New BeppoSAX-WFC results on superbursts

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Abstract. Presently seven superbursters have been identified representing 10% of the total Galactic X-ray burster population. Four superbursters were discovered with the Wide Field Cameras (WFCs) on BeppoSAX and three with the All-Sky Monitor and Proportional Counter Array on RXTE. We discuss the properties of superbursters as derived from WFC observations. There are two interesting conclusions. First, the *average* recurrence rate of superbursts among X-ray bursters that are more luminous than 10% of the Eddington limit is 1.5 yr per object. Second, superbursters systematically have higher α values and shorter ordinary bursts than most bursters that have not exhibited superbursts, indicating a higher level of stable thermonuclear helium burning. Theory predicts hitherto undetected superbursts from the most luminous neutron stars. We investigate the prospects for finding these in GX 17+2.

INTRODUCTION

Three years ago the discovery of a new type of thermonuclear runaway process on a neutron star was reported: that of unstable carbon burning. The BeppoSAX Wide Field Cameras (WFCs) in 1996 detected a flare from the X-ray burster 4U 1735-44 which, according to Cornelisse et al. [1], was very reminiscent of type-I X-ray bursts (fast rise, exponential decay, black body spectrum, cooling during decay) but was roughly 10^3 as long and energetic. A similar flare was detected from 4U 1820-303 in 1999 with the PCA on RXTE and Stroymayer & Brown [2] proposed that the longevity was due to the fact that not hydrogen or helium was being burned, like in ordinary bursts, but carbon, thus following an early model for $\gamma-$ray bursts by Woosley & Taam [3]. This proposal was further developed by a number of authors since then, motivated also by the subsequent detection of five more superbursts [4–8]. Cumming & Bildsten [9] introduced the ingredient of a heavy element ocean which relaxes the carbon reservoir constraints and allows recurrence times to be substantially smaller than a decade. Recently, an eighth superburst was discovered in archival WFC data (see Fig. 1) which significantly increases the parameter range of superbursts [10]. Superbursts have e-folding decay times between 1 and 6 hours, peak luminosities (after subtraction of the persistent emission) between 0.4 and 3.4×10^{38} erg s^{-1}, and occur on neutron stars that accrete between 0.1 and 0.25 times Eddington (see recent review by Kuulkers [11]; for a compilation of the 4 WFC-detected superbursts see Fig. 2).

As pointed out by Strohmayer [12], superbursts provide the prospect of powerful diagnostics of neutron stars in LMXBs. A quick TOO turn around could provide enhanced statistics to find and accurately measure narrow spectral features and determine from their gravitational redshift constraints on the neutron star mass-radius relation (like was recently done with XMM-Newton observations of EXO 0748-676 [13]). Also, they may reveal constraints on the binary orbit through Doppler shifts of the millisecond burst oscillation frequency. This was partly demonstrated in 4U 1636-536 [8].

Despite its demise in May 2002, (archival) data from the BeppoSAX Wide Field Cameras are still actively pursued. For a small part that is because for a few percent of the observations the raw data processing was only recently accomplished. Another motivation is that more complex data are now being tackled with more sophisticated soft and hardware. In light of this, new results have been obtained with respect to superbursts which are discussed here (see also [10]).

RECURRENCE TIME

The number of superbursts is now up to a level that the recurrence time can be better constrained. This parameter is important for fine-tuning the superburst model. It may particularly provide better constraints on the mass fraction of the carbon in the flash layer and the fraction of the liberated energy being carried away by neutrinos (e.g., [2, 9]). Only once recurrence has been observed

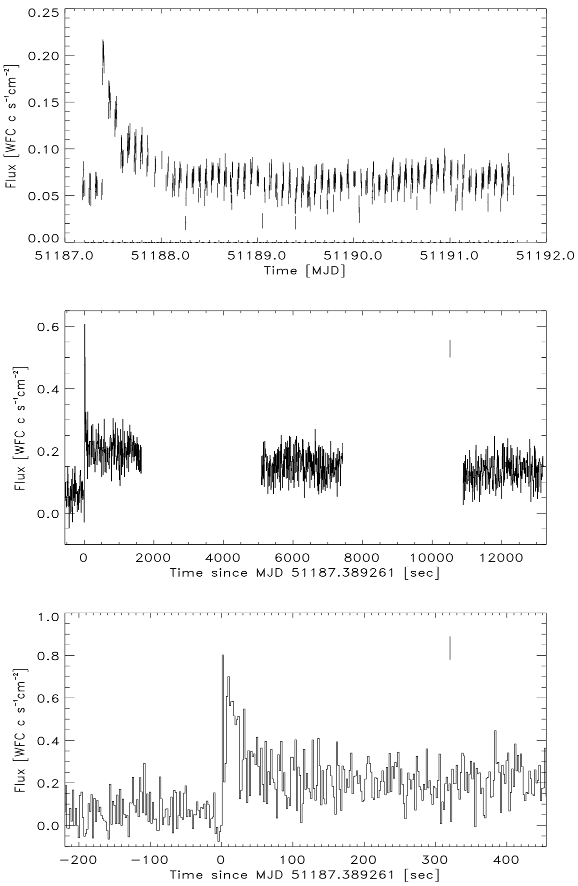

FIGURE 1. 2-28 keV WFC light curves of the most recently published superburst which came from 4U 1254-69. The top panel shows the light curve during a 5-d long observation (gaps are earth occultations; low points indicate dipping activity; 300-s resolution), the middle panel zooms in at 8-s resolution, and the bottom panel at 2-s resolution.

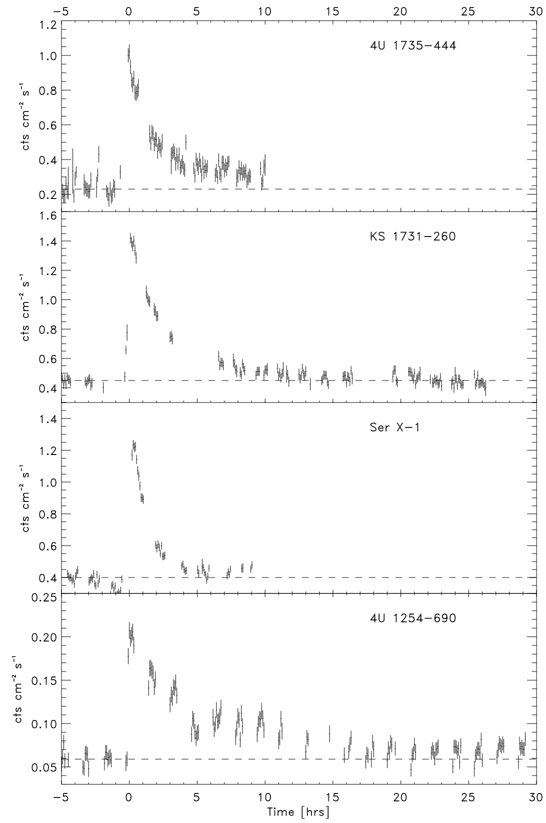

FIGURE 2. 2-28 keV light curves of the 4 WFC-detected superbursts so far, in order of discovery. The dashed lines indicate the average pre-burst flux level.

thus far: in 4U 1636-536 with an interval time of 4.7 yr [7]. The question is whether this is a representative number for all superbursters and whether this is an accurate number since intermediate superbursts may have escaped detection during the 4.7 yr interval.

Currently, seventy-five X-ray bursters are known in our Galaxy [14]. Twenty-seven of these (give or take two) have been persistent sources for at least 10 years (we include the long-duration transients KS 1731-260 and 4U 1724-307). The seven superbursters are part of this group. The WFCs have extensive coverage of these objects. The net exposure times summed over all observations is 7.9 yr (i.e., the average time per object is 0.3 yr). If all 27 objects are identical in their superburst behavior, the implied superburst recurrence rate is once per 2 yr. However, theory predicts [9] that sources with luminosities below 0.1 times Eddington will not exhibit superbursts. We estimate the number of remaining bursters at 18. The WFC exposure on these is 5.9 yr, implying a superburst recurrence time of 1.5 yr. If we go one step further and exclude those systems that have luminosities larger than 0.25 times Eddington (the Z-sources GX 17+2 and Cyg X-2, and Cir X-1), for which presumably different recurrence times apply [9], the average recurrence time is 1.2 yr. These recurrence times are smaller than expected (e.g., [9] and [15]).

α AND STABLE HELIUM BURNING

In order to produce sufficient amounts of carbon to fuel a superburst, one needs to burn helium for a sufficiently long time and avoid that the carbon is destroyed by subsequent proton and alpha captures, and breakout reactions from the hot CNO cycle [15–17]. The manners in which carbon may be destroyed imply that 1) the hydrogen abundance should preferably be at a minimum level in the burning mixture and 2) the helium should preferably be burned in a stable manner to avoid the temperature to rise above the threshold for initiation of the hot CNO cycle as happens in unstable burning [16] (in other words, stable helium burning would produce the carbon while (un)stable hydrogen burning in another layer would produce the heavy elements that provide ignition conditions for smaller amounts of carbon as proposed in [9]). Diagnostics for the hydrogen content in the helium-burning layer and stability of the burning are provided by the so-called α parameter and the duration of ordinary bursts.

α is defined as the ratio of the integrated radiation energy between two consecutive bursts and the fluence of the burst concluding this interval. The persistent emission is due to the release of gravitational energy in the accretion disk around the neutron star. Per nucleon this amount to ≈200 MeV. The energy released in thermonuclear burning depends on the chain of nuclear reactions. When hydrogen is burned, the rapid proton capture process dominates the energy production at 7 MeV per nucleon. When hydrogen is absent, the triple alpha process dominates the energy production at 1.6 MeV per nucleon. If the gravitational and thermonuclear energy production transforms solely to isotropic radiation, α should be about 30 for hydrogen-dominated bursts and 130 for helium-dominated bursts.

Accurate α determinations have been made for about 10 systems with EXOSAT [18]. Van Paradijs et al. [19] noticed an interesting measurement that α occasionally is very large in 4U 1735-44, namely almost 8000. They attributed this in part to stable helium burning, despite the fact that this is inconsistent with theory [20].

The accurate measurement of α is difficult. Firstly, continuous coverage is needed between bursts and this is difficult for observations from low-earth orbit satellites given that typical burst recurrence times are hours. This explains the succes of the high flying EXOSAT. Secondly, one needs broad-band spectral coverage to measure with a reasonable accuracy the bolometric flux. Particularly for the persistent emission this is relevant, since often a considerable fraction of the flux is outside the typical 2-10 keV bandpass. Thirdly, one needs sufficient sensitivity to be able to also detect the weak X-ray bursts. For LMXBs that are at distances smaller than the canonical 8 kpc this is not really an issue, even for modest-sized instruments, but for distances beyond that smaller instruments become insufficient. These issues can only be resolved if one uses an instrument in a high-earth orbit with coverage up to 100 keV in a staring observation of at least a day duration. Possibly INTEGRAL observations could contribute to accurate α measurements.

Alternatively, one may resort to statistical studies. If large numbers of bursts are detected while a system is in the same bursting regime, the average bursting rate in combination with the average persistent and burst spectrum will provide a reasonable estimate of α. This kind of data is abundantly provided by the WFCs for the majority of X-ray bursters (e.g., [21] and [14]). A systematic spectral analysis of all persistent and burst data has not been performed yet, but a simplified definition of α alleviates this shortcoming. Instead of the energy fluence ratio, we use the observed photon fluence ratio. The usefulness of this definition has been confirmed in [10] and, in fact, the photon-based α values do not differ by more than a few tens of percents of the energy-based values. There is a small caveat: the WFCs are only sensitive enough to peak fluxes roughly brighter than 0.3 Crab. This may artificially overestimate α somewhat in 4U 1254-690. We list in table 1 the results, separated for confirmed superbursters and others. We also list the e-folding decay times for the average burst profiles. This decay time is a good diagnostic for the relative amount of hydrogen burning in the burst. With one exception, the table shows a clear dichotomy between superbursters and other bursters: for superbursters α is high and the decay time short. This strongly suggests that unstable helium burning occurs in a hydrogen-poor environment and that stable helium burning is important. This for the first time provides observational evidence for a clear difference in non-superburst characteristics between superbursters and other bursters.

The one exception, 4U 1705-44, should provide a test to the predictive power of this diagnostic. So far, no superburst has been observed from this system with the WFCs nor RXTE/ASM.

TABLE 1. Average burst properties of all superbursters (above the dividing line) and six non-superbursters, as observed with BeppoSAX-WFC. From [10].

Object name	$\alpha^{(a)}$	$\tau^{(b)}$ [sec]
4U 1254-690	4800	6.0 ± 2.0
4U 1636-536	440	6.2 ± 0.1
KS 1731-260[c]	780	5.6 ± 0.2
4U 1735-444	4400	3.2 ± 0.3
GX 3+1	2100	4.6 ± 0.1
4U 1820-303	2200	4.5 ± 0.2
Ser X-1	5800	5.7 ± 0.9
EXO 0748-676	140	12.8 ± 0.4
4U 1702-429	58	7.7 ± 0.2
4U 1705-44	1600	8.7 ± 0.4
GX 354–0	97	4.7 ± 0.1
A 1742-294	130	16.8 ± 1.0
GS 1826-24	32	30.8 ± 1.5

[a] α is ratio of average persistent 2–28 keV flux (in WFC c $s^{-1}cm^{-2}$) times average wait time between two bursts (2nd column) and burst fluence (in WFC c cm^{-2}); [b] e-folding decay time of the average 2–28 keV burst profile; [c] This is a transient and only data are given for persistent flux levels comparable to when the superburst occurred.

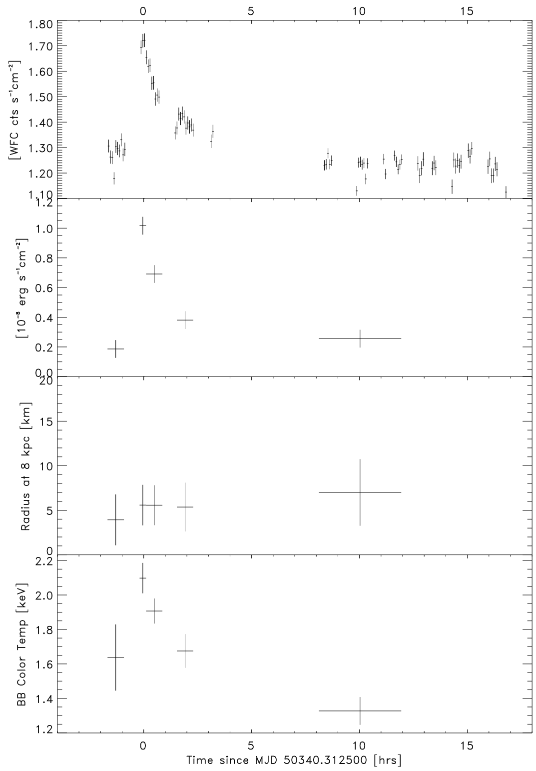

FIGURE 3. 2-28 keV light curve and time-resolved spectroscopy of a likely first superburst from GX 17+2. Before the spectroscopy, the persistent spectrum was subtracted as determined from before these data.

TESTING A PREDICTION: SUPERBURSTS IN HIGH-LUMINOSITY SYSTEMS

Cumming & Bildsten [9] predict that for a carbon mass fraction $X_{12} < 0.1$ any neutron star accreting faster than 0.1 times the Eddington limit should exhibit superbursts. For a mass accretion rate close to Eddington, the recurrence time is predicted to be a few weeks and the cooling time scale about 1 hr. The seven superbursters discovered up to now accrete at most at one quarter of the Eddington limit. As noted by Cumming & Bildsten [9], this may be a selection effect. The dynamic range available for superbursts in near-Eddington systems is much less than in weaker systems: if the system is emitting at 90% of Eddington, the signal-to-background ratio is 0.1 at maximum while it may be 10 if the persistent luminosity level is near 10% of Eddington. Furthermore, the amplitude of the variability in the more luminous systems may be similar to the peak flux of superbursts.

In order to test the theory, we initiated a search in WFC data for superbursts in one of the few well-known persistently high-luminosity X-ray bursters, GX 17+2. It appears that indeed this system exhibits superbursts. An example is presented in Fig. 3. The e-folding decay time of this flare is 1.9 hr, which is a factor of 25 longer than the longest ordinary burst observed from GX 17+2 thus far (which is already realtively long for an ordinary burst with a decay time of 4.5 minutes; [22]). The spectrum is consistent with black body emission showing cooling during the decay. The fast rise of the flare candidate seems markedly different from the flares commonly observed in this Z-source. Thus, this appears a genuine superburst which would fit theoretical predictions excellently. We are continuing to analyze the WFC data in detail to find more superburst candidates from this source and fine tune discriminating diagnostics against accretion-type flares. Furthermore, we are pursuing data from other persistently high-luminosity LMXB bursters such as Cyg X-2.

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