Astron. Astrophys. 357, L21–L24 (2000)

ASTRONOMY AND ASTROPHYSICS

LETTER

Letter to the Editor

The longest thermonuclear X-ray burst ever observed?

A BeppoSAX Wide Field Camera observation of 4U 1735−44

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Received 3 March 2000 / Accepted 30 March 2000

Abstract. A long flux enhancement, with an exponential decay time of 86 min, is detected in 4U 1735−44 with the BeppoSAX Wide Field Cameras. We argue that this is a type I X-ray burst, making it the longest such burst ever observed. Current theories for thermonuclear bursts predict shorter and more frequent bursts for the observed persistent accretion rate.

Key words: accretion, accretion disks – stars: neutron – book reviews – X-rays: bursts

1. Introduction

Of the ≃150 low-mass X-ray binaries known in our galaxy, about 40% show occasional bursts of X-rays, in which a rapid rise, lasting from less than a second to ≃10 s, is followed by a slower decay, lasting between ≃10 s to minutes. During the decay the characteristic temperature of the X-ray spectrum decreases. An X-ray burst is explained as energy release by rapid nuclear fusion of material on the surface of a neutron star and thus an X-ray burst is thought to identify the compact object emitting it unambiguously as a neutron star. If the burst is very luminous, reaching the Eddington limit $L_{\rm Edd}$, the energy release may temporarily lift the neutron star atmosphere to radii of order 100 km. Reviews of observations of X-ray bursts are given by Lewin et al. (1993, 1995).

The properties of a burst depend, according to theory, on the mass and radius of the neutron star, on the rate with which material is accreted onto the neutron star, and on the composition of the accreted material. It is hoped that a detailed study of X-ray bursts can be used to determine the mass and radius of the neutron star, via the relation between luminosity, effective temperature and flux, and via the changes in the general relativistic correction to this relation when the atmosphere expands from the neutron star surface to a larger radius. However, the physics of the X-ray burst is complex. There is evidence that the emitting area does not cover the whole neutron star and changes with the accretion rate. Reviews of the theory of X-ray bursts are given by Bildsten (1998, 2000).

In this paper we describe a long flux enhancement that we observed with the Wide Field Cameras of BeppoSAX in the X-ray burst source 4U 1735−44, and argue that this event is the longest type I X-ray burst ever observed. In Sect. 2 we describe the observations and data extraction, in Sect. 3 the properties of the flux enhancement. A discussion and comparison with earlier long bursts is given in Sect. 4. In the remaining part of this section we briefly describe earlier observations of 4U 1735−44.

4U 1735−44 is a relatively bright low-mass X-ray binary. Smale et al. (1986) fit EXOSAT data in the 1.4-11 keV range with a power law of photon index 1.8 with an exponential cutoff above 7 keV, absorbed by an interstellar column $N_{\rm H} \simeq 5 \times 10^{20}{\rm cm}^{-2}$. The flux in the 1.4-11 keV range is $\simeq 4 \times 10^{-9}{\rm erg\,cm^{-2}s^{-1}}$. Van Paradijs et al. (1988) show that a sum of thermal bremsstrahlung of $\simeq 10$ keV and black body radiation of $\simeq 2$ keV, absorbed by an interstellar column $N_{\rm H} < 8 \times 10^{20}{\rm cm}^{-2}$, adequately describes EXOSAT data in the same energy range and at a similar flux level, obtained one year later. A similar spectrum, with a higher absorption column $N_{\rm H} \simeq 3.4 \times 10^{21}{\rm cm}^{-2}$, fits the Einstein solid-state spectrometer and monitor proportional counter data (Christian & Swank 1997). During GINGA observations, the source was somewhat brighter, at $\simeq 9 \times 10^{-9}{\rm erg\,cm^{-2}s^{-1}}$ in the 1-37 keV range (Seon et al. 1997).

Bursts were detected at irregular time intervals during each of the five occasions in 1977 and 1978 that SAS-3 observed 4U 1735−44, leading to a total of 53 detected bursts (Lewin et al. 1980). EXOSAT detected one burst in 1984 (Smale et al. 1986) and five bursts during a continous 80 hr observation in 1985 (Van Paradijs et al. 1988), one rather bright burst was detected with GINGA in 1991 (Seon et al. 1997), and five X-ray bursts with RXTE in 1998 (Ford et al. 1998). Burst intervals range from about 30 minutes to more than 50 hrs. Three of the bursts observed with EXOSAT and the single burst observed with GINGA were radius expansion bursts (Damen et al. 1990,

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Seon et al. 1997), and have been used to determine the distance to 4U 1735−44 as about 9.2 kpc (Van Paradijs and White 1995).

4U 1735−44 was the first X-ray burster for which an optical counterpart was found: V926 Sco (McClintock et al. 1977). From optical photometry an orbital period of 4.65 hrs was derived (Corbet et al. 1986).

2. Observations and data extraction

The Wide Field Camera experiment (Jager et al. 1997) is located on the BeppoSAX platform which was launched early 1996 (Boella et al. 1997). It comprises two identically designed coded-aperture multi-wire Xenon proportional counter detectors. The field of view of each camera is 40×40 degrees full width to zero response, which makes it the largest of any flown X-ray imaging device with good angular resolution. The angular resolution is $5'$ full width at half maximum, and the accuracy of the source location is upward of $0.7'$, depending mainly on the signal-to-noise ratio. The photon energy range is 2-28 keV, and the time resolution is 0.5 ms. Due to the coded mask aperture the detector data consist of a superposition of the background and shadowgrams of multiple sources. To reconstruct the sky image an algorithm is employed which is based on cross correlation of the detector image with the coded mask (Jager et al. 1997).

Since the fall of 1996, the Wide Field Cameras observe the field around the Galactic Center on a regular basis during each fall and spring. The first campaign was a nine-day near-continuous observation from August 21 until August 30, 1996. About 30% of the time, viz. ≃35 minutes per orbit, is lost due to earth occultation and due to passage through the South Atlantic Anomaly.

3. A long X-ray flux enhancement of 4U 1735−44

In Fig. 1 we show the lightcurve of 4U 1735−44 as observed with the WFC between 21 and 30 August 1996. The persistent countrate varies between 0.2 and 0.3 counts $\mathrm{cm^{-2}s^{-1}}$. Immediately after the earth occultation on MJD 50318.1 a strong enhancement (factor ≃3) in the X-ray intensity was seen which subsequently decayed exponentially. An expanded lightcurve of this event is also shown in Fig. 1. The position derived for this event is $3\farcs2 \pm 3\farcs4$ from the position of 4U 1735−44 as derived from its persistent emission. (Both positions share the same systematic error, and thus their relative position is much more accurate than their absolute positions, which have errors of $\simeq 1'$.) We conclude that the event is from 4U 1735−44.

To the persistent flux we fit the two models discussed in the introduction, i.e. a power law with high energy cutoff, and a sum of bremsstrahlung and black body spectra, in the 2-24 keV range. The spectrum before and after the event are for the intervals MJD 50317.8-50318.1 and MJD 50319.7-50320.8, respectively. The results are given in Table 1. We note that the values of the fit parameters are similar to those for earlier observations. Notwithstanding the different flux levels before and after the flux enhancement, the hardness of the spectrum (also shown in Fig. 1) is similar. The persistent flux corresponds to an X-ray luminosity at 9.2 kpc of $4.4 \times 10^{37}\mathrm{erg\,s^{-1}}$ in the 2-28 keV band. In our fits we set the interstellar absorption at a fixed value of $N_\mathrm{H} = 3.4 \times 10^{21}\mathrm{cm^{-2}}$; the hard energy range of the WFC is not much affected by absorption, and fits for different assumed absorption values give results similar to those listed in Table 1.

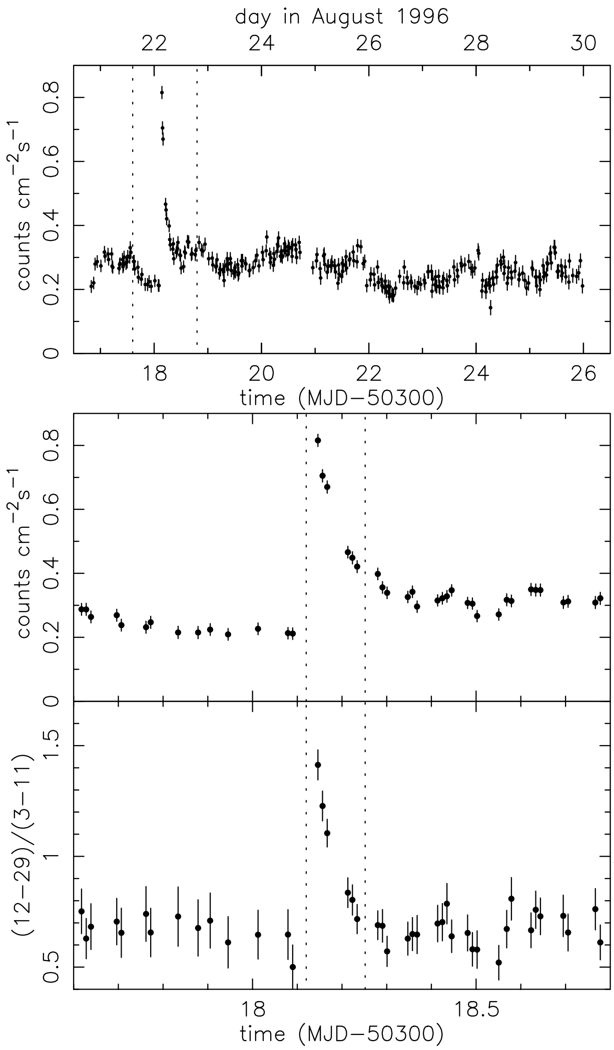

Fig. 1. Top: The nine day lightcurve of 4U 1735−44 as observed with the WFC in August 1996. Countrates are for channels 1-31 (energy range 2-28 keV). Each time bin corresponds to 15 minutes. A large enhancement in intensity starts near MJD 50318.1 and ends about ≃4.0 hours later. The vertical dotted lines indicate the time interval for which the countrate and hardness ratio are shown in the expanded view of the lower frames. The hardness ratio shown is the ratio of the countrate in channels 12-29 (5-20 keV) to that in channels 3-11 (2-5 keV). During the flux enhancement the exponential softening expected for a type-I X-ray burst is clearly visible. The vertical dotted lines indicate the time interval for which we add the data to obtain the burst spectrum.

To describe the flux decline we first fit an exponential $C = C(0)e^{-t/\tau}$ to the observed countrate in the 2-28 keV range. The fit is acceptable (at $\chi^2_\nu = 1.6$ for 33 d.o.f.) and $\tau = 86 \pm 5$ min. Fits to the counts in the 2-5 keV and 5-20 keV ranges give decay times of 129 ± 15 and 67 ± 5 min, respectively, in accordance with the observed softening of the flux during de-

Table 1. Results of the modeling of the X-ray spectrum. We fit a cutoff photon powerlaw spectrum $N(E) = N_{\rm o} E^{-\Gamma} e^{-(E-E_{\rm o})/E_{\rm w}}$ and a sum of a bremsstrahlung of temperature $T_{\rm br}$ and black body spectrum of temperature $T_{\rm bb}$ and radius R to the data before and after the burst. For the burst, we fix the parameters of either the cutoff power law or the bremsstrahlung component to the values found after the burst, and fit for a blackbody added to these. The absorption column is fixed at the value of $N_{\rm H} = 3.4 \times 10^{21}{\rm cm}^{-2}$ found by Christian & Swank (1997). For each model we give the total flux in the range observed with the WFC, i.e. 2-28 keV, as well as, for comparison with earlier observations, in the range of 1.4-11 keV.

cutoff power law	before	after
χ^2_ν (dof)	0.9 (23)	0.9 (23)
Γ	1.84±0.07	1.55±0.06
$E_{\rm o}$ (keV)	9.4±1.1	6.2±0.4
$E_{\rm w}$ (keV)	3.6±1.7	6.9±0.7
F_{2-28} (10^{-9}erg cm^{-2}s^{-1})	3.44±0.10	4.31±0.08
$F_{1.4-11}$ (10^{-9}erg cm^{-2}s^{-1})	3.53±0.06	3.91±0.04
brems plus black body	before	after
χ^2_ν (dof)	1.1 (23)	1.0 (23)
$kT_{\rm br}$ (keV)	7.8±0.6	8.0±1.3
$kT_{\rm bb}$ (keV)	0.	1.6±0.2
R (km)	0.	3.8±0.9
F_{2-28} (10^{-9}erg cm^{-2}s^{-1})	3.80±0.09	4.32±0.10
$F_{1.4-11}$ (10^{-9}erg cm^{-2}s^{-1})	3.40±0.05	3.87±0.04
added blackbody for burst	+cutoff	+brems
χ^2_ν (dof)	1.3 (25)	1.3 (25)
$kT_{\rm bb}$ (keV)	1.70±0.05	1.69±0.04
R (km)	6.1±0.3	7.2±0.3
F_{2-28} (10^{-9}erg cm^{-2}s^{-1})	7.42±0.05	7.43±0.05
$F_{1.4-11}$ (10^{-9}erg cm^{-2}s^{-1})	6.76±0.04	6.71±0.04

cline (see Fig. 1). We fit the spectrum during the flux enhancement as follows. First we add all the counts obtained between MJD 50318.10 and 50318.25. We then fit the total spectrum with the sum of a black body and either a cutoff power law spectrum or a thermal bremsstrahlung spectrum. In these fits, the parameters of the power law and bremsstrahlung component are fixed at the values obtained for the fit to the persistent spectrum after the event. The resulting parameters for the black body are also listed in Table 1. At the observed maximum the bolometric flux was $(1.5 \pm 0.1) \times 10^{-8}{\rm erg\,cm^{-2}s^{-1}}$ which for a source at 9.2 kpc corresponds to a luminosity of $1.5 \times 10^{38}{\rm erg\,s^{-1}}$. The start of the flux enhancement is not observed, but if we assume that its maximum is at the Eddington limit of $1.8 \times 10^{38}{\rm erg\,s^{-1}}$ (for a neutron star mass of $1.4 M_\odot$) and that the decay time is constant, then maximum was reached 23.6 min before the source emerged from earth occultation, leaving at most 12.4 min for the rise to maximum (since the start of the data gap). The decay from maximum was therefore much longer, by a factor >8, than the rise. The fluence in the observed part of the burst is $5.1 \times 10^{-5}{\rm erg\,cm^{-2}}$, corresponding to 5.2×10^{41} erg; this is a lower limit to the energy released during the full event.

We have also made fits to the first and second half of the event separately, and find temperatures for the blackbody component of 2.1-2.2 keV and 1.3-1.4 keV for the first and second half respectively, confirming the softening. For the blackbody radius we find 5.7-6.5 km and 8.5-8.8 km, for the first and second half, respectively. This apparent increase in radius is probably due to the difference between the observed colour temperature and the actual effective temperature of the black body; when we apply corrections to the colour temperature as given by van Paradijs et al. (1986) the value for the radius in the first part of the burst increases to 14 km, whereas that for the second half is unchanged.

4. Discussion

In addition to the thermonuclear X-ray bursts, also called type I bursts, low-mass X-ray binaries show other sudden enhancements in X-ray flux. Type II bursts are different from type I bursts in that type II bursts do not show cooling of the characteristic temperature of the X-ray spectrum during the decline. X-ray flares have an irregular flux evolution. Type II bursts are thought to be accretion events; the nature of flares is unknown.

The flux enhancement of 4U 1735−44 shows a smooth exponential decay of the countrate and of the characteristic temperature. Its rise must have been shorter than the decline. A black body gives a good fit to the observed spectrum, for a radius as expected from a neutron star, similar to earlier, ordinary bursts of 4U 1735−44. All these properties indicate a type I burst. The only special property of the new burst is its duration, which when expressed as the ratio of fluence $E_{\rm b}$ and peak flux $F_{\rm max}$: $E_{\rm b}/F_{\rm max} > 3400$ s, is more than 300 times longer than the longest burst observed previously from this source (see Lewin et al. 1980). This duration also translates in a fluence which is several orders of magnitude larger than the previous record holder for 4U 1735−44, because the peak flux is similar to those of normal type I bursts. The fluence of a type I burst which burns all matter deposited onto a neutron star since the previous burst must be ≃1% of the accretion energy released by deposition of this matter. We do not have a measurement to the previous burst, but in seven days following the burst no other burst was observed. Multiplying this time by the persistent luminosity we obtain $\simeq 2.7 \times 10^{43}$ erg, or about 50 times the energy of the burst, well in the range of previously observed ratios for type I bursts.

The presence of clear cooling argues against a type II burst; this and the smooth decay argues against a flare. If the flux enhancement were due to an accretion event, the amount of matter dropped extra onto the neutron star (assuming a mass of $1.4 M_\odot$ and a radius of 10 km) must have been $> 3 \times 10^{21}$ g, which may be compared to the average accretion rate of 2.3×10^{17} g s^{-1} derived for the persistent flux. If the inner part of the accretion disk would have depleted itself onto the neutron star during the flux enhancement, one would expect the accretion rate immediately after to be lower than before. The observations suggest the opposite.

We conclude that a type I X-ray burst is the best explanation for the enhanced flux event. We consider it significant that the occurrence of this burst is accompanied by the absence of any ordinary – i.e. short – burst throughout our 9-day observation, whereas all previous observations of 4U 1735−44 did detect ordinary bursts (see Introduction).

Searching the literature for long bursts we find that the longest type I burst published previously is a radius expansion burst observed with SAS-3, probably in 4U 1708−23 (Hoffman et al. 1978; see also Lewin et al. 1995). The ratio of fluence and peak flux for that burst was $\simeq 500$ s, so that the BeppoSAX WFC burst of 4U 1735−44 lasted at least six times longer. Other events published as long bursts from Aql X-1 (Czerny et al. 1987) and from X 1905+000 (Chevalier and Ilovaisky 1990) are in fact relatively short bursts followed by an enhanced constant flux level which persisted for several hours: in both cases the flux declined to 1/e of the peak level within 20 s. These events are clearly different from the long exponential bursts seen in 4U 1708−23 and 4U 1735−44.

From the theoretical point of view, a long interval between bursts would allow hydrogen to burn completely before the onset of the burst, so that the energetics of the burst is dominated by pure helium burning. If matter accreted at a rate of 2.3×10^{17} g s^{-1} during one week, the energy released by helium burning is compatible with the energy of the observed burst. The problem with this model is that theory predicts for this accretion rate that the burst initiates well before hydrogen burning is completed, i.e. that bursts are more frequent and less energetic, in accordance with those previously observed of 4U 1735−44. Indeed, Fujimoto et al. (1987) find that a burst of 10^4 s duration occurs only for accretion rates $\dot{M} < 0.01\dot{M}_{\rm Edd}$. The persistent flux during the BeppoSAX observation is a factor $\simeq 20$ higher than this limit; observations previous to ours have consistently found 4U 1735−44 at a similar luminosity.

An alternative model for bursts with a duration of 10^4 s is accretion of pure helium at an accretion rate in excess of the Eddington limit ($\dot{M} > 5\times\dot{M}_{\rm Edd}$, Brown & Bildsten 1998). The orbital period and optical spectrum indicate a main-sequence, i.e. hydrogen-rich, donor star (Augusteijn et al. 1998).

Perhaps the main challenge for any theoretical explanation is that the properties of the persistent flux during our nine day long observation, during which a single very long X-ray burst was observed, are not different from those during earlier observations with EXOSAT when more frequent ordinary bursts were found.

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