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Indications for a slow rotator in the Rapid Burster from its thermonuclear bursting behaviour

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ABSTRACT

We perform time-resolved spectroscopy of all the type I bursts from the Rapid Burster (MXB 1730–335) detected with the Rossi X-Ray Timing Explorer. Type I bursts are detected at high accretion rates, up to \( \approx \)45 per cent of the Eddington luminosity. We find evidence that bursts lacking the canonical cooling in their time-resolved spectra are, nonetheless, thermonuclear in nature. The type I bursting rate keeps increasing with the persistent luminosity, well above the threshold at which it is known to abruptly drop in other bursting low-mass X-ray binaries. The only other known source in which the bursting rate keeps increasing over such a large range of mass accretion rates is the 11 Hz pulsar IGR J17480–2446. This may indicate a similarly slow spin for the neutron star in the Rapid Burster.

Key words: stars: neutron – X-rays: binaries – X-rays: bursts – X-rays: individual: MXB 1730–335.

1 INTRODUCTION

First discovered by Lewin et al. (1976), the Rapid Burster (MXB 1730–335, hereafter RB) is a neutron star (NS) low-mass X-ray binary (LMXB) located in the globular cluster Liller 1, with a recent distance measurement of 7.9 ± 0.9 kpc (Valenti, Ferraro & Origlia 2010). It is a recurrent transient, which had very regular outbursts every \( \sim 210 \) d for most of the time up to MJD \( \sim 51500 \), after which the outburst recurrence time abruptly dropped to \( \sim 100 \) d (Masetti 2002).

The RB is unique in that it features both type I and type II bursts. While the former are due to the heating and cooling of the surface after a thermonuclear flash in the underlying layers (for a recent review see Galloway et al. 2008, hereafter G08), type II bursts are most likely due to the release of gravitational energy from the inner accretion disc during sudden accretion events (as first pointed out by Hoffman, Marshall & Lewin 1978), probably linked to magnetic gating of the accretion flow (Lamb et al. 1977; Spruit & Taam 1993; D’Angelo & Spruit 2010). Consequently, these two categories of bursts can differ greatly in duration, recurrence time, energy and spectral properties (for a review, see Lewin, van Paradijs & Taam 1993, hereafter LPT93).

Typically, type I burst recurrence times \( t_{\text{rec}} \) are of the order of hours. Although some type I bursts have been reported to recur within \( \sim 200 \) s (e.g. Keek et al. 2010) only one source – IGR J17480–2446, hereafter T5X2 – exhibited that behaviour for prolonged series of bursts lasting for hours, instead of multiple events consisting just of two, three or four bursts. Linares et al. (2012, hereafter L12) reported T5X2 to constantly increase in burst rate as its persistent luminosity rose from 0.1 to 0.5 of the Eddington luminosity \( L_{\text{Edd}} \), with bursts transitioning to a mHz quasi-periodic oscillation (QPO), with a period as short as 240 s.

This behaviour is well in agreement with models for thermonuclear bursts. Theory predicts the bursting rate to keep increasing with the persistent luminosity almost up to the Eddington limit, when stable burning sets in (Fujimoto, Hanawa & Miyaji 1981; Heger, Cumming & Woosley 2007); still, the burst rate for the majority of burst sources is observed to decrease dramatically above a few per cent of the Eddington luminosity (e.g. Cornelisse et al. 2003; fig. 16 in G08). Although the basic physics of type I bursts is well understood, this discrepancy between the expected and observed \( t_{\text{rec}} \) remains an unsolved issue in our understanding of the phenomenon.

The unusual properties of T5X2 probably set it apart from the other bursting sources, and could possibly explain its extremely regular bursting behaviour (L12). T5X2 is an 11 Hz pulsar with a reported magnetic field between \( 10^6 \) and \( 10^{10} \) G (Miller et al. 2011; Papitto et al. 2011), making it the slowest rotating pulsar known, and possibly one of the high magnetic field bursters as well. Slow rotation could prevent turbulent mixing from stabilizing burning at low mass accretion rates (Keek, Langer & in ’t Zand 2009) and reduces the influence of the Coriolis force on flame spread and confinement (Spitkovsky, Levin & Ushomirsky 2002). Magnetic confinement, which probably accounts for the presence of burst oscillations in T5X2 (Cavecchi et al. 2011), could limit...
burning to a constant portion of the stellar surface, while the burning area may vary with mass accretion rate in other sources (Bildsten 2000).

As already mentioned, the presence of type II bursts is probably indicative of a prominent dynamic role of the magnetic field B in the RB. We therefore seek to investigate whether its type I burst behaviour shows analogies to T5X2 that could be explained in terms of a slow spin or of surface magnetic field effects, related to a magnetic gating mechanism in the accretion flow.

We perform a systematic study of all the type I bursts from the RB detected with the Proportional Counter Array (PCA) onboard the Rossi X-Ray Timing Explorer (RXTE), increasing the number of bursts over that already known by a factor of 2. We observe bursts over one of the largest ranges in persistent flux, and interestingly find that the burst rate increases to high values with the mass accretion rate. We discuss the implications of this behaviour in our understanding of the peculiar RB.

Section 2 describes the data selection, with particular care devoted to how we excluded spurious bursts (type II, or type I from a different source). Section 3 explains the analyses, spectral and morphological, performed on the bursts and the persistent emission. In Section 4 we report our results on the burst behaviour as a function of the persistent luminosity of the RB. Finally, we discuss the implications of our findings for the burst regimes and the source spin in Section 5.

## 2 OBSERVATIONS

### 2.1 Data set

The PCA (Jahoda et al. 2006) consists of five co-aligned Proportional Counter Units (PCUs) that combine to a total effective area of 6000 cm\(^2\) at 6 keV, in a 2–60 keV bandpass. The photon energy resolution is 18 per cent full width at half-maximum at 6 keV and the time resolution is programmable down to 1 μs. The field of view (FOV) is circular, with radius ≈1° (full width to zero response).

The RB has been extensively monitored with the PCA, from the beginning of the mission in early 1996 until its shutdown in 2012 January. We collected all PCA data that we could find when the RB was in the FOV of an active PCU, for a total exposure time of 2.83 Ms [this is the sum of all so-called good-time intervals, excluding times when RXTE is slewing, near to a South Atlantic Anomaly (SAA) passage, or experiences a large particle rate].

A major issue of the PCA data is that the RB has an angular separation of only 0.56 to the persistently active burster 4U 1728–34. In fact, most observations (67 per cent) were aimed at 4U 1728–34. The RB was the aimpoint for 14 per cent of the time, so that both sources are in the FOV for 82 per cent of the time (including as well 1 per cent when neither source was at the centre of the FOV). During the remaining 18 per cent, the PCA aimpoint was offset so that only the RB is inside the FOV, decreasing the collimator response by a factor of ≥0.4, but allowing for spectroscopic measurements unaffected by contributions from other sources. We note that, due to the transient nature of the source, only 32 per cent of the data (or 0.91 Ms) were taken whilst the source was actually active.

### 2.2 Identification of RB type I bursts

We employed the STANDARD 1 data product, consisting of 0.125 s resolved photon count rates per PCU without any photon energy resolution, to search for bursts. Our method consists primarily of a computer algorithm to search for statistically significant upward fluctuations above a steady background on time-scales of 1–300 s. We verified the result of this search by a careful visual inspection of the light curves and the identified bursts. We additionally applied the criterion that the RB should be active, as may be verified with independent RXTE-All-Sky Monitor (ASM) or International Space Station (ISS)-Monitor of All-Sky X-Ray Image (MAXI) measurements, to exhibit bursts. The computer algorithm was set to accept fluctuations above the background if they have a significance accumulated over the burst that is at least 10σ and if they are accompanied by a stable pointing of the PCA. The algorithm is efficient as long as there are time intervals before or after a burst within 300 s where the background can be measured confidently. As a result some long type II bursts may be missed that have no flat background between them and bursts that occur during slews with the RB in the field of view. Through a visual inspection, however, we made sure that type I bursts with the typical fast-rise exponential-decay profile were included even if they occurred during a slew. We find a total of 7261 bursts, including 121 type I bursts and 7140 type II bursts. The latter number is a lower limit.

Type I bursts from 4U 1728–34 are easily recognizable by their short durations (≤10 s, typical of H-poor nuclear fuel) and by their brighter (often Eddington limited) peak fluxes, bimodally distributed about a mean of 9.2 × 10⁸ erg cm⁻² s⁻¹ for the bursts showing photospheric radius expansion (PRE) and 4.5 × 10⁸ erg cm⁻² s⁻¹ for normal bursts (Fox et al. 2001; Galloway et al. 2003; G08), a factor of 6 brighter than most bursts from the RB. For an angular separation of 0.56, this ratio decreases by 40 per cent when the RB is at the centre of the FOV and there are some type II bursts from the RB which come close to half the peak flux of bursts from 4U 1728–34. Still, these are rare and the bursts can be distinguished by their time profile.

It is also straightforward to exclude most type II bursts. Long-lasting, flat-topped bursts, preceded and followed by dips in the persistent emission are clearly recognizable as type II, as are the intermediate-duration bursts showing multipeaked decays (Tan et al. 1991). The shortest type II bursts, the only ones featuring single, short peaks and a fast rise, are potentially ambiguous. They however have very short (<10 s) decays and recur very fast in series of 8–40 bursts, making their cumulative energy release incompatible with a thermonuclear origin (LPT93, see Section 5 for further discussion). When a type I burst hides in a sequence of such bursts it is easily recognized by its much slower decay.

We nevertheless acknowledge that we could have erroneously misidentified a few type I bursts as type II. We intend to publish a comprehensive overview of all type I and II bursting behaviour of the RB elsewhere, with a detailed description of the burst identifications. Here we concentrate on the 121 type I X-ray bursts that we identified from the RB in the PCA data. 65 have already been reported (Fox et al. 2001; G08). Of these bursts, some have only been partially observed, due to their proximity to the beginning or end of a pointing, and some are surrounded or even covered by trains of fast-recurring type II bursts. These bursts are not suitable for analysis, especially when the persistent emission is very low, because part of the accretion is then taking place through the type II bursts, implying that in this case the persistent flux does not even qualitatively reflect the actual mass accretion rate on the surface, and a relation between burst properties and the persistent emission should therefore no longer be expected. Consequently, we only focus on type I bursts from observations in which no type II bursts were observed.
3 ANALYSIS

We set out to determine a number of key parameters for all bursts.

3.1 Burst durations and recurrence times

Using the 1 s resolution light curve, we modelled the tail of the burst light curve, when the intensity is less than 90 per cent of the peak intensity minus the pre-burst level, with one or – when necessary – two exponential decay functions. We used these fits to determine the burst duration $t_{\text{dur}}$, defined as the time difference between the burst start time (see G08) and the time when the intensity drops below 10 per cent of the peak intensity minus the pre-burst level, when the burst count rates are still significantly above the noise, so that variations in the persistent count rate do not affect our estimate of the burst duration. Generally speaking, single exponentials provide sufficiently good fits to shorter bursts ($t_{\text{dur}} \sim 50$ s), while two exponentials are necessary for longer bursts ($t_{\text{dur}} \sim 100$ s). Although such a definition of the burst duration is not affected by the varying noise level at different persistent count rates, the burst emission is still not over at $t_{\text{dur}}$. Spectra were therefore extracted up to the time $t_{\text{end}}$ when the intensity decreases to within 2σ of the pre-burst level.

We then used the exponential fits to estimate how much fluence of the burst may have been contained in the far tail of the light curve (i.e. after $t_{\text{end}}$). This factor, below 5 per cent for most bursts, was added to the burst fluence and to its uncertainty (see Section 3.2.2) to avoid a systematic effect towards less energetic bursts at higher persistent count rates.

The burst recurrence time $t_{\text{rec}}$ is defined as the time elapsed between the start time of the previous burst and that of a given burst. When data gaps occurred, the recurrence time was labelled an upper limit. In five cases, however, the observed $t_{\text{rec}}$ was very close to being an integer multiple ($\sim 2$ or 3 times longer) of the recurrence time observed in the adjacent bursts, which was seen to be stable over series of up to five bursts, and a burst occurring with the average value of $t_{\text{rec}}$ would have fallen in a data gap (see Fig. 1). Therefore, we assumed these bursts to be recurring on a regular time-scale and divided their observed $t_{\text{rec}}$ by the integer amount of times that gave a nearly constant burst rate.

3.2 Burst energetics

Throughout our analysis, the particle and cosmic background, as determined with FTOOL PCA BACKEST, were subtracted from all spectra. Response matrices were generated with PCARSP (v 11.7.1). All active PCUs were employed, and a correction was applied for deadtime (although it is always small for the RB). Low-energy absorption by the interstellar medium was taken into account using the model of Morrison & McCammon (1983), with an equivalent hydrogen column density of $N_H = 1.6 \times 10^{22}$ cm$^{-2}$ (Frogel, Kuchinski & Tiede 1995; Masetti et al. 2000; Falanga et al. 2004). Following the RXTE Cook Book prescription,1 the analysis was limited to the 3–30 keV range, and a systematic error of 0.5 per cent was added to the results.

To determine the energetics of the bursts and of the persistent emission, we performed a time-resolved spectroscopic analysis according to the following procedure.

1 See http://heasarc.nasa.gov/docs/xte/recipes/cook_book.html
than 1 h before or after the burst was often available. We used these uncontaminated spectra to estimate the persistent flux $F_{\text{pers}}$ in the range 3–25 keV, resorting to the same three-component model mentioned earlier. All but six such measurements were taken within 1500 s from the burst onset. In all cases, we took care to verify the stability of the average count rate over the interval between the measurement and the burst. The count rate variation in the RB over the course of an hour was always below 5 per cent. All fits were satisfactory, giving $\chi^2_{\text{red}} \lesssim 1.5$ for 40–50 degrees of freedom. Note that in the case of short recurrence time bursts, a single $F_{\text{pers}}$ measurement may apply to multiple bursts.

For each of these uncontaminated observations, a bolometric correction $c_{\text{bol}}$ was calculated from the portion of the observation excluding 4U 1728–34. We fitted an absorbed Comptonization model (COMPRT in XSPEC) to the spectrum extracted for each PCU in the energy range 3–25 keV, and integrated the best-fitting model to give the flux over this range. We then created (in XSPEC) a ‘dummy’ (ideal) response covering the broader energy range of 0.1–200 keV, and calculated the integrated, unabsorbed flux over that range. The bolometric correction for a given PCU was estimated as the ratio of these two fluxes, and the value adopted for each observation was the mean of the values for the active PCUs, with the standard deviation of the values over all PCUs adopted as the uncertainty. The Comptonization model was chosen over the phenomenological (disc blackbody plus power law) because the Comptonization model has a finite integral for any choice of the input parameters. In fact, because the persistent spectrum was generally soft, the electron scattering temperature $kT_e$ was typically a few keV, and could be well constrained by the spectrum up to 25 keV. For a few of the observations, the spectrum was harder, and in some cases the $kT_e$ could not be constrained by the fit. For most of those observations, the addition of a Gaussian component improved the fit sufficiently that the $kT_e$ could be constrained; for a few examples it was possible to constrain the plasma temperature for all but PCU #3, and for those observations that spectrum was excluded.

We adopt $F_{\text{pers}} = c_{\text{bol}} F_{3–25\text{keV}}$ as the bolometric intensity for the source in each observation. We also often refer to its ratio to the Eddington flux $F_{\text{Edd}}$. To derive the latter, we apply the distance estimate to the Eddington luminosity:

$$L_{\text{Edd}} = 3.5 \times 10^{38} \left( \frac{M}{1.4 M_\odot} \right) \left( \frac{1}{1+X} \right) \text{erg s}^{-1},$$

(1)

with $M$ the stellar mass and $X$ the hydrogen fraction (e.g. G08). This corresponds to an Eddington flux from the disc $F_{\text{Edd}} = 2.8 \times 10^{-8} \text{erg cm}^{-2} \text{s}^{-1}$ for a ‘canonical’ NS with mass $M = 1.4 M_\odot$ and radius $R = 10$ km, accreting solar-composition material ($X = 0.7$).

3.2.2 The bursts

The burst data were divided into a number of time bins, varying in duration to keep the photon count, and hence the relative error on the derived quantities, approximately constant. The bin duration was constrained to be at most 1 s during the burst rise, to be able to track the initially rapidly varying temperature. The minimum bin duration possible was constrained by the time resolution of STANDARD 1 data, at 0.125 s.

Spectra were extracted for each time bin from event files, the time resolution of which varied between 1 and 125 μs. The non-burst emission was not subtracted. Spectra during the bursts were modelled by the combination of blackbody radiation (leaving free temperature and emission area, to account for the varying burst emission, and multiplied by a model for interstellar absorption with $N_H = 1.6 \times 10^{22}$ cm$^{-2}$) and the model as found for the non-burst spectrum discussed above, keeping the parameters of the latter fixed to the pre-burst values.

The assumption underlying this ‘standard’ procedure is that $F_{\text{pers}}$ is constant during the burst. The well-known caveat (van Paradijs & Lewin 1986) is the possibility that the persistent emission actually varies during the burst, giving rise, for instance, to systematic errors for the radii that can get very large in the burst tails. Variations could arise because of radiation effects on the inner accretion disc, or because of the NS becoming sufficiently hot to contribute to the persistent spectrum. Worpel, Galloway & Price (submitted) noted a rise in persistent emission during radius-expansion bursts which they attribute to radiation drag effects. We performed a similar analysis, adding a multiplicative factor $f_a$ by which the persistent emission is multiplied, as a variable parameter in our spectral fits. However, even for the most luminous burst, the effect appeared negligible, with $f_a = 1.06 \pm 0.29$ at the burst peak. It therefore seems unlikely that this is a major factor for RB bursts, which are all significantly sub-Eddington.

The blackbody description of our burst spectra is always satisfactory. This simple, physically founded model provides a fairly accurate means to obtain bolometric fluxes and fluences as follows. The blackbody fit to each measured spectrum results in the measurement of two parameters: the temperature, expressed in $kT$, and normalization $N$, expressed in terms of the square of the radius in km of a sphere assumed to emit the blackbody radiation at a distance of 10 kpc. The values of both these parameters come with a 1σ uncertainty which defines a 68 per cent confidence margin for a one parameter fit. The burst bolometric flux is calculated from Stefan–Boltzmann law:

$$F_{\text{bb}} = 1.07 \times 10^{-11} N \left( \frac{kT}{1 \text{keV}} \right)^4 \text{erg cm}^{-2} \text{s}^{-1}.\tag{2}$$

To determine the uncertainty in $F_{\text{bb}}$, we sample 10 000 values of $kT$ and $N$ from Gaussian distributions centred at the fitted values and with standard deviations equal to the respective 1σ uncertainties, calculate for each sample $F_{\text{bb}}$ and from the 10 000 samples calculate the mean and standard deviation. The fluence is calculated from the sum of all bolometric fluxes times the integration times of the related spectra and the uncertainty in the fluence from the root of the quadratic sum of the uncertainty in all terms. Since the errors in $kT$ and $N$ were treated as if these parameters are independent, the error in the burst bolometric flux can be considered as conservative.

Some uncertainty remains for the fluence, for the burst radiation in the possibly long tail where it drowns in the noise. We estimated this tail contribution from the exponential fits discussed in Section 3.1.

3.2.3 Determination of $\alpha$ and $\beta$

The ratio of the integrated bolometric persistent flux to the burst fluence $\alpha \equiv F_{\text{pers}} f_{\text{bol}} / F_{\text{bol}}$ could be precisely determined only for 16 bursts. The other bursts suffered from source confusion (see Section 2.1) or data gaps making $t_{\text{bol}}$ only an upper limit. For five additional bursts, however, we could establish the recurrence time fairly confidently even in the presence of data gaps (see Section 3.1), bringing the total number of bursts with a known value for $\alpha$ to 21, including four bursts lacking spectral evidence for cooling in their decays (see Section 4.1). Errors on $F_{\text{pers}}$ and $F_{\text{bol}}$ are nearly always below 10 per cent, and the resulting errors on $\alpha$ are generally below 20 per cent.
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Figure 2. Fast recurring, non-cooling type I bursts. Concerning the offset in count rate around the last burst, see Fig. 1.

We also looked at the ratio of the burst peak to persistent flux \( \beta \equiv \frac{F_{\text{peak}}}{F_{\text{pers}}} \), which we could derive for 57 bursts. The errors on the peak flux were somewhat large, which propagated to errors on \( \beta \) getting large especially at the lower end of the \( F_{\text{pers}} \) range.

4 RESULTS

4.1 Lack of cooling

We fail to find evidence for cooling in six bursts, meaning the temperature difference \( \Delta T = T_{\text{peak}} - T_{\text{dur}} \) is consistent with zero within error bars, with the blackbody temperature \( T_{\text{peak}} \) measured at the flux peak and \( T_{\text{dur}} \) at the time \( t_{\text{dur}} \). They occurred at the beginning of the 1997 June–July outburst, at the highest level of \( F_{\text{pers}} \) we observed in all data (see Fig. 2). The highest value for which cooling is not observed is \( \beta = 0.37 \pm 0.09 \), while the lowest value among bursts with a cooling tail is \( \beta = 0.50 \pm 0.10 \). On average \( \beta = 0.30 \pm 0.13 \) for the non-cooling bursts. Their \( \alpha \) values range from 87 ± 13 to 153 ± 26, consistent with a thermonuclear origin, and they have time profiles typical for type I bursts (see Section 2.2). This convinces us that they are not type II bursts, for which reported values of \( \alpha \) range from 0.15 to 4.29 (Tan et al. 1991; Masetti et al. 2000).

4.2 Burst behaviour as a function of accretion rate

In Fig. 3 all burst parameters are plotted against the bolometric accretion flux \( F_{\text{pers}} \) and its ratio to the Eddington flux \( F_{\text{Edd}} \). The RB produces regular type I bursts over a much wider range of persistent flux than seen in other systems, from \((2.7 \pm 0.2) \times 10^{-9} \) to \((12.5 \pm 0.3) \times 10^{-9} \) erg cm\(^{-2}\) s\(^{-1}\) or between 10 and 45 per cent of \( F_{\text{Edd}} \).

Some trends in burst parameters versus persistent flux are clearly visible in Fig. 3. The ratio \( \beta \) clearly decreases with increasing \( F_{\text{pers}} \), until it falls below the threshold \( \beta = 0.7 \) which Linares, Chakrabarty & van der Klis (2011) suggest determines whether cooling can be detected in PCA data (Linares, Chakrabarty & van der Klis 2011). This is not only trivially due to the increase in \( F_{\text{pers}} \). The peak fluxes show a decreasing trend with increasing \( F_{\text{pers}} \), down from a maximum of \( F_{\text{peak}} = (13.6 \pm 2.6) \times 10^{-9} \) erg cm\(^{-2}\) s\(^{-1}\). On the other hand, the non-cooling bursts at the highest \( F_{\text{pers}} \) show much lower peak fluxes, averaging \( F_{\text{peak}} \simeq 3.7 \times 10^{-9} \) erg cm\(^{-2}\) s\(^{-1}\).

Figure 3. Peak flux \( F_{\text{peak}} \), ratio \( \beta \), fluence \( E_{\text{b}} \), burst duration \( t_{\text{dur}} \), burst recurrence time \( t_{\text{rec}} \), and ratio \( \alpha \) plotted against the bolometric unabsorbed \( F_{\text{pers}} \) (lower x-axis) and its ratio to the Eddington flux (upper x-axis). Horizontal error bars refer to the lower x-axis. Empty and filled symbols correspond to cooling and non-cooling bursts, respectively, triangles indicate upper or lower limits, squares refer to \( t_{\text{rec}} \) values (and the corresponding \( \alpha \) values) that were inferred dividing the observed value by an integer to match the ones in the nearby bursts (see Section 3.1). For the ‘cooling threshold’ at \( \beta = 0.7 \), see Section 4.2. The fit to \( t_{\text{rec}} \) is for cooling bursts only.
Most importantly, the recurrence time \( t_{\text{rec}} \) falls steadily with increasing \( F_{\text{pers}} \), down to a minimum of 467 s. Regardless of \( F_{\text{pers}} \), the bursts appear to be very regularly clocked (see Figs 1 and 2). A fit to the recurrence times yields a power law with index \(-1.81 \pm 0.04\). The fit however is unacceptably poor, with \( \chi^2_{\text{red}} = 22.1 \) for 22 degrees of freedom. Excluding the non-cooling bursts, this becomes a flatter \(-0.95 \pm 0.03\), with \( \chi^2_{\text{red}} = 3.46 \) for 17 degrees of freedom. The impossibility of fitting a single relation is due to the steepening of the relation in the non-cooling regime, as is clear from Fig. 3. However, too few non-cooling bursts are available and they span too narrow an \( F_{\text{pers}} \) range for a fit to this latter regime to be meaningful.

Despite the large spread in values, both \( E_b \) and \( t_{\text{dur}} \) seem to stay relatively constant until the highest persistent fluxes. A drop then occurs, coincidently with the disappearance of cooling from the burst spectra. One might suspect this to be due to the poorer statistics in the burst tail at large \( F_{\text{pers}} \) — a sizeable fraction of the burst fluence might be lost in the noise. However we defined \( t_{\text{dur}} \) and \( E_b \) exactly to avoid such an effect (see Section 3.1). We therefore believe this drop to be genuine. The average rise time shows no correlation with the persistent flux \( (t_{\text{rise}} \approx 7.1 \text{ s}, \text{ with standard deviation } \sigma \approx 2.1 \text{ s}) \), although its average value is different for the cooling and non-cooling bursts (6.8 and 9.6 s, respectively), perhaps hinting at a late change in bursting regime. Together with the change in burst duration \( t_{\text{dur}} \), which on the other hand seems to get shorter at the highest accretion rates, this makes for bursts becoming somewhat more symmetric in shape.

Excluding the bursts at the highest accretion rates, nearly constant \( \alpha \) values are observed for the cooling bursts, although at lower \( F_{\text{pers}} \) the longer \( t_{\text{rec}} \) means that only often upper limits on \( \alpha \) can be measured. For the cooling bursts for which \( \alpha \) is well constrained, on average \( \alpha \approx 46 \) with a standard deviation of \( \approx 10 \). Including the bursts for which we divided \( t_{\text{rec}} \) by an integer value estimated by comparison with the surrounding bursts (see Section 3.1 and Fig. 1) yields an average \( \alpha \approx 44 \) with a standard deviation of \( \approx 9 \), reinforcing our inference that our assumption of stable recurrence in the burst tail at large \( F_{\text{pers}} \) is a reasonably good approximation. For all but one burst we analysed, \( F_{\text{pers}} \) lies above this value and we confirm that no type II bursts are observable in the light curves. It is therefore unlikely that type II bursting activity resumes at the highest \( F_{\text{pers}} \) levels, with \( \alpha \) values two orders of magnitude larger than usual and smooth exponential decays rather than the multipeaked decays type II bursts of similar duration are reported to show (Tan et al. 1991).

The paucity of identified non-cooling bursts is due not only to the relatively short time the source spends at the highest accretion rates during an outburst, but also to the drop in outburst peak flux after MJD 51500. Masetti (2002) reported a drop in both the outburst peak flux and recurrence time by roughly by a factor of 2 after that date.

5.2 Bursting regimes

We showed that the RB keeps emitting type I bursts at an ever increasing rate, over a range of \( F_{\text{pers}} \) from \((2.7 \pm 0.2) \times 10^{-9} \) to \((12.5 \pm 0.3) \times 10^{-9} \) erg cm\(^{-2}\) s\(^{-1}\). Assuming a distance of 7.9 kpc, this corresponds to \((2.6 - 9.3) \times 10^{-7} \text{ erg s}^{-1}\), or \((10-45)\) per cent \( L_{\text{edd}} \). The X-ray flux is however known to be a poor proxy of the real mass accretion rate (van der Klis 2001), so that the real range in \( M \) that the source is spanning remains uncertain. Accounting for the uncertainty in the distance, the maximum luminosity at the time of a burst ranges between 35 and 53 per cent of \( L_{\text{edd}} \).

The burst rate keeps increasing over such a large range in \( F_{\text{pers}} \), which is a striking similarity between the RB and T5X2, and it sets these two sources apart from all other known bursters (e.g. Cornellisse et al. 2003; fig. 16 in G08). The trend in \( F_{\text{peak}} \) is also similar. As mentioned, we do not observe a continuous decrease in \( E_b \) and \( t_{\text{dur}} \). These trends are, however, rather dubious in T5X2 when looking at the individual bursts, and only become clear switching to the daily averages of these burst properties (see figs 7 and 9).
in L12). A larger number of available bursts in T5X2 is due to a bursting rate that initially grows faster: \( t_{\text{rec}} \propto F_{\text{pers}}^{-1.5} \), up to \( F_{\text{pers}}/\dot{M}_{\text{Edd}} \simeq 0.3 \), after which it settles on a flat \( t_{\text{rec}} \propto F_{\text{pers}}^{-1} \). The latter relation seems closer to the one followed by the RB for all but the highest \( F_{\text{pers}} \) levels: excluding non-cooling bursts, we fit \( t_{\text{rec}} \propto F_{\text{pers}}^{\alpha \approx -0.95 \pm 0.03} \).

This is consistent with the empirical relations \( t_{\text{rec}} \propto F_{\text{pers}}^{-1.05} \) found in GS 1826–24 (Galloway et al. 2004) and \( t_{\text{rec}} \propto F_{\text{pers}}^{-1.1} \) in the accreting millisecond pulsar IGR J17511–3057 (Falanga et al. 2011), and it is indicative of a fuel with a significant H fraction, where the proportionality expected is roughly \( t_{\text{rec}} \propto m^{-1} \), while the steeper index initially observed in T5X2 agrees with models for pure He burning (Cumming & Bildsten 2000). In the RB there seems instead to be a transition from a flatter to a steeper regime, but the data are too limited to measure the slope of the latter.

All bursts have \( \alpha \) values between 35 ± 5 and 153 ± 26, with a weighted average \( \alpha = 44 \pm 14 \). Values of \( \alpha \) for the cooling bursts are indicative of a fuel composition that is compatible with the solar H abundance, in line with the observed long burst durations typical of the H burning rp-processes. The higher \( \alpha \) values that are measured at the highest levels of \( F_{\text{pers}} \) are unlikely to be due to a smaller H fraction in the burst fuel, as this is the opposite of what would be expected for the burst with the shortest \( t_{\text{rec}} \). Instead, the sudden rise in \( \alpha \) might be due to the onset of semistable He burning in between the bursts. If some fraction of the fuel is burning in between bursts, this will make overall less material available to burn in a burst, therefore, reducing the fluence and making \( \alpha \) grow larger.

This explanation seems to be backed up by theoretical modelling of the burst time-scales and energetics in this transitional regime. Keek, Heger & in ’t Zand (2012) studied models of the NS envelope after a superburst. Bursting is initially quenched because of the hot envelope; the first bursts reappearing after the superburst are less energetic, feature a slower rise and a faster decay than the bursts before it. As the envelope cools down further, \( t_{\text{rec}} \) become longer, \( t_{\text{rise}} \) shortens, \( t_{\text{dur}} \) lengthens and the bursts become again as energetic as they were before. We suggest that the same transition could be taking place in the RB as the mass accretion rate decreases during the outburst decay. Unfortunately, no observations are available for the time prior to the appearance of the non-cooling bursts to look for stable burning or the mHz QPOs expected from marginally stable burning at higher mass accretion rates.

It is also worth pointing out that we are not looking at the so-called short-waiting-time bursts described by Keek et al. (2010), which are thought to be due to incomplete burning of the fuel in the preceding burst, leading to rapidly following, smaller bursts, in sequences of up to four events. Within such sequences, the bursts following the first one are on average less bright, cooler and less energetic than the initial burst, and their decay profiles lack the longer decay component from the rp-process, suggesting they take place in a hydrogen-depleted layer. These short-waiting-time bursts show \( \alpha \simeq 5 \) (Boirin et al. 2007), a value so low that the fuel must be left over from the preceding burst. We therefore exclude this incomplete-burning scenario to explain the very short \( t_{\text{rec}} \) we report in the RB, given the stability of the burst properties across multiple events, the long burst tails indicating the presence of H-burning processes and the aforementioned \( \alpha \) values typical of ordinary type I bursts and the largest in the sample.

### 5.3 Bursts at the highest \( \dot{M} \): indications for a slow spin?

That the bursting rate keeps increasing over such a large range in \( F_{\text{pers}} \) is a striking similarity between the RB and T5X2. Such behaviour, although predicted by theory (Fujimoto et al. 1981; Heger et al. 2007), has so far been reported in no other source.

When analysing a sample of BeppoSAX Wide Field Camera (WFC) data on nine X-ray bursters, both transient and persistent sources in the Galactic Centre, Cornelisse et al. (2003) found the burst rate to peak at \( L \simeq (1.4–2.1) \times 10^{37} \) erg s\(^{-1} \) before dropping by a factor of 5. Above this threshold, all sources also showed significantly shorter bursts, recurring less regularly. It is difficult to interpret this change in behaviour. Cornelisse et al. (2003) suggested that it might be due to the transition from unstable to stable burning, so that bursts above the critical luminosity are in a pure He regime (the so-called case 2; Fujimoto et al. 1981), where they take a longer time to build up and have much shorter (\( \lesssim 10 \) s) tails due to the absence of prolonged H burning via the rp-processes (LPT93). He burning has a much stronger \( T \) dependence, meaning local conditions set by perturbations in the layer steadily burning H have a larger importance in setting ignition conditions, leading to variations in \( t_{\text{rec}} \). This seems however an unlikely explanation.

First, \( \alpha \) values should increase significantly while switching to the less efficient burning of He, contrary to the result of G08, who reported \( \alpha \) values above the threshold to stay constant or decrease slightly. Secondly, after an initial drop, the bursting rate should start again increasing through the transition from case 2 to case 1 (the He triggered, mixed H/He bursts), again contrary to what is observed.

Thirdly, case 1 bursts have been observed at lower mass accretion rates (e.g. in GS 1826–24; Galloway et al. 2004), suggesting the transition from case 3 to case 2 takes place at lower \( \dot{M} \). Another possibility is that this threshold corresponds to the onset of semistable He burning (e.g. in ‘t Zand et al. 2003), which starts depleting the layer of nuclear fuel. The theory of thermonuclear burning however places such a transition near at or above Eddington luminosities, inconsistent with the low luminosity (around 10 per cent of \( L_{\text{Edd}} \)) at which it is observed (Cornelisse et al. 2003; G08). A final possibility involves variation in burning area. As pointed out by Bildsten (2000), the observed flux only reflects the overall mass accretion rate \( \dot{M} \), while the burning regime depends on the mass accretion rate per unit area \( \dot{m} \equiv \dot{M}/A_{\text{eff}} \), with \( A_{\text{eff}} \) the surface area of the igniting region. If this area increases with a stronger than linear dependence on \( \dot{m} \), it might actually decrease with increasing persistent flux.

T5X2, by contrast, is very different and behaves more in line with theoretical expectations. L12 reported that T5X2 showed a constant increase in burst rate as its persistent luminosity rose from 0.1 to 0.5 \( L_{\text{Edd}} \), with bursts gradually evolving into a mHz QPO (with a period as short as 240 s) until the onset of stable burning. They posited that this (up to then) unique match between theory and observations was due to the very slow spin of T5X2. Spinning at only 11 Hz, T5X2 rotates an order of magnitude more slowly than all other bursters whose rotation rate has been measured via burst oscillations. At 11 Hz, rotation is only minimally dynamically relevant, whereas at 100 Hz and above its effects are much stronger (Watts 2012). Rotation should, for example, affect the burning process (and its stability) by triggering turbulent mixing (Keek et al. 2009). This would stabilize He burning at lower accretion rates per unit area than for a non-rotating source, skewing the theoretical prediction.

Given the relatively strong \( B \) field in T5X2, one might wonder whether it is the magnetic field rather than the rotation rate that determines the unusual bursting behaviour in this source. Although the field is weak enough that fuel confinement is unlikely to be effective (Brown & Bildsten 1998), Cavecchi et al. (2011) argued that dynamical magnetic effects may act to confine the spreading flame front after ignition, leading to stalling and explaining the
presence of burst oscillations in this source. Magnetic channelling should also lead to a reduction in shearing instabilities and rotational mixing in the surface layers independent of the slow rotation (L12). Without further study, it has been hard to distinguish these two possibilities for T5X2. However the RB may provide a clue, since in this source there is no evidence for magnetic channelling (in the form of persistent accretion-powered pulsations).

If rotation rate is the main factor determining the bursting behaviour in T5X2, then the similarity exhibited by the RB implies that it too may rotate slowly. Patruno et al. (2012) argued that T5X2 has entered its spin-up phase in an exceptionally recent time (a few 10 yr), and that also the total age of the binary is extremely low (∼10 yr). It therefore has not only a slow spin, but also a relatively high magnetic field (between 10⁸ and 10¹¹ G; Miller et al. 2011; Papitto et al. 2011). If the RB also rotates slowly, one may speculate that it too is at a similar evolutionary point, a young LMXB with a strong magnetic field. Where it differs from T5X2, however, is that it also exhibits type II bursts. Interestingly, the only other source known to exhibit type II bursts is the slow pulsar GRO J1744–28, which spins at just 2.14 Hz (Finger et al. 1996). It has a reported magnetic field in the range (2–20) × 10¹⁰ G (Sturner & Dermer 1996; Cui 1997), intermediate between the weak fields (B ≤ 10¹⁰ G) thought to reside in LMXBs and the strong fields (B ≃ 10¹²–10¹³ G) found in X-ray pulsars. The B value for GRO J1744–28 is probably large enough to confine burning to a stably burning portion of the surface, explaining the lack of type I bursts.

Confirming the spin rate of the RB is unfortunately difficult, since to date there have been no observations of either accretion-powered pulsations or burst oscillations from this source. A low significance claim of a 306 Hz modulation in a set of stacked burst spectra was reported by Fox et al. (2001). However results from stacked burst spectra have in the past proved misleading, see for example the case of EXO 0748–676: stacked burst spectra suggested a spin of 45 Hz (Villarreal & Strohmayer 2004) whereas the true burst oscillation frequency is now known to be 552 Hz (Galloway et al. 2010). G08 have also already searched for burst oscillations, but only for frequencies above 10 Hz. We are planning a more thorough and dedicated investigation, to look into the overall timing behaviour of the source, with particular regard to low-frequency phenomena (Bagnoli, in’t Zand & Watts, in preparation).

The lack of persistent pulsations or magnetically confined burst oscillations could be explained by scattering in an optically thick Comptonizing cloud, which might degrade the signal and hide the modulation (Titarchuk, Cui & Wood 2002), although this seems to be an unlikely explanation for at least three other LMXBs (Göğüş, Alpar & Gilfanov 2007). Alternatively, no pulsations would be observed if the dipole moment of the magnetic field were very closely aligned with the rotation axis of the NS (Chen & Ruderman 1993). Indeed this would be supported by models for type II bursts (e.g. Spruit & Taam 1993) that involve unstable disc–magnetosphere interactions in which matter builds up at the magnetospheric radius until a critical gas pressure is reached. This would not be possible in a highly inclined dipole model, where matter can always stream directly to the star along a field line. More stringent constraints come by D’Angelo & Spruit (2011, 2012), who argue episodic accretion occurs because of an inner disc radius hovering around the corotation radius rc (the radius at which the Keplerian frequency equals the NS spin). They notice that the kind of instability they model would not be possible in the case of a strongly misaligned dipole, where at different longitudes the disc would be truncated inside and outside rc, thereby always allowing for some accretion to occur (Perna, Bozzo & Stella 2006) and preventing the build-up of a mass reservoir to release later in a type II burst. Although such a strongly aligned configuration might seem unlikely, especially for relatively young systems, this is in agreement with the fact that we only know two type II burst sources, compared to over a hundred type I bursters. T5X2 could perhaps not show type II bursts because it is a more strongly misaligned rotator than the RB and the bursting pulsar.

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REFERENCES


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