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The Periodic Bursters XB 1323–619 and GS 1826–24: Longterm Evolution of the Nuclear Burning régime and Comparison with Theory

M. Bałucińska-Church[1,2] ⋆, D. Reed[1] and M. J. Church[1,2]

[1] School of Physics and Astronomy, University of Birmingham, Birmingham B15 2TT, UK
[2] Astronomical Observatory, Jagiellonian University, ul. Orla 171, 30-244, Cracow, Poland

Abstract The majority of X-ray burst sources do not display a burst rate that increases with luminosity as expected, but this is seen in the two clocked bursters XB 1323–619 and GS 1826–24. We present a detailed investigation of these two sources which in the case of the first source, spans 18 years. Based on measurements of the burst rate, X-ray luminosity, the α-parameter and the two time constants generally present in the burst decays, we demonstrate the importance of the *rp* nuclear burning process. A detailed comparison with theory shows that although the burst rate in each source agrees well with the theoretical value, there is a difference of more than a factor of 5 in the burst rate at a given luminosity between the sources. We show that the main reason for this is that the two sources have substantially different emitting areas on the neutron star in non-burst emission, a factor often neglected. Variation of this area may explain the inverse relation of burst rate with luminosity in the majority of burst sources.

Key words: physical data and processes: accretion: accretion disks — stars: neutron — stars: individual: XB 1323–619, GS 1826–24 — X-rays: binaries

1 INTRODUCTION

X-ray bursting has been known for many years (Grindlay et al. 1976) as a phenomenon taking place in many low mass X-ray binaries (LMXB) of luminosities less than 10^{38} erg s^{-1} consisting of a rapid rise in intensity by a factor of $\sim$20, followed by an exponential decay over about 50 seconds and repeating on a timescale of hours. Bursting is usually not seen in higher luminosity sources forming the Z-track class which exhibit intensity increases as flaring over much longer timescales. Thus if we divide LMXB by luminosity into Atoll or Z-track sources, X-ray bursting is generally observed in the Atoll class. Bursting appears unrelated to inclination angle since it is seen not only in Atoll sources not displaying orbital-related behaviour but also in dipping sources which are seen at high inclination. X-ray bursting has been extensively studied (Lewin et al. 1995; Strohmayer & Bildsten 2006) and it was realized at an early stage to consist of unstable nuclear burning. Measured values of the α-parameter, defined as the ratio of the energy released in steady mass accretion to the integrated energy of the burst, agreed well with values expected for unstable burning. Thus X-ray bursting was recognized as explosive burning of recently accreted material on the surface of the neutron star (Woosley & Taam 1976), the material building up on the neutron star over a period of hours.

In spite of this, understanding of X-ray bursting is relatively poor. On the above basis the rate of X-ray bursting would be expected to be generally stable when the luminosity of a sources is stable since then the mass accretion rate $\dot{M}$ is stable, but bursting rate is rather erratic in most sources. Even worse, the rate of bursting should increase when source luminosity increases, as less time is required to accumulate the

⋆ E-mail: mbc@star.sr.bham.ac.uk

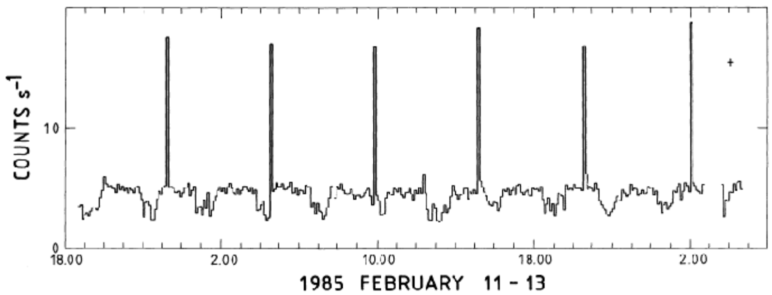

Fig. 1 *Exosat* lightcurve of XB 1323–619. Regular bursting takes place every 5.33 hr whereas X-ray dipping occurs at the orbital period of 2.93 hr.

necessary mass and achieve the required plasma density and temperature on the surface of the neutron star for unstable burning, but many sources display the opposite of this (van Paradijs et al. 1988).

In two sources, which may be called the "clocked bursters", bursting is close to being exactly periodic and the burst rate increases with luminosity: GS 1826–24 (the original clocked burster) and XB 1323–619 which we have studied over an extended period as one of the $\sim$10 dipping LMXB. In the present work, we make detailed comparisons of these two well-behaved sources with each other, and with the theory of unstable burning, to identify the reasons why the sources differ so much from each other, and to try to understand their behaviour in terms of theory. This would facilitate the understanding of the majority of burst sources that are not well-behaved.

2 RESULTS OF ANALYSIS OF XB 1323–619

2.1 Evolution of Burst Rate and Luminosity

An example of regular bursting from the *Exosat* observation of XB 1323–619 is shown in Figure 1 (Parmar et al. 1989). We have observed this source subsequently using *ASCA*, *BeppoSAX* (Bałucińska-Church et al. 1999), *Rossi-XTE* (Barnard et al. 2001) and *XMM* (Church et al. 2005). We show here a compilation of results from these observations covering the period 1985 to the present. In the case of the *Exosat* observation we have analysed the archival data to derive the burst decay time constants not previously obtained as described below. In all of these observations it was clear that the bursting remained regular; however the rate of bursting clearly increased. In all cases the occurrence of bursting was consistent with a regular rate so that in sections of data without bursting, the bursting would have occurred in data gaps due to Earth occultation and South Atlantic Anomaly passage. The increase of burst rate was due to the increase in mass accretion rate shown by the systematically increasing X-ray luminosity (see below and Fig. 3). In the case of the *XMM* observation, the burst rate appeared less regular, and there was more variation in the burst height than previously seen.

In Figure 2 we show the mean time between bursts Δt as a function of time measured in Modified Julian Days for all of the observations with X-ray telescopes since 1985, including 3 observations with *RXTE*. The last observation shown is the 2003 observation with *RXTE*. With the exception of this last observation there is a remarkable linearity of Δt with MJD such that, if continued, Δt would become zero on January 11, 2008. In reality, Δt could not actually become zero, although a very fast burst rate may be possible. In fact, the pattern of behaviour changes before the 2003 *RXTE* observation as the point for this observation departs significantly from the linear relation of Δt versus time.

The 1 – 10 keV X-ray luminosity (non-burst) was increasing non-linearly during this period of 1985 – 2003, as shown in Figure 3 (left panel), which also clearly shows the sharp drop in luminosity in the 2003 *RXTE* observation. However, the dependence of burst rate ($1/\Delta t$) on luminosity was linear, as shown in the right panel, and this linear dependence confirms that XB 1323–619 behaves as expected from theory. Moreover, when the luminosity decreased in 2003, the point for the 2003 *RXTE* observation continued to follow the same linear relation.

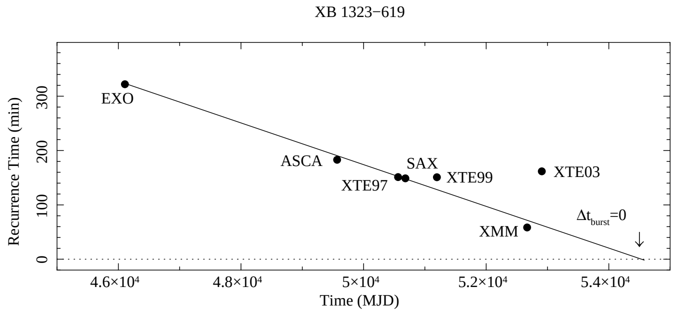

Fig. 2 Evolution of bursting in XB 1323–619 as a function of time: 1985–2003.

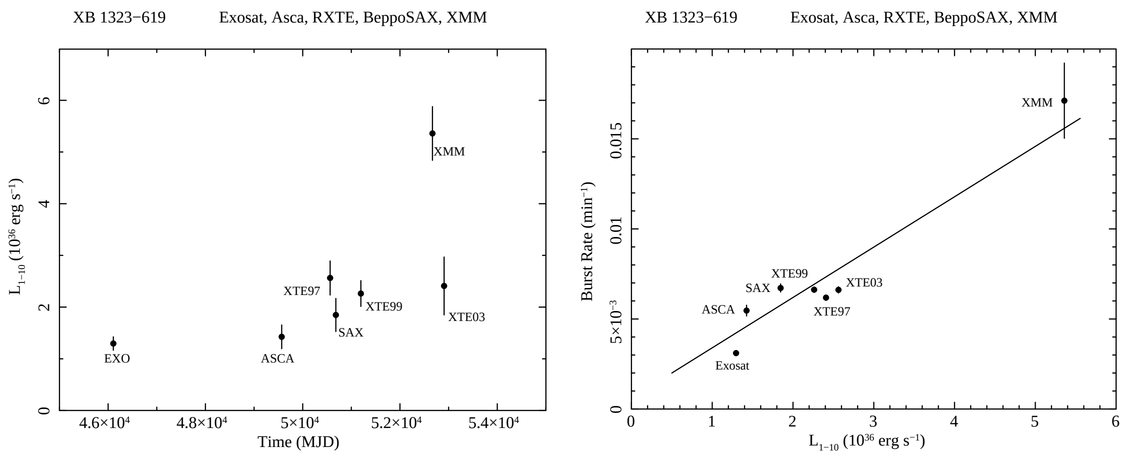

Fig. 3 Left: evolution of X-ray luminosity with time; right: the linear dependence of burst rate on luminosity.

2.2 Evolution of Nuclear Burning Régime and Burst Profile

In Figure 4 we show our measurements of the α-parameter, defined as the ratio of the non-burst fluence to the burst fluence. In this figure, the bursts are shown equally spaced as a time sequence ignoring the large time gaps between observations. The burst fluence was obtained by spectral fitting, for example, in the *RXTE* data dividing the burst into 2-second long spectra and fitting each of these with a blackbody model so as to obtain the flux in each segment, and adding these. In some cases, this was not possible because of the limited number of counts in each burst. In this figure, we include a point for the single burst in the 1984 *Exosat* observation, which did not allow plotting in the previous figures as the burst rate was unknown. It can be seen that until the *XMM* observation, there was a constant α of $\sim$45. A value of 30 would show H burning and values of 100 more would indicate He burning based on the known nuclear energy release per reaction, thus the results show mixed H and He burning. In *XMM* a much higher $\alpha \sim$100 – 150 was seen showing an increased contribution of He burning.

For all of the observations, we also examined the exponential burst decays, fitting these to obtain the decay time constants as shown in Figure 5. Generally, each burst consisted of a normal fast decay with τ_1 $\sim$5 s, followed by a much slower second decay, i.e. a long tail to each burst with τ_2 $\sim$40 s, indicative of the rp burning process. A pre-cursor is formed in the initial fast burning but the further burning is rate limited at so-called waiting points in the reaction chain. The rp-process takes place when the stable burning between bursts causes higher temperatures. Firstly, the CNO cycle becomes the hot CNO cycle at 2×10^8 K, since proton capture by ^{13}N becomes faster than β-decay. At 4×10^8 K, production of ^{17}F, ^{18}Ne and ^{18}F occurs, till at 8×10^8 K, ^{21}Na and ^{19}Ne form break-out products for the cycle and these are the seeds for successive

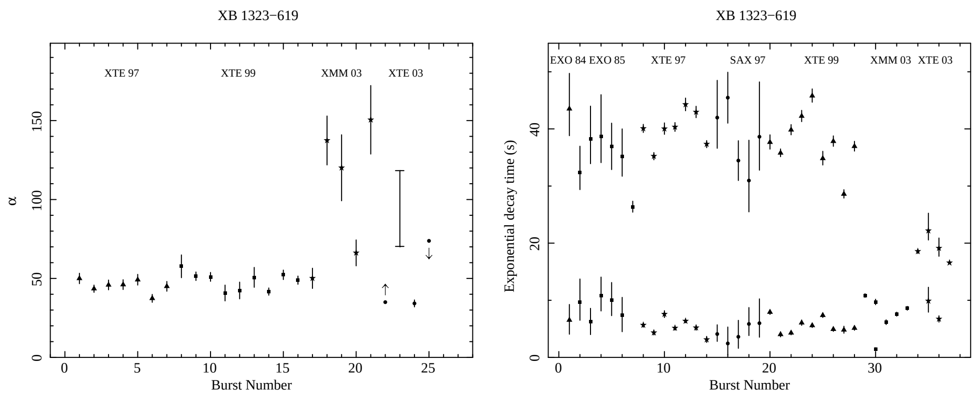

Fig. 4 Left: Variation of the α-parameter showing the strong change in the nature of nuclear burning; right: time constants of the burst decays: τ_1 for the prompt decay, and τ_2 for the later slow decay of the burst (see text).

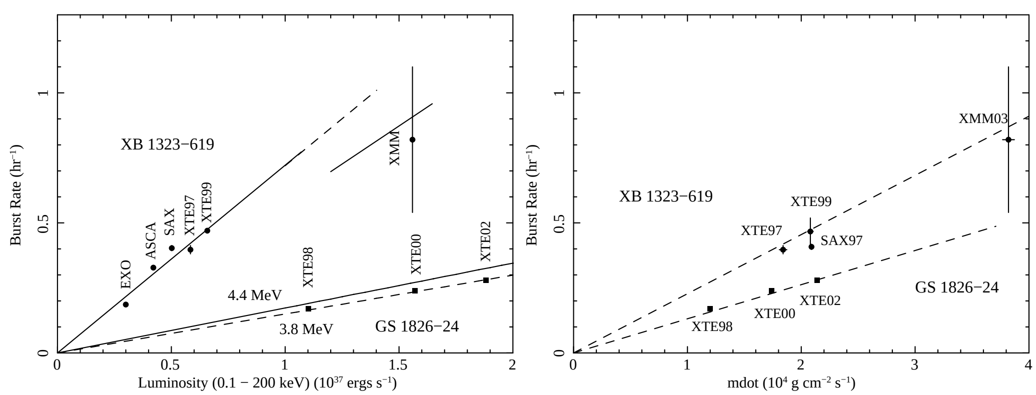

Fig. 5 Comparison with theory. Left: burst rate as a function of luminosity showing the major difference in burst rate between the two sources; right: burst rate re-plotted as a function of $\dot{m}$ showing the much more consistent behaviour of the two sources.

proton capture in the rp-process forming heavy elements. In most of the historical observations, the long tail in each burst exists. However, following the change of behaviour of bursting that was seen in the *XMM* observation, the long tail was not seen and the subsequent reduction in τ_2 (Fig. 4) indicates less rp-burning, a reason for which may be the more complete burning of H to He inbetween bursts. This is consistent with the increase of α seen with *XMM* as expected if the length of each burst is reduced so that the burst fluence decreases.

3 COMPARISON OF XB 1323–619 AND GS 1826–24

During the present work we also carried out a reanalysis of the three *XTE* observations of GS 1826–24 made in 1998, 2000 and 2002, analysis having previously been made by Galloway et al. (2004). We found complete agreement with their work and in addition were able to obtain bolometric X-ray luminosities in the wide band 0.1 – 200 keV as used below. In Figure 5 we show the measured burst rates in both sources as a function of X-ray luminosity L. In XB 1323 – 619 the 0.1 – 200 keV flux and luminosity were also obtained from our best-fit spectral models in each observation. Both sources behave as expected by simple theory, the burst rate increasing linearly with L.

The luminosity L depends on mass accretion rate $\dot{M}$:

$$L = \frac{GM}{R} \cdot \frac{\Delta M}{\Delta t} \quad \text{so that} \quad \Delta t = \frac{GM\Delta M}{RL}$$

where Δt is the burst recurrence time and ΔM is the so-called ignition mass that accumulates between bursts. The ignition mass is obtained from the measured burst fluence F and the theoretical energy release per gram of burning matter E via $\Delta M = F/E$, where E is 4.4 MeV per nucleon for the rp-process (Fujimoto et al. 1987). In the case of XB 1323–619, ΔM is found to be 2.68×10^{20} g leading to a theoretical rate of bursting: $(\Delta t)^{-1} = 0.719\, L_{37}$ hr^{-1} for M = 1.4 $M_{\odot}$ and R = 10 km. In Figure 5 we plot this theoretical relation which was obtained using data from the 1997 and 1999 *RXTE* observations. It is clear that all of the data points lie well on this line, confirming that the nature of the nuclear burning did not change in any of the observations before that with *XMM*. In *XMM*, the measured fluence changed substantially so the theoretical line was re-calculated and plotted separately. In all cases, however, there was good agreement with theory. In the case of GS 1826–24, Galloway et al. (2004) obtained the value of E by fitting the data as shown in Figure 5. We show two theoretical lines: one for E = 3.8 MeV per nucleon (dashed) as obtained by Galloway et al., and also the line for 4.4 MeV per nucleon, which does not fit so well.

Thus in each source there is good agreement with theory derived on known energy releases and the measured burst fluences in each case. However, the slopes of the linear dependences on L differ by the large factor of 5.5 showing a major differences between the two clocked bursters, and it is this difference we aim to understand. The right panel of Figure 5 shows the same results, but plotted as a function not of luminosity proportional to mass accretion rate $\dot{M}$, but of $\dot{m}$, the mass accretion rate per unit X-ray emitting area of the neutron star, on the basis that this is the more important parameter in the theory of stable and unstable nuclear burning (e.g. Bildsten 1998). It can immediately be seen that the difference between the two sources is substantially reduced to the 40% level. This is discussed in more detail below.

4 DISCUSSION

To obtain $\dot{m}$ as measured during a burst, we needed the blackbody emitting area, and this was simply derived using the blackbody radius $R_{\rm BB}$ obtained at the peak of the burst by spectral fitting, giving the area $A = 4\,\pi\, R_{\rm BB}^2$ and thus $\dot{m} = \dot{M}/A$. Figure 5 (right) shows that although GS 1826–24 was at all times substantially more luminous than XB 1323–619, the sources were more equal in terms of $\dot{m}$. The values of $\dot{m}$ of about 2×10^4 g cm^{-2} s^{-1} lie in the régime of nuclear burning where He burns unstably in a mixed H/He environment (Fujimoto et al. 1981; Fushiki & Lamb 1987; Bildsten 1998). We note that we could have assumed the whole neutron star was bursting but in this case the nuclear burning would be He burning in a He environment - not as seen. Or we could possibly use the non-burst $R_{\rm BB}$ from spectral fitting typically 1 km in which case $\dot{m}$ would be 2×10^5 g cm^{-2} s^{-1}, i.e. in the stable region of nuclear burning - clearly incorrect, showing that the approach of measuring $R_{\rm BB}$ at the peak of bursts was correct.

In our previous *ASCA* survey of LMXB, we investigated the relative luminosities of the neutron star blackbody emission and that of the dominant Comptonized emission of the ADC, in view of the small contribution of the blackbody in most LMXB when simple theory suggests it should be $\sim$50%. The results revealed a simple geometric relation that the height of the emitter on the neutron star was equal to the height of the inner accretion disk obtained from the measured luminosity using standard disk theory (Church & Bałucińska-Church 2001) valid over 3 decades of source luminosity. On the basis of this we are able to calculate the half-height of the emitter h of the non-burst emission in the two sources, which is difficult to measure by spectral fitting in these weak sources, and compare this with the values derived from spectral fitting in bursts:

XB 1323–619: h = 0.10 km, burst h = 1.4 km.

GS 1826–24: h = 0.75 km, burst h = 3.8 km.

It is clear that the smaller non-burst h leads to a burst involving less area on the neutron star. Clearly also, a spreading of the unstable burning takes place giving a large increase in area compared with non-burst emission, and the larger the initial area, the more the area after spreading.

5 CONCLUSIONS

We have shown that marked differences in the burst rate occur between XB 1323–619 and GS 1826–24. and have shown that the difference is mostly due to the very different emitting areas of non-burst emission on the neutron star, a factor that has not generally been allowed for in discussion of X-ray bursting. If we view the burst rate as a function of $\dot{m}$, the accretion rate per unit emitting area, we find that the sources follow relations that agree within 40%, so that both can be explained to this accuracy by the same model. It is expected that the non-burst emitting area will be an important factor in the other burst sources and in future work we will test the hypothesis that in sources where the burst rate decreases with L, this behaviour can be explained in terms of the non-burst area increasing with L so that $\dot{m}$ decreases.

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DISCUSSION

BOŻENA CZERNY: Can you apply the model of the boundary layer to the spread of the burning material, e.g. by taking into account the increase of the pressure due to burning ?

MONIKA BAŁUCIŃSKA-CHURCH: The model of Inogamov & Sunyaev for the spreading accretion layer on the surface of the neutron star includes pressure in describing the spreading layer atmosphere, so, in principle, it may be possible to allow for increased pressure.