

X-ray spectral and timing properties of the 2001 superburst of 4U 1636–536

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Abstract. Preliminary results are reported on the spectral and timing properties of the spectacular 2001 superburst of 4U 1636–536 as seen by the RXTE/PCA. The (broad-band) power-spectral and hardness properties during the superburst are compared to those just before and after the superburst. Not all of the superburst emission can be fitted by pure black-body radiation. We also gathered BeppoSAX/WFC and RXTE/ASM data, as well as other RXTE/PCA data, obtained days to months before and after the superburst to investigate the normal X-ray burst behavior around the time of the superburst. The first normal X-ray burst after the 2001 superburst was detected $\simeq 23$ days later. During inspection of all the RXTE/ASM data we found a third superburst. This superburst took place on June 26, 1999, which is $\simeq 2.9$ yrs after the 1996 superburst and $\simeq 1.75$ yrs before the 2001 superburst. The above findings are the strongest constraints observed so far on the duration of the cessation of normal X-ray bursts after a superburst and the superburst recurrence times.

SUPERBURSTS

Superbursts are a recently discovered new mode of unstable thermo-nuclear burning on the surface of a neutron star. These neutron stars reside in so-called low-mass X-ray binaries (LMXBs) in which it continuously receives fresh material from a donor star. A large fraction of these LMXBs are known to exhibit short (seconds to minutes) so-called Type I X-ray bursts which are due to unstable thermo-nuclear burning of H and/or He (for reviews, see Lewin et al. [15]; Strohmayer & Bildsten [17]). These ‘normal’ X-ray bursts appear as rapid (~ 1 – 10 s) increases in the X-ray flux, followed by an exponential-like decline. They recur with a frequency (typically hours to days) which is (partly) set by the supply rate of the fresh fuel. The (net) burst X-ray spectra are well described by black-body emission from a compact object with ~ 10 km radius and color temperature of ~ 1 – 2 keV. The color temperature increases during the burst rise and decreases during the decay, reflecting the heating and subsequent cooling of the neutron star surface. Typical integrated burst energies are in the 10^{39} to 10^{40} erg range.

The durations and output energies of superbursts are roughly a factor of a thousand more than that of the normal X-ray bursts. They display, however, the usual relatively fast rise and exponential decay, as well as the hardening during the rise and subsequent softening during the decay, as seen in normal X-ray bursts. Also, the (net) superburst X-ray spectra are described in the same way as the normal X-ray bursts. For an overview of the superburst properties we refer to Kuulkers [13], and references therein.

The current view is that the superbursts are due to the energy release of unstable burning of C, which is the left over from the stable and unstable burning of H and He (Cumming & Bildsten [7]; Strohmayer & Brown [18]). Additional energy may be released through photo-desintegration triggered by the superburst (Schatz et al. [20]).

The first superburst was discovered with the BeppoSAX/WFCs to come from the X-ray burster 4U 1735–444 (Cornelisse et al. [2]). Another superburst was independently found with the RXTE/PCA, originating from the X-ray burster 4U 1820–303 (Strohmayer & Brown [18]; see also Ballantyne & Strohmayer [1]).

Thereafter, six more events have been seen to occur in five other X-ray bursters with the BeppoSAX/WFCs (Cornelisse et al. [3]; Kuulkers et al. [14], see also in 't Zand et al. [11]), RXTE/PCA (Strohmayer & Markwardt [19]) and RXTE/ASM (Wijnands [22]; Kuulkers [12]). The fact that only eight such events have been found so far indicates that they must be rare. Two superbursts from 4U 1636–536 were seen to occur $\simeq 4.7$ yrs apart (Wijnands [22]); observational estimates of the recurrence times are on the order of a year (see, e.g., Kuulkers [12]; in 't Zand et al. [10]).

4U 1636–536 is a regular X-ray burster and a so-called ‘atoll’ source (e.g., van der Klis et al. 1990). We here present preliminary results focussed on the X-ray behavior of the source during and around the superburst which occurred on 2001 Feb 22.

The 2001 superburst as seen by the RXTE/PCA

A first account of the RXTE/PCA data during the 2001 superburst from 4U 1636–536 is given by Strohmayer & Markwardt [19]. Note that this is event was also seen by the RXTE/ASM (Wijnands [22]; see also below). Strohmayer & Markwardt [19] found a highly coherent 582 Hz pulsation during a small part (~ 800 s) of the superburst.

The light curve (see also Strohmayer & Markwardt [19]), as well as the hardness curve, of the superburst are shown in Fig. 1. Clearly, they resemble the curves usually seen for normal X-ray bursts, except for the duration of a few hours. A high time resolution (0.125 s) light curve of the superburst is shown by Kuulkers [13], including data from the slew just before the third orbit of data on 4U 1536–536. This light curve showed an increase in count rate of a few 1000 c s^{-1} about 125 s before the precursor X-ray burst. It was pointed out to us by Tod Strohmayer that this increase is actually due to the turn-on of PCU 3; this was not taken into account when doing the collimator response correction. The superburst, therefore, did *not* start ~ 125 s before the precursor X-ray burst, but between ~ 145 s and ~ 46 min before the precursor.

A color-color diagram (CD) of all public data on 4U 1636–536 between Feb 28, 1996 and April 10, 2002 is shown in Fig. 2 (this is an extension of the data set used by Di Salvo et al. [9]). The superburst (shown in red) started at the bottom part of the CD, i.e., in the so-called ‘banana’ branch. During the rise to superburst peak the source hardened, while during the decay it softened, with the hard colors even dropping below pre-superburst values. At the end of the observation the source resumed its pre-superburst colors again.

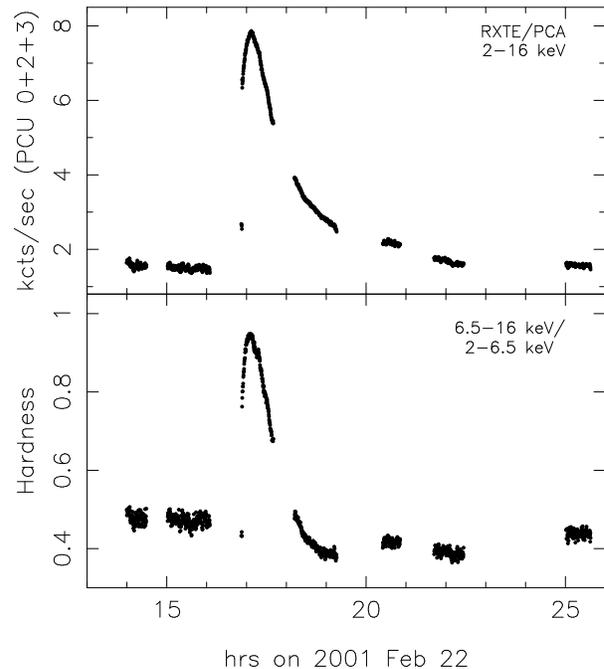


FIGURE 1. RXTE/PCA 2–16 keV light curve (*Top*) and hardness (ratio of the count rates in the 6.5–16 keV and 2–6.5 keV energy bands) curve (*Bottom*) of the 2001 superburst of 4U 1636–536. Note that slew data are not included, and that the count rates are not corrected for background and dead time. Standard 2 data are used from PCU’s 0, 2 and 3; the time resolution is 16 s.

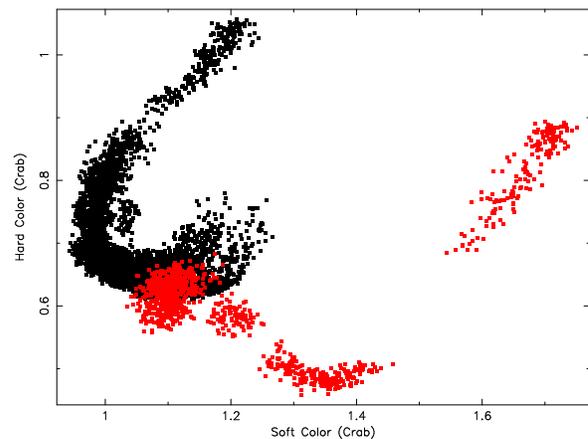


FIGURE 2. Color-color diagram of 4U 1636–536 using Standard 2 data between Feb 28, 1996 and April 10, 2002. The data on Feb 22, 2002 are indicated in red. Soft and hard color are defined as the ratio of the count rates in the 3.5–6.4 keV and 2.0–3.5 keV bands, and, respectively, the 9.7–16 keV and 6.4–9.7 keV bands. The count rates are normalized to the Crab (see Di Salvo et al. [9]; van Straaten et al. [20]) and not corrected for dead time.

We investigated the broad-band timing behavior using the high-time resolution modes available during parts of the observation (see Strohmayer & Markwardt [19]). No strong features are seen before and after the superburst, except for some very-low frequency noise. This is as expected from previous analyses of the timing behavior at the corresponding portion of the CD (see Di Salvo et al. [9]). The high-timing data during the superburst, however, show a hint of a quasi-periodic oscillation near 1150 Hz. A more careful analysis is in progress.

Using the Standard 2 mode data we extracted X-ray spectra at 16 s time resolution throughout the 2001 superburst. As is common practice for normal X-ray bursts, we subtracted the average pre-superburst X-ray spectrum from the superburst spectra. The residual spectra were modeled by pure black-body emission (keeping the interstellar absorption, N_{H} , fixed at 3×10^{21} atoms cm^{-2} , see e.g., Christian & Swank [4]). As the superburst flux increased the color temperature increased from $\simeq 1$ keV up to 2.35 keV, while during the decay the color temperature decreased again. The inferred black-body radius was more or less constant ($\simeq 6$ km at 6 kpc). The fits are, however, not perfect throughout the whole burst, with the strongest deviations seen when the superburst flux had dropped to about half its peak value. The deviations are very similar to those seen during the superburst from 4U 1820–303, and may show the influence of the superburst emission on the accretion disk surrounding the neutron star (Strohmayer & Brown [18]; Ballantyne & Strohmayer [1]). The total integrated superburst flux is about 0.65×10^{42} erg (at 6 kpc).

BeppoSAX/WFC and RXTE/ASM measurements around the 2001 superburst

In Fig. 3 (bottom) we show in black the WFC light curves acquired around the 2001 superburst of 4U 1636–536, as well as in gray the RXTE/ASM 1-day average and in red the RXTE/PCA light curves. The BeppoSAX/WFC observations did not cover the superburst; the RXTE/ASM, however, did cover it (Wijnands [22]; see also below). In the top of the bottom panel figure we annotate with bars the times of normal X-ray bursts as seen by the BeppoSAX/WFC (black) and the RXTE/PCA (red). Clearly, the source showed normal X-ray bursts before the superburst, with an average rate of about 6 per day. Observations after the 2001 superburst are sparse; the first BeppoSAX/WFC and RXTE/PCA observations were ~ 23 days, respectively, ~ 42 days after the superburst. During both observations a normal X-ray bursts was seen. We note that the peak count rates during the normal X-ray bursts are a factor of ~ 1.5 – 2 higher than that reached during the precursor burst during the

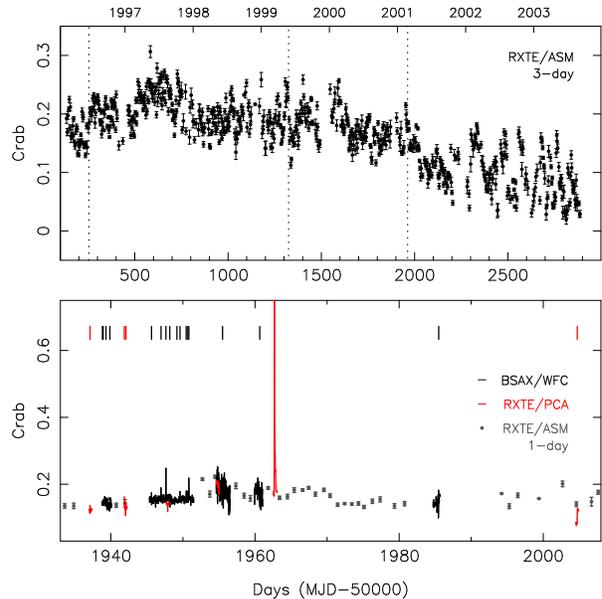


FIGURE 3. *Top:* RXTE/ASM (1.5–12 keV) light curve of 4U 1636–536 from Jan 6, 1996 to Sep 4, 2003. The data shown are 3-day averages and normalized to the Crab count rate. With dotted lines we indicate the times of the 3 superbursts seen from 4U 1636–536 (see text). *Bottom:* The BeppoSAX/WFC (2–28 keV) light curve at 15-min time resolution during the interval Jan 21 to Apr 9, 2001 is shown in black. Data which were less than 0.5 day apart were connected to guide the eye. They were normalized to the Crab count rate. In gray we show the RXTE/ASM 1-day average data points, as well as in red the RXTE/PCA 15-min average light curves, in the same period; within an RXTE/PCA observation the data are connected. In the top part of the bottom panel we show with vertical bars the times of occurrence of normal X-ray bursts.

superburst. This is consistent with an early ignition of a H/He layer by the superburst as it starts (Cumming [5]).

RXTE/ASM superbursts

In the top panel of Fig. 3 we show the long-term RXTE/ASM 3-day average light curve of 4U 1636–536. The source varies on time scales of days to months to years. It may be interesting to note that this light curve resembles that of KS 1731–260 during the first 4 year of the RXTE mission. Apart from the 2001 event, a superburst was also seen by the RXTE/ASM on June 19, 1996 (Wijnands [22]). In Fig. 4 we show the latter event on the left, whereas the 2001 event is shown on the right. During the inspection of the individual RXTE/ASM dwell light curves (see, e.g., Wijnands [22]), we found, however, another candidate superburst. This candidate, which occurred on June 26, 1999, is shown in the middle panels of Fig. 4. Although the peak of the light curve (top)

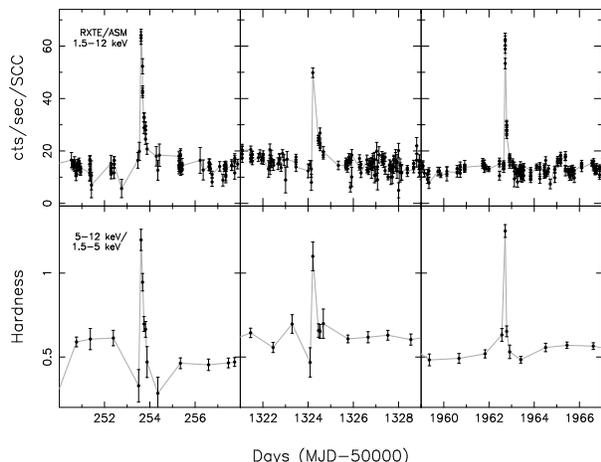


FIGURE 4. RXTE/ASM 1.5–12 keV light curves (*top*) and hardness curves (*bottom*) around the superbursts seen from 4U 1636–536 in 1996 (Wijnands [22]; *left*), 1999 (see text; *middle*) and 2001 (Wijnands [22]; Strohmayer & Markwardt [19]; *right*). For the light curves we show the individual 90-s average RXTE/ASM dwell data points. Hardness is defined as the ratio of the count rates in the 5–12 keV and 1.5–5 keV bands; values are averages of nearby dwells. Data points are connected in light gray to guide the eye.

consists of 1 data point only, the data points after that are on average higher than data before and after. To guide the eye, we have connected the data points; the light curve of the candidate is consistent with a fast rise plus slower exponential decay light curve. In the bottom panel we show the hardness curve in the same period; the hardness values during the peak and during the decay, as well as their evolution, are very similar to those of the superbursts in 1996 and 2001. Based on the similarities we regard the 1999 event as a real superburst; if true, then the recurrence times between the 1996 and 1999 events and the 1999 and 2001 are $\simeq 2.9$ yrs and $\simeq 1.75$ yrs, respectively.

SUMMARY

In this proceedings paper we have shown some preliminary results on the analysis of RXTE/PCA, RXTE/ASM and BeppoSAX/WFC data obtained during and around the 2001 superburst seen from the X-ray burster 4U 1636–536. We found that during the first observation after this superburst, i.e., 23 days later, a normal X-ray burst occurred. Previously, we found that normal X-ray bursts seem to cease to occur for up to a month after the superbursts of Ser X-1 (Cornelisse et al. [3]) and KS 1731–260 (Kuulkers et al. [14]). Our observed upper limit on the duration of the cessation of normal X-ray bursts after the 2001 superburst puts strong constraints on the modeling of the thickness of the layer where

the superburst originates as well as where the energy is deposited (Cumming & Macbeth [8]).

We also investigated the entire RXTE/ASM data set on 4U 1636–536 and found evidence for a third superburst, which occurred in 1999 (the first superburst occurred in 1996). The shortest observed superburst recurrence time is now $\simeq 1.75$ yrs, which is more or less in agreement with previous estimates (roughly one superburst per year; Kuulkers [12]; in 't Zand et al. [10]). Superburst recurrence times may constrain the original composition of the material which was deposited on the neutron star (Cumming [5]; see also Cumming [6], and the discussion in Kuulkers [13]).

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