Observations of Eddington-limited type-I X-ray bursts from 4U 1812–12

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Abstract. During more than 3 years (August 1996–October 1999) monitoring of a $40° \times 40°$ sky region around the Galactic Centre by the Wide Field Cameras on board *BeppoSAX*, a total of 8 type-I bursts have been detected from a sky position consistent with that of 4U 1812−12, a likely neutron-star low-mass X-ray binary. We present the results of a detailed study of the bursts of 4U 1812−12, about 15 years after the last reported observations of X-ray bursts from this source (Murakami et al. 1983). Clear evidence for photospheric radius expansion due to Eddington-limited burst luminosity is present in most of the observed events, allowing an accurate estimate of the source distance (~ 4 kpc) and its burst parameters.

Key words: stars: binaries: general – stars: novae, cataclysmic variables – stars: individual: 4U 1812–12 – X-rays: bursts – X-rays: stars

1. Introduction

Since its first *Uhuru* detections (Forman et al. 1976; Forman et al. 1978), 4U 1812−12 was observed by several satellite X-ray experiments: *OSO 7* (1M 1812-121, Markert et al. 1979), *Ariel V* (3A 1812-121, Warwick et al. 1981), *HEAO 1* (1H 1815−121, Wood et al. 1984), and *EXOSAT* (GPS 1812-120, Warwick et al. 1988). From these observations, it is clear that 4U 1812−12 is a persistent, though variable, source. *Uhuru* found a 2–10 keV maximum intensity of $\sim 5 \times 10^{-10}$ erg cm^{-2}s^{-1} and a variability of a factor of at least 2 (Forman et al. 1978). Similar variability characteristics were observed by *Ariel V*, as the source varied in the range $\sim 3 - 6 \times 10^{-10}$ erg cm^{-2}s^{-1} in the same energy band (Warwick et al. 1981), while lower intensities of $\sim 2 \times 10^{-10}$ erg cm^{-2}s^{-1} and $\sim 3 \times 10^{-10}$ erg cm^{-2}s^{-1} were measured by *HEAO 1* (2–10 keV, Wood et al. 1984) and *EXOSAT* (2–6 keV, Warwick et al. 1988). The 3–10 keV source spectrum as obtained by the *EXOSAT* GSPC was best fitted by a power law (Gottwald et al. 1995). 4U 1812−12

has been monitored by *RXTE*-ASM since February 1996[1], confirming its previously reported characteristics. The source is always detected, with an average 2–10 keV flux of $\sim 3.8 \times 10^{-10}$ erg cm^{-2}s^{-1} (~ 20 mCrab) and a variability of a factor $\lesssim 3$ on ~ 1 week time scale. Hard X-ray (up to ~ 200 keV) persistent emission from 4U-1812−12 was discovered by *CGRO*-OSSE (**??**).

Three X-ray bursts were detected from this source in 1982 by *Hakucho* (Murakami et al. 1983). Two of the events showed clear evidence for photospheric radius expansion, and reached a maximum 1–22 keV intensity of $\sim 1.7 \times 10^{-7}$ erg cm^{-2}s^{-1}. The burst spectra were consistent with a ~ 2.5 keV blackbody emission, and showed evidence for softening during the exponential decay (*e*-folding time $\tau \sim 20$ s). This indicated the bursts to be type-I, i.e. thermonuclear flashes originating on the hot surface of a neutron star, and the source to be likely located in a low-mass X-ray binary. During the observation no persistent emission was detected above 20 Uhuru flux units ($\sim 5 \times 10^{-10}$ erg cm^{-2}s^{-1} in 2–10 keV). In any case this is not in disagreement with the identification of the *Hakucho* burster with the persistent source 4U 1812−12. Murakami et al. 1983 also proposed the association of the burst source with the transient Ser X-2, observed once in 1965 (Friedman et al. 1967). More recently, a single-peaked burst from 4U 1812−12 was observed by the *BeppoSAX*-WFC instrument on 1997 Mar 12.2209 UT (Burderi et al. 1997). The event had a peak intensity of 1.2 and 0.6 Crab in the 1.5–10 keV and 10−26 keV band respectively, and a decay time of ~ 20 s.

4U 1812−12 is classified as an atoll source, which is common among the type-I X-ray bursters, and shows band-limited noise and a ~ 0.8 Hz QPO (Wijnands & van der Klis 1999).

In this paper we investigate the burst characteristics of 4U 1812−12, about 15 years after the *Hakucho* observations of its type-I bursts. The event observed by Burderi et al. (1997) is also re-analysed. Through a homogeneus sample of Eddington-limited type-I X-ray bursts, we accurately estimate the source distance and test the reliabilty of near-Eddington bursts as a

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[1] the ASM measurements are publicly available at URL `http://www.space.mit.edu/XTE`
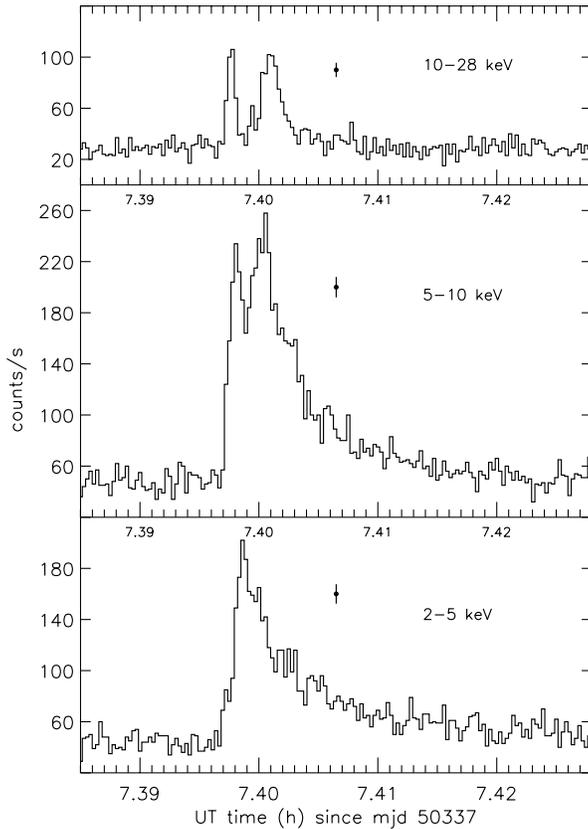
Fig. 1. Time profiles of burst C in three energy bands. The double-peaked structure becomes more evident at higher energies.

standard candle. In the next section we briefly introduce the Wide Field Cameras telescopes and report on the observations of 4U 1812−12. Time-resolved spectroscopy of the bursts is presented in Sect. 3, while the scientific implications of our results are discussed in Sect. 4.

2. Observations

The Wide Field Cameras (WFC) on board the *BeppoSAX* satellite consist of two identical coded aperture multi-wire proportional counters (Jager et al. 1997) pointing in opposite directions. Each camera covers a $40° \times 40°$ full width to zero-response field of view, the largest ever flown for an arcminute resolution X-ray telescope. With their source location accuracy in the range $1'-3'$ (99% confidence), a time resolution of 0.488 ms, and an energy resolution of 18% at 6 keV, the WFCs are effective in studying X-ray transient phenomena in the 2–28 keV bandpass. The imaging capability and the good instrument sensitivity (5–10 mCrab on-axis in 10^4 s, depending on the number of sources in the field) allow an accurate monitoring of complex sky regions, like the Galactic centre.

One of the main scientific objectives of the WFCs is the study of the timing and spectral behaviour of both transient and persistent sources of the Galactic Bulge region on time scales ranging from seconds to years. To this end, an observation program of systematic wide field monitoring of the Sgr A sky region

has been carried out since August 1996 (see e.g. Heise 1998; Heise et al. 1999; Ubertini et al. 1999). This program consists of a series of observations, each lasting ~ 60 ks, nearly weekly spaced throughout the two visibility periods (August-October and February-April) of the Galactic Centre region.

The WFC Galactic Bulge monitoring program is contributing significantly in the study of X-ray bursting sources. Up to now, a total of 15 new objects were discovered in ~ 3.2 years observing time, thus enlarging the population of the bursters by $\sim 35\%$ (Heise et al. 1999; Ubertini et al. 1999). The data of the two cameras are systematically searched for bursts and flares by analyzing the time profiles of the detectors in the 2–11 keV energy range with a time resolution down to 1 s. Reconstructed sky images are generated for any statistically meaningful event and the accuracy of the reconstructed position, which of course depends on the burst intensity, is typically better than $5'$. This analysis procedure has led to the identification of ~ 950 X-ray bursts (156 of which are from the *Bursting Pulsar* GRO J1744−28) in a total of about 4×10^6 s net observing time (e.g. Cocchi et al. 1998a).

Whenever the WFCs point at the Galactic Centre region, 4U 1812−12 is in the field of view, though at a rather offset position, being $\sim 18°$ away from Sgr A ($l_{\mathrm{II}} = 18.0°, b_{\mathrm{II}} = 2.4°$). Due to the source's relatively low intensity and to the unfavourable pointing, the WFC data is not sensitive enough to study the persistent emission with sufficient accuracy. A total of 8 X-ray bursts were detected at a position consistent with that of 4U 1812−12 during all the time spent on the source by the WFCs both in primary and in secondary observing mode (~ 4 Ms net time in 3.2 years). None of the observed bursts can be associated with other known sources.

We analysed all the observed bursts, including the one already investigated by Burderi et al. (1997). The main characteristics of the observed bursts (hereafter burst A,B,...,H, chronologically) are summarised in Table 1. One of the bursts, namely burst C, was observed with much better statistics than the others, as it was in a more favourable position ($\sim 10°$ offset). For this reason, burst C was analysed with a higher time resolution than the others.

3. Data analysis and results

Energy-resolved time histories of the bursts were constructed by accumulating the detector counts associated with the shadowgram obtained for the sky position of the analysed source, thus improving the signal-to-noise ratio of the profile. For a given source, the background is the sum of (part of) the diffuse X-ray background, the particles background and the contamination of other sources in the field of view. Source contamination is the dominating background component for crowded sky fields like the Galactic Bulge. Nevertheless, the probability of source confusion during a short time-scale event (10–100 s) like an X-ray burst is negligible. The time profiles of burst C were accumulated in three different energy bands (2–5, 5–10, and 10–28 keV, see Fig. 1). The time histories of the other bursts, due to their limited counting statistics, were obtained for the bands 2–8 and

Table 1. Summary of the characteristics of the observed bursts. Average spectral parameters are calculated for the first 30 s of burst data.

	burst A	burst B	burst C	burst D	burst E	burst F	burst G	burst H
date	1996 Aug.22	1996 Aug.29	1996 Sep.11	1997 Mar.12	1997 Mar.30	1998 Sep.30	1998 Oct.7	1999 Sep.22
UT (h)	16.9158	5.6625	7.3972	5.3021	21.2650	21.9400	1.8097	7.7229
$\tau_{2-28\,\text{keV}}$	15.0 ± 1.3	14.5 ± 1.2	15.1 ± 0.5	14.1 ± 0.6	13.9 ± 1.0	14.2 ± 1.2	10.6 ± 1.1	12.1 ± 1.0
$\tau_{2-8\,\text{keV}}$	16.8 ± 1.7	18.0 ± 1.4	20.1 ± 0.6	16.4 ± 0.8	17.9 ± 1.6	18.0 ± 1.7	15.1 ± 1.8	19.0 ± 2.1
$\tau_{8-28\,\text{keV}}$	7.3 ± 1.2	5.8 ± 0.9	6.9 ± 0.4	6.3 ± 0.7	4.1 ± 0.6	4.4 ± 0.7	6.8 ± 1.1	6.1 ± 0.7
kT (keV)	$1.98^{+0.07}_{-0.06}$	$1.85^{+0.04}_{-0.05}$	$1.98^{+0.03}_{-0.02}$	$1.96^{+0.03}_{-0.04}$	2.10 ± 0.06	$1.99^{+0.06}_{-0.05}$	2.26 ± 0.07	$2.33^{+0.08}_{-0.07}$
R_{bb}[a]	$20.1^{+1.4}_{-1.3}$	$21.8^{+1.3}_{-1.1}$	$20.2^{+0.5}_{-0.4}$	$20.9^{+0.8}_{-0.7}$	15.6 ± 0.9	$19.5^{+1.1}_{-1.0}$	$15.0^{+1.0}_{-0.9}$	$13.6^{+0.9}_{-0.8}$
χ^2_r	1.57	0.89	1.53	1.13	1.69	1.36	1.18	0.75
I_{peak}[b]	4.69 ± 0.32	4.21 ± 0.27	4.36 ± 0.14	4.87 ± 0.21	4.66 ± 0.28	4.81 ± 0.33	4.32 ± 0.37	4.68 ± 0.33
fluence[c]	2.91 ± 0.17	2.81 ± 0.14	3.14 ± 0.10	2.93 ± 0.12	2.26 ± 0.12	3.02 ± 0.16	2.37 ± 0.15	2.25 ± 0.13

[a] blackbody radius, for a 10 kpc distance;
[b] peak intensity, in Crab units, 2–28 keV band;
[c] bolometric, in 10^{-6} erg cm^{-2}. The bursts e-folding times τ are given in s.

8–28 keV only (Fig. 2). The 2–28 keV time profiles of all the bursts are characterized by fast rise times (within a few seconds) and longer exponential decay with e-folding times of ~ 15 s. The high energy time histories of almost all the bursts show clear evidence for double-peaked profiles (see Fig. 1 and Fig. 2) and their e-folding times are significantly shorter (~ 4–7 s) than the ones of the low energy profiles (~ 15–20 s), as reported in Table 1.

The integrated spectra of the eight bursts are all consistent with absorbed blackbody radiation with average colour temperatures of ~ 2 keV and an average blackbody radius of the emitting sphere of ~ 20 km assuming a standard 10 kpc source distance (Table 1). The spectra were subtracted for the source persistent emission, which accounts for only $\sim 0.5\%$ of the burst peak intensity. The N_H parameter could not be satisfactorily constrained for any of the bursts, so we kept its value fixed according to the interpolated value computed at the source position, namely $N_H = 7.3 \times 10^{21}$ cm^{-2} (Dickey & Lockman 1990).

Time-resolved spectra were accumulated for all the bursts, in order to study the time evolution of their spectral parameters. Thanks to the good counting statistics, the spectral analysis of burst C could be performed with a time resolution of 1 s. Conversely, for each of the other bursts only four time resolved spectra could be obtained with a poorer time resolution (4 s). The time intervals of the four spectra were chosen to match the first-peak, interpeak, second-peak and decay phases in the corresponding 8–28 keV burst time profiles (Fig. 2). Since all the obtained spectra are consistent with absorbed blackbody emission, the time histories of the colour temperature and the emitting sphere radius can be determined (Table 2 and Fig. 3). The blackbody radii were calculated assuming isotropic emission at a source distance of 10 kpc and not correcting for gravitational redshift and conversion to effective blackbody temperature from color temperature (see Lewin et al. 1993 for details). A radius expansion by a factor of ~ 5 is observed in burst C while, probably due to the larger time bins used, a lower expansion factor (~ 2) is obtained for all the other bursts but burst H, which does not show evidence for radius variations.

4. Discussion

Following the classification proposed by Hoffman et al. 1978, X-ray bursts are classified into two main types (*type-I*, *type-II*, see Lewin et al. (1993) for a comprehensive review).

On the basis of the spectral and timing properties of the eight bursts observed by the WFCs, it is apparent that 4U 1812−12 is a type-I burster. In fact, the blackbody emission and the measured colour temperatures of ~ 2 keV are consistent with type-I bursting. Moreover, spectral softening is observed in the time resolved spectra of the bursts (Table 2 and Fig. 3), and the bursts time profiles can be fitted with exponential decays whose characteristic times are significantly shorter at higher energies (see e.g. Table 1). These results confirm the measurements obtained 15 years earlier by *Hakucho* (Murakami et al. 1983), indicating 4U 1812−12 is a neutron-star low-mass X-ray binary.

The photospheric radius expansion derived from the time resolved spectral analysis of most of the observed bursts can be interpreted as adiabatic expansion during a high luminosity (Eddington-limit) type-I burst. Actually, the double-peaked profiles observed in the high energy (above 8 keV) time histories of the bursts (with the only exception of burst H) are typical of super-Eddington events (e.g. Lewin et al. 1995). Even though burst H is not double-peaked, its peak luminosity is consistent with those of the other observed events. Moreover, its 8–28 keV time profile could be associated with the flat-top profiles of some observed Eddington-limited type-I bursts (Lewin et al. 1995), so burst H too can be regarded as an event with peak luminosity close to the Eddington limit. We also notice that the two bursts which show less clear evidence for photospheric radius expansion, namely bursts E and H, are the less energetic ones, their fluences being the lowest observed (Table 1). We can regard their total energy release ($\sim 5 \times 10^{39}$ erg assuming a 4 kpc distance, see later) as the minimum needed to drive the expansion of the photosphere of the neutron star in 4U 1812−12.

Eddington-luminosity X-ray bursts can lead to an estimate of the source distance, assuming the burst emission to be isotropic and the peak flux to be very close to the Eddington luminosity. Actually, the peak intensities observed for the eight events
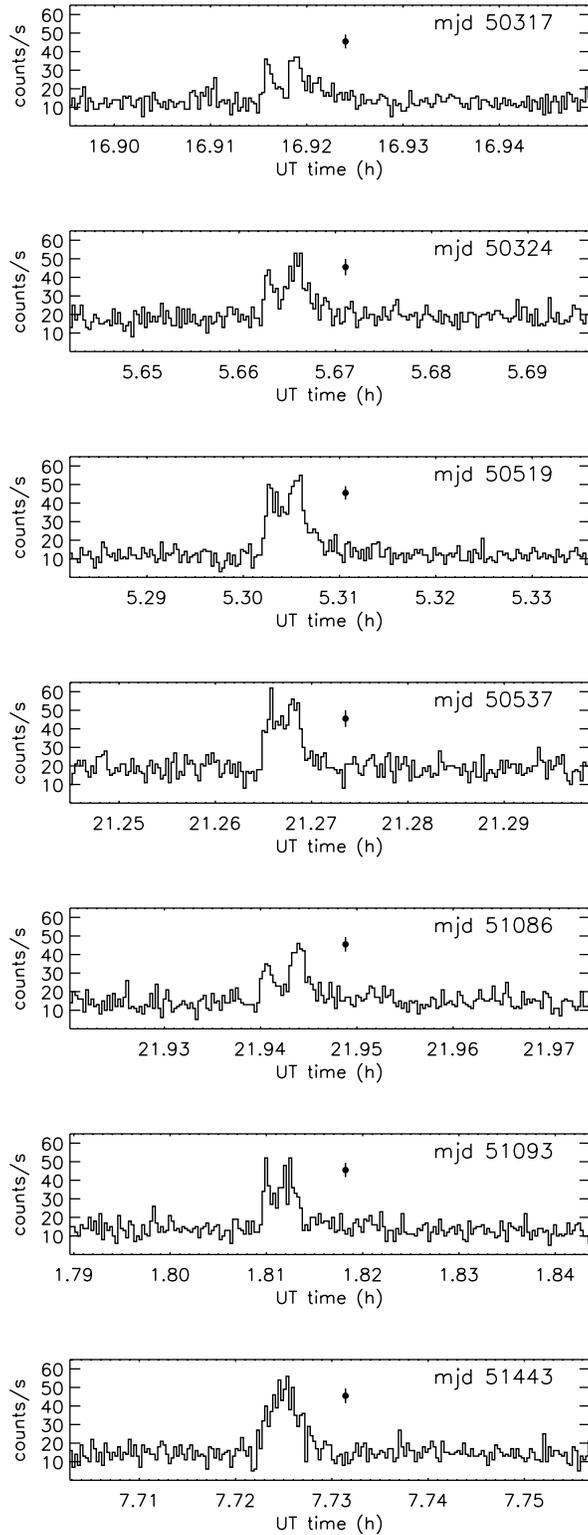
Fig. 2. Time histories of the A,B,D,E,F,G,H (starting from top) bursts in the 8–28 keV energy band. Eddington-luminosity effects are observed in all the profiles.

Table 2. Time resolved spectral analysis of bursts A,B,D,E,F.

time range[a]	kT (keV)	$R_{km}/d_{10\ kpc}$	χ_r[b]
mjd 50317 burst (A)			
$0s - 4s$	$2.42^{+0.21}_{-0.18}$	$15.2^{+2.8}_{-2.1}$	0.78[c]
$4s - 9s$	1.60 ± 0.10	$35.3^{+5.1}_{-4.0}$	0.95[c]
$9s - 14s$	$2.36^{+0.14}_{-0.13}$	$17.5^{+2.3}_{-1.8}$	1.22
$14s - 35s$	$1.81^{+0.12}_{-0.10}$	$18.0^{+2.6}_{-2.1}$	0.87
mjd 50324 burst (B)			
$0s - 4s$	2.15 ± 0.14	$16.7^{+2.5}_{-2.0}$	0.75
$4s - 10s$	$1.54^{+0.07}_{-0.06}$	$37.2^{+3.7}_{-3.1}$	0.47
$10s - 15s$	$2.16^{+0.10}_{-0.09}$	$20.2^{+2.0}_{-1.7}$	0.79
$15s - 35s$	1.76 ± 0.14	$17.7^{+2.2}_{-1.8}$	0.76
mjd 50519 burst (D)			
$0s - 4s$	2.68 ± 0.16	$20.9^{+0.8}_{-0.7}$	1.68
$4s - 10s$	$1.80^{+0.05}_{-0.04}$	$30.7^{+1.7}_{-1.6}$	1.15
$10s - 15s$	$2.24^{+0.08}_{-0.07}$	$19.7^{+1.4}_{-1.2}$	1.39
$15s - 36s$	1.65 ± 0.06	$20.8^{+1.6}_{-1.4}$	1.10
mjd 50537 burst (E)			
$0s - 4s$	2.34 ± 0.15	$15.6^{+2.2}_{-1.8}$	1.30
$4s - 10s$	2.15 ± 0.08	$20.3^{+1.7}_{-1.5}$	1.39
$10s - 15s$	$2.61^{+0.15}_{-0.14}$	$13.0^{+1.6}_{-1.3}$	0.96
$15s - 32s$	$1.33^{+0.10}_{-0.08}$	$27.6^{+4.5}_{-3.5}$	1.09
mjd 51086 burst (F)			
$0s - 5s$	$2.48^{+0.18}_{-0.17}$	$12.4^{+2.0}_{-1.6}$	0.72
$5s - 12s$	1.70 ± 0.07	$31.7^{+3.0}_{-2.5}$	0.76
$12s - 17s$	2.51 ± 0.12	$15.7^{+1.7}_{-1.4}$	0.84
$17s - 37s$	1.68 ± 0.09	$18.9^{+2.5}_{-2.0}$	0.85
mjd 51093 burst (G)			
$0s - 4s$	2.76 ± 0.16	$11.7^{+1.6}_{-1.2}$	1.46
$4s - 10s$	$2.10^{+0.09}_{-0.10}$	$22.1^{+2.2}_{-1.9}$	0.57
$10s - 14s$	$2.60^{+0.19}_{-0.17}$	$12.9^{+2.0}_{-1.6}$	1.37
$14s - 34s$	$1.91^{+0.14}_{-0.12}$	$14.2^{+2.2}_{-1.8}$	1.23
mjd 51443 burst (H)			
$0s - 4s$	$2.40^{+0.16}_{-0.14}$	$15.5^{+2.2}_{-1.8}$	0.81
$4s - 9s$	2.50 ± 0.10	$15.8^{+1.4}_{-1.3}$	1.35
$9s - 14s$	2.58 ± 0.15	$13.6^{+1.8}_{-1.5}$	1.01
$14s - 34s$	$1.54^{+0.16}_{-0.15}$	$17.8^{+4.7}_{-3.1}$	0.78

[a] The zero is the burst time (see Table 1);
[b] 27 d.o.f.;
[c] 26 d.o.f.

are all consistent with a constant value of 4.53 ± 0.09 Crab (2–28 keV); the associated reduced χ^2 is 1.03 for 7 d.o.f.. This average peak intensity extrapolates to an unabsorbed bolometric flux of $(15.03 \pm 0.29) \times 10^{-8}$ erg cm^{-2} s^{-1}. The consistency of the peak luminosities of all the bursts with a constant value supports the adoption of the peak bolometric intensities of super-Eddington bursts as a standard candle. An average luminosity of Eddington-limited bursts was empirically calculated by Lewin et al. (1995) on a sample of bursters whose distance was estimated with other methods: a luminosity value
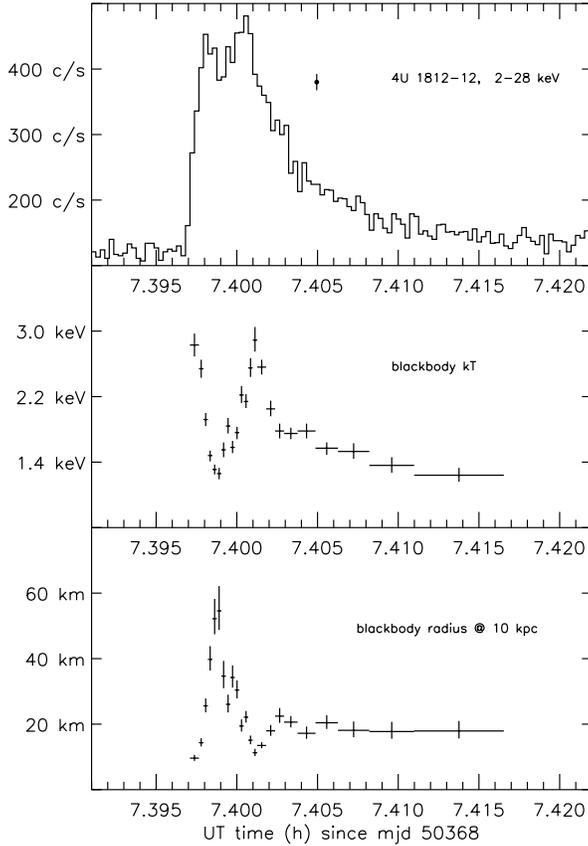
Fig. 3. Time histories of the 2–28 keV count rate (upper panel), of the blackbody colour temperature (central panel), and of the blackbody radius (lower panel), as observed for burst C.

of $(3.0 \pm 0.6 \times 10^{38} \text{ erg s}^{-1})$ was obtained. The adoption of this standard luminosity leads to a distance value $d = 4.1 \pm 0.5$ kpc for 4U 1812−12. On the other hand, assuming the theoretical Eddington luminosity for a typical $1.4 \, M_\odot$ neutron star $(\sim 2 \times 10^{38} \text{ erg s}^{-1})$ we obtain $d \sim 3.3$ kpc. For the calculated distance of ~ 4 kpc, and with the simple assumptions on the burst emission made in Sect. 3, an average radius of 8 ± 1 km for the blackbody emitting region during the bursts is obtained. This value, which supports the neutron-star nature of the collapsed object, should indeed be regarded as a lower limit for the actual neutron star radius, according to Ebisuzaki, Hanawa & Sugimoto (1984).

Assuming the source's persistent spectrum to be consistent with the one suggested by Barret et al. (2000) for the X-ray bursters in low state, i.e. a Comptonized spectrum with electron temperature $kT_e \sim 25$ keV and $\tau \sim 3$, the bolometric luminosity of 4U 1812−12 can be extrapolated. For a distance of ~ 4 kpc and an average 2–10 keV persistent intensity of $\sim 4 \times 10^{-10} \text{ erg cm}^{-2}\text{s}^{-1}$, we obtain $L_{bol} \sim 5.6 \times 10^{36} \text{ erg s}^{-1}$. We also derive, for a canonical $1.4 \, M_\odot$ neutron star with a radius of 10 km, an average accretion rate of $\sim 5 \times 10^{-10} \, M_\odot \text{y}^{-1}$. These values are common among low-mass X-ray binaries.

Due to the non-continuous WFCs coverage of the Galactic Centre region and to the *BeppoSAX* orbit characteristics,

we cannot accurately establish the burst occurrence rate of 4U 1812−12. In any case the minimum observed intervals are 6.53 d and 6.16 d for bursts A-B (August 1996) and F-G (October 1998) respectively, and such intervals are of the same order of magnitude as the one measured by *Hakucho* in 1982 (4.61 d). Under the hypothesis that the above values are the actual wait times for bursts B and G, we can calculate the ratio $\alpha = E_p/E_b$, where E_b and E_p are the bolometric fluences of the burst and of the persistent emission between two contiguous bursts, respectively. Average 2–10 keV intensities of $(4.4 \pm 0.4) \times 10^{-10} \text{ erg cm}^{-2}\text{s}^{-1}$ and $(3.5 \pm 0.9) \times 10^{-10} \text{ erg cm}^{-2}\text{s}^{-1}$ were measured by *RXTE*-ASM between bursts A-B and F-G respectively. Again, with the former assumptions on the spectrum of the persistent emission, we determine $\alpha = (6.4 \pm 1.0) \times 10^2$ and $\alpha = (5.8 \pm 1.9) \times 10^2$ for the two events. These values are consistent with each other and are within the observed range (10–10^3, distribution peaking at $\sim 10^2$) for the α parameter of known X-ray bursters, even if on the higher side. This is suggestive of helium-burning with no spare fuel left for the next burst, and possibly of steady burning of part of the accreted matter (Lewin et al. 1993; van Paradijs et al. 1988).

As pointed out above, the eight bursts we analysed show very similar features. Moreover, their characteristics are also consistent with those of the bursts detected by *Hakucho* (Murakami et al. 1983). For the *Hakucho* bursts, 1–22 keV peak intensities of ~ 4.6 Crab were measured. Also the event that Burderi et al. (1997) reported to have very different burst parameters, i.e. single peak profile and much lower luminosity (1.2 Crab in 1.5–10 keV), is actually very similar to the others, according to the results of our re-analysis (burst D). The above consistencies, together with the ~ 5–6 d burst wait times observed by both *Hakucho* and *BeppoSAX*, suggest the burst characteristics of the binary 4U 1812−12 to be remarkably stable in observations spanning ~ 15 years apart.

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