. One-day averages of ASM count rates for outbursts of the Rapid Burster (90-s data points are also plotted during the outburst rise). The peaks of the outbursts have been aligned. The data are from (a) 1996 March 29 to May 27 (outburst peak: 1996 April 14), (b) 1996 October 15 to November 18 (outburst peak: 1996 October 31), (c) 1997 June 10 to August 8 (outburst peak: 1997 June 26), and (d) 1998 January 25 to March 13 (outburst peak: 1998 January 30). Short vertical lines indicate days when PCA observations were made. Horizontal lines indicate periods in which the RB was observed to be in Phase II (type II burst-dominated); during other periods the RB was in Phase I (type I burst-dominated). Arrows point to the fitted centre of a Gaussian curve which may indicate the presence of a reflare (see text). Prior to the start of an outburst, the RB flux detected with the ASM is consistent with zero.

Table 2. Parameters describing the best-fitting curve of each Rapid Burster outburst. The outburst rise is linear, while during outburst decay the ASM flux $\propto e^{-t/\tau}$. The times of the additional peaks (modelled as Gaussians) are given in days since the primary peak. We do not identify any additional peaks during the 1996 November or 1997 June/July outbursts. Modified Julian Day (MJD) is given by Julian Day (JD) minus 2 400 000.5.

Outburst	Start time (t_0 , MJD)	Rise time ($t_p - t_0$, days)	Peak flux (P , ASM count s $^{-1}$)	τ (days)	Additional Peaks		
					Centre ($t_n - t_p$, days)	Amplitude (A_n , ASM count s $^{-1}$)	Width (σ_n , days)
May 1996	50186.2 $\pm$ 2.0	2.4 $\pm$ 0.04	16 $\pm$ 2	7.9 $\pm$ 0.5	8 $\pm$ 0.5	3.0 $\pm$ 0.2	0.5 $\pm$ 0.2
"					13 $\pm$ 0.5	2.8 $\pm$ 0.2	0.5 $\pm$ 0.2
Nov 1996	50386.0 $\pm$ 1.2	1.9 $\pm$ 0.03	26 $\pm$ 2	8.6 $\pm$ 0.7	—	—	—
Jun 1997	50624.1 $\pm$ 1.5	1.7 $\pm$ 0.16	26 $\pm$ 2	8.5 $\pm$ 0.8	—	—	—
Jan 1998	50841.4 $\pm$ 1.4	3.1 $\pm$ 0.06	21 $\pm$ 2	6.0 $\pm$ 0.7	17 $\pm$ 1.0	5.7 $\pm$ 0.5	3.3 $\pm$ 0.7
"					23 $\pm$ 0.5	1.6 $\pm$ 0.6	0.4 $\pm$ 0.3

Table 3. The evolution of Rapid Burster outbursts observed by *RXTE* (1 PCA count s $^{-1}$ $\approx$ 3×10^{-12} erg cm $^{-2}$ s $^{-1}$; 2–20 keV).

Days of Outburst	Phase	PE Level (PCA count s $^{-1}$)	Burst Behaviour
1–17	I	5000 $\rightarrow$ 1000	Type I bursts 200–250 s duration 1500–3000 s between bursts Possible type II bursts
18–19	II Mode 0	1000 $\rightarrow$ 700	Type II bursts long, flat-topped bursts 100–700 s duration Occasional type I bursts
20–21	II Mode I	200–500	Type II Bursts 8–40 rapid bursts (8–12 s duration), followed by a large burst (20–30 s duration) ‘ringing’ during burst decay Small type I bursts may follow large type II bursts
22–35	II Mode II	200–500	Type II Bursts burst intervals can be very regular 40–100 s between bursts burst durations can vary from 5–25 s ‘ringing’ during burst decay Occasional small type I bursts

X-ray flux then declines exponentially over the next ~ 35 d. During the 1996 May and 1998 January/February outbursts, there are indications of reflares. In both cases, in addition to the main peak, two additional peaks are preferred, as determined by F -tests (F -test probabilities with two additional peaks are 99.8 and 99.3 per cent, respectively). There is no evidence for additional peaks during the 1996 November or 1997 June/July outbursts. These reflares are reminiscent of the behaviour of soft X-ray transients (Augusteijn, Kuulkers & Shaham 1993; for a review of soft X-ray transients, see Tanaka & Lewin 1995). During a one-day period between days 5 and 6 of the 1997 June/July outburst (1997 June 29 and 30), there is a sudden decrease in the average flux from the source (see Fig. 2c).

An outburst can be parametrized by:

$$F(t) = \begin{cases} \frac{P}{t_p - t_0} (t - t_0), & t_0 < t \leq t_p \\ P e^{-(t-t_p)/\tau} + \sum_n A_n \exp \left[-\frac{(t-t_n)^2}{2\sigma_n^2} \right], & t > t_p \end{cases}$$

Here, P is the peak flux (ASM counts s $^{-1}$), t_0 is the time of the outburst start (days), t_p is the time of outburst peak (days), and n parameterizes the additional peaks, with A_n the amplitude of the

n th additional peak (in ASM counts s $^{-1}$), t_n its peak time (days), and σ_n its Gaussian width. The fitted parameters for each outburst are summarized in Table 2.

Our PCA observations of the RB occurred intermittently during four outbursts. The source was observed at varying intervals during each outburst. All four sets of observations, however, are consistent with one global evolutionary pattern for a RB outburst. A RB outburst can be divided into two phases. Phase I is dominated by type I bursts with a strong PE, lasting for 15–20 d. The PE declines steadily during this phase. Phase II consists of several different modes of type II bursting, and lasts until the end of the outburst. Table 3 summarizes the evolution of the RB outbursts.

3.1 Phase I

Within the first 1–3 days of a RB outburst, the persistent emission level rises quickly to its peak level of ~ 5000 PCA count s $^{-1}$ (1 count s $^{-1}$ $\approx$ 3×10^{-12} erg cm $^{-2}$ s $^{-1}$, 2–20 keV). Although there have been no PCA observations in this initial rising phase, there have been a few observations near the peak of an outburst. The PE level does not remain constant for any appreciable amount of time; it declines steadily during Phase I from its peak level down to ~ 1000 count s $^{-1}$ by the end of the phase.

Figure 3. The Rapid Burster during the outburst of 1997 June/July. (a) and (b) Type I bursts during Phase I (days 5 and 13 of the outburst). Notice the long tails during the burst decay. (c) Long type II burst during Mode 0 of Phase II (day 19 of the outburst; notice the dip in the PE following the burst). (d) Type II bursts during Mode II of Phase II (day 23 of the outburst). Contributions from 4U 1728–34 have been removed. Panel (b) has been corrected for aspect; this was necessary as that burst occurred during an offset pointing (see text).

We observed Phase I to last for 15–20 d. The bursts during this phase that could be positively identified were exclusively type I bursts. The RB type I bursts have a profile similar to type I bursts observed from some other LMXBs (Figs 3a and b). Typical burst durations were 200–250 s, with ~ 1500 – 3000 s between bursts. We observed peak excess count rates for these bursts to be typically 2000 – 5000 counts s^{-1} . The rise times for the bursts decrease as Phase I progresses. Initially, the rise times were 10–20 s; however, by day 3 of the outburst the rise times had decreased to 3–5 s.

The spectra of 33 out of 35 bursts observed during this phase soften during the burst decay, indicating that they are type I bursts (Figs 4a and b). Two bursts did not show detectable spectral softening, and are therefore difficult to classify as either type I or type II (Fig. 5). These bursts occurred on day 2 of the June/July 1997 outburst (1997 June 26), when the PE was at its highest level observed with the PCA (~ 5000 counts s^{-1}); moreover, both bursts had peak excess count rates of <1500 PCA counts s^{-1} . It is possible that these were type II bursts. However, given that these two bursts resemble the other bursts observed during the early stages of Phase I, we feel that they are most likely type I bursts.

3.2 Phase II

We consider Phase II, which is dominated by type II bursts, to begin with the first type II burst. Phase II can be generally divided

Figure 4. Spectral evolution of Rapid Burster bursts. Hardness is a measure of the blackbody temperature of the excess burst counts above persistent emission. (a) A type I burst that occurred on 1997 June 26 (day 2 of the outburst). When the persistent emission is at such a high level, type I bursts do not always have their characteristic profile. (b) A type I burst that occurred on 1997 July 7 (day 13 of the outburst). Note the drop in the persistent emission level since the burst shown in (a); also note the long tail during the burst decay. (c) A long type II burst that occurred on 1997 July 13 (day 19 of the outburst). Note the lack of spectral evolution and the shape of the burst, making it unquestionably a type II burst (see Tan et al. 1991).

into three subphases, each having a different pattern of type II bursts. Although the start of type II bursting indicates the beginning of Phase II, type I bursting does not cease. Type I bursts identical to those from the first phase can be seen during the initial stages of Phase II. In addition, short type I bursts can be observed throughout Phase II. Although we will describe these subphases in the sequence that we observed them to occur, it is important to note that historically the RB has not always followed the same sequence (see Section 4).

On day 18 of the 1997 June/July outburst, the RB produced two long, flat-topped type II bursts. These bursts had durations of 180 s and >420 s (this burst was observed in progress as the spacecraft slewed on to the source). There was very little spectral evolution during the bursts (Fig. 3c). Dips were present in the PE following both of the bursts, although there was no dip prior to the only complete burst we observed in this phase. In the last 30 s of the shorter burst, the familiar ‘ringing’ of RB type II bursts was evident (Fig. 3c). This ‘ringing’ during burst decay is only clearly evident if the bursts are less than ~ 200 s in duration (Tan et al. 1991). This pattern of flat-topped type II bursts was first observed with *Hakucho* in 1979 August, and was called ‘Phase II’ by Kunieda et al. (1984a). This should not be confused with our use of Phase I and Phase II, which describe phases of type I

Figure 5. Two bursts from the early stages of Phase I (1997 June 26, day 2 of the outburst). Hardness is a measure of the blackbody temperature of the excess burst counts above persistent emission. The persistent emission level was at its peak during this portion of the outburst. The burst profiles, which are not easily distinguishable as either type I or type II burst profiles, and the poorly constrained spectral evolution make these bursts difficult to classify as type I or type II bursts. Note the slow rise of both bursts.

Figure 6. Rapid Burster bursts from the 1998 January/February outburst. (a) Phase II, Mode I (day 20 of the outburst). Note the enhanced emission following the large type II bursts. (b) A 400-s segment of panel (a). (c) Bursts during Phase II, Mode II (day 23 of the outburst). Note the type II burst that occurred during the decay of a type I burst (at time ~ 100 s). Also note the ‘ringing’ that can be seen during type II burst decay in all three figures.

burst-dominated and type II burst-dominated emission, respectively. We propose instead to designate this mode (type II bursts >100 s) as ‘Mode 0’, to indicate the fact that it appears to be the initial mode of Phase II. On 1997 July 13, a type I burst was observed while the RB was in Mode 0.

The next burst pattern is characterized by several (8–40) short type II bursts, followed by a larger type II burst (Figs 6a and b). Following Marshall et al. (1979), we refer to this as ‘Mode I’. We observed the RB emission in this pattern on 1998 February 16, which was day 20 of that outburst. There was a long delay following each of the large type II bursts before the occurrence of the next type II burst. The shorter bursts had durations of 8–12 s, with ~ 10 s between bursts, while the longer bursts lasted for 20–30 s. The pause following a large type II burst varied from 50 to 350 s. There was also a period of enhanced X-ray emission following the large type II bursts. All of the type II bursts observed during this phase exhibited the time-scale-invariant profile. Type I bursts can also occur in this phase, usually during the PE period immediately following a large type II burst. This mode is the one observed when the RB was discovered by Lewin et al. (1976).

The final pattern is made up of many short type II bursts in a nearly regular pattern (Figs 3d and 6c), which was designated ‘Mode II’ by Marshall et al. (1979). We observed this mode as the final phase before the end of each outburst seen with *RXTE* (we did not observe the end of the outburst of the RB in 1996 November, since it was too close to the Sun to be observed). The burst profiles are all time-scale-invariant, and exhibit ‘ringing’ during burst decay (Tawara et al. 1985; Tan et al. 1991). Burst durations are 5–25 s, with bursts occurring every 40–100 s. We did observe type I bursts during this phase, some of which occur

Figure 7. The total energy in all type II bursts observed with *RXTE*. The total energy in each burst (2–20 keV, assuming isotropic emission and a distance of 8 kpc) is plotted against the approximate time of its occurrence. Circles indicate type II bursts of the 1996 May outburst; triangles indicate type II bursts of the 1997 June/July outburst; squares indicate type II bursts of the 1998 January/February outburst. There were no type II bursts observed during the 1996 November outburst. The transition from Mode I to Mode II occurs at approximately day 22 of these outbursts. The results shown in this figure show a striking similarity to those presented by Marshall et al. (1979) in a similar figure. The reader is encouraged to consult the original figure by Marshall et al.

simultaneously with type II bursts (Fig. 6c). At the latest point in an outburst in which we observed Mode II (1997 July 24; day 30 of the outburst), the burst separation had increased to ~ 500 s.

Mode I and Mode II are distinguishable in Fig. 7. The burst energy E has been plotted for each burst at the approximate day of the outburst in which the burst occurred. There is a bimodal distribution of burst energies during Mode I, while Mode II exhibits a single-peaked distribution.

3.3 E - Δt relation

Since its discovery, the RB has been known to have a proportional relationship between the fluence of a type II burst and the waiting time to the *next* type II burst (Lewin et al. 1976). In this sense, the RB behaves like a relaxation oscillator. We have calculated the total energy of 398 type II bursts that occurred during the 1997

Figure 8. E - Δt relation. We have assumed isotropic emission and a source distance of 8 kpc. Open squares are type II bursts of Mode I observed during 1998 February 16 (day 20 of the outburst). Those in the boxed region are the large type II bursts of the same mode that were followed by a segment of enhanced PE. Filled squares are type II bursts of Mode II from 1998 February 19 (day 23 of the outburst). Open stars are type II bursts from 1997 July 17 (also day 23 of the outburst; Mode II). Filled circles are type II bursts of Mode II that occurred on 1997 July 20 (day 26 of the outburst). Open hexagons are also type II bursts of Mode II; they occurred on day 29 of the outburst. Filled triangles are type I bursts from Phase I. Note that only bursts occurring on a given day may exhibit a single E - Δt relation, since the time-averaged X-ray luminosity ($E/\Delta t$) decreases during an outburst.

Table 4. E - Δt relation parameters for type II bursts, where α is the power-law index, β is the energy in a type II burst that ‘generates’ a 100 s waiting time to the next burst, and ℓ is the time-averaged type II burst luminosity (see also Fig. 8).

Date	Day of Outburst	α	β (10^{39} erg)	ℓ (10^{37} erg s $^{-1}$)
16 Feb	20 [†]	0.52 ± 0.21	8.5 ± 0.5	8.0 ± 0.2
19 Feb	23	0.94 ± 0.12	3.4 ± 0.2	3.1 ± 0.1
17 Jul	23	0.43 ± 0.13	1.6 ± 0.3	1.7 ± 0.1
20 Jul	26	0.48 ± 0.13	0.53 ± 0.02	1.2 ± 0.1

[†] Only includes the large bursts of Mode I (boxed region of Fig. 7).

June and 1998 January outbursts, assuming isotropic emission and a source distance of 8 kpc. These are plotted against the waiting time to the next burst in Fig. 8. In addition, 11 type I bursts from Phase I are included in the figure.

In general, the relationship between the energy in a burst and the waiting time to the next burst can be described by a power law of the form $E = \beta(\Delta t/100 \text{ s})^\alpha$ (Kunieda et al. 1984a). Here, we have defined β to be the energy in a type II burst that ‘generates’ a 100-s waiting time to the next burst. In rare cases, this E - Δt relation can be approximately linear ($\alpha = 1$). One relation does not hold for all bursts in an outburst, because the time-averaged type II X-ray burst luminosity ($\ell = E/\Delta t$) decreases during an outburst (Fig. 2). During our 2–4 ks observations on any given day, however, α and β remained relatively constant. The derived values of ℓ show a progressive decrease as the outburst evolves. Values for α , β and ℓ are summarized in Table 4.

The short type II bursts that occurred during Mode I appear to have a nearly constant burst interval, Δt , over a large range of fluences. We do not have enough data points to define a meaningful relation for the bursts that occur at the very end of an outburst (open hexagons in Fig. 8). Finally, the E - Δt relation is not relevant for type I bursts (filled triangles in Fig. 8).

4 HISTORICAL PERSPECTIVE

The RB has been observed intermittently since its discovery in 1976 (Fig. 1). Various satellites have observed the RB at a variety of wavelengths. X-ray observations of the RB are summarized in Table 5.

Using the 218-d average period determined from the ASM data, we folded the record of RB observations with this value (Fig. 9). The few outbursts that were observed from 1984 to 1989 seem to fit the pattern reasonably well, while those outbursts prior to 1984 do not fit. In fact, a good fit for the outbursts from 1976 to 1983 is obtained with a 181-d period. Other periods, from 100 to 300 d, were also used to fold the data, but none produced better agreement with the observed outbursts than the 181- and 218-d periods. Although years have passed without any positive detections of the RB in outburst, Fig. 9 indicates that very few of the observations during those years fell in the estimated outburst windows. It therefore seems likely that the RB goes into outburst at semiregular intervals of 6–8 months. Continued monitoring with the *RXTE* ASM will be essential to confirm and characterize this behaviour.

RB outbursts observed with other satellites have generally followed the evolution that we have described, with some exceptions. In all observations in which the RB was in Phase I (1983 August, 1997 June and 1998 January), Phase II was observed several days later (Kunieda et al. 1984b). There were two occasions, however, when Phase II may not have been preceded by Phase I. From 1978 March 8 to 15, *SAS-3* observations indicated that the RB was not in outburst. However, on 1978 March 18, both *SAS-3* and *HEAO 1* observed the RB in Phase II (Mode I) (Jernigan et al. 1978). *Hakucho* observations from 1979 July 31 to August 7 detected no bursts from the RB. On 1979 August 8, rapid repetitive bursts were observed from the RB, indicating that it was in Phase II (Mode II) (Kunieda et al. 1984a). If Phase I occurred in these cases, it must have been extremely short-lived. In all other observations of the RB in outburst, there is a large enough gap (two weeks) between the last pre-outburst observation and the

Table 5. X-ray observations of Rapid Burster outbursts from 1971 to 1998. Phase(s) indicates the burst phase(s) observed with each satellite. Mode(s) indicates the mode(s) observed when the RB was in Phase II.

Obs Date	Satellite	Phase(s)	Mode(s)
Mar 71	<i>Uhuru</i>	undetermined	
May 72	<i>Uhuru</i>	undetermined	
Apr 73	<i>Copernicus</i>	undetermined	
Feb 75	<i>Copernicus</i>	undetermined	
Mar 76	<i>SAS-3</i>	II	I
"	<i>Ariel V</i>	II	II → I
Apr 77	<i>Ariel V</i>	II	II → I → II
Sep 77	<i>SAS-3</i>	II	II
Mar 78	<i>HEAO I</i>	II	I
"	<i>SAS-3</i>	II	II
Oct 78	<i>SAS-3</i>	II	II
Mar 79	<i>SAS-3</i>	II	0 → II
"	<i>Einstein</i>	II	II
Aug 79	<i>Hakucho</i>	II	0 → II
Apr 83	<i>ASTRON</i>	I	
Aug 83	<i>Tenma</i>	I	
"	<i>ASTRON</i>	I	
"	<i>EXOSAT</i>	I → II	II
"	<i>Hakucho</i>	II	0 → II
Jul 84	<i>Tenma</i>	II	0 → I → II
"	<i>EXOSAT</i>	II	II
Aug 85	<i>EXOSAT</i>	II	0 → II
Aug 88	<i>Ginga</i>	II	I → II
Jan 89	<i>Ginga</i>	?	
May 96	<i>RXTE</i>	II	II
Nov 96	<i>RXTE</i>	I	
Jun 97	<i>RXTE</i>	I → II	0 → II
Jan 98	<i>RXTE</i>	I → II	I → II

observation of Phase II for Phase I to have occurred ‘normally’. It thus seems that there is a strong indication that the Phase I to Phase II pattern is characteristic of the RB outbursts.

In all RB observations, Phase II has been observed as the final phase of the outburst. There are indications that the RB follows the progression within Phase II that we have described; that is ‘Mode 0 → Mode I → Mode II’. In 1984 July, *Tenma* and then *EXOSAT* observed the RB transition from Mode 0 to Mode I to Mode II (Kawai et al. 1990; Lubin et al. 1991). *HEAO I* and *SAS-3* in 1978 March, and *Ginga* in 1988 August, observed the transition from Mode I to Mode II (Hoffman et al. 1978b; Jernigan et al. 1978; Dotani et al. 1990). Many satellites have observed Mode 0, and later Mode II, without seeing Mode I in between. These include *SAS-3* in 1979 March (Basinska et al. 1980), *Hakucho* in 1979 August and in 1983 August (Inoue et al. 1980; Kunieda et al. 1984a,b), and *EXOSAT* in 1985 August (Stella et al. 1988a; Lubin et al. 1992). However, Mode I might have occurred between these observations, since all of the observations were intermittent. All of these observations saw Phase II, Mode II, as the final Mode before the end of the outburst.

Dips in the persistent emission prior to and just following a type II burst are common when the RB is in Mode 0, as is enhanced PE following the large type II bursts of Mode I. This enhanced PE during Mode I can be clearly seen in the first *SAS-3* observation of the RB (Lewin et al. 1976), in the *HEAO I* observation from 1978 March (Hoffman et al. 1978b), and in the *Ginga* observations of 1988 August (Dotani et al. 1990). They are also clearly evident in Mode 0 in observations made by *SAS-3* in 1979 March (Basinska et al. 1980), by *Hakucho* in August 1979 (Kunieda et al. 1984a), and by *EXOSAT* in 1985 (Stella et al. 1988a; Lubin et al. 1993).

Figure 9. Observations of the Rapid Burster (1971–1998), folded with a 218-d period (2 cycles per line). Modified Julian Day (MJD) is listed along the ordinate. Filled boxes indicate observations that occurred when the RB was active. Open boxes indicate observations in which the RB was inactive. Single lines indicate observations of less than one day in which the RB was inactive. The observations marked with ‘*’ indicate periods in which the source may have been active, but this is uncertain (White et al. 1978). Dashed lines indicate 65-d windows. MJD 40994 corresponds to 1971 February 12.

We observed with *RXTE* a post-burst dip on 1997 July 13 (Mode 0), but no pre-burst dip. However, *Tenma* observed the RB in Mode 0 in 1983 August, and did not detect any preceding or following dips in 15 long (>100 s) type II bursts (Kunieda et al. 1984b). Of course, instrument sensitivity is an important factor in the detectability of dips in the PE, and *Tenma* may not have been sensitive enough to observe such dips.

There are some exceptions to this evolutionary pattern, however. When the RB was discovered in 1976, Mode I was observed, followed by Mode II. The RB then briefly returned to Mode I before ending in Mode II (Lewin et al. 1976; Ulmer et al. 1977; Marshall et al. 1979). In April of 1977, *Ariel V* and *SAS-3* saw the RB in Mode II, then Mode I, and then finally Mode II again (White et al. 1978; Marshall et al. 1979).

In addition, the duration of the subphases of Phase II can vary. We observed Mode 0 and Mode I to last for no more than ~3 d each. In 1979, however, *Hakucho* observed Mode 0 from August 8 to 16 (Kunieda et al. 1984a). In 1984, *Tenma* observed Mode 0 from July 2 to 5, and Mode I from July 6 to 9 (Tawara et al. 1985).

There are also many idiosyncrasies associated with Phase II. In 1977 September, when the RB was in Mode II, a larger than normal type II burst followed a type I burst on four occasions (Hoffman, Marshall & Lewin 1978a). This led to the realization that the type I bursts must have come from the RB. Also, Lubin et al. (1993) reported ‘glitches’ that were observed following 10 of 84 long type II bursts observed with *EXOSAT* in 1985 August.

5 DISCUSSION AND SUMMARY

In four RB outbursts observed with *RXTE* we have noted a more or less consistent evolutionary pattern that is also reasonably consistent (though not exclusively) with previous observations of the RB. The outbursts begin suddenly and rise to their peak persistent emission (PE) level within 3 d. Type I bursts dominate for 15–20 d, with a steadily declining level of PE (Phase I). By approximately day 18 of the outbursts, type II bursts appear (Phase II). There are three main types of type II burst patterns: long, flat-topped bursts; a series of short bursts followed by a large burst; and rapid bursts at regular intervals. The rapid, regular bursts are the final phase of any outburst.

During the three outbursts in which Phase II was observed, the phase did not begin until the PE luminosity had decreased to $\sim 2 \times 10^{37} \text{ erg s}^{-1}$. It seems likely that the PE level has important implications for the burst behaviour of the RB.

In addition, the fact that type I bursts observed during Mode I occur preferentially during the period of enhanced PE has important implications for the mechanism that triggers type I bursts. Since the periods of enhanced PE always follow a large type II burst, it seems plausible that the thermonuclear flash is triggered by the extra amount of material that has been accreted onto the neutron star.

Using the relation $E = \beta(\Delta t/100 \text{ s})^\alpha$ to relate the energy of a type II burst, E , to the waiting time to the next burst, Δt , we find α values in the range 0.43–0.94 for Mode II and the large type II bursts of Mode I. The short type II bursts of Mode I have a relatively constant burst separation, Δt , of ~ 10 s, even though they vary in energy.

The current average recurrence time for RB outbursts is ~ 218 d. This agrees reasonably well with all observed outbursts after 1983. For outbursts prior to 1984, an average of ~ 180 d seems more suitable.

The possible reflares that might be present in two out of four outbursts observed with *RXTE* are reminiscent of the echoes observed in some soft X-ray transients. This could be the result of an echo of the main outburst, in which either the companion star or the disc itself is heated by X-rays from the main outburst. The increased mass flow to the accretion disc that results from the heating of the companion star, or the excitation of the accretion disc if the disc itself is heated, could produce a response that we observe as a reflare of X-ray emission (Augusteijn, Kuulkers & Shaham 1993; Tanaka & Lewin 1995). The delay between the onset of the outburst and the echo, in this model, is related to the time required for matter to be transferred from the location in the disc where the disc instability occurs to the surface of the neutron star.

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NOTE ADDED IN PROOF

Since the submission of this paper we have observed two further outbursts of the Rapid Burster, in 1998 August and 1999 March.

The 1998 August outburst occurred entirely in Phase II, evolving from Mode 0 to Mode I and concluding in Mode II. The 1999 March outburst began in Phase I, but quickly transitioned to Phase II, Mode I, and then ended in Mode II. Thus the behaviour of this source continues to exhibit dramatic variations from outburst to outburst, as it has historically (see Section 4).

REFERENCES

- Augusteijn T., Kuulkers E., Shaham J., 1993, *A&A*, 279, L13
 Barr P., White N. E., Haberl F., Stella L., Pollard G., Gottwald M., Parmer A. N., 1987, *A&A*, 176, 69
 Basinska E. M., Lewin W. H. G., Cominsky J., Van Paradijs J., Marshall F. J., 1980, *ApJ*, 241, 787
 Dotani T. et al., 1990, *ApJ*, 350, 395
 Grindlay J. E., Hertz P., Steiner J. E., Murray S. S., Lightman A. P., 1984, *ApJ*, 282, L13
 Guerriero R., Lewin W. H. G., Kommers J., 1997, *IAU Circ.* 6689
 Guerriero R., Fox D., Lewin W., Rutledge R., Moore C., Van der Klis M., Van Paradijs J., 1998, *IAU Circ.* 6815
 Hoffman J. A., Marshall H. L., Lewin W. H. G., 1978a, *Nat*, 271, 630
 Hoffman J. et al., 1978b, *Nat*, 276, 587
 Inoue H. et al., 1980, *Nat*, 283, 358
 Jernigan G., McClintock J., Marshall H., Chartres M., Hoffman J., Lewin W., 1978, *IAU Circ.* 3204
 Kawai N., Matsuoka M., Inoue H., Ogawara Y., Tanaka Y., Kunieda H., Tawara Y., 1990, *PASJ*, 42, 115
 Kommers J. M., Fox D. W., Lewin W. H. G., Rutledge R. E., Van Paradijs J., Kouveliotou C., 1997, *ApJ*, 482, L53
 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
 Kunieda H. et al., 1984a, *PASJ*, 36, 215
 Kunieda H. et al., 1984b, *PASJ*, 36, 807
 Levine A. M., Bradt H., Cui W., Jernigan J., Morgan E., Remillard R., Shirey R., Smith D., 1996, *ApJ*, 469, L33
 Lewin W. H. G., Joss P. C., 1983, in Lewin W. H. G., Van den Heuvel E. P. J., eds, *Accretion-Driven Stellar X-Ray Sources*. Cambridge Univ. Press, Cambridge, p. 41
 Lewin W. H. G. et al., 1976, *ApJ*, 207, L95
 Lewin W. H. G., Van Paradijs J., Taam R. E., 1993, *Space Sci. Rev.*, 62, 223 (LVT93)
 Lewin W. H. G., Rutledge R. E., Kommers J. M., Van Paradijs J., Kouveliotou C., 1996a, *ApJ*, 462, L39
 Lewin W. H. G. et al., 1996b, *IAU Circ.* 6506
 Lewin W. H. G., et al., 1996c, *IAU Circ.* 6409
 Liller W., 1977, *ApJ*, 213, L21
 Lubin L. M., Stella L., Lewin W. H. G., Tan J., Van Paradijs J., Van der Klis M., Penninx W., 1991, *MNRAS*, 249, 300
 Lubin L. M., Lewin W. H. G., Rutledge R. E., Van Paradijs J., Van der Klis M., Stella L., 1992, *MNRAS*, 258, 759
 Lubin L. M., Lewin W. H. G., Van Paradijs J., Van der Klis M., 1993, *MNRAS*, 261, 149
 Marshall H. L., Ulmer M. P., Hoffman J. A., Doty J., Lewin W. H. G., 1979, *ApJ*, 227, 555
 Moore C. B., Rutledge R. E., Fox D. W., Guerriero A. A., Lewin W. H. G., Fender R., Van Paradijs J., 1999, *ApJ*, submitted
 Ortolani S., Bica E., Barbuy B., 1996, *A&A*, 306, 134
 Rutledge R. E., Lubin L. M., Lewin W. H. G., Vaughan B., Van Paradijs J., Van der Klis M., 1995, *MNRAS*, 277, 523
 Rutledge R. E., Moore C., Fox D., Lewin W. H. G., Van Paradijs J., 1998, *IAU Circ.* 6813
 Stella L., Haberl F., Lewin W. H. G., Parmar A., Van Paradijs J., White N., 1988a, *ApJ*, 324, 379
 Stella L., Haberl F., Lewin W. H. G., Parmar A., Van der Klis M., Van Paradijs J., 1988b, *ApJ*, 327, L13

- Strohmayer T. E., Zhang W., Swank J., Smale A., Titarchuk L., Day C., 1996, *ApJ*, 469, L9
- Tan J., Lewin W. H. G., Lubin L. M., Van Paradijs J., Penninx W., Van der Klis M., Damen E., Stella L., 1991, *MNRAS*, 251, 1
- Tanaka Y., Lewin W. H. G., 1995, in Lewin W. H. G., Van Paradijs J., Van den Heuvel E. P. J., eds, *X-Ray Binaries*. Cambridge Univ. Press, Cambridge, p. 126
- Tawara Y., Hayakawa S., Kunieda H., Makino F., Nagase F., 1982, *Nat*, 299, 38
- Tawara Y., Kawai N., Tanaka Y., Inoue H., Kunieda H., Ogawara Y., 1985, *Nat*, 318, 545
- Ulmer M. P., Lewin W. H. G., Hoffman J. A., Doty J., Marshall H., 1977, *ApJ*, 214, L11
- Van Paradijs J., 1995, in Lewin W. H. G., Van Paradijs J., Van den Heuvel E. P. J., eds, *X-Ray Binaries*. Cambridge Univ. Press, Cambridge, p. 536
- Van Paradijs J., Lewin W. H. G., 1986, *A&A*, 157, L10
- White N. E., Mason K. O., Carpenter G. F., Skinner G. K., 1978, *MNRAS*, 184, 1p
- Zhang W., Giles A. B., Jahoda K., Soong Y., Swank J. H., Morgan E. H., 1993, *Proc. SPIE*, 2006, 324

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