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Kuulkers, E.; van der Klis, M.; van Paradijs, J.A.

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BURSTLIKE EVENTS IN THE Z SOURCE CYGNUS X-2

E. KUULKERS,¹ M. VAN DER KLIS, AND J. VAN PARADIJS

Astronomical Institute “Anton Pannekoek,” University of Amsterdam, Center for High Energy Astrophysics, Kruislaan 403,
 1098 SJ Amsterdam, The Netherlands; ekuulkers@astro.estec.esa.nl, michiel@astro.uva.nl, jvp@astro.uva.nl

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ABSTRACT

We have found nine burstlike events in *EXOSAT* data of the Z source Cyg X-2. Their durations are of the order of several seconds. Within the limited counting statistics we cannot find an indication for cooling during the burstlike events, which would have indicated that they are bona fide type I bursts, i.e., thermonuclear flashes on the surface of the neutron star. However, we find that typical X-ray burst properties (α , τ , γ , fitted blackbody radii) hint at a type I burst origin. No evidence is found for coherent pulsations during the burstlike events.

In order to determine the source state, i.e., to get an indication for the mass accretion rate, during the burstlike events, we studied the color-color diagrams during the corresponding observation periods. The burstlike events occurred in all branches in the X-ray color-color diagram, i.e., in the horizontal branch, the normal branch, and the flaring branch.

Subject headings: accretion, accretion disks — binaries: close — stars: individual: (Cygnus X-2) — X-rays: stars

1. INTRODUCTION

The presence of neutron stars in low-mass binaries (LMXBs) is revealed by the occurrence of X-ray bursts or pulsations in these systems (see, e.g., Lewin, van Paradijs, & van der Klis 1988; Lewin, van Paradijs, & Taam 1993). No pulsations, however, have been found in the six brightest persistent LMXBs, despite substantial efforts (Vaughan et al. 1994 and references therein). These sources exhibit three different spectral states (branches) with correlated temporal behavior (Hasinger & van der Klis 1989). They were dubbed the Z sources because of the Z pattern the branches form in the X-ray color-color diagram: horizontal branch (HB; top stroke of the Z), normal branch (NB; middle stroke), and flaring branch (FB; end stroke). The Z sources are thought to have a mass accretion rate near the Eddington critical rate (Lamb 1989).

The only direct indications so far of the presence of neutron stars in the Z sources have been provided by a few X-ray bursts. To date several bursts have been observed in the Z source GX 17+2 (Tawara et al. 1984; Kahn & Grindlay 1984; Sztajno et al. 1986; Kuulkers et al. 1994b, 1995a), and one burst has been reported in Cyg X-2 (Kahn & Grindlay 1984). The burst of GX 17+2 were found to be thermonuclear flashes on the neutron star (Sztajno et al. 1986), while it is unclear whether this is the cause of the burstlike event observed in Cyg X-2. To our knowledge, X-ray bursts have not been observed in the other Z sources.

In this paper we report previously undetected burstlike events which occurred during several of the *EXOSAT* observation periods. We present the properties of these bursts and their occurrence in the framework of the Z diagram.

2. OBSERVATIONS AND ANALYSIS

Cyg X-2 was observed with the Medium Experiment (ME) on board *EXOSAT* (Turner, Smith, & Zimmermann 1981;

White & Peacock 1988) during several observation periods. The ME had a layer of eight argon detectors (1–20 keV) on top of a layer of eight xenon detectors (5–35 keV). The data from both layers could be selected individually. In this paper we mostly use the argon-related data, unless noted otherwise. An overview of all Cyg X-2 *EXOSAT* observations is given in Table 1.

In our analysis we use color-color diagrams (CDs) (see, e.g., Hasinger & van der Klis 1989). We used three energy bands, with the following energy boundaries: 0.9–3.1, 3.1–6.4, and 6.4–19.7 keV. The soft color is defined as the ratio of the background- and dead-time-corrected² count rates of the 3.1–6.4 keV to the 0.9–3.1 keV band, and the hard color as the corrected count rate ratio of the 6.4–19.7 keV to the 3.1–6.4 keV band.³ The X-ray intensity we report is the count rate of the 0.9–19.7 keV band, corrected for background, dead time (see footnote 2), and collimator response.

3. RESULTS

3.1. Burstlike Events

3.1.1. Light Curves

In Figure 1, several light curves (1983 day 258, 1985, day 176/177, 1985 day 177/178, 1985 day 205, 1985 day 206, and 1985 day 301/302) of Cyg X-2 are shown with a 5 s time resolution. Transitions of the source from one branch to another are indicated. It can be clearly seen that the smooth overall light curve variations are suddenly interrupted by burstlike events. In total, nine burstlike events can be distinguished in the *EXOSAT* ME data. Light curves of the obser-

² The dead time is determined from the “qualified event rate” supplied by the *EXOSAT* housekeeping data (e.g., Andrews & Stella 1985).

³ At the start and end of the observation periods 1985 day 205 and 206, data were obtained in the HER5 mode (see Table 1). The lower energy boundary of the first energy band during this mode was 1.4 keV. This affected the soft color in the CDs; we therefore corrected the soft color (multiplication factor of 0.94) in order to match the NBs of the other observations.

¹ Present address: ESA/ESTEC, Astrophysics Division (SA), P.O. Box 299, NL-2200 AG Noordwijk, The Netherlands.

BURSTLIKE EVENTS IN CYG X-2

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TABLE 1
EXOSAT ME ARGON OBSERVATION LOG OF CYG X-2

Date	Day ^a	Start (UT) (hr:minute)	End (UT) (hr:minute)	HER ^b Mode	Time Resolution	Spectral State	Configuration ^c	Orbital Phase ^d
1983 Jul 5/6	186/187 ^e	10:28	06:00	3	10 s	FB?	WA	0.10–0.19
1983 Sep 13	256	23:04	23:59	4	2.5 s	NB	H2	0.27
1983 Sep 14	257	00:08	01:09	4	2.5 s	NB	H1	0.27–0.28
1983 Sep 15	258	18:40	19:52	4	2.5 s	NB/FB	H2	0.45–0.46
		19:52 ^f	22:09 ^f	4	2.5 s	NB/FB	H1	0.46–0.47
1983 Sep 18	261	16:06	18:54	4	0.3/2.5 s	HB	H2	0.75–0.76
		18:59	19:14	4	2.5 s	HB	H1	0.76
1983 Sep 20/21	263/264	23:00	01:36	4	0.3/2.5/10 s	NB	H1	0.98–0.99
1983 Sep 22	265	15:52	19:09	4	0.3/2.5/5 s	NB	H2	0.15–0.17
1984 Jul 23	205 ^g	02:08	17:01	5	0.3/10 s	HB	H1	0.08–0.14
1985 Jun 25/26	176/177	23:34	08:31	4	2.5 s	HB/NB	WA	0.40–0.44
1985 Jun 26	177	08:35	11:17	4	2.5 s	NB	H2	0.44–0.45
1985 Jun 26/27	177/178	22:20	01:00	4	2.5 s	NB	WA	0.50–0.51
1985 Jul 24	205	02:16	16:31	5/7 ^h	1 s/3 ms	HB/NB/FB	WA	0.26–0.32
1985 Jul 25	206	01:25	13:39	5/7 ⁱ	1 s/3 ms	HB/NB	WA	0.36–0.41
1985 Oct 28	301	15:08	15:38	2/7	1 s/4 ms	HB	H2	0.06–0.07
1985 Oct 28/29	301/302	15:42	03:50	2/7	1 s/4 ms	HB	WA	0.07–0.12
1985 Oct 29	302	13:31	14:18	2/7	1 s/4 ms	HB	WA	0.16
1985 Nov 14/15	318/319	23:50	12:54	2/4/7 ^j	1/10 s/4 ms	NB/FB	WA	0.83–0.88

^a January 1 = day 1.^b HER (High Energy Resolution) mode number.^c ME on source configuration: WA = whole array, H1 = half 1, H2 = half 2.^d X-ray phase using the ephemeris given by Crampton & Cowley 1980.^e Calibration raster scan.^f Analog to digital converter (ADC) problems (see Chiapetti et al. 1987, 1990).^g Interrupted by observations in OBC mode MDIR2 (15:33–16:19).^h During 02:16–03:46, 04:00–04:12, and 14:48–16:31 HER5, rest HER7. During 07:49–14:41 sampling rate was 8192.ⁱ During 01:25–02:00 and 13:31–13:39 HER5, rest HER7.^j 23:50–00:38 HER4, rest simultaneous HER2/HER7.

vation periods 1985 day 301/302 and day 206 were also given by Hasinger (1988) but at a much lower time resolution, i.e., 256 s. The burstlike events remained undetected due to the low time resolution. The events occur during both high-intensity and medium-intensity levels (see Kuulkers, van der Klis, & Vaughan 1995b). Inspection of the housekeeping data excluded a solar or detector origin. No such events have been seen in EXOSAT observations of several other sources and their background observations, which were examined in the same way (see, e.g., Berger & van der Klis 1994; Kuulkers et al. 1994a, 1995a, b; Oosterbroek et al. 1995).

The times of the burstlike events are given in Table 2, together with several of their properties. The durations of the burstlike events are on the order of several seconds. The three burstlike events observed at 1985 day 301/302 (B7–B9) are found to occur with intervals at ~ 3.2 and ~ 4.0 hr (see Table 2).

During most of the observation periods, data were also obtained in modes of high time resolution (see Table 2). In Figures 2a–2f (argon) and Figures 3a–3c (argon and xenon) we show the light curves of the burstlike events at a higher time resolution (0.125 s). Intensity here is given as the total dead-

TABLE 2
PROPERTIES OF THE BURSTLIKE EVENTS

Number	Year	Date ^a	Start (UT) (hr:minutes)	t_{burst}^b (s)	HTR Mode ^c	Time Resolution	Ar/Xe Data ^d	Branch Location	Orbital Phase ^e	α^f
B1	1983	258	19:10:26	~ 3	E4 ^g	31 ms	A + X	Lower FB	0.45	> 1963
B2	1985	177	07:26:34	~ 3	T5	2.0 ms	A	Upper NB	0.43	> 17009
B3	1985	178	00:25:14	~ 5	T5	2.0 ms	A	Lower NB	0.51	> 6839
B4	1985	205	10:02:33	~ 3	E7	2.9 ms	A	Middle HB	0.29	> 5982
B5	1985	205	15:32:14	~ 3	E5	1.0 s	A	Upper NB	0.31	> 2900
B6	1985	206	07:39:12	~ 3	E7	2.9 ms	A	Upper NB	0.38	> 26227
B7	1985	301	19:22:34	~ 3	E7/T5	3.9 ms	A/X	Left HB	0.08	> 12368
B8	1985	301	22:42:10	~ 3	E7/T5	3.9 ms	A/X	Left HB	0.10	~ 6685
B9	1985	302	02:37:46	~ 3	E7/T5	3.9 ms	A/X	Left HB	0.11	~ 10622

^a January 1 = day 1.^b Burst duration, defined as the difference between the start and end of the burst.^c Highest time resolution mode available. E = high energy resolution; T = high time resolution.^d Argon (A) and/or xenon (X) data available.^e X-ray phase using the ephemeris given by Crampton & Cowley 1980.^f If no previous burstlike event is known, a lower limit is given.^g In this case the only high time resolution data available is the so-called I4 data from the HER4 mode (one channel covering all argon and xenon channels).

FIG. 1.—*EXOSAT* ME light curves of six observation periods of Cyg X-2 at a time resolution of 5 s. Intensity is the dead-time-, background-, and collimator response-corrected count rate in the 0.9–19.7 keV range. Indicated are the branches in which the source was during the observations. Sharp spikes can be seen which interrupt the smooth light curve variations. These are burstlike events. Start times (UT hr:minute) for the different observation periods are 18:40 (1983 day 258), 23:33 (1985 day 176/77), 22:20 (1985 day 177/178), 03:06 (1985 day 205), 01:25 (1985 day 206), and 15:42 (1985 day 301/302).

time⁴ and background-corrected count rate. The numbers (B1–B9) correspond to the different burstlike events as given in Table 2 in chronological order. On 1985 day 301/302 and day 302, data were obtained in the argon HER7 mode, simultaneously with the HTR5 xenon (5–30 keV) mode. The burstlike events B7–B9 are not significant in the xenon data, which means that they are relatively soft. This strengthens the conclusion that they are intrinsic to the source and not due to solar activity because the spectral signature of solar particle events in *EXOSAT* is hard. As an example, we show in Figure 3d the light curve of a solar flare seen when *EXOSAT* pointed to Sco X-1 (1986 March 11, day 70). The solar flare was relatively hard, i.e., it showed up only in the xenon data. The house-

⁴ Since the light curves of the burstlike events exhibit large variations in count rate, we cannot determine the dead-time factor from the housekeeping data which have only 32 s resolution. Moreover, because of the processing by the on-board computer (OBC), HER-mode data suffered considerable variable dead time; see e.g., Kuulkers et al. (1994a). We therefore determined the dead-time factors from the relations as given by, e.g., van der Klis (1989) for the HER-mode data and the HTR-mode (High Time Resolution, not OBC processed) data. In the case of HER7 data, we also took into account the nonregistered counts at energies larger than ~ 20 keV, which also affect the total dead time induced by the OBC.

FIG. 2.—High time resolution argon light curves of the burstlike events B1–B6 (see text). The intensity is corrected for dead time and background.

keeping data of this observation revealed that this flare originated from solar particle events.

We determined the ratio, α , of the average persistent flux to the time-averaged flux emitted in burstlike events (see, e.g., van Paradijs, Penninx, & Lewin 1988a; Lewin et al. 1993). To first order we assume that the shape of the spectrum of the burst is comparable to that of the persistent emission and use the averaged count rate as the flux. The persistent average count rate (HTR data: all channels; HER data: 0.9–19.7 keV) is determined between the previous burst to the burst one examines. When no information of a previous burstlike event is known, we take the average count rate from the start of the observation (or from the start of a data gap) to the burst in question and calculate a lower limit to α . The average count rate during the burst is corrected for dead time using the relations given by, e.g., van der Klis (1989) (see footnote 3), while the persistent average count rate is corrected for dead time using the qualified event data. The results are given in Table 2. The values for α (reflecting the ratio between gravitational and nuclear burning energy per gram of accreted matter; Lewin et al. 1993) are found to be large (> 2000). The burst characteristics γ (ratio of the mean persistent preburst flux and the net peak burst flux) and τ (ratio of the total integrated net burst flux and the net burst peak flux; this is another representation of the burst duration) are found to have values of 0.8–1.8 and 1.4–2.0 s, respectively.

The orbital phases of the burstlike events (see Table 2) were determined using the orbital ephemeris of Crampton &

FIG. 3.—(a–c). High time resolution light curves for burstlike events during the same observation period (1985 day 301/302) B7–B9. The intensity is corrected for dead time and background. Simultaneous argon (*top*) and xenon (*bottom*) data were available. The burstlike events appear to be soft. (d) Solar particles causing a flare during an observation of Sco X-1 (1986 day 70). This figure stresses that the “flares” induced by solar particles are generally hard, i.e., they show up only in the xenon band (*bottom*) and not in the argon band (*top*).

Cowley (1980). All events happened between orbital phases 0.0 and 0.5. We attribute this preference for the first half of the binary cycle to a selection effect, because most of the observations (six of a total of eight) were obtained between orbital phases 0.0 and 0.5 (see Table 1).

We constructed an average burstlike event profile of the events observed in the HER7 mode (B4 and B6–B9) in three energy bands: 0.9–3.1 keV, 3.1–6.4 keV, and 6.4–19.7 keV. For each individual burst we first created light curves in the three bands and the three bands added together (total count rate) at a time resolution of ~ 70 ms. The start of a burstlike event was determined from the total count rate and defined as the point in the light curve which differed more than $\sim 4\sigma$ from the mean persistent intensity. The five bursts were first averaged and then rebinned (10 points were averaged, which resulted in a time resolution of ~ 0.7 s) to create the light curves displayed in Figure 4. The errors are determined from the variance of the 10 points in each bin. It can be seen that the burstlike events last longer in the highest energy band (Fig. 4d) compared to the two lower energy bands (Figs. 4b and 4c). To quantify this we fitted exponential decay curves to the burst profiles in the different energy bands. The characteristic decay times in the three energy bands are 1.65 ± 0.16 s, 1.76 ± 0.16 s, and 2.41 ± 0.43 s, from the lowest energy band to the highest energy band, respectively. This reveals that the longer duration in the highest energy band is only marginally significant ($< 2\sigma$) but still is inconsistent with that expected for spectral cooling (i.e., shorter burst duration at higher energies).

3.1.2. Burst Position in the Color-Color Diagram

The position along the Z track in the CD can be used as an indicator of the mass accretion rate (Hasinger et al. 1990; Vrtilik et al. 1990). Therefore, an interesting question is as follows: in which spectral state do the burstlike events occur? In Figure 5 we show the CD for the relevant observation

periods (see Kuulkers et al. 1995b) with arrows pointing to the position of the source in the Z near the time of the burstlike events. We find no clear dependence of the burst occurrence on position in the CD.

3.1.3. Burst Spectral Analysis

3.1.3.1. Introduction

In the sources with a high accretion rate, such as Cyg X-2 and GX 17+2, blackbody fits to net burst spectra estimated by subtracting the persistent flux from the burst flux can be systematically affected by the contribution of the same neutron star surface layers that emit the burst to the persistent emission (van Paradijs & Lewin 1985; Sztajno et al. 1986). This means that when one is modeling net burst flux as blackbody radiation (see e.g., Lewin et al. 1993), one may incorrectly estimate the blackbody radiation.

Following Sztajno et al. (1986) we therefore applied a spectral analysis consisting of several steps. First (Step 1) we analyzed the burstlike events in a “standard” way, i.e., by performing blackbody fits to the net burst flux (burst spectrum minus persistent emission spectrum). Second (Step 2), we made two-component fits to the combined persistent and burst emission. One component is the blackbody radiation arising from the neutron star surface (increasing during the burst), while the other component represents the radiation due from the accretion disk. This disk component is assumed to be the same just before and during the burstlike events and to be not influenced by the burst. This component was therefore fixed during the burst spectral fits and determined from the two-component fits to the persistent emission of 300 s duration just before the burstlike events start. Like Sztajno et al. (1986), we used for this emission a thermal bremsstrahlung component. In our analysis we used only those spectra with the full energy resolution and with the whole array pointed to the source (B2, B3, and

FIG. 4.—Average light curve of the burstlike events B4 and B6–B9 in the three HER7 energy bands together (a) and separately (b–d) at a time resolution of 0.7 s. The light curves are corrected for background and dead time.

B7–B9). We fitted the observed spectra between ~ 1 and ~ 15 keV, which is more or less the well-calibrated energy range (see Haberl 1992). In our persistent emission fits, we included an iron emission line that was centered at 6.7 keV and had a FWHM of 0.1 keV (see Hasinger et al. 1985, 1990). The corresponding equivalent width (EW) was fitted. During the burst spectral analysis the iron line component was also fixed.

In the previous steps we modeled the contribution from the neutron star as a blackbody. However, hot neutron stars may produce spectra which deviate from a blackbody (see Sztajno et al. 1986 and references therein). As a result, the temperature fitted in blackbody fits is a “color temperature” (T_{bb}), which is higher than the effective temperature (T_{eff}); the ratio $T_{\text{bb}}/T_{\text{eff}}$ increases with T_{eff} (e.g., London, Taam, & Howard 1984). Accordingly, the fitted (apparent) blackbody radii are also affected (e.g., Sztajno et al. 1986). In Step 3, therefore, we used the relation between apparent blackbody radius and color temperature as obtained for 4U 1636–53 (Sztajno et al. 1985) to correct empirically for this effect and determine the true blackbody radius (see, e.g., van Paradijs et al. 1986). We assumed here, of course, that this relation also holds for Cyg X-2. As this method is strictly empirical, we are not affected by uncertainties in model atmospheres (e.g., Sztajno et al. 1986). Like Sztajno et al. (1986) we assumed that for $kT_{\text{bb}} < 1.25$ keV the radii are unaffected, while for $kT_{\text{bb}} > 1.25$ keV the correction varies linearly with temperature (e.g., van Paradijs et al. 1986).

We will first present the results of the fits to the preburst persistent emission and then for the burst analyses. We found that the preburst spectral parameters matched the postburst (300 s) spectral parameters.

3.1.3.2. Persistent Spectral Parameters

The results of the fits to the persistent emission are given in Table 3. T_{br} and F_{br} are the thermal bremsstrahlung temperature and flux ($1\text{--}15$ keV in 10^{-8} ergs s^{-1} cm^{-2}), respectively, while T_{bb} , R_{bb} , and F_{bb} are the blackbody temperature, radius, and flux ($1\text{--}15$ keV), respectively. F_{tot} is the total flux between 1 and 15 keV. The bremsstrahlung spectrum (plus a blackbody component, when necessary) fitted the data very well (all $\chi^2_{\text{red}} < 1$). The errors quoted for N_{H} , T_{br} , and T_{bb} are determined from error scans with $\Delta\chi^2 = 1$ and so are single parameter errors at 1σ . Since F_{tot} , F_{br} , F_{bb} , and EW are integrated quantities, their errors are determined as follows:⁵ we first performed error scans for all spectral parameters in the χ^2 space with $\Delta\chi^2 = 1$ (see above). Then we subsequently fixed each component to its minimum and maximum value, while the other parameters were free. The spectrum was then fitted again, and we obtained minimum and maximum values for F and EW. This gave us several sets of ranges in F and EW. The largest range in values was used as an estimate of the uncertainty in the optimal value of F and EW.

In the left HB, where the HB curves up (see Fig. 5, around B7 and B8), only one component (i.e., thermal bremsstrahlung) was required to describe the data. In these cases the contamination of the net burst spectra by the persistent blackbody component of the hot neutron star atmosphere is negligible. The mean value of N_{H} matches the value found from *Ginga* data ($\sim 0.3 \times 10^{22}$ cm^{-2} ; Hasinger et al. 1990). An iron line was significantly present in the *EXOSAT* data in the HB

⁵ Performing error scans for integrated quantities within the current version of XSPEC is not possible.

TABLE 3
PERSISTENT CYG X-2 SPECTRAL PARAMETERS ~ 300 s BEFORE BURSTLIKE EVENTS: I^a

Burst	N_{H} (10^{22} cm^{-2})	T_{br} (keV)	T_{bb} (keV)	R_{bb} ^b (km)	F_{tot} ^c ($10^{-8} \text{ ergs s}^{-1} \text{ cm}^{-2}$)	$F_{\mathrm{bb}}/F_{\mathrm{br}}$ ^c	EW ^d (keV)	$\chi^2_{\mathrm{red}}/\mathrm{dof}$
B2.....	0.34 ± 0.07	7.16 ± 0.41	1.17 ± 0.04	10.0 ± 1.2	1.596 ± 0.012	0.22 ± 0.06	20 ± 27	0.88/39
B3.....	0.44 ± 0.07	4.24 ± 0.20	1.15 ± 0.06	9.8 ± 1.4	1.416 ± 0.012	0.22 ± 0.04	17 ± 34	0.71/39
B7.....	0.26 ± 0.02	6.36 ± 0.08	...	...	1.161 ± 0.006^e	0	90 ± 21	0.57/41
B8.....	0.36 ± 0.03	5.85 ± 0.09	...	...	1.250 ± 0.009^e	0	74 ± 28	0.97/41
B9.....	0.25 ± 0.07	6.10 ± 0.34	1.05 ± 0.09	7.6 ± 2.3	1.347 ± 0.014	0.09 ± 0.06	72 ± 37	0.82/39

^a For determination of errors see text.

^b Assuming a distance of 8 kpc (Cowley et al. 1979).

^c Fluxes from 1 to 15 keV.

^d Iron line fixed at 6.7 keV, with a fixed FWHM of 0.1 keV. EW = equivalent width.

^e In these fits: $F_{\mathrm{tot}} = F_{\mathrm{br}}$.

(around B7, B8, and B9), while it seemed to be absent or very weak in the NB. All blackbody radii in the two-component fits are consistent with blackbody emission from the neutron star surface at ~ 10 km radius.

To facilitate the comparison with other fit results (see Hasinger et al. 1990), we also performed two-component fits using a Boltzmann-Wien spectrum, i.e., a cutoff power-law component (White et al. 1986), in combination with a blackbody component. N_{H} and the power-law index, α_{pl} , were fixed to $0.3 \times 10^{22} \text{ cm}^{-2}$ and 1.2, respectively (see Hasinger et al. 1990), because N_{H} and α_{pl} are badly determined in these two-component fits. Moreover, α_{pl} and the cutoff energy of the power law, E_{cut} , are strongly correlated and thus ill determined (see, e.g., Hasinger et al. 1990). The results of the fits can be found in Table 4. F_{pl} and E_{cut} are the integrated flux (1–15 keV) from the power-law component and the cutoff energy of this

power law, respectively. In this case also one component was sufficient for the persistent spectra before the burstlike events B7 and B8. Again, the blackbody radii are more or less consistent with $R_{\mathrm{bb}} \sim 10$ km.

When we compare our *EXOSAT* fit results with those obtained from *Ginga* data by Hasinger et al. (1990, their Table 3a), we see that the values are roughly the same. The left HB is not present in the *Ginga* data. We find that in this part of the CD the iron line is prominent, while it was absent in the right HB and the NB. Both *EXOSAT* and *Ginga* data indicate that it becomes prominent again near the NB/FB vertex.

Our conclusion is that both two-component models seem to fit the observed persistent spectra quite well. We note that our application of both models does not imply a judgment on their physical merits. Our purpose here is to describe the spectral properties of the bursts in the presence of strong persistent emission.

3.1.3.3. Burst Spectral Parameters

In both steps of our burst spectral analysis N_{H} was fixed to the value derived for the persistent emission (see Table 3). Since the burstlike events are of very short duration, the burstlike event spectra are rather noisy. The spectral results (Table 5) are therefore not of high statistical quality. Moreover, because the lengths of the burstlike events are comparable to the time resolution of the spectral data (2.5 s during B2 and B3 and 1 s during B7–B9), the spectra do not cover the same portion of each burst, which makes it harder to intercompare them.

Only in the case of B7–B9 could we divide the burstlike events into two parts in order to look for a possible temperature and blackbody radius change during the bursts (see Table 5).

As can be seen in Table 5, the spectral fit results in Step 1 differ for the burstlike events that occurred in the HB (B7–B9) as compared to the two burstlike events that occurred in the NB (B2 and B3).⁶ T_{bb} and R_{bb} are ~ 1.1 keV and ~ 14 km (significantly larger than the persistent blackbody radii), respectively, for the former burstlike events, and ~ 2.0 keV and ~ 3 km, respectively, for the latter burstlike events. This difference may reflect the presence of persistent blackbody radiation near events B2 and B3. Blackbody temperatures and radii similar to B2 and B3 were found from spectral fitting of the net burst emission in GX 17+2 (Sztajno et al. 1986) and Cir X-1 (Tennant, Fabian, & Shafter 1986). The net burst spectra of B7–B9 lack this contamination (or it is very small; see § 3.1.3.2). If we split the burstlike events into two in the cases

⁶ Note that both groups of events also occurred on different dates.

FIG. 5.—Color-color diagram (CD) of the observation periods shown in Fig. 1. Soft and hard color are defined in the text. The different symbols refer to the different observation periods (open circles: 1983 day 258; open squares: 1985 day 176/177; stars: 1985 day 177/178; plus signs: 1985 day 205; filled circles: 1985 day 206; asterisks: 1985 day 301/302). All points are 200 s averages. A typical error bar is shown. Arrows indicate the different position in the CD during which the burstlike events occurred.

TABLE 4
PERSISTENT CYG X-2 SPECTRAL PARAMETERS ~ 300 s BEFORE BURSTLIKE EVENTS: II

Burst	E_{cut} (keV)	T_{bb} (keV)	R_{bb}^a (km)	F_{tot}^b (10^{-8} ergs s^{-1} cm^{-2})	$F_{\text{bb}}/F_{\text{pl}}^b$	EW ^c (keV)	$\chi^2_{\text{red}}/\text{dof}$
B2.....	6.11 ± 0.14	1.13 ± 0.04	10.3 ± 0.8	1.597 ± 0.002	0.21 ± 0.01	22 ± 28	0.86/40
B3.....	4.02 ± 0.09	1.06 ± 0.04	11.9 ± 0.9	1.426 ± 0.002	0.24 ± 0.01	31 ± 31	0.75/40
B7.....	5.24 ± 0.05	...	...	1.143 ± 0.002^d	0	76 ± 23	1.13/42
B8.....	5.02 ± 0.05	...	...	1.249 ± 0.002^d	0	60 ± 29	0.87/42
B9.....	4.98 ± 0.09	1.02 ± 0.16	5.1 ± 2.1	1.339 ± 0.002	0.03 ± 0.02	58 ± 29	0.87/40

^a Assuming a distance of 8 kpc (Cowley et al. 1979).

^b Fluxes from 1 to 15 keV.

^c Iron line fixed at 6.7 keV, with a fixed FWHM of 0.1 keV. EW = equivalent width.

^d In these fits: $F_{\text{tot}} = F_{\text{pl}}$.

B7–B9, we find no evidence of spectral cooling (or hardening). Only a marginal indication ($\sim 2\sigma$) for a decrease in the blackbody radii is seen for B7 and B8.

The effect of the Step 2 analysis can be clearly seen for the burstlike events B2 and B3. The blackbody temperature is lower while the blackbody radius is larger with respect to Step 1. We note that these differences in the temperature and radii derived with the two methods are similar in the case of GX 17+2 (Sztajno et al. 1986). However, T_{bb} and R_{bb} for B2 and B3 still differ from the values obtained for B7–B9. As expected, T_{bb} and R_{bb} obtained for B7–B9 do not differ much from the results for Step 1.

The Step 3 analysis has the clearest effect on B2 because in this event the deviation from a blackbody is expected to be largest (see § 3.1.3). The blackbody radius eventually found (~ 10.5 km) is close to the value found for the blackbody emission in the persistent emission just before the burst (see Table 3).

We conclude that the blackbody radii found (assuming a distance of the source of 8 kpc; Cowley, Crampton, & Hutchings 1979) between ~ 9 and ~ 15 km are consistent with an origin of the events in the vicinity of the neutron star and comparable to the values for the persistent emission. For the burstlike events with no indication of a contamination by the

TABLE 5
FIT RESULTS OF SPECTRA OF BURSTLIKE EVENTS

Burst	T_{bb} (keV)	F_{bb} (10^{-8} ergs s^{-1} cm^{-2})	R_{bb}^a (km)	χ^2_{red}	dof	$R_{\text{bb}}^{a,b}$ (km)
Step 1						
B2 ^c	2.10 ± 0.24	0.36 ± 0.05	3.3 ± 0.9	1.09	43	...
B3.....	1.92 ± 0.25	0.23 ± 0.03	3.2 ± 0.8	0.96	43	...
B7.....	1.19 ± 0.07	0.54 ± 0.03	13.1 ± 1.4	1.12	43	...
B8.....	1.11 ± 0.07	0.51 ± 0.03	14.7 ± 1.8	0.84	43	...
B9.....	1.07 ± 0.08	0.37 ± 0.02	13.4 ± 2.1	1.13	43	...
Burst Spectra Split ^d						
B7a.....	1.08 ± 0.07	0.56 ± 0.04	16.0 ± 2.2	0.78	43	...
B7b.....	1.27 ± 0.10	0.52 ± 0.04	11.2 ± 1.8	1.03	43	...
B8a.....	1.04 ± 0.08	0.66 ± 0.04	18.8 ± 2.9	1.12	43	...
B8b.....	1.15 ± 0.12	0.33 ± 0.04	11.0 ± 2.3	0.74	43	...
B9a.....	1.08 ± 0.10	0.40 ± 0.04	13.5 ± 2.6	0.99	43	...
B9b.....	0.98 ± 0.11	0.32 ± 0.04	14.9 ± 3.6	0.98	43	...
Step 2						
B2.....	1.57 ± 0.08	0.60 ± 0.03	8.2 ± 0.7	1.03	43	10.4 ± 0.9
B3.....	1.33 ± 0.07	0.50 ± 0.02	8.4 ± 0.8	0.94	43	8.9 ± 0.8
B7.....	1.29 ± 0.07	0.46 ± 0.03	12.8 ± 1.4	1.29	43	13.1 ± 1.4
B8.....	1.11 ± 0.07	0.51 ± 0.03	14.2 ± 1.7	0.82	43	14.2 ± 1.7
B9.....	1.07 ± 0.06	0.48 ± 0.02	15.0 ± 1.7	1.10	43	15.0 ± 1.7
Burst Spectra Split						
B7a.....	1.09 ± 0.08	0.48 ± 0.04	15.5 ± 2.1	0.79	43	15.5 ± 2.1
B7b.....	1.30 ± 0.12	0.44 ± 0.04	10.9 ± 1.7	1.01	43	11.3 ± 1.8
B8a.....	1.04 ± 0.08	0.66 ± 0.04	18.2 ± 2.8	1.12	43	18.2 ± 2.8
B8b.....	1.16 ± 0.12	0.33 ± 0.04	10.6 ± 2.2	0.73	43	10.6 ± 2.2
B9a.....	1.09 ± 0.08	0.53 ± 0.04	15.2 ± 2.2	0.97	43	15.2 ± 2.2
B9b.....	1.01 ± 0.09	0.42 ± 0.04	15.9 ± 2.9	1.00	43	15.9 ± 2.9

^a Assuming a distance of 8 kpc (Cowley et al. 1979).

^b Correction to non-Planckian spectrum.

^c 2.5 s spectrum for B2 and B3, and 2 s spectrum for B7–B9.

^d a and b denote the first and the second part of the burst, respectively.

neutron star flux, we find blackbody temperatures of ~ 1.2 keV.

3.1.4. Pulsations

We performed Fast Fourier Transforms (FFTs) in order to look for a pulse signal in the power spectra during the bursts. We follow the procedure as outlined by van der Klis (1989) and Vaughan et al. (1994). Given the property that noise powers follow a χ^2 distribution, one can set a threshold above which (with a certain confidence) one detects only source power. We used a confidence level of 99% in our analysis. When no power is detected above the threshold, one can set an upper limit to the signal. If one assumes that the underlying signal is sinusoidal, a limit can be obtained on the maximum modulation strength (see Vaughan et al. 1994).

The argon HER mode data (during B1 and B4–B9) suffered large variable dead time (see, e.g., Kuulkers et al. 1994a). This adversely influences the detection and sensitivity level in a power spectrum (see van der Klis 1989). Therefore, HER-mode data were inspected only for a clear peak in the power spectrum and were not used to derive upper limits.

Two second FFTs were performed for B1, B2, and B4–B9 and a 4 s FFT was performed for B3. We found no significant peak in the power spectra of any of the burstlike events but only very low frequency noise due to the burst profile. Using the HTR-mode data, we placed upper limits to the modulation strengths in B2 and B3. In these cases we are sensitive in the range 1–256 Hz. For B2 the 99% confidence upper limit to the sinusoidal amplitude of periodic modulation is 13.7% of the mean flux at 1 Hz and 21.6% at the Nyquist frequency (256 Hz), while for B3 we find 11.6% and 18.2% at 1 Hz and 256 Hz, respectively. When we combined these power spectra, we derived upper limits of 8.1% and 12.3% at 1 Hz and 256 Hz, respectively. We conclude that between 1 and 256 Hz no evidence for a sinusoidal signal is found during the two burstlike events with modulation strengths larger than $\sim 10\%$.

4. DISCUSSION

We have found nine burstlike events in the *EXOSAT* ME data of Cyg X-2. In 1984, Kahn & Grindlay reported one burstlike event in Cyg X-2 from data of the *Einstein Observatory*. Their observations did not have a good time and spectral resolution, so that a very detailed comparison is not possible. However, as in the case of our nine burstlike events, the event reported by Kahn & Grindlay (1984) had a short duration (~ 3 s), $\alpha > 2000$, $\gamma \gtrsim 0.6$, and a fitted net burst blackbody temperature between 1.2 and 2 keV.

We found no evidence for a temperature decrease during the burstlike events. From the average burst profiles, we can exclude spectral softening at a rate normal for type I bursts. This means we cannot on the basis of this criterion distinguish between a type I burst (thermonuclear flash) or a type II burst (accretion disk instability) origin (Hoffman, Marshall, & Lewin 1978; see also Lewin et al. 1993 and references therein). Additionally little or no spectral softening was seen during bursts from GX 17+2 (Tawara et al. 1984; Sztajno et al. 1986) and from a series of bursts in Cir X-1 (Tennant et al. 1986). Like Cyg X-2, these sources accrete matter at relatively high rates; the burst spectra in these sources may therefore be affected by the persistent radiation from the neutron star (see Sztajno et al. 1986). However, when we applied the method of Sztajno et al. (1986) to our bursts, there was still no evidence for spectral

softening. This is in contrast with the results of Sztajno et al. (1986) for GX 17+2.

Three burstlike events were seen to occur with recurrence times between 3 and 4 hr, which is similar to recurrence times in other burst sources which accrete at high rates (see below and, e.g., Lewin et al. 1993 and references therein). We determined typical burst properties, α (> 2000), γ (0.8–2 s), and τ (1.2–2 s) for all the burstlike events. The relations between these typical burst properties were studied by van Paradijs et al. (1988a), using various burst sources. Our values ($\log \alpha > 3.3$, $\log \gamma \sim 0.1$, and $\log \tau \sim 0.2$) are consistent with these relations, if one extrapolates the trends seen in Figures 1 and 2 of van Paradijs et al. (1988a).⁷ The blackbody radii found during the burstlike events ($9 \text{ km} \lesssim R_{\text{bb}} \lesssim 15 \text{ km}$) after correcting for the effect of the persistent blackbody radiation from the neutron star surface (see Sztajno et al. 1986) are consistent with radii expected for neutron stars ($\sim 10 \text{ km}$; see, e.g., Lewin et al. 1993) and are comparable to the blackbody radii obtained for the persistent emission. Similar values for the blackbody radii are also found for many burst sources with persistent luminosity substantially below the Eddington limit (see Lewin et al. 1993 and references therein). So, although we do not see spectral cooling during the burstlike events, several important burst properties are similar to those of bona fide type I bursts.

For the other bursting Z source, GX 17+2, Sztajno et al. (1986) showed that two X-ray bursts observed with *EXOSAT* were type I X-ray bursts. Typical α values in this source are larger than ~ 1000 , while γ is found to be larger than ~ 1.4 (Tawara et al. 1984; Sztajno et al. 1986), so that these parameters are comparable to those of Cyg X-2. Similar high values of α were also seen in the bright bursting atoll source 4U 1735–44, where several short type I bursts occurred after long waiting times (van Paradijs et al. 1988b). High values of α and γ probably indicate that prior to the type I bursts, hydrogen and helium are stably burning (e.g., van Paradijs et al. 1979; see also Lewin et al. 1993). All three sources (GX 17+2, 4U 1735–44, and Cyg X-2) have X-ray luminosities above a limit near $0.3L_{\text{edd}}$ at which sources cease to show regular type I bursting behavior.

At these high mass accretion rates ($\dot{M}$), however, helium burning can perhaps become sometimes unstable; this may result in (relatively) weak X-ray bursts (Bildsten 1993, 1995). It was recently proposed that at high $\dot{M}$ only patches on the neutron star burn. In this case one would expect to find the blackbody radii during the bursts to be significantly smaller than the radius of a neutron star, which is not confirmed by our observations. The burning fronts are thought to propagate with a relatively low ($\sim 300 \text{ cm s}^{-1}$) speed (Bildsten 1993, 1995). One would then expect to see pulsating X-rays due to the rotation of the patches as the neutron star spins (Bildsten 1993, 1995; see also Schoelkopf & Kelley 1991). Evidence for regular pulsations (~ 7.6 Hz) during a burst in Aql X-1 was reported by Schoelkopf & Kelley (1991). We find no evidence for a periodic modulation in the range 1–256 Hz during the burstlike events, with an upper limit to the modulation

⁷ In their paper γ ($L_{\text{pers}}/L_{\text{peak}}$, where L_{pers} and L_{peak} are the persistent and peak luminosity, respectively) is determined for radius expansion bursts. In these cases L_{peak} equals L_{edd} (Eddington luminosity), and so $\gamma < 1$. For Cyg X-2 we have $L_{\text{pers}} \sim L_{\text{edd}}$, and a peak luminosity less than L_{edd} , which results in $\gamma \gtrsim 1$.

strength of $\sim 10\%$. If the burstlike events are due to the burning patches on the neutron star, the neutron star should have a spin period smaller than ~ 4 ms or the patch should cause an overall modulation strength less than $\sim 10\%$ in the 1–256 Hz range.

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