Thermonuclear burst physics with RXTE

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Abstract. Recently we have made measurements of thermonuclear burst energetics and recurrence times which are unprecedented in their precision, largely thanks to the sensitivity of the *Rossi X-ray Timing Explorer* (*RXTE*). In the "Clocked Burster", GS 1826−24, hydrogen burns during the burst via the rapid-proton (rp) process, which has received particular attention in recent years through theoretical and modelling studies. The burst energies and the measured variation of alpha (the ratio of persistent to burst flux) with accretion rate strongly suggests solar metallicity in the neutron star atmosphere, although this is not consistent with the corresponding variation of the recurrence time. Possible explanations include extra heating between the bursts, or a change in the fraction of the neutron star over which accretion takes place. I also present results from 4U 1746−37, which exhibits regular burst trains which are interrupted by "out of phase" bursts.

INTRODUCTION

Unstable thermonuclear ignition of accreted fuel on neutron stars (NSs) in low-mass X-ray binaries (LMXBs) is triggered once a critical column density is reached in the fuel layer (e.g. [1]). Regular bursting is surprisingly uncommon, and only one source is known to consistently burst regularly (GS 1826−24; [2]). The conditions required for regular bursting likely include steady accretion and uniform spreading of the accreted fuel over the NS surface, as well as complete fuel consumption. If the accretion rate is sufficiently steady the critical density for ignition will be reached after a fixed time. If, additionally, all the accreted fuel is burnt during each burst, then each burst will be ignited after the same interval, leading to regular bursting. Clearly, relaxation of any one of these conditions will lead to variations in the burst interval, and deviations away from regular bursting.

Here we present recent results obtained via measurement of thermonuclear burst properties in GS 1826−24 and the globular cluster source 4U 1746−37 with *RXTE*. In GS 1826−24 we found regular bursting at a range of accretion rates, which allows us to constrain the composition of the burning fuel. In 4U 1746−37 we found trains of regular bursts interrupted by bursts which were "out of phase". We discuss possible mechanisms for this phenomenon, as well as future observational tests to distinguish between them.

OBSERVATIONS AND ANALYSIS

We obtained public *RXTE* data from the HEASARC archive at `http://heasarc.gsfc.nasa.gov` and searched for bursts in 1-s binned Standard-1 data. We found a total of 24 bursts from GS 1826−24, and 28 bursts from 4U 1746−37. For each burst we extracted full-range (2–60 keV) time-resolved spectra every 0.25 s from high-time resolution PCA data modes (GoodXenon or Generic Event, where available), and fitted an absorbed blackbody to each spectrum after subtracting the persistent emission. We estimated the observed bolometric flux from the blackbody fit parameters, and accumulated the measured fluxes to derive the burst fluence. We also extracted non-burst spectra from both PCA and HEXTE (15–200 keV) and fitted to absorbed Comptonisation models in order to estimate the persistent flux level, and hence the accretion rate $\dot{M}$. Full details of the analysis procedures may be found in Galloway et al. 2004, in preparation.

We also made simulations to predict ignition conditions for thermonuclear bursts following [3]. We calculate the temperature profile of the accumulating layer of hydrogen and helium, and adjust its thickness until a thermal runaway occurs at the base. The temperature is mostly set by hydrogen burning via the hot CNO cycle, and therefore the CNO mass fraction Z, which we refer to as the metallicity. We assume a constant level of flux from the crust, at $Q_{\rm crust} = 0.1$ MeV per nucleon [4].

RESULTS: GS 1826−24

We observed bursts from GS 1826-24 over a factor of 1.7 range in persistent intensity. The bursts from a given epoch were consistent with a single recurrence time, which varied with accretion rate as $\Delta t \propto \dot{M}^{-1.05}$ (assuming that $\dot{M}$ is proportional to the persistent intensity F_X; Fig. 1). All the bursts had similar lightcurves, and exhibited long tails likely powered by rp-process hydrogen burning. The burst fluence increased by $\approx 5\%$ over the observed range of F_X, and the ratio of persistent to burst fluence α decreased by $\approx 10\%$. The mean value of $\alpha = 41.7 \pm 1.6$ is in the range expected for mixed H/He burning during the bursts.

The decrease in α with $\dot{M}$ implies that stable burning of hydrogen takes place between the bursts, and suggests solar metallicity ($Z \approx 0.02$) in the accreted layer. Solar metallicity models also give good agreement with the observed burst energies, while low-metallicity models do not. However, the relatively steep variation in Δt with $\dot{M}$ suggests little variation in the fuel composition at ignition, which in turn implies low CNO metallicity. Otherwise, hydrogen burning between the bursts would lead to an increased H-fraction at ignition as Δt became shorter, leading to (relatively) delayed ignition and increased burst fluence.

There are several possible ways to reconcile the solar metallicity models with the fluence and Δt measurements. Firstly, studies of timing and spectra of LMXBs indicate that L_X is not always a good indicator of $\dot{M}$ (e.g. [5]), while we have assumed $L_X \propto \dot{M}$ here. Secondly, extra heating of the accumulating layer would act to reduce the critical mass and bring the observations and theory into agreement. One possibility is that residual heat from the ashes of previous bursts heats the layer [6, 7], although time-dependent simulations are required to test this. Thirdly, if the fraction of the NS surface covered by fuel changes with $\dot{M}$, the changing local accretion rate per unit area could also reconcile the models and observations. We found that the blackbody radius $R_{\rm bb}$ in the tail of the bursts decreased by $\approx$20% between the observed epochs. If this indicates a change in covering fraction, it would almost be enough to explain the discrepancy. However, the covering fraction decrease with $\dot{M}$ is opposite to the increase suggested by [1] to explain trends in burst properties.

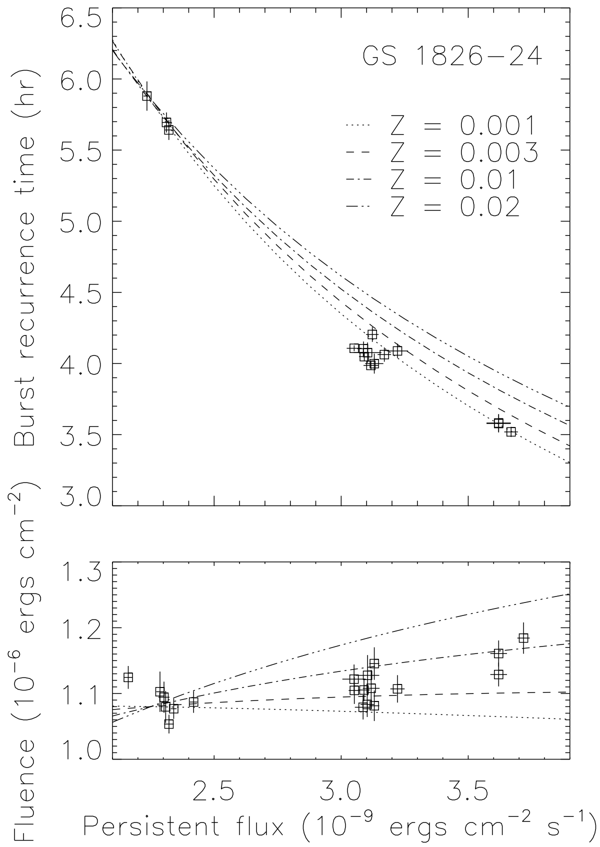

FIGURE 1. Variation of the burst recurrence time (*upper panel*) and the burst fluence (*lower panel*) as a function of the estimated bolometric persistent flux in GS 1826−24, from *RXTE* measurements between 1997–2002. Error bars indicate the 1σ uncertainties. The curves show theoretical calculations for a range of metallicities: $Z = 0.02, 0.01, 0.003$, and 0.001. The solid angle (R/d) and gravitational energy have been chosen in each case to match the observed fluence and recurrence time at $F_{\rm p} = 2.25 \times 10^{-9}$ erg cm^{-2} s^{-1}. For $Z = 0.02, 0.01, 0.003$, and 0.001, this gives $R/d = 13, 10, 8, 6$ km @ 10 kpc, and $Q_{\rm grav} = 175, 196, 211, 215$ MeV per nucleon, where $Q_{\rm grav} = GM/R$ is the gravitational energy from accretion. Reproduced from [2].

4U 1746−37

A well-known dipper and burst source with an orbital period of 5.7 hr [8, 9], 4U 1746−37 is located in the globular cluster NGC 6441. The peak fluxes of the 28 bursts in public *RXTE* observations were bimodally distributed, with 15 bursts reaching fluxes between (1.0–3.5) $\times 10^{-9}$ ergs cm^{-2} s^{-1} (here we refer to these as "faint" bursts), and the remaining 13 peaking at between (4.3–7.1) $\times 10^{-9}$ ergs cm^{-2} s^{-1} ("bright" bursts).

The bursts appeared to occur regularly on two occasions. On 1998 November 7th we observed 5 faint bursts (as well as the tail of a 6th burst), each separated by $\approx$ 1.2 hr, and with rather uniform properties (fluence, peak flux, timescale etc.). However, we also observed a bright burst which was not consistent with a $\approx$ 1.2 hr recurrence time. Burst #16, which exhibited photospheric radius-expansion (PRE) and reached a peak of 5.1×10^{-9} ergs cm^{-2} s^{-1}, occurred 1.84 hr after the

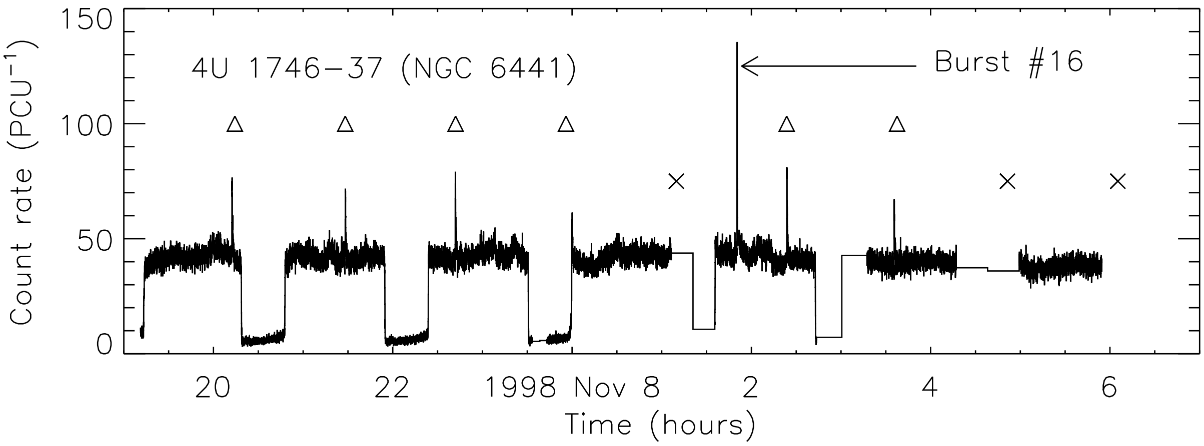

FIGURE 2. 2–60 keV intensity measured over the field of 4U 1746−37 on 1998 November 7–8. The regular dips in the lightcurve are due to occultations of the source by the Earth due to the ≈ 90 min satellite orbit. The triangles show the predicted times of bursts according to the ephemeris determined from bursts #12–15, 17 and 18. The crosses show where regular bursts may have occurred, but could not be observed due to data gaps.

previously observed burst, which was inferred from the observation of a burst tail at the end of the occultation (#15; Fig. 2). Neglecting burst #16, the remaining bursts were consistent with a rather steady recurrence time of 1.23 ± 0.01 hr, with an rms error between the observed and predicted burst times of just 0.034 hr. The actual recurrence time for burst #16 could have been as short as 35 min if a faint burst had occurred 1.23 hr after burst #15, although the source was occulted at the time.

On 1996 October 25–27, when the source was substantially fainter, we also observed two successive bursts on three instances, again with rather uniform properties. However, the majority of the bursts this time were bright, reaching peak fluxes $\gtrsim 4.5 \times 10^{-9}$ ergs cm^{-2} s^{-1}; and secondly, the recurrence time was 3–3.3 hr. Again, we observed a regular train of bursts with rather homogeneous properties, interrupted this time by a faint burst at a time which was not consistent with the approximately periodic recurrence of the other bursts.

These deviations from patterns of otherwise regular bursting are puzzling for two reasons. Firstly, the regular bursting indicates that the critical column depth for burst ignition occurs on a regular basis; for the out-of-phase bursts, what causes the fuel layer to ignite prior to achieving the critical density? Secondly, assuming constant $\dot{M}$ and complete consumption of the available fuel in the regular bursts, the fluence of the out-of-phase bursts appear to be inconsistent with the amount of fuel accreted since the previous burst.

We suggest three possible explanations for the observed burst properties:

1. The bright bursts originate from 4U 1746−37, but the faint bursts originate from a second bursting source not positionally coincident with 4U 1746−37. Two bursting sources would naturally explain the bimodal distribution burst properties, as well as the two distinct patterns of regular bursting. If the second source was located significantly off the satellite aimpoint, the observed flux would be reduced due to the decrease in collimator efficiency with increasing off-axis angle, thus explaining the relative weakness of the fainter bursts. However, neither a deep sky map produced from ASM scans of the region around 1998 November 7–8 nor *Chandra* observations detected a second source in the field [9], although this could be because the second source was quiescent at the time. We also attempted to constrain the origin of the bursts by exploiting the small differences in pointing between the different proportional counter units (PCUs) comprising the *RXTE* PCA. We combined the count rates from individual PCUs from 7 faint bursts observed with similar spacecraft attitude, in order to increase the signal-to-noise ratio. We found that the most probable region for the origin of the faint bursts runs across the field of view approximately NW to SE, centered on the position of 4U 1746−37. Thus, we found no evidence that the faint bursts originate from a different position within the field of NGC 6441.

2. The bright bursts originate from 4U 1746−37, and the faint bursts originate from a second bursting source within NGC 6441. Given the low probability of positional coincidence for two unrelated bursting LMXBs within $\approx 1°$ of each other, combined with the concentration of NSs in globular clusters, the most likely site for a second burst source in the field of 4U 1746−37 is NGC 6441. One final piece of evidence comes from measurements of the asymptotic blackbody radius for the bursts. If the second bursting source was not related to NGC 6441, then we would expect the distance to the source to be different. For two NSs emitting X-ray bursts at different distances, we then expect that the blackbody radii should also be significantly different. Instead, we find that the blackbody radii are essentially identical for both classes of bursts. This suggests the second source has approximately the same distance as 4U 1746−37, and hence is most likely within NGC 6441.

3. The bursts all originate from a single bursting source in NGC 6441, 4U 1746−37. This hypothesis is somewhat difficult to accept, as discussed above, because of the bimodal distribution of properties of the non-PRE bursts from the area, the apparently bimodal distribution of burst recurrence times, and the interruption of regular trains of one type of burst by bursts of a second type.

One source could produce both types of bursts if it had undergone a transition from the regime of unstable hydrogen ignition to that of unstable He ignition. In 1996 October for the steady bright bursts from 4U 1746−37 we estimate $\alpha \approx 50$, while in 1998 November the α-value for the steady faint bursts was much higher, at ≈ 220. The former value is typical for bursts which burn mixed H/He [2], while the latter is more typical for pure He bursts. Thus, the bright steady bursts may arise from mixed H/He burning triggered by unstable H ignition at very low accretion rates, while the intermittent faint bursts burn the resulting He ashes; while in 1998 November, when $\dot{m}$ was higher, the regular faint bursts are triggered instead by unstable He burning. We estimate the accreted column at the time of ignition for the regular bright bursts assuming cosmic abundances (giving energy generation of $Q_{\rm nuc} = 4.4$ MeV per nucleon) to be $y \approx 2.5 \times 10^7\ {\rm g\,cm^{-2}}$. This is consistent with a H flash but is at the lower limit of the He ignition curve (e.g. [3]). For the faint bursts, assuming they burn pure helium so that $Q_{\rm nuc} = 1.6$ MeV per nucleon, the column is $y \approx 5.2 \times 10^7\ {\rm g\,cm^{-2}}$ which is consistent with a He flash.

Additional observations at different accretion rates are a crucial test of such a mechanism for giving rise to the bursts observed so far. If the properties of the two classes of bursts can be shown to vary independently, this would strengthen the case for two separate sources. High spatial resolution observations with *Chandra* or *XMM-Newton* may then be used to test for two distinct origins for the two classes of bursts.

A final point which presents additional difficulties for understanding the properties of this source is the overall frequency of the bursts. The broadband persistent flux from the source on 1996 October and 1998 November was (0.268 ± 0.012) and $(1.93 \pm 0.07) \times 10^{-9}\ {\rm ergs\,cm^{-2}\,s^{-1}}$, respectively. For a source distance of 11 kpc, these fluxes correspond to a spherically-averaged accretion rate of 0.025 and $0.18\,\dot{m}_{\rm Edd}$ (where we assume $\dot{m}_{\rm Edd} = 8.8 \times 10^4\ {\rm g\,cm^{-2}\,s^{-1}}$). For a NS accreting solar metallicity material with a hydrogen fraction $X = 0.7$ at these rates the model predicts recurrence times of 44 and 4.1 hr, respectively. That the observed recurrence times (3.1 and 1.22 hr) were so short in comparison may be an indication that the accretion does not completely cover the NS surface, so that the local accretion rate is much higher.

DISCUSSION

The precise measurements of burst properties possible with *RXTE* allow tests of burst theory to unprecedented levels of precision. For both sources discussed here, the bursting behaviour may be significantly altered because accretion is not taking place over the entire NS surface. Measurements of blackbody radii from burst spectra offer at best a qualitative way to measure the area of accretion, unless the deviations of the spectra from pure blackbodies can be accounted for and the effective temperature measured accurately. This can likely only be achieved with measurements by dedicated spectroscopic instruments like *Chandra* or *XMM-Newton*. Such studies, when combined with the extensive archival observations of bursters accumulated by *RXTE* over its lifetime are thus an excellent way to improve our understanding of burst physics. Future observations in previously unexplored ranges of accretion rate will also further constrain the burst physics.

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