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Two-phase X-ray burst from GX 3+1 observed by *INTEGRAL*

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ABSTRACT

INTEGRAL detected on August 31, 2004, an unusual thermonuclear X-ray burst from the low-mass X-ray binary GX 3+1. Its duration was 30 min, which is between the normal burst durations for this source ($\lesssim$10 s) and the superburst observed in 1998 (several hours). We see emission up to 30 keV energy during the first few seconds of the burst where the bolometric peak luminosity approaches the Eddington limit. This peculiar burst is characterized by two distinct phases: an initial short spike of ~6 s consistent with being similar to a normal type I X-ray burst, followed by a remarkable extended decay of cooling emission. We discuss three alternative schemes to explain its twofold nature: 1) unstable burning of a hydrogen/helium layer involving an unusually large amount of hydrogen; 2) pure helium ignition at an unusually large depth (unlikely in the present case); and 3) limited carbon burning at an unusually shallow depth triggered by unstable helium ignition. Though none of these provide a satisfactory description of this uncommon event, the former one seems the most probable.

Key words. binaries: close – stars: individual: GX 3+1 – stars: neutron – X-rays: bursts

1. Introduction

Many of the observed low-mass X-ray binary systems are known to exhibit type I X-ray bursts. The X-ray light curves of such events are characterized by a fast rise time followed by an exponential decay. The decay time varies from burst to burst, but is generally between a few seconds and a few minutes. For a given burst the decay times are shorter at higher energies. They are produced by unstable burning of accreted matter on the surface of the neutron star. The emission can be described well by black-body radiation with temperatures, kT, in the range of a few keV. The energy dependent decay time of these bursts is attributed to the cooling of the neutron star photosphere resulting in a gradual softening of the burst spectrum. For a review, see, e.g., Lewin et al. (1993); Strohmayer & Bildsten (2003).

GX 3+1 is a well-known X-ray burster, exhibiting exclusively short ($\lesssim$10 s long) bursts (see den Hartog et al. 2003, and references therein) except once when it exhibited an hours-long so-called "superburst" (Kuulkers 2002). Superbursts are thought to arise from carbon shell flashes in the layers below the surface (e.g., Cumming & Bildsten 2001). One short burst was shown to exhibit photospheric radius expansion from which a distance of ~5 kpc could be estimated (Kuulkers & van der Klis 2000).

In this letter we present an analysis of a second unusual burst from GX 3+1 which was observed on August 31, 2004 with the *International Gamma-Ray Astrophysics Laboratory* (*INTEGRAL*) and first reported by Brandt et al. (2004).

2. Observations and data analysis

The data were obtained with *INTEGRAL* (Winkler et al. 2003) between August 30 and September 3, 2004. The observation was divided into a sequence of pointings separated by ~2° on the sky. Each pointing had a duration of one hour. For the X-ray monitor, *JEM-X*, this pointing strategy implies that the visibility of any given source changes significantly every hour. At the time of the burst the *JEM-X* effective area for GX 3+1 was about 60% of the on-axis value. In the previous pointing it had been only 15% and in the following one it increased to 95%. In our analysis we have used data from the "burst" pointing and the following pointing ("science windows" 9 and 10 from *INTEGRAL* revolution 230).

We use data from *JEM-X* (Lund et al. 2003) from 3 to 25 keV, and from *IBIS/ISGRI* (Ubertini et al. 2003;

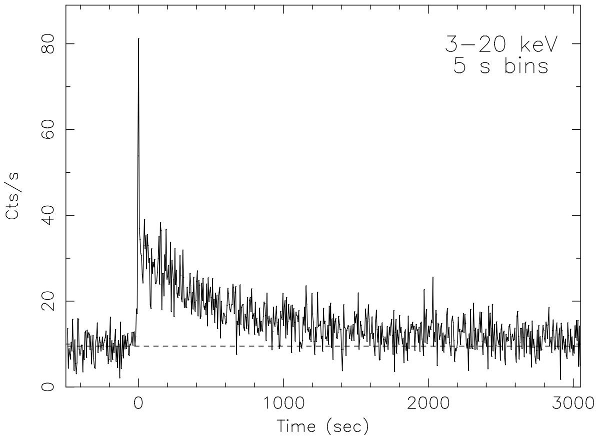

Fig. 1. Long X-ray burst from GX 3+1 on August 31, 2004. The time zero corresponds to UTC 18:55:11.

Lebrun et al. 2003) at energies between 18 and ~50 keV. Data reduction and analysis were performed using the standard Offline Science Analysis (*OSA*) v.5.0 (Courvoisier et al. 2003) and public *JEM-X* specific software (Lund et al. 2004).

All the light curves in this paper are based on events selected according to the detector illumination pattern for GX 3+1. For *ISGRI* we selected "source"-events using an illumination threshold of 0.6; for *JEM-X*, which utilizes a different type of mask (Lund et al. 2003), we used a lower threshold of 0.25.

3. Results

3.1. Burst light curves

Figure 1 displays the *JEM-X* light curve in the 3 to 20 keV band with a time resolution of 5 s for the full science window in which the unusual burst from GX 3+1 was observed. The burst consists of two distinct phases: an initial short spike and an extended decay phase. Figure 2 shows the initial spike with 0.5 s resolution for a number of energy bands. The spike emission is well visible all the way up to 30 keV. The 18−30 keV band from *ISGRI* light curve shows indications of a double peak structure during the spike phase. We have verified that the background count rate is stable over the full science window in which the burst is observed. We can therefore exclude interference from other time variable sources within the field-of-view.

3.2. Spectral analysis

We have performed a time resolved spectral analysis based on the *JEM-X* data (*ISGRI* detected GX 3+1 only for a few seconds during the spike phase of the burst and for such a short time the data are inadequate for a reliable spectral analysis). The energy range covered by *JEM-X* does not allow us to constrain well the interstellar column density N_{H}. Therefore, we have fixed in all our spectral fits the N_{H}-value at 1.6×10^{22} atoms cm^{-2} as derived by Oosterbroek et al. (2001).

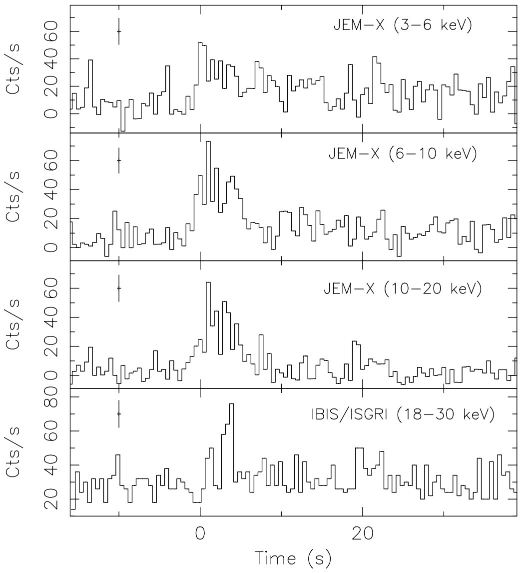

Fig. 2. Light curves of the initial part of the X-ray burst with 0.5 s binning in selected energy bands. A reference error bar is shown in the corner of each panel. The background has been subtracted from the *JEM-X* light curves, but not from the *ISGRI* one.

We have determined the spectral evolution during the burst and compared the burst spectra to the persistent source spectrum which we extracted from the subsequent science window. The burst is divided into time intervals as shown in Fig. 3, the shortest interval being ~8 s during the spike. We defined the energy channels in the burst spectral analysis such to assure a uniform distribution of counts in all spectral channels. Following an approach proposed by van Paradijs & Lewin (1986) (see also Sztajno et al. 1986), we have modelled the total burst emission averaged during each time interval by using the same two spectral components as for the persistent emission. The model contains a black-body (BB) component for the thermal emission and a power-law (PL) component for the Comptonized photons. The power-law component is thought to originate far from the neutron star – in the accretion disk environment – and consequently is not expected to be strongly affected by the events on the neutron star. Therefore we determine the power-law contribution through a fit to the persistent emission, and then keep this component fixed throughout the analysis of the burst spectra. The upper panel of Fig. 3 displays the bolometric luminosity (0.1−200 keV) of the source obtained from the two-component spectral model assuming a distance of 5 kpc. The inferred black-body temperature and apparent black-body radius are shown in the middle and lower panels, respectively. The softening of the emission towards the end of the decay phase is also indicated by the e-folding decay times going from 1110 ± 170 s in 3−6 keV to 510 ± 160 s in 10−20 keV. The best fit parameters for the persistent emission and for the spike are given in Table 1 as well as usual burst parameters.

We note that a two-component spectral analysis of the total burst emission may not always be an accurate approach (Kuulkers et al. 2002). Therefore, we also checked that the net burst emission (by subtracting the persistent emission during the burst) is satisfactorily described by a black-body model, and repeating the spectral analysis we found the same trend showing a maximum luminosity only a factor 1.3 lower, and a slightly deeper decrease of the temperature (by a factor 1.2)

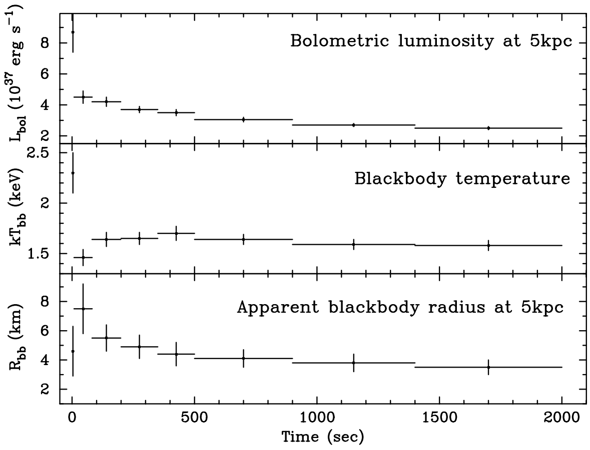

Fig. 3. Results of the time resolved spectral analysis.

Table 1. Burst analysis results.

Dataset (*JEM-X*) model	Persist. BB & PL	Spike BB & PL
$N_H{}^a$ (10^{22} atoms cm^{-2})	1.6	1.6
kT_{bb} (keV)	$1.7^{+0.1}_{-0.1}$	$2.3^{+0.5}_{-0.4}$
R_{bb} (km)	$2.6^{+0.6}_{-0.3}$	$4.6^{+1.9}_{-1.5}$
Γ	$3.6^{+0.5}_{-0.5}$	3.6 (fixed)
$L_{(5-25\ \mathrm{keV})}$ (10^{37} erg s^{-1})	0.73	5.9
χ^2/d.o.f.	88/76	27/29
Burst parameters		
$L_{peak}{}^b$	$E_b{}^c$	γ^d
1.6×10^{38}	2.1×10^{40}	$\simeq$0.14

[a] Parameter fixed; see text. [b] 2s spike maximum luminosity (erg s^{-1}); see text. [c] Net burst fluence (erg). [d] $\gamma \equiv L_{pers}/L_{peak}$.

simultaneously with a slightly higher increase of the radius (by a factor 1.3).

3.3. ASM *observations*

In Fig. 4 we show the 1.5–12 keV light curve from August 1996 to December 2005 of GX 3+1. This light curve is based on 10-day averages of the "dwells" executed by the *RXTE*/*ASM*. The *ASM* count rate has been converted into flux using 1 Crab Unit for 75 cts/s (e.g. Levine et al. 1996). The persistent flux shows variations of about a factor two on a ∼6 yr time scale. Normal type I X-ray bursts have been observed at all intensity levels of GX 3+1 (den Hartog et al. 2003). We note that both our burst and the superburst observed by Kuulkers (2002) have been observed slightly before the persistent flux from the source reaches its minimum. The persistent emission just prior to the superburst (MJD 50973) was around 0.22 Crab, and 0.18 Crab prior to our burst which occurred on MJD 53248. Our burst was not seen by the *ASM*, so we cannot compare directly the intensities of the two bursts in the *ASM* energy band.

4. Discussion

Two distinct phases are evident in the burst from GX 3+1 observed on August 31, 2004: an initial hard spike of duration ∼6 s followed by an extended quasi–exponential decay phase lasting for more than 2000 s.

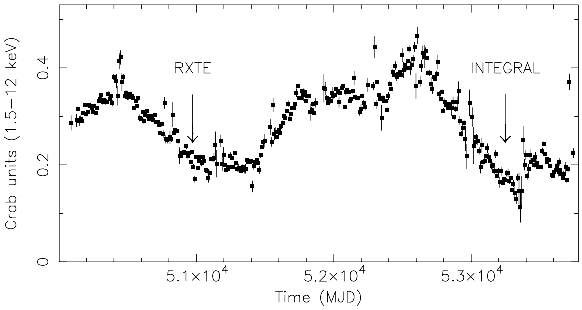

Fig. 4. *RXTE*/*ASM* light curve for GX 3+1. Arrows indicate *RXTE* superburst and *INTEGRAL* long burst.

The initial spike has a rise time of 1.3±0.1 s and fades away with a decay time 3 ± 1 s. The spike is similar in shape to normal type I burst from GX 3+1 of which almost hundred have been observed to date (den Hartog et al. 2003). The 18−30 keV emission of our burst shows a double peak structure which may appear statistically marginal, but the main part of this emission is clearly delayed with respect to the burst onset. These characteristics could indicate a radius expansion episode during the peak phase. We also note that the net-burst peak luminosity (see Table 1), as derived from a 2 s rebinned lightcurve during the spike phase, appears to be similar to the peak luminosity observed for the radius expansion burst from GX 3+1 described by Kuulkers & van der Klis (2000).

Only one previous observation exists for a radius expansion from GX 3+1, but the most unusual characteristic of our burst is the extended decay phase lasting for more than 30 min. This is almost three orders of magnitude longer than the normal type I bursts from GX 3+1. The rise of the long lasting emission cannot be disentangled from the spike emission, and we cannot say for sure which of the two events triggered the other one. We note that a similar kind of burst may have been observed from Aql X-1 (Czerny et al. 1987). At the end of this observation ∼2500 s after the burst maximum the count rate was still ∼25% higher than before the burst. Other bursts with decay times of 20 to 30 min have occasionally been observed from other sources (see e.g. in 't Zand et al. 2002; Kuulkers et al. 2002; Molkov et al. 2005). Some of these bursts also exhibited initial spikes, but these spikes when present had softer spectra than the main burst (e.g. Kuulkers et al. 2002). In our case the spike is much harder than the emission during the decay phase. Our burst is also clearly different from the 1998 superburst in terms of duration, decay time and total fluence.

Given that the total luminosity of the source during the first few hundred seconds of the decay phase is less than half of the peak luminosity we consider it unlikely that the source is still radiating at the (hydrogen) Eddington luminosity during the decay phase (this would require the source to be at 8 kpc). Moreover, it is difficult in such a picture to reconcile the observed increase in the emission temperature with the decrease in the bolometric flux (see Fig. 3). Ideally an isotropically emitting sphere supported by radiation pressure should maintain a constant luminosity during the contraction phase. The observed evolution may possibly be understood if the emission is not isotropic but dominated by a band or a localized spot on the stellar surface. We have searched for burst oscillations in the frequency range from 1 to 400 Hz to confirm the notion of non-isotropic emission from a rotating neutron star but have not detected any significant variations; we can put an upper limit of 5% on the amplitude of a simple sinusoidal variation.

Assuming a source distance of 5 kpc we have estimated the persistent bolometric (0.1–200 keV) luminosity of GX 3+1 to be $L_{\rm pers} \sim 2.2 \times 10^{37}$ erg s^{-1}. We consider it safe to estimate the bolometric luminosity based on the *JEM-X* data since we expect ~70% of the flux to be contained within 4−25 keV range. The corresponding persistent mass accretion rate is $\dot{M} = L_{\rm pers}\ \eta^{-1}\ {\rm c}^{-2} \approx 1.2 \times 10^{17}$ g s^{-1} (12% $\dot{M}_{\rm Edd}$), where $\eta \sim 0.2$ is the accretion efficiency for a neutron star. This corresponds to an accretion rate per unit area $\dot{m} = \dot{M}/A_{\rm acc} \sim 10^4$ g cm^{-2} s^{-1}, assuming a 10 km radius for the neutron star.

GX 3+1 has now been observed to produce three kinds of type I X-ray bursts: normal, short helium flashes (e.g. den Hartog et al. 2003), one superburst (Kuulkers 2002), and the present unusually long burst. Bursts, with a duration more than 1000 s are rare, and present theory provides three possible scenarios for such bursts – the burning of a large pile of hydrogen and helium, the burning of an unusually thick layer of helium (see, e.g., in 't Zand et al. 2005; Cumming et al. 2005), or the carbon flash (see, e.g., Strohmayer & Bildsten 2003, and references therein). The longevity of a mixed H/He flash is due to the hydrogen. While helium fusion through triple-α burns the fuel within less than 1 s, the rate of hydrogen fusion through rapid proton capture is limited by slow β decays (see, e.g., Strohmayer & Bildsten 2003; Lewin et al. 1993, and references therein). Mixed H/He burning is expected to occur at mass accretion rates below approximately 1% and above 5% of the Eddington limit for a solar composition of the fuel. Between the two thresholds pure helium flashes occur which result in ~10 s bursts like usually observed in GX 3+1. The lower threshold is related to the turn-off of stable hydrogen burning. Thus, suddenly hydrogen becomes available for burning in flashes and these are expected to become longer; also, the temperature drops which influences ignition conditions and burst rates. Our burst appeared when the source went into a 10-yr intensity low at a luminosity close to 2×10^{37} erg/s, which happens to coincide with a transition luminosity observed in other bursters (Cornelisse et al. 2003). Usually, the burst durations increase to at most a few hundred seconds, but sometimes they are similar as in the present burst (Czerny et al. 1987). The energetics of the burst are consistent with this scenario. The radiated energy can be fueled by solar composition material after accreting at 10% of Eddington for ~9.4 h. No other bursts were detected in the 5.5 h continuous *INTEGRAL* observations preceding our burst. In the nine days prior to the burst *JEM-X* accumulated ~60 h exposure on GX 3+1 without detection of any burst which at least suggests that the burst rate was low and accreted piles could become high enough.

The pure helium burning scenario is unlikely, because the appreciable accretion rate (0.12 times Eddington) results in such strong heating that the layer would flash before a sufficiently large thickness is reached to power such a long burst (Cumming et al. 2005). Furthermore, the two-phased character of the burst profile appears at odds with this scenario.

The third option, premature ignition of a carbon layer, may require a special helium detonation geometry capable of producing a local shock wave in the carbon layer below. The difficulty is that in order to achieve the observed decay time the carbon burning needs to occur much deeper than the helium layer. Compared to a superburst the duration is only consistent with a relatively small amount of carbon (few times 10^{10} gr cm^{-2} for a mass fraction $\lesssim$0.1) and the temperature needed to ignite the carbon might be too large (see Cumming & Bildsten 2001).

In conclusion, though we do not have a full and consistent picture of the conditions that led to the peculiar X-ray burst from GX 3+1, we consider the mixed H/He scenario as the most likely one.

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