RECURRENT VERY LONG TYPE I X-RAY BURSTS IN THE LOW-MASS X-RAY BINARY 4U 1636–53

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ABSTRACT

Two flares with a duration of several hours are reported for the low-mass X-ray binary 4U 1636–53. The characteristics of these flares (i.e., decay timescales, spectral softening, fluences) are very similar to those of the very long type I X-ray bursts recently found in several other low-mass X-ray binaries, suggesting that the flares in 4U 1636–53 are also very long type I X-ray bursts. This would make this source the fifth to exhibit this phenomenon and the first one for which multiple bursts have been found. Interestingly, all five sources accrete at approximately 10% of the Eddington mass accretion rate. Although a chance coincidence or a selection effect cannot be ruled out at present, this correlation is suggestive and might indicate that such very long type I X-ray bursts can occur only at a narrow range of mass accretion rates.

Subject headings: accretion, accretion disks — stars: individual (4U 1636–53) — X-rays: stars

1. INTRODUCTION

Type I X-ray bursts in low-mass X-ray binary (LMXB) systems are thought to be due to thermonuclear flashes on the surfaces of neutron stars, which occur when the unstable burning of helium or hydrogen ignites the unburned matter on the surfaces of the neutron stars. These bursts are characterized by fast rise times (of order seconds), long decay times (seconds to minutes), spectral softening during the bursts, and recurrence times of hours to days. In addition, their X-ray spectra can usually be described very well by blackbody radiation. The exact physics behind type I X-ray bursts is very complex, but it is thought that the properties of the bursts are governed by the properties of the neutron star (radius, mass, magnetic field strength) and by the properties of the accreted matter (accretion rate, composition of the material). For reviews about the X-ray bursts and the physics involved, see, e.g., Lewin, van Paradijs, & Taam (1993) and Bildsten (1998).

In recent years, exciting new discoveries have been reported concerning type I X-ray bursts. Soon after the launch of the Rossi X-Ray Timing Explorer (RXTE; Bradt, Rothschild, & Swank 1993) at the end of 1995, nearly coherent oscillations (called burst oscillations, with frequencies of 300–600 Hz) were found during the type I X-ray bursts of several LMXBs (e.g., Strohmayer et al. 1996). These burst oscillations are most likely due to spin frequency of the neutron star (see Strohmayer 2001 for a review about burst oscillations), demonstrating that at least several LMXBs harbor rapidly spinning neutron stars as expected if the neutron stars LMXBs are the progenitors of the millisecond radio pulsars. Cornelisse et al. (2000) reported an extremely long (hours) type I X-ray burst (a “superburst”) from 4U 1735–44 using the Wide Field Camera (WFC) on board BeppoSAX. Such superbursts have now also been reported in several other sources (4U 1820–30: Strohmayer 2000; KS 1731–260 and Serpens X-1: Heise, in ’t Zand, & Kuulkers 2000). The physics behind such superbursts is not yet well known, which is mostly a result of the very recent discovery of such bursts and the limited information available about them. However, it was suggested that they are not regular hydrogen or helium flashes but due to unstable carbon burning (Strohmayer 2000). Here I present recurrent superbursts from the LMXB 4U 1636–53 as observed with the All-Sky Monitor (ASM; Levine et al. 1996) on board RXTE.

2. THE RXTE/ASM LIGHT CURVE OF 4U 1636–53

The RXTE/ASM light curve\(^1\) of 4U 1636–53 is shown in Figure 1 (up to 2001 March 22, 13:33 UTC). Clearly visible is the very recent flarile event on 2001 February 22 17:10 UTC (event 2), just at the end of the light curve. This flare triggered this study, and a close-up of it is shown in Figure 2b. Clearly, the rise of this flare is faster than the decay time. The ratio between the count rate in the range 5–12 keV and the one in the range 1.5–3 keV is given in Figure 2d, which shows that the flux at the peak of the event is harder than the persistent emission but its spectrum softens considerably during the decay.

As can be seen from Figure 1, another flarile event occurred prior to the 2001 February 22 one on 2001 June 19 14:42 UTC (event 1), which is shown in detail in Figure 2a. The event has a similar peak count rate, profile, and 5–12 keV/1.5–3 keV count rate ratio (Fig. 2c) to those of event 2 (Fig. 2d). These similarities between the two events strongly suggest that they are due to the same physical mechanism, demonstrating that this behavior of 4U 1636–53 is recurrent.

The events were fitted with an exponential function in order to determine a characteristic decay timescale. The results are listed in Table 1. The first event likely has a longer duration (about twice as long) than the second event, although the sporadic sampling of the events with the RXTE/ASM might have artificially caused this effect. It is clear, however, that both events lasted more than 1 hr and possibly as long as 3 hr. The decay time for event 2 decreased with photon energy (Table 1), which is consistent with the spectral softening of its spectrum during the decay (Fig. 2b). The decay time for event 1 increases with photon energy, although the inverse cannot be excluded because of the large errors. A smaller decay time at higher energies (similar to that of event 2) is more likely given the softening of the spectrum during the decay of event 1.

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A detailed spectral analysis of the events is not possible because of the lack of energy resolution of the RXTE/ASM data (only three energy channels). Therefore, the total peak count rates of the events have been converted into a flux es-

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timate using PIMMS. As an input spectrum, a blackbody was used with $kT$ of 2 keV (assuming the events in 4U 1636–53 are superbursts as claimed in § 3; see Cornelisse et al. 2000 for the temperature of the superburst in 4U 1735–44) and a column density of $4.7 \times 10^{21}$ cm$^{-2}$ (Schulz 1999; note that, because of the relative high energy of the first energy channel of the RXTE/ASM [1.5 keV], the flux results are rather insensitive to the exact column density). The derived maximum unabsorbed fluxes at the peaks of the events are $2.4 \times 10^{-8}$ ergs s$^{-1}$ cm$^{-2}$ (1.5–12 keV), which for a distance of 5.9 kpc (Augusteijn et al. 1998) corresponds to a luminosity of $1.0 \times 10^{38}$ ergs s$^{-1}$. This is only a lower limit to the peak luminosity; because of the erratic sampling by the RXTE/ASM, the true peak might not have been observed. For the same reason, the total fluences of the events are rather uncertain, but they are likely to be in the range $(0.5–1) \times 10^{42}$ ergs.

Apart from the two very obvious flares, the RXTE/ASM light curve of 4U 1636–53 shows evidence for several smaller flares (Fig. 1). For these flares, no exponential decays nor a significant softening of the spectra are observed, although this might be due to the sampling of the RXTE/ASM data. It is unclear whether (any of) those smaller flares are due to the same mechanism as the two large events discussed above. A possible alternative explanation is that these smaller flares are due to “normal” type I X-ray bursts that happened to occur at the time that the source was observed with the RXTE/ASM.

3. DISCUSSION

Two flares were found in the RXTE/ASM light curve of 4U 1636–53, with characteristic exponential decay profiles that last for several hours. The limited energy resolution of the RXTE/ASM data does not allow a detailed spectral analysis, but it is clear that during the decay the flares become considerably softer. The total peak luminosities and fluences are of the order of $10^{38}$ ergs s$^{-1}$ and $10^{42}$ ergs, respectively. All these characteristics are very similar to similar flares found with the BeppoSAX/WFC for 4U 1735–44 (Cornelisse et al. 2000) and the RXTE proportional counter array (PCA) for 4U 1820–30 (Strohmayer 2000). These flares were interpreted as very long type I X-ray bursts (“superbursts”). The similarities between

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**Fig. 1.** The 1.5–12 keV ASM light curve of 4U 1636–53 showing the two very long X-ray events.

**Fig. 2.** The 1.5–12 keV ASM light curves of 4U 1636–53 for (a) event 1 and (b) event 2 and 5–12 keV/1.5–3 keV count rate curves of (c) event 1 and (d) event 2.
those superbursts and the flares observed for 4U 1636−53 strongly suggest that the latter events are also superbursts. This conclusion is strengthened by the fact that, during the second event, data were also obtained with the RXTE/PCA, which again suggest that this flare is a superburst (T. Strohmayer 2001, private communication). These high time and spectral resolution RXTE/PCA data during this superburst open the exciting possibility of studying a second superburst in great detail (after the one already reported for 4U 1820−30; Strohmayer 2000).

4U 1636−53 is the fifth source that exhibits such superbursts, demonstrating that this phenomenon is common among the neutron star LMXBs. So far, 4U 1636−53 is the only source for which more than one superburst has been detected. Two clear superbursts have been observed from this source, although some of the smaller flares might also be related to the superburst phenomenon. Because of the erratic sampling of RXTE/ASM, it is also possible that several other superbursts were missed. Therefore, the time span between the two superbursts of 4.7 yr reflects only an upper limit on the recurrence time of superbursts in 4U 1636−53.

Now, with five sources that exhibit these superbursts identified, a remarkable trend is visible. All five sources are relatively bright, with a peak intrinsic luminosity of 0.1−0.3 times the Eddington luminosity (L_Edd) for a 1.4 M_☉ accreting neutron star. No neutron star LMXB with considerably higher (>0.5L_Edd) or lower (<0.1L_Edd) peak luminosity has (so far) shown a superburst, although this might well be possible because of a chance coincidence or a selection effect. Because of the higher statistics, the brightness of the superburst sources makes it easier to conclusively identify a possible superburst with a real superburst. However, this argument is invalid for the brightest neutron star LMXBs, for which even better statistics are available. Those systems already show less normal type I X-ray bursts, so the mechanism behind the suppression of the normal bursts might also suppress superbursts. A quick look of the RXTE/ASM light curves of the LMXBs currently monitored by RXTE did not reveal for those sources an obvious event like the superbursts in 4U 1636−53. A more detailed analysis might reveal less obvious events, but such a study is beyond the scope of this Letter. A detailed study of the RXTE/ASM light curves and/or the BeppoSAX/WFC data of all the burst sources is necessary to perform a statistical analysis in order to determine accurately how significant the above-noted correlation is.

Although it cannot be excluded that the above correlation is due to chance coincidence or selection effects, it is also possible that this correlation is real and that such bursts can occur only above a certain (averaged) mass accretion rate. If this is true, then good candidates to also exhibit superbursts will be the relatively bright neutron star LMXBs 4U 1728−34, 4U 1705−44, and 4U 1702−42. The preliminary examination of their RXTE/ASM light curves did not reveal a convincing superburst. However, this does not mean that they did not exhibit such bursts or cannot exhibit them in the future, because the superbursts reported in 4U 1735−44 and 4U 1820−30 are not present in the RXTE/ASM light curves of these sources because of the lack of coverage by the instrument at the time of the bursts. Furthermore, no obvious superbursts are present in the RXTE/ASM light curves of KS 1731−260 and Serpens X-1 (the times of the occurrence of the superbursts in these sources have not been published yet), although a possible candidate superburst occurred in KS 1731−260 at 1996 September 23 12:58 UTC. However, the evidence is inconclusive (i.e., no evidence for spectral softening is observed) so it is not possible to claim this event as a superburst.

The nature and the physics of superbursts are not well known, which is mostly due to the very recent discovery of such bursts and the limited amount of information available about them. Long type I X-ray bursts had already been investigated by Fujimoto et al. (1987), but they predicted that such very long bursts would occur only at an accretion rate below 1% of the critical Eddington rate. However, as already pointed out for 4U 1735−44 by Cornelisse et al. (2000), all five sources exhibiting superbursts accrete well above this level. This discrepancy might be due to the fact that Fujimoto et al. (1987) considered only hydrogen and helium flashes and not carbon flashes, which Strohmayer (2000) suggests as a mechanism for the superburst in 4U 1820−30. He found that, just prior to the superburst in 4U 1820−30, a regular helium flash occurred, demonstrating that a helium flash nature for the superburst in this source can be excluded, suggesting that the superburst might be due to a carbon flash. Taam & Picklum (1978) studied carbon flashes and found that such bursts occur for accretion rates between 10^{-10} and 10^{-9} M_☉ yr^{-1}, which is only slightly lower than the accretion rates observed for the five superburst sources (see also Strohmayer 2000).

However, Brown & Bildsten (1998) argued that, only for pure helium-accreting sources, enough carbon is expected to remain available after normal type I bursts that a carbon burst could occur. Therefore, carbon bursts could explain the superburst in 4U 1820−30, which has a white dwarf companion, but it is less likely that they can explain the superbursts in 4U 1636−53 for which hydrogen has been observed in its optical spectrum (see, e.g., Canizares, McClintock, & Grindlay 1979; Augusteijn et al. 1998). More theoretical investigations are needed to determine whether all superbursts are due to carbon flashes or that a different mechanism is necessary for the superbursts in certain sources.

Instruments like the BeppoSAX/WFC and the RXTE/ASM are good to study many sources simultaneously to increase the chances of observing a superburst, but they have limited capabilities (limited spectral and timing resolution and/or limited sensitivity). In order to get a better understanding of superbursts, high-resolution spectral instruments and/or high timing resolution instruments are necessary. However, because of the rarity of superbursts, such data are difficult to obtain. It is very
fortunate that such data exist now, not only for the superburst in 4U 1820–30 (Strohmayer 2000), but also for one in 4U 1636–53 (T. Strohmayer 2001, private communication).

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