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THE PROPERTIES OF BURSTS WITH SHORT RECURRENCE TIMES FROM THE TRANSIENT X-RAY SOURCE EXO 0748−676

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ABSTRACT

On 1986 January 13/14 *EXOSAT* performed a 11.3 hr observation of the transient X-ray burst source EXO 0748−676. The source was in a low state and emitted 11 type I X-ray bursts, of which 10 were analyzed in detail. The properties of the bursts were similar to those found in previous low-state observations reported in Gottwald *et al.* (1986). The total energy emitted in the persistent flux between bursts divided by the total energy emitted in the following burst was ~ 25 with a constant apparent blackbody radius during the burst decay of 4.4 km. A regular burst pattern was identified where long and short recurrence intervals followed each other. The wait time to a burst and the total emitted energy in that burst displayed a linear relation but with an offset energy of 0.3×10^{-7} ergs cm^{-2} at zero burst interval. We discuss this behavior in context of incomplete consumption of fuel and its subsequent reconsumption in the following bursts. The amount of unburned fuel was found to be $\sim$10%–15% of the total available nuclear energy.

Subject headings: radiation mechanisms — X-rays: bursts

I. INTRODUCTION

The occurrence of type I X-ray bursts with very short recurrence times of the order of ~ 10 minutes (hereafter called double bursts; see, e.g., Matsuoka 1985; Gottwald *et al.* 1986, hereafter called Paper I) is not well understood in the context of the thermonuclear flash model for X-ray bursts (see, e.g., Ayasli and Joss 1982; Fujimoto, Hanawa, and Miyaji 1981; Taam 1981). In such short intervals it is not possible to accrete sufficient material to fuel a thermonuclear flash. Either a storage mechanism or incomplete nuclear burning during the previous burst must be responsible for this phenomenon (Matsuoka 1985). One reason why little progress has been made in its understanding is the relatively rare occurrence of these events. In 9 yr up to the launch of *EXOSAT* in 1983 only seven of of the hundreds of type I bursts detected were double (cf. Matsuoka 1985).

The highly eccentric orbit of the European X-ray astronomy satellite *EXOSAT* allowed long uninterrupted exposures so that burst patterns could be studied in detail. *EXOSAT* performed long continuous observations of many X-ray bursters, and analysis of the observations to date has revealed two burst sources that exhibit double burst events. Four double bursts were detected from the 3.8 hr eclipsing binary EXO 0748−676 (Paper I; Parmar *et al.* 1986, hereafter called Paper II). XB 1705−44 displayed three bursts with recurrence times between 5 and 18 minutes (Langmeier *et al.* 1987). For EXO 0748−676 the double burst phenomenon only occurred when the source was in low intensity state (Paper I) and was part of an overall correlation of the burst properties of EXO 0748−676 with changing mass accretion rate. When the level of the persistent emission decreased by a factor of 6 the α-ratio of the total energy emitted in the persistent flux between bursts divided by the total energy emitted in the following burst decreased from greater than 60 to 20–30. In addition the burst durations were longer, and the apparent radii in the burst tails decreased from 9 to 4 km. These results are in accordance with the expected dependence of the ignition of the flash with accretion rate (Fujimoto, Hanawa, and Miyaji 1981). However, it was not clear how double bursts could be formed and why they should occur only at low accretion rate.

In this paper we report a further 18.3 hr *EXOSAT* observation of EXO 0748−676 performed in 1986 January which, in conjunction with the earlier observations and a burst model proposed by Fujimoto *et al.* (1987), provides further insight into the double burst phenomenon.

II. PERSISTENT EMISSION

The *EXOSAT* observation started on 1986 January 13 at 11:45 UT and lasted until 06:05 UT the following day. The experiments and the data aquisition modes used were identical to those described in Paper I. Spectra were obtained in the 1–15 keV energy band from the eight argon detectors of the medium energy experiment (ME; Turner, Smith, and Zimmermann 1981) with a time resolution of 1 s in 64 channels. One ME array half was offset to monitor the background, and the pointing directions of the two halves were exchanged every 4 hr to optimize the background subtraction. In the analysis of the persistent flux we also included the count rate recorded by a channel multiplier array (CMA) with the 3000 Lexan filter at the focus of the low-energy imaging telescope (LEIT; de Korte *et al.* 1981).

Figure 1 shows the 1.5–15.0 keV light curve of the observation. A total of 11 bursts were seen with, in addition, five eclipses and irregular intensity dips preceding the eclipse. The time-averaged 1–10 keV rate derived from intervals when the source was not bursting, dipping, or eclipsing was 18.0 ± 0.1 cts s^{-1}. This value was similar to the low-state observations reported in Paper II. The structure of the light curve resembles that from 1985 February 26 and 1985 March 10 (Fig. 9*a* in Paper II) with a deep dip centered at phase 0.65 that is followed by a more shallow dip at phase 0.90. The phase following the eclipse is the only one unaffected by dipping activity.

The ME spectrum obtained from intervals free of dipping activity was well described either by a power-law model with photon index $\Gamma = 1.35 \pm 0.05$ with an equivalent hydrogen column density $N_H = (6.4 \pm 0.8) \times 10^{21}$ H cm^{-2} ($\chi^2 = 38.1$ for

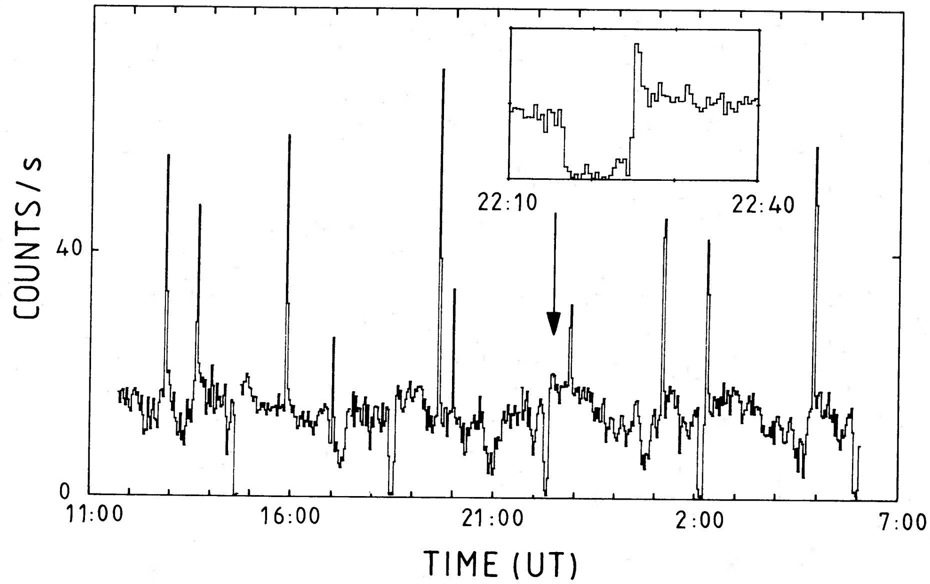

FIG. 1.—The light curve of EXO 0748−676 in the energy band 1.5–15.0 keV. Time resolution is 2 minutes. No dead time correction has been applied. The inset shows the part of the light curve from 22:10 UT to 22:40 UT with a time resolution of 25 s. At the end of the eclipse one burst occurred whose tail could still be seen.

37 degrees of freedom [d.o.f.]) or by a thermal bremsstrahlung model with $kT = 55.0 \pm 9.0$ keV and an $N_H = (4.7 \pm 0.7) \times 10^{21}$ H cm^{-2} ($\chi^2 = 33.2/37$ d.o.f.). When the count rate recorded by the LEIT is included in the spectral fitting the best-fit parameters for the power law and thermal bremsstrahlung model were unchanged within the uncertainties, although the quality of the fits was slightly poorer ($\chi^2 = 58.2/38$ d.o.f. for the power-law model and $\chi^2 = 51.9/38$ d.o.f. for the thermal bremsstrahlung model). A power law with a high energy exponential cutoff model (cf. Paper II) gave a better fit with $\Gamma = 0.82 \pm 0.03$, $kT = 12.0$ $(-1.1, +0.5)$ keV, $N_H = (0.1 \pm 0.1) \times 10^{21}$ H cm^{-2} ($\chi^2 = 37.2/37$ d.o.f.). Quoted errors are 1 σ confidence. The 0.1–20 keV flux is $(5.0 \pm 1.0) \times 10^{-10}$ ergs cm^{-2} s^{-1}. The uncertainties reflect the flux range found for the various trial models. We did not detect any significant blackbody component in the persistent flux. For color temperatures in the range $\sim$0.5–1.5 keV the contribution of a blackbody component was estimated to be less than 10%.

III. BURST PROPERTIES

In total 10 bursts were detected in their entirety with, in addition, the tail of an 11th burst seen after an eclipse at $\sim$22:23 UT. Figure 1 shows that the bursts alternated between long and short recurrence times. The longer recurrence time was 8700 ± 800 s, while the shorter one was 2700 ± 1300 s. The minimum separation between bursts was 23 minutes. If each burst event is counted separately, the burst frequency is 0.6 burst hr^{-1} (with an upper limit of 0.7 burst hr^{-1}). This is suggestive of double burst behavior, albeit with somewhat longer burst recurrence times.

In Figure 2 the 1.5–15.0 keV profiles of eights bursts are shown. On the left-hand side are the bursts following a long interval and on the right-hand side those following a short interval. The former display a larger integrated number of counts in each burst (C_t), have a higher peak count rate (C_p), and a larger duration (C_t/C_p). The corresponding average values are $C_t = 9574 \pm 1600$ cts, $C_p = 225 \pm 6$ cts s^{-1}, and $C_t/C_p = 43 \pm 7$ s (left-hand side) compared with $C_t = 3941 \pm 1280$ cts, $C_p = 161 \pm 19$ cts s^{-1}, and $C_t/C_p = 25 \pm 8$ s (right-hand side). The individual correlation between the burst duration and the recurrence time is given in Figure 3. A striking similarity exists between the profiles of the two bursts with the shortest recurrence times of 1367 s and 1850 s and the four second bursts in double bursts reported in Paper I. As t_{rec} increases for shorter recurrence time bursts (on the right-hand side) their profiles become wider and begin to resemble the bursts following a long recurrence interval (on the left-hand side). The latter are indistinguishable from the slow bursts seen from EXO 0748−676 in the low state (Paper I).

The spectral analysis of the bursts was performed following the method outlined in Paper I. Briefly, we accumulated dead-time–corrected PHA spectra with a time resolution of 2 s during the initial burst phase that was increased to 10 s during burst decay. Spectra of the persistent emission obtained from dip-free periods close to the bursts were subtracted to yield background-subtracted burst spectra. The partly eclipsed burst at 22:23 UT was discarded from the spectral analysis. Table 1 provides the burst onset times, the recurrence times t_{rec}, the peak fluxes f_{peak}, the integrated burst fluxes f_{total}, and the α-ratios.

A blackbody model was folded through the detector response and fitted to each spectrum, giving a color temperature kT_c. The reduce χ^2_r was typically $\sim$1.2. The upper limit on the equivalent hydrogen column density was $\sim 0.8 \times 10^{22}$ H cm^{-2}, consistent with that found for the persistent emission. The 0.1–20 keV flux at the source was obtained from the best-fitting spectral parameters, and the luminosity L_a and the apparent blackbody radius R_a were calculated assuming spherical emission and a distance of 10 kpc. We note that the color temperature kT_c systematically overestimates the temperature and hence underestimates the apparent blackbody radii (cf. London, Taam, and Howard 1984; Ebisuzaki and Nomoto 1985).

It has been pointed out by van Paradijs and Lewin (1986) that if a substantial persistent blackbody component from the neutron star surface is present that is comparable in strength to the blackbody flux from the burst, the subtraction of the persistent spectrum is no longer justified. In that case a reliable

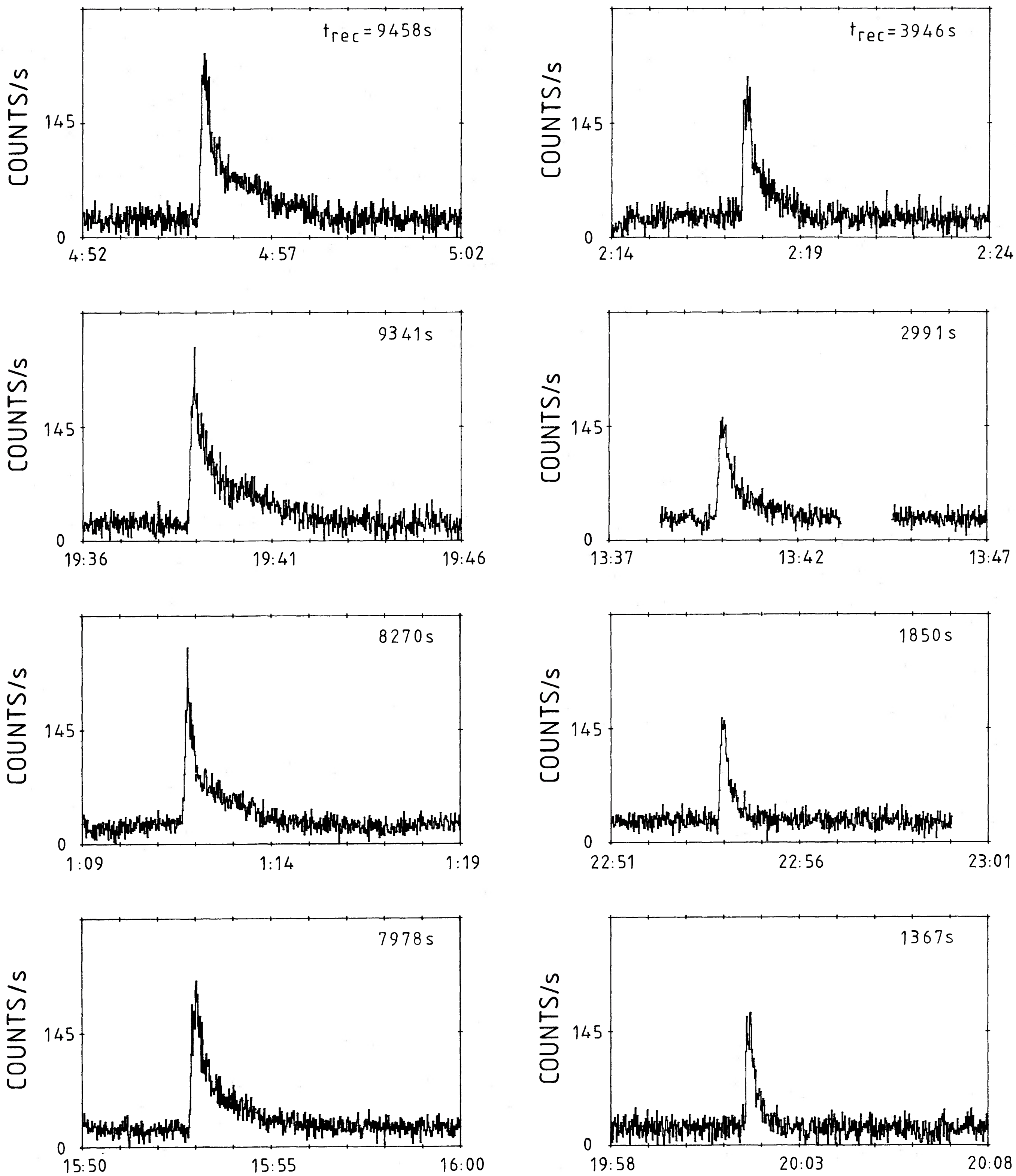

FIG. 2.—The 1.5–15.0 keV light curves of the bursts with long recurrence times (*left-hand side*) and short recurrence times (*right-hand side*). All bursts are plotted with a time resolution of 1 s. Note the difference in duration and peak count rate between both groups. No dead time correction was performed. At the peaks this correction amounts to 1.13 (*left-hand*) and 1.11 (*right-hand*).

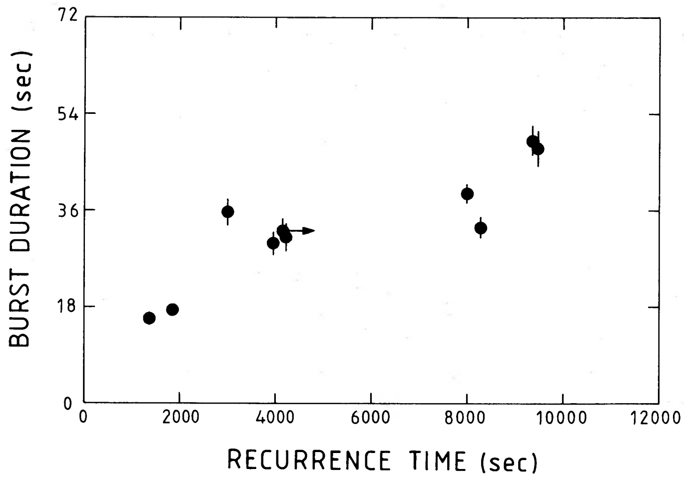

FIG. 3.—The relation between burst duration and recurrence time for all bursts from the 1986 low-state observation.

color temperature can be obtained only from a two-component fit to the combined persistent flux and burst spectrum. Since there is no major blackbody component in the persistent spectrum of EXO 0748−676 and the burst flux exceeded the persistent flux in the burst tails, this effect should not be relevant here.

Figure 4 displays the evolution of the bursts in the first 60 s after the onset (without corrections for relativistic effects). It is the equivalent presentation to Figures 6*c*, *d* in Paper I. Open circles denote the second bursts in the two bursts with recurrence times of 1367 s and 1850 s. Both the distribution of kT_c and L_a are carbon copies of the evolution of the slow bursts discussed in Paper I. They are characterized by a peak temperature of $\sim$2.15 keV and a peak luminosity of $\sim 5.1 \times 10^{37}$ ergs s^{-1}. In the tails kT_c does not decay below $\sim$1.5 keV. The bursts with very short $t_{\rm rec}$ have a lower peak kT_c of 1.9–2.0 keV which cools more rapidly. Figure 5 shows the dependence of L_a and R_a on kT_c. The symbols are the same as in Figure 4. The lines marked "f" and "s" indicate the mean location of the data points of the fast and slow bursts in Paper I. The α-ratio ranged from 15 to 34 with the bursts with long $t_{\rm rec}$ having an α between 25 and 34, and those with short $t_{\rm rec}$ an α-value between 15 and 27.

IV. DISCUSSION

Using *EXOSAT* we have followed the evolution of the outburst of the transient burst source EXO 0748−676 for $\sim$1 yr. The strength of the persistent emission and the characteristics of the X-ray light curve during the 1986 observation suggest that this low state was similar to the low state in 1985 between February 26 and March 10.

After an outburst in 1979 the bursting X-ray transient 4U 1608−52 also remained "on" at a low level for more than 1 yr (White, Kaluzienski, and Swank 1983). 4U 1608−52 resembles EXO 0748−676 in other ways. In particular some properties of the bursts of 4U 1608−52 during the 1979 outburst showed a similar dependence on the strength of the persistent emission as seen from EXO 0748−676 (Murakami *et al.* 1980; Paper I).

The top panel of Figure 6 displays the correlation between $t_{\rm rec}$ and the total observed burst energy E_b. The slow bursts from the 1985 observations are included (*open circles*). All second bursts in double bursts gather at $t_{\rm rec} < 2000$ s and low E_b. The data follow a linear relation. It can be expressed as $E_b = 1.3 \times 10^{-11} t_{\rm rec} + 0.3 \times 10^{-7}$ ergs cm^{-2} with $\chi^2 = 41$ for 18 d.o.f. This linear relation between the total emitted burst energy and the recurrence time is one of the best examples found to date. However, the E_b offset of 0.3×10^{-7} ergs cm^{-2} ($t_{\rm rec} = 0$ s) cannot be explained by classical thermonuclear flash models where all the accumulated fuel is ignited. The existence of a nonnegligible E_b offset reflects the problem of fuel replenishment in bursts with very short recurrence times. For the α-ratios as defined by the bursts with higher $t_{\rm rec}$, the observed E_b values of the bursts following a short $t_{\rm rec}$ are too high to result from the thermonuclear burning of the freshly accreted material.

Fujimoto *et al.* (1987) propose a model to explain the burst characteristics of 4U 1636−53 (Lewin *et al.* 1986) where a similar problem of fuel replenishment between bursts exists. These bursts with an average $E_b \sim 1 \times 10^{-7}$ ergs cm^{-2} and $t_{\rm rec} \sim 100$ minutes were called dwarf bursts. Based on an earlier suggestion by Hanawa and Fujimoto (1984) that a substantial fraction of nuclear fuel can survive in the outer layers, Fujimoto *et al.* (1987) discuss how this material could be transported to layers where the pressure and temperature conditions are suited to trigger a flash. Turbulent motions caused by instabilities in the surface layers and convective zones caused by shell flashes may mix and heat the unburned and the freshly accreted fuel so that it can be ignited, resulting in a dwarf burst. The same mechanism may be responsible for the second burst in a double burst. Because of the very short $t_{\rm rec}$ the second bursts contain a total energy which is of the order of the unburned fuel.

If we assume that during some bursts from EXO 0748−676 a fraction ΔE of the nuclear fuel is not burned, we have to

TABLE 1

BURST PROPERTIES

Burst Onset (1986 day/UT)	$t_{\rm rec}$ (s)	$f_{\rm peak}$ (0.1–20 keV) (10^{-9} ergs cm^{-2} s^{-1})	$f_{\rm total}$ (0.1–20 keV) (10^{-7} ergs cm^{-2})	α
13 12:53:01	>4140	4.71 ± 1.71	1.22 ± 0.12	>17
13 13:39:52	2991	2.50 ± 0.74	0.85 ± 0.13	18
13 15:52:50	7978	4.06 ± 0.49	1.32 ± 0.10	30
13 17:03:05	4215	3.52 ± 2.28	0.78 ± 0.18	27
13 19:38:46	9341	4.35 ± 1.24	1.87 ± 0.15	25
13 20:01:33	1367	3.06 ± 1.42	0.46 ± 0.09	15
13 22:23:00	~8460	...	...	...
13 22:53:50	1850	2.26 ± 0.39	0.40 ± 0.05	23
14 01:11:40	8270	3.81 ± 0.98	1.22 ± 0.09	34
14 02:17:26	3946	3.74 ± 1.36	0.91 ± 0.09	22
14 04:55:04	9458	5.64 ± 2.45	1.63 ± 0.20	29

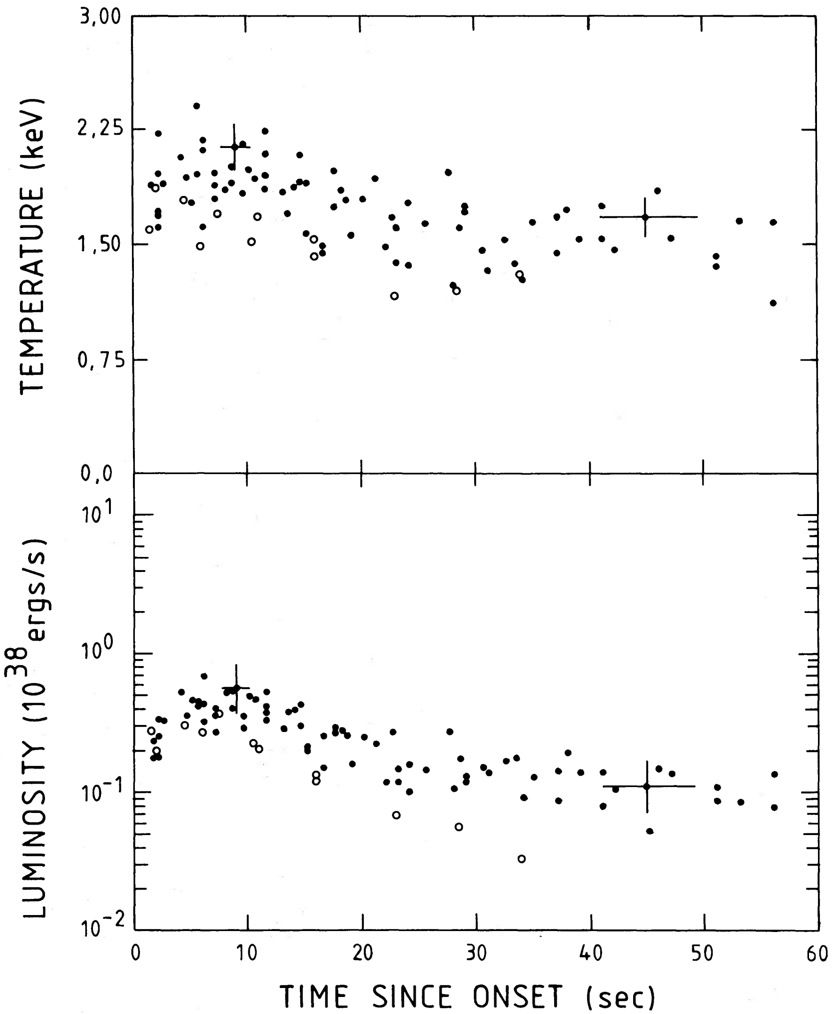

FIG. 4.

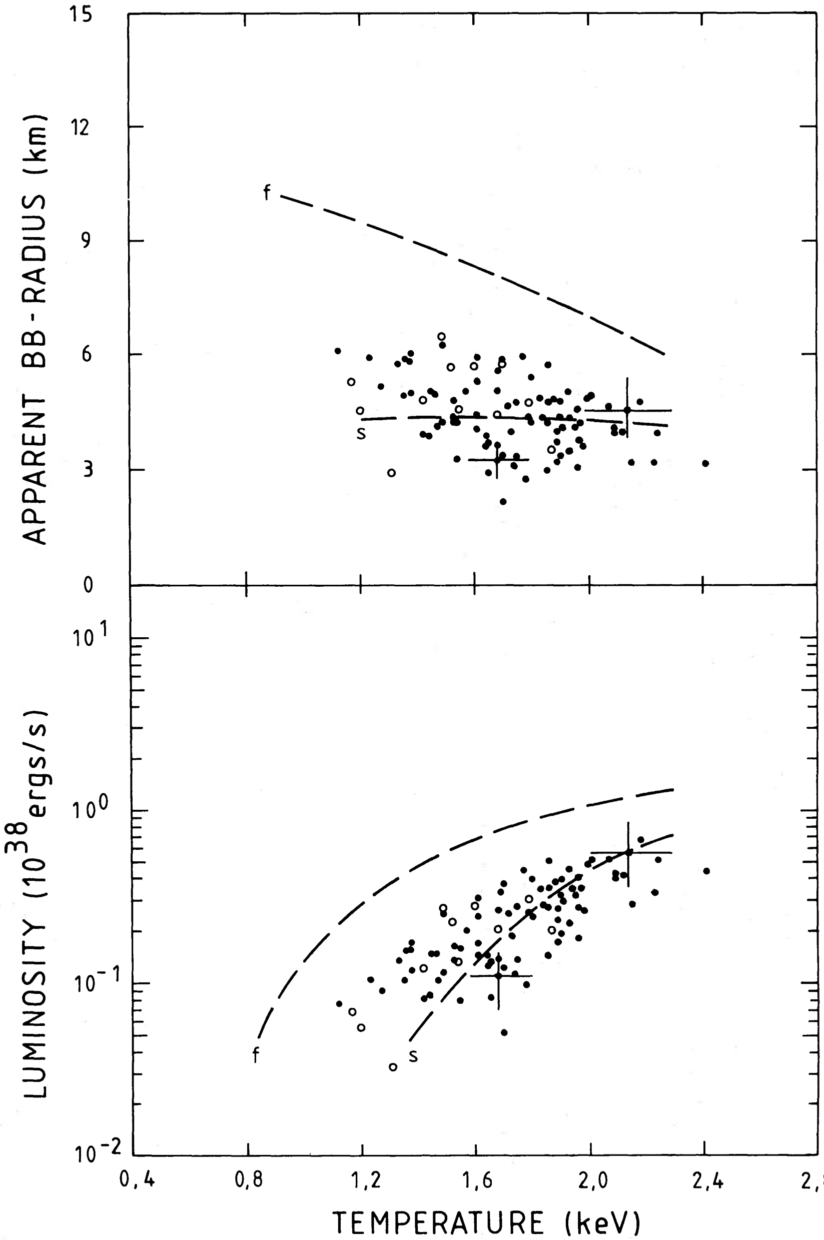

FIG. 5.

FIG. 4.—The evolution of the color temperature kT_c and the luminosity L_a in the first 60 s of the bursts. Open circles denote the bursts with recurrence times of 1367 s and 1850 s. L_a is calculated from kT_c for the energy range 0.1–20 keV with an assumed distance of 10 kpc. Typical 1 σ errors are shown.

FIG. 5.—The dependence between color temperature kT_c and apparent blackbody radius R_a; respectively, luminosity L_a (0.1–20 keV, distance 10 kpc). The symbols are the same as in Fig. 4. Dashed lines indicate the dependence for the fast ("f") and slow ("s") bursts found in Paper I.

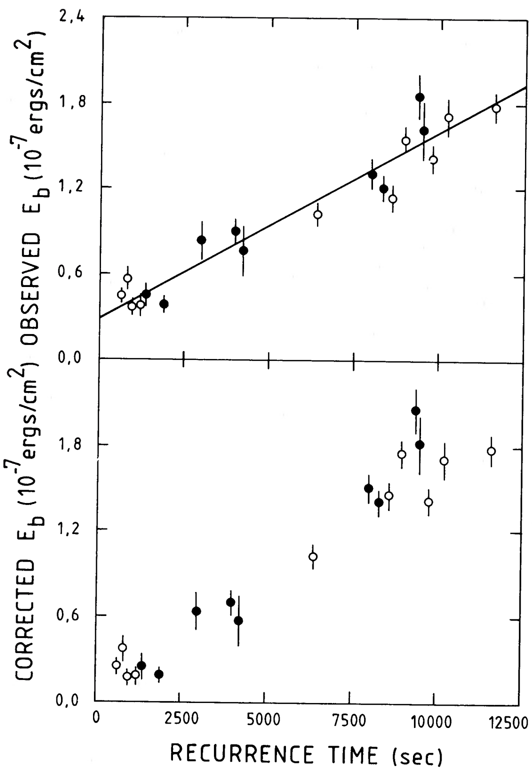

FIG. 6.—The linear dependence between observed total emitted burst energy E_b and recurrence time t_{rec} (*top panel*). The best-fitting line is shown. For a persistent flux of 4×10^{-10} ergs cm^{-2} s^{-1} it corresponds to $\alpha = 30$. In the bottom panel the corrected total emitted burst energy is plotted v. recurrence time. The correction of the E_b values was made using $\Delta E = 0.2 \times 10^{-7}$ ergs cm^{-2}. Open circles denote the slow bursts from Paper I.

modify the following relation between total burst energy E_b, persistent flux f_p and recurrence time t_{rec}

$$E_b = \alpha^{-1} f_p t_{rec} \tag{1}$$

to the expression

$$E_b = \alpha^{-1} f_p t_{rec} - \Delta E \; . \tag{2}$$

In the succeeding burst the unburned material is consumed so that

$$E_b = \alpha^{-1} f_p t_{rec} + \Delta E \; . \tag{3}$$

Equation (3) must be valid for all bursts whose t_{rec} is too short to replenish fuel only via accretion, i.e., $t_{rec} < 6000$ s (Fig. 6*a*). Generally these bursts have α-values <25. All bursts preceding the bursts with short t_{rec} can be expected to have not burned their total available energy so that they obey equation (2). In Figure 6*a* these are most of the bursts gathering at $t_{rec} >$ 6000 s ($\alpha > 25$). The bursts with long t_{rec} which were not followed by a second burst within a short t_{rec} were considered to follow equation (1).

With f_p in the range of the 1985/1986 observations of 3×10^{-10} ergs cm^{-2} s^{-1} to 5×10^{-10} ergs cm^{-2} s^{-1} a least-squares solution yielded $\alpha = 25 \pm 5$, $\Delta E = (0.20 \pm 0.05) \times 10^{-7}$ ergs cm^{-2}. The uncertainties reflect the different best fits for different f_p values. If we correct the observed E_b values according to equations (2) and (3) we obtain the t_{rec}/E_b relationship displayed in the bottom panel of Figure 6. This figure represents the dependence of the total emitted burst energy (which originates only in the freshly accreted matter) and the recurrence time free of effects of unconsumed (stored) burst fuel down to very short t_{rec}. The individual deviations from the strict linear relation point to a scatter in ΔE for each pair of bursts. However, the individual ΔE cannot be too different from our best-fit average ΔE since the rms deviation amounts to only 0.2×10^{-7} ergs cm^{-2}. An increase in bursts energy with t_{rec} was also found in 4U 1636−53 down to $t_{rec} \sim$ 36 minutes (Lewin *et al.* 1986), whereby it was shown that nuclear energy in the order of 10^{-7} ergs cm^{-2} can survive a burst. The same source also exhibited a linear relation between t_{rec} and burst flux in optical bursts (Pedersen *et al.* 1982). 4U 1728−34 showed evidence that with longer recurrence times the average E_b was higher too (Basinska *et al.* 1984).

Assuming a distance of 10 kpc, a ΔE of 0.2×10^{-7} ergs cm^{-2} corresponds to a total energy of 2.4×10^{38} ergs. This amount of fuel must have survived in at least $\sim$60% of the bursts of EXO 0748−676 when it was in a low state. A slow burst fueled by freshly accreted material has a total luminosity of $\sim 1.8 \times 10^{39}$ ergs a factor of 8 higher.

The reconsumption of fuel may account for the evolution of the burst profiles in Figure 2. For bursts with very short t_{rec} consumption of the unburned nuclear fuel dominates over the burning of the freshly accreted material (there was not sufficient time to accrete an appreciable amount of matter). With increasing t_{rec} the relative fraction of the stored fuel compared to the newly accumulated material decreases, and the flashes become similar to the bursts with long recurrence times.

Fujimoto *et al.* (1987) estimated the amount of nuclear energy that can survive a burst and be reconsumed afterward to be 13%–17% of the available burst energy, consistent with our result. However, it should be stressed that care must be taken in a too detailed quantitative comparison of our results with Fujimoto *et al.*'s predictions for 4U 1636−53. One parameter which most likely plays an important role in the mixing mechanism is the accretion rate (persistent flux). In Paper I we have shown that in EXO 0748−676 the burst properties change dramatically with the strength of the persistent emission. In particular our slow bursts display an α-value of $\sim$25 while in 4U 1636−53 the average α of the dwarf bursts was $\sim$100. This may indicate differences either in the hydrogen/helium ratio in the burst fuel, in the anisotropy of the burst and persistent emission (see below), or in the properties of the underlying neutron star between the sources.

Finally, Lapidus and Sunyaev (1985) discuss that an anisotropy can exist in the persistent and burst flux due to the interaction between burst emission and accretion disk. For systems like EXO 0748−676 with a high inclination angle electron scattering of the burst emission by the accretion disk would suppress the burst flux causing the α-ratio to be overestimated by a factor 1.5–2.5. This would reduce the already low values of α found for the low-state bursts from this source to be 8–17, which seems very unlikely. In the light of our observations of EXO 0748−676 the understanding of anisotropy effects in X-rays bursters still needs further improvement (cf. Lewin *et al.* 1986).

V. CONCLUSIONS

We have observed EXO 0748−676 in a low state and found 11 bursts of the slow mode (Paper I). The bursts show a regular pattern with a long recurrence time always followed by a short one. The long intervals lasted $\sim$130 to 160 minutes while the short cover the range $\sim$20–70 minutes. The total emitted burst energy depends linearly on the recurrence time, but with an offset in energy of $\sim 0.3 \times 10^{-7}$ ergs cm^{-2}. We suggest that the bursting behavior indicates the survival and reconsumption of nuclear fuel in different bursts. This result supports a model proposed by Fujimoto *et al.* (1987) where incomplete nuclear burning is responsible for bursts with short recurrence times. We estimated the amount of unburned nuclear fuel to be 10% to 15% of the total available nuclear burst energy.

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