A&A 411, L487–L491 (2003)
DOI: 10.1051/0004-6361:20031586

Astronomy & Astrophysics

Letter to the Editor

A superburst from 4U 1254-69

J. J. M. in 't Zand[1,2], E. Kuulkers[3], F. Verbunt[2], J. Heise[1,2], and R. Cornelisse[4]

[1] SRON National Institute for Space Research, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands
[2] Astronomical Institute, Utrecht University, PO Box 80000, 3508 TA Utrecht, The Netherlands
[3] ESA-ESTEC, Science Ops. & Data Systems Div., SCI-SDG, Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands
[4] Dept. of Physics and Astronomy, University of Southampton, Hampshire SO17 1BJ, UK

Received 9 September 2003 / Accepted 9 October 2003

Abstract. We report the detection with the BeppoSAX Wide Field Cameras of a superburst from 4U 1254-69. The superburst is preceded by a normal type-I X-ray burst, has a decay time that is the longest of all eight superbursts detected so far and a peak luminosity that is the lowest. Like for the other seven superbursts, the origin is a well-known type-I X-ray burster with a persistent luminosity level close to one tenth of the Eddington limit. Based on WFC data of all persistently bright X-ray bursters, the average rate of superbursts is 0.51 ± 0.25 per year per persistently bright X-ray burster. Some systems may have higher superburst rates. For all superbursters, we present evidence for a pure helium layer which is burnt in an unstable *as well as a stable* manner.

Key words. stars: neutron – X-rays: binaries – X-rays: bursts – X-rays: individual: 4U 1254-69

1. Introduction

4U 1254-69 is a persistently bright low-mass X-ray binary (Griffiths et al. 1978) exhibiting type-I X-ray bursts (Mason et al. 1980; Courvoisier et al. 1986). A type-I X-ray burst is a seconds-to-minutes long X-ray event caused by a thermonuclear flash in the upper layers of a neutron star that is receiving matter from a nearby, usually Roche-lobe filling, companion star (for reviews see Lewin et al. 1993; Strohmayer & Bildsten 2003). Courvoisier et al. (1986) discovered periodic dipping activity with a period of 3.88 ± 0.15 hr and identified this as the binary orbital period. The dips are caused by obscuration of the central source by a bulge on the outer edge of the accretion disk. The inclination is close to edge-on but not completely because no eclipses are observed ($68 < i < 73$; Motch et al. 1987). Motch et al. and Courvoisier et al. estimate through independent methods distances of 9–14 and 8–15 kpc respectively. Recent X-ray studies by Smale et al. (1999, 2002), Iaria et al. (2001) and Boirin & Parmar (2003) show that dipping activity is not present during each orbit.

A few years ago the BeppoSAX Wide Field Cameras (WFCs; Jager et al. 1997) brought about the discovery of thermonuclear flashes with durations and energetics 10^3 times higher than for ordinary type-I X-ray bursts (Cornelisse et al. 2000). These so-called superbursts are rare, with an estimated frequency of once per few years per object. So far, seven superbursts have been detected from six sources: one from 4U 1735-44 (Cornelisse et al. 2000), Ser X-1 (Cornelisse et al. 2002), KS 1731-260 (Kuulkers et al. 2002), 4U 1820-303 (Strohmayer & Brown 2002), GX 3+1 (Kuulkers 2002) and two from 4U 1636-536 within 4.7 yr (Wijnands 2001; Strohmayer & Markwardt 2002). It is thought that unstable carbon burning (Woosley & Taam 1976; Strohmayer & Brown 2002) in a heavy-element ocean (Cumming & Bildsten 2001), possibly combined with photo-disintegration-triggered nuclear energy release (Schatz et al. 2003), is responsible for most superbursts.

In the present paper we report the WFC detection of the eighth superburst, from 4U 1254-69.

2. Burst detections

Measurements with the RXTE All-Sky Monitor (ASM; Levine et al. 1996) provide the most complete picture of the persistent 2–12 keV flux from 4U 1254-69 in recent years, see Fig. 1. They reveal that the source is persistently present. There are no strong week-to-week variations, but there is a slow trend: during 1999 through 2000 it was about 30% fainter than before or after. The average flux is 2.42 ± 0.01 ASM c s^{-1}, or 32 mCrab. This is, within a few tens of percents, equal to many previous measurements (Courvoisier et al. 1986; Uno et al. 1997; Iaria et al. 2001; Boirin & Parmar 2003), although in the 1970s 4U 1254-69 appears to have been much more variable on long time scales (see Griffiths et al. 1978 and references therein).

The BeppoSAX WFCs acquired a total exposure time of 10.3 Ms on 4U 1254-69. This exposure includes times when the satellite attitude reconstruction is not optimum. The detrimental effect on the quality of the data is only limited when considering *brief* X-ray bursts because the attitude is not expected

Send offprint requests to: J. J. M. in 't Zand, e-mail: jeanz@sron.nl

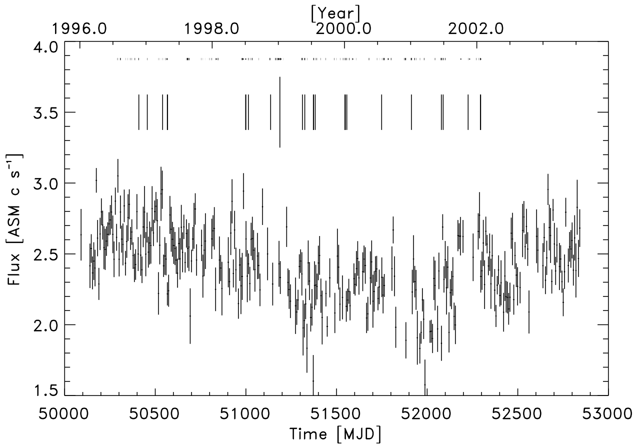

Fig. 1. 2–12 keV RXTE-ASM light curve of 4U 1254-69 at a 1-week time resolution. Data points with errors in excess of 0.2 c s^{-1} were excluded from this plot. The horizontal lines in the top indicate the WFC coverage of the source and the vertical lines the bursts detected with the WFC. The long vertical line indicates the time of the superburst.

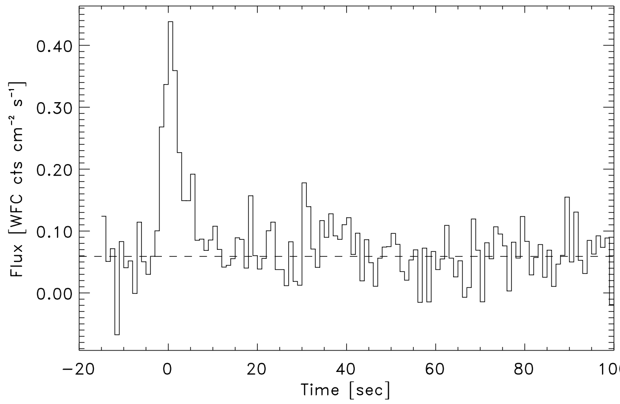

Fig. 2. The average 2–28 keV profile over all normal bursts observed from 4U 1254-69, except the one related to the superburst. The dashed line refers to the persistent flux level.

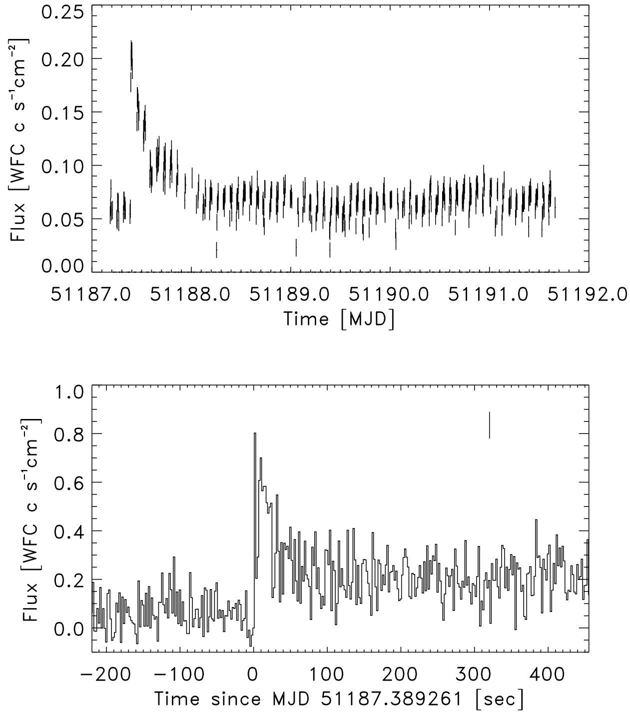

Fig. 3. Light curves obtained with the WFC on January 9–13, 1999 at 300 s resolution (*top panel*) and focused on the burst onset at 2 s resolution (*bottom panel*, with vertical line indicating a typical 1σ error). The bandpass is 2–28 keV.

to change much within a few tens of seconds. Confinement to good-attitude data would result in ignoring 28% of the data.

Unfortunately, the source is rather distant. This implies that X-ray bursts, whose luminosity can at maximum peak at the Eddington limit, are relatively faint. For 16 kpc the 2–10 keV peak flux would be of order one third that of the Crab. If the bursts are short, as appears to be the case for the six X-ray bursts reported so far in some detail (Courvoisier et al. 1986; Smale et al. 2002), they are near the detection limit of the WFCs. Nevertheless, we carried out a systematic search for bursts. To optimize the detection limit for expected bursts, we searched with a time resolution of 4 s in the full bandpass for increases above the persistent flux level. The 4σ detection threshold varies between 0.2 and 0.3 Crab units (2–28 keV). In total 26 bursts were identified. Their times are indicated in Fig. 1. The shortest wait time between two bursts is 2.5 hr and subday wait times were observed in 4 other pairs of bursts (see also Smale et al. 2002). The burst peak flux varies between 0.4 and 0.7 WFC c s^{-1}cm^{-2} (0.2 to 0.3 Crab units). Most bursts appear to be short: the average profile of the bursts (Fig. 2) has an e-folding decay time of 6 ± 2 s and shows no flux after about 15 s. Due to the limits of the WFC sensitivity, we are unable to study these bursts in any spectral detail, except for the brightest burst in a rather limited sense, and we cannot confirm the type-I classification. Furthermore, we cannot claim to have a complete database of bursts. Our observations suggest that the source bursts regularly except possibly during late 1997 through early 1998, but the gap may be due to pure chance. The average observed burst rate is 2.5 ± 0.5 per Ms. Thus, one would expect on average 2.1 bursts during the gap. Based on Poissonian statistics, the probability to find none by coincidence is 12%.

In Fig. 3 we present the light curve as measured with WFC unit 1 during a long observation between January 9.2 and 13.7, 1999, when a flare occurred reminiscent of a superburst. This is the only such flare we found in the whole data set for 4U 1254-69. The flare onset is on 9.389 January (UT), when a short normal X-ray burst occurred. This ordinary X-ray burst is the brightest of the sample of 26. It appears to consist of two peaks roughly 8 s apart. The question arises whether the drop in flux is due to dipping activity in this established dipper. During the observation clear dipping activity is observed several times, for instance at MJD 51187.597, 51188.255 and 51189.072. From the 3.93336 hr orbital period (Motch et al. 1987) we predict that the period of dipping activity nearest to the burst onset is between MJD 51187.416 and 51187.450. This interval starts 2310 s after the burst onset and is during a data gap. Thus, the double-peaked nature of the burst unlikely is related to dipping and is probably intrinsic to the neutron star. The flare following the normal X-ray burst lasts approximately 14 hr. It decays in an exponential-like manner with a fitted e-folding time of 6.0 ± 0.3 hr (after excluding the dipping intervals; $\chi^2_\nu = 1.47$ with 488 d.o.f.). During the five days following the superburst the decay levels off to a flux level that is 10 ± 3% higher than the pre-burst level.

We do not find any evidence for the flare to start prior to the normal burst, like for the second superburst in 4U 1636–536 (Strohmayer & Markwardt 2002), but the statistical quality of our data is rather limited to make a conclusive statement. In a two-minute interval prior to the normal burst, the highest flux consistent with our data bridges 20% of the difference between the pre-burst flux and the superburst peak flux (excluding the normal burst). This is roughly equal to what was measured in 4U 1636-536 (Strohmayer & Markwardt 2002).

3. Confirmation of superburst nature

Type-I X-ray bursts, including superbursts, are characterized by black body continua and cooling during the decay. Therefore, two crucial tests are that the black body radiation model is a better description than any other reasonable model and that the temperature decreases. To study the possibly varying spectrum during the flare, we generated ten spectra: one for each of nine 100-min long BeppoSAX orbits during the flare and one for all pre-burst data combined. The resulting spectra have sufficient statistical quality for a meaningful analysis. First, we modeled these data with absorbed thermal bremsstrahlung. We kept the hydrogen column density that parameterizes the low-energy interstellar absorption (Morrison & McCammon 1983) fixed to 3.2×10^{21} cm^{-2} (see Iaria et al. 2001; Boirin & Parmar 2003) and note that the 2–28 keV spectrum is not very sensitive to such low densities. While the thermal bremsstrahlung model describes the pre-burst data well ($\chi^2_\nu = 0.65$), it does not do so for the flare data ($\chi^2_\nu = 2.46$, 2.02, 1.86 and 1.31 for the first 4 flare spectra with $\nu = 26$). Adding a black body component while tying the bremsstrahlung parameter values to those for the pre-burst spectrum significantly improves the fit ($\chi^2_\nu = 0.69$, 0.67, 0.82 and 1.01 for the first 4 flare spectra with $\nu = 26$). Substituting the black body model for a second bremsstrahlung model does not provide an improvement ($\chi^2_\nu = 3.08$, 2.40, 2.15 and 1.57 for the first 4 flare spectra with $\nu = 26$) and neither does substitution by a power law ($\chi^2_\nu = 3.72$, 3.18, 2.63 and 1.69 for the first 4 flare spectra with $\nu = 26$). We conclude that a black body model describes the flare spectrum best. The fit results are given in Fig. 4. It is clear that the black body temperature decreases during the decay of the flare. Thus, the flare has all the characteristics of other superbursts and we confirm the superburst nature. In Table 1 we list the basic characteristics of this superburst.

Also plotted in Fig. 4 is the time-resolved spectroscopy of the precursor burst. This is the brightest normal burst that we detected. Although the black body model is an adequate description of the data, and the resulting temperature typical for type-I X-ray bursts, we formally cannot confirm this as an X-ray burst because we cannot prove cooling. Nevertheless, 4U 1254-69 is a known burster with bursts of similar duration and we consider it very unlikely that this is something else than a type-I burst.

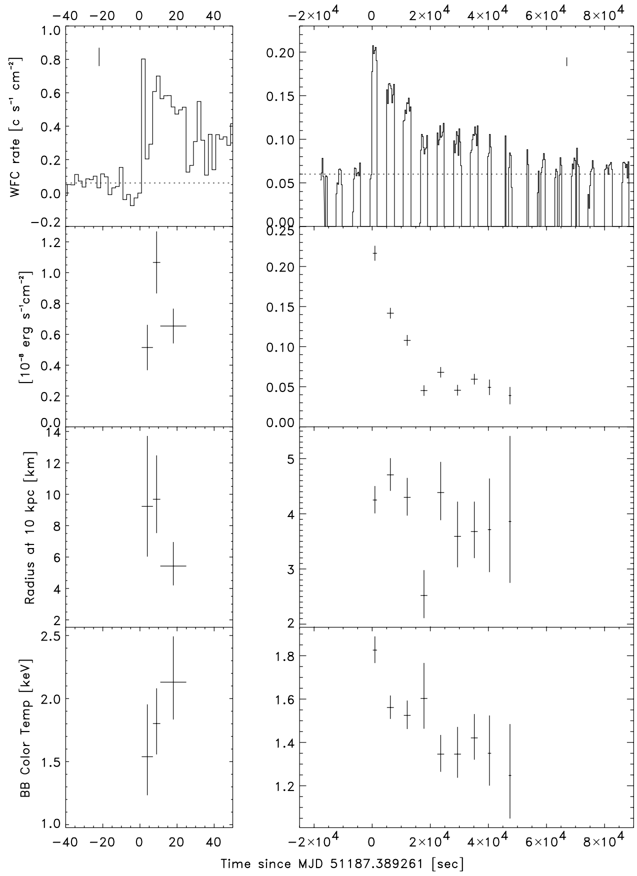

Fig. 4. Time-resolved spectroscopy of the superburst (right) and the normal type-I precursor burst (left). Note the different y scales in both columns of plots. In the top panels, a dashed line indicates the pre-burst flux level for guiding purposes and solid vertical lines indicate the typical 1σ error. The time resolution of the observed photon flux is 2 s in the left and 300 s in the right panel. In the other panels errors are 1σ values. The 2nd row of panels show the bolometric flux of the black body component. The decreased flux levels near 1.8×10^4 and 7.5×10^4 s are due to dipping activity.

The precursor burst has a remarkable feature: it is double peaked. This suggests that the burst invoked strong photospheric radius expansion due to near-Eddington luminosities (e.g., Lewin et al. 1993). This would be the first detection of a radius-expansion burst in 4U 1254-69. Keeping in mind that the statistical quality of our data is insufficient to confirm the expansion directly through black body model fits, we derive a distance estimate: $d = 13 \pm 3$ kpc. This is consistent with previous estimates (Courvoisier et al. 1986; Motch et al. 1987).

We note that the 2–28 keV spectrum after the superburst (i.e., after MJD 51188.0; see Fig. 3) can be adequately modeled by thermal bremsstrahlung. The temperature varies between 5.2 ± 0.2 and 6.5 ± 0.3 keV and the 2–28 keV flux varies between 7.7 and 9.2×10^{-10} erg cm^{-2} s^{-1} on a 1-day time basis (6.7 to 7.3×10^{-10} erg cm^{-2} s^{-1} between 2 and 10 keV).

4. Discussion

The fortunate circumstance exists that a high-quality broadband spectrum was taken of 4U 1254-69 just two weeks

Table 1. Characteristics of 4U 1254-69 superburst. A distance of 13 kpc has been assumed (see text). For comparison the range of values for the other seven superbursts has been provided in the last column if useful (in the same units; from Kuulkers et al. 2002 and Strohmayer & Markwardt 2002).

Duration	14 ± 2 hr	4–12
Precursor?	Yes	3 times
τ_{exp} (hr)	6.0 ± 0.3	1–2
kT_{max} (keV)	1.8 ± 0.1	2–3.0
L_{peak} (10^{38} erg s^{-1})	0.44 ± 0.2	0.8–3.4
L_{pers} (L_{edd})	0.13 ± 0.03	0.1–0.25
E_b (10^{42} erg)	0.8 ± 0.2	0.5–>1.4
τ (=E_b/L_{peak}) (hr)	5.0 ± 1.7	1.2–2.0
γ (=L_{pers}/L_{peak})	0.66 ± 0.16	0.1–0.5
$t_{no\ bursts}$ (d)	<124.7	>7
Donor	H/He‡	He and H/He

‡From Motch et al. (1987).

Table 2. Average burst properties of all superbursters (above the dividing line) and six non-superbursters, as observed with BeppoSAX-WFC.

Object name	$T_C^{(a)}$	$\alpha^{(b)}$	$\alpha^{(c)}$	$\tau^{(d)}$ [s]
4U 1254-69	4.6	4800		6 ± 2 (15)
4U 1636-536	0.6	440	44–336[1]	6.2 ± 0.1 (67)
KS 1731-260(e)	0.8	780	30–690[2]	5.6 ± 0.2 (37)
4U 1735-444	2.4	4400	220–7728[3]	3.2 ± 0.3 (34)
GX 3+1	1.2	2100	1700–21 000[4]	4.6 ± 0.1 (61)
4U 1820-303	1.5	2200		4.5 ± 0.2 (47)
Ser X-1	2.9	5800		5.7 ± 0.9 (7)
EXO 0748-676	1.0	140	18-34[5]	12.8 ± 0.4 (155)
4U 1702-429	0.3	58		7.7 ± 0.2 (107)
4U 1705-44	1.1	1600	55–1455[6]	8.7 ± 0.4 (74)
GX 354–0	0.2	97	105–140[7]	4.7 ± 0.1 (417)
A 1742-294	0.4	130		16.8 ± 1.0 (141)
GS 1826-24	0.2	32	41[8]	30.8 ± 1.5 (248)

(a) Average wait time between bursts in days. (b) 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}). (c) α from literature if covering the largest persistent flux range known ([1] Lewin et al. 1987; [2] Muno et al. 2000, [3] van Paradijs et al. 1988b; [4] den Hartog et al. 2003; [5] Gottwald et al. 1987; [6] Gottwald et al. 1989; [7] Basinska et al. 1984; [8] Galloway et al. 2003). (d) e-folding decay time of the average 2–28 keV burst profile; between parentheses the number of bursts averaged. (e) This is a transient and only data are given for persistent flux levels comparable to when the superburst occurred.

before the superburst. Iaria et al. (2001) determined the 2–10 keV flux at 6.9×10^{-10} erg cm^{-2} s^{-1} which compares well to the flux in the days after the superburst. The unabsorbed 0.1 to 100 keV flux on 23 December 1998 was 1.4×10^{-9} erg cm^{-2} s^{-1}. For a distance of 13 kpc this translates to a luminosity of 2.9×10^{37} erg s^{-1}. This is roughly 15% of the Eddington limit for a 1.4 $M_\odot$ neutron star with a hydrogen-dominated atmosphere (2×10^{38} erg s^{-1}). Thus, the superburst follows the rule of the other superbursts in occurring on objects that accrete at 5 to 10 times below Eddington (Wijnands 2001; Kuulkers et al. 2002).

The suggestion is strong in three previous cases that a superburst quenches normal type-I bursting activity for tens of days (Cornelisse et al. 2000, 2002; Kuulkers et al. 2002). For 4U 1254-69 this is hard to prove, given the low burst frequency. The last normal burst prior to the superburst was seen 51 days earlier, and the first one following the superburst 125 days later (while it should be noted that there is a long data gap from 20 to 120 days after the superburst). Therefore, our data do not prove nor disprove the presence of quenching in 4U 1254-69.

The superburst from 4U 1254-69 shows extremes in two parameters (Table 1): the peak luminosity is two times lower than the previous minimum value and the decay time is three times longer than the previous maximum. These two extremes approximately cancel out in the total burst energetics. The long decay must be due to either a relatively deep flash location, a smaller neutron star mass, the presence of relatively heavy elements, or a combination of these circumstances (Cumming & Bildsten 2001).

The superburst from 4U 1254-69 is the fourth for which coincidence with a normal type-I burst could be proven. Like in 4U 1636-536 (Strohmayer & Markwardt 2002) and KS 1731-260 (Kuulkers et al. 2002), the precursor from 4U 1254-69 has a peak flux that is higher than that of the superburst (roughly three times). This emphasizes the exceptional superburst from 4U 1820-30 (Strohmayer & Brown 2002) with a precursor that was *weaker* than the superburst which must be related to the exceptional nature of the donor star.

In Table 2 we list a few burst properties for all superbursters and for six bursters which have not yet shown superbursts. The properties are averaged over the complete WFC database. One is the α-parameter which is defined as the ratio of the persistent fluence between bursts and the burst fluence. Since there has not yet been a systematic spectral analysis of the thousands of WFC-detected bursts, we employ an alternative α which is based on the ratio of the *number of observed photons* rather than on *intrinsic radiation energy*. This is a useful alternative since we only compare data from a single instrument. For a few sources, verification with the literature of the alternative α with the true α (see Table 2) shows that the two are not far apart. It turns out that superbursters generally have much higher average α-values[1] than the other bursters.

Another property is the e-folding decay time of the average 2–28 keV burst profile. We generated such profiles by selecting bursts with peak significances in excess of 3σ at 1 s resolution, aligning the bursts at their peaks, and averaging the fluxes weighted by the inverse square of the statistical 1σ error. An

[1] α may occasionally be low while not significantly affecting the high average over long time scales. This is particularly well documented for 4U 1820-303 (e.g., Cornelisse et al. 2003).

exponential function was fitted to the tail of the average profile (from 1 s on after the peak) with as free parameters the normalization, e-folding decay time and background level. It turns out that superbursters have generally shorter decay times than the other bursters, with a boundary value of about 6 s. A decay time as short as 6 s indicates the presence of a helium-rich layer. Such a layer is formed through stable burning of accreted hydrogen at global mass accretion rates in excess of one tenth the Eddington limit (Fujimoto et al. 1981; Bildsten 1998) as is the case for the superbursters, except for 4U 1820-303 which is thought to have a helium-rich donor star (for a recent discussion on that, see Cumming 2003).

The high α suggests that a sizeable fraction of the helium is burned in a *stable manner* rather than an unstable burst-like manner (e.g., Van Paradijs et al. 1988a). Thus, favorable conditions for a superburst appear to include the presence of a pure helium layer which is burned in a stable as well as unstable fashion. This supports inferences by Strohmayer & Brown (2002), Cumming (2003) and Woosley et al. (2003) that only stable helium burning can generate sufficient amounts of carbon for triggering a superburst.

We note that EXO 0748-676, 4U 1728-34 (GX 354-0) and GS 1826-24 are examples of frequently bursting sources that do not show high α values. These sources will, therefore, unlikely exhibit superbursts. Conversely, our analysis identifies one new prospective superburster: 4U 1705-44.

The WFC observations have thus far resulted in the detection of four superbursts. The effective observation time for superburst detection[2] added over all 27 persistently bright X-ray bursters is 7.9 yr (in other words, the average observation time per source is 0.3 yr). Thus, the average superburst frequency is 0.51 ± 0.25 per year per object. Considering that superbursts may occur in only a selection of X-ray bursters (like those with persistent flux levels in excess of 0.1 times Eddington), the rate may actually be larger by up to a factor of two. Therefore, the WFC observations yield an average superburst recurrence time that lies between 0.7 and 4 years (at 70% confidence).

Acknowledgements. JZ acknowledges support from the Netherlands Organization for Scientific Research (NWO). Gerrit Wiersma, Jaap Schuurmans, Nuovo Telespazio and the ASI BeppoSAX Science Data Center are acknowledged for continued support, and the ASM/RXTE team for providing ASM standard data products to the public.

References

Basinska, E. M., Lewin, W. H. G., Sztajno, M., Cominsky, L. R., & Marshall, F. J. 1984, ApJ, 281, 337

Bildsten, L. 1998, in The Many Faces of Neutron Stars, ed. A. Alpar, R. Buccheri, & J. van Paradijs, NATO ASI Ser. C 515 (Dordrecht: Kluwer), 419

Boirin, L., & Parmar, A. 2003, A&A, 407, 1079

Cornelisse, R., Heise, J., Kuulkers, E., Verbunt, F., & in't Zand, J. J. M. 2000, A&A, 357, L21

Cornelisse, R., Kuulkers, E., in't Zand, J. J. M., Verbunt, F., & Heise, J. 2002, A&A, 382, 174

Cornelisse, R., in't Zand, J. J. M., Verbunt, F., et al. 2003, A&A, 405, 1033

Courvoisier, T. J.-L., Parmar, A. N., Peacock, A., & Pakull, M. 1986, ApJ, 309, 265

Cumming, A. 2003, ApJ, 595, 1077

Cumming, A., & Bildsten, L. 2001, ApJ, 559, L127

Fujimoto, M. Y., Hanawa, T., & Miyaji, S. 1981, ApJ, 247, 267

Galloway, D. K., Cumming, A., Kuulkers, E., et al. 2003, ApJ, accepted [astro-ph/0308122]

Gottwald, M., Haberl, F., Parmar, A. N., & White, N. E. 1987, ApJ, 323, 575

Gottwald, M., Haberl, F., Langmeier, A., et al. 1989, ApJ, 339, 1044

Griffiths, R. E., Gursky, H., Schwartz, D. A., et al. 1978, Nature, 276, 247

den Hartog, P. R., in't Zand, J. J. M., Kuulkers, E., et al. 2003, A&A, 400, 633

Iaria, R., Di Salvo, T., Burderi, L., & Robba, N. R. 2001, ApJ, 548, 883

Jager, R., Mels, W. A., Brinkman, A. C., et al. 1997, A&AS, 125, 557

Kuulkers, E. 2002, A&A, 383, L5

Kuulkers, E., in 't Zand, J. J. M., van Kerkwijk, M. H., et al. 2002, A&A, 382, 503

Levine, A. M., Bradt, H., Cui, Wei et al. 1996, ApJ, 469, L33

Lewin, W. H. G., Penninx, W., van Paradijs, J., et al. 1987, ApJ, 319, 893

Lewin, W. H. G., van Paradijs, J., & Taam, R. E. 1993, Space Sci. Rev., 62, 223

Mason, K. O., Middleditch, J., Nelson, J. E., & White, N. E. 1980, Nature, 287, 516

Morrison, R., & McCammon, D. 1983, ApJ, 270, 119

Motch, C., Pedersen, H., Courvoisier, T. J.-L., Beuermann, K., & Pakull, M. W. 1987, ApJ, 313, 792

Muno, M. P., Fox, D. W., Morgan, E. H., & Bildsten, L. 2000, ApJ, 542, 1016

Schatz, H., Bildsten, L., & Cumming, A. 2003, ApJ, 583, L90

Smale, A., & Wachter, S. 1999, ApJ, 527, 341

Smale, A., Church, M. J., & Bałucińska-Church, M. 2002, ApJ, 581, 1286

Strohmayer, T. E., & Brown, E. 2002, ApJ, 566, 1042

Strohmayer, T. E., & Markwardt, C. B. 2002, ApJ, 577, 337

Strohmayer, T. E., & Bildsten, L. 2003, in Compact Stellar X-Ray Sources, ed. W. H. G. Lewin, & M. van der Klis (Cambridge University Press), in press [astro-ph/0301544]

Uno, S., Mitsuda, K., Aoki, T., & Makino, F. 1997, PASJ, 49, 353

van Paradijs, J., Penninx, W., & Lewin, W. H. G. 1988a, MNRAS, 233, 437

van Paradijs, J., Penninx, W., Lewin, W. H. G., Sztajno, M., & Truemper, J. 1988b, A&A, 192, 147

Woosley, S., & Taam, R. E. 1976, Nature, 263, 101

Woosley, S., Heger, A., Cumming, A., et al. 2003, ApJ, submitted [astro-ph/0307425]

Wijnands, R. 2001, ApJ, 554, L59

[2] This is simply the elapse time of an observation, including the data gaps due to earth occultations and passes over the South Atlantic Anomaly which are shorter than half an hour.