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EXOSAT OBSERVATIONS OF 4U 1705−44: TYPE I BURSTS AND PERSISTENT EMISSION

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ABSTRACT

The bright galactic X-ray source 4U 1705−44 was observed four times with the European X-ray observatory *EXOSAT*. During the *EXOSAT* observations the persistent emission of 4U 1705−44 varied from 1.3 to 10.7×10^{-9} ergs cm^{-2} s^{-1} in the 1–20 keV energy band. For the first time type I X-ray bursts were detected from this source. We found the properties of the bursts correlated with the source intensity. In total we detected 24 type I bursts during the low intensity observations (1.4–2.5 $\times 10^{-9}$ ergs^{-2} s^{-1}). No bursts were detected during the maximum intensity state. At minimum flux 4U 1705−44 was bursting at a nearly constant frequency of $\sim$0.5 hr^{-1}. In a medium intensity state the burst rate decreased to $\sim$0.2 hr^{-1}. In addition the burst shape changed with increasing intensity from a slow burst profile with a decay time of 100 s to a fast profile with a decay time of 25 s. The peak luminosity of the bursts shows no dependence on the source brightness and range from 13 to 18 $\times 10^{-9}$ ergs cm^{-2} s^{-1}, which is comparable to the maximum observed flux of the persistent emission. Four of the bursts were observed within only 5–18 minutes after a proceeding burst. These waiting times are too short to provide enough nuclear fuel via accretion if one assumes that all fuel is consumed totally in every burst. The spectrum during maximum was best-fitted by a two-component model, a blackbody together with a Boltzmann-Wien law and an additional iron K emission line. At minimum intensity the spectrum becomes drastically harder.

Subject headings: stars: individual (4U 1705−44) — X-rays: binaries — X-rays: bursts

I. INTRODUCTION

The source 4U 1705−44 is a bright, low-mass X-ray binary centered in the direction of the Galactic bulge (Forman, Jones, and Tananbaum 1978; Forman, Jones, and Cominsky 1978; Ponman 1982; Markert *et al.* 1979). It is reported to be highly variable on short time scales (25% in 2 hr) and persistently bright. Its observed intensities range from 0.3 to 6.8 $\times 10^{-9}$ ergs cm^{-2} s^{-1} in the 2–11 keV band on longer time scales (Bradt and McClintock 1983). The X-ray flux of 4U 1705−44 shows an indication of intensity dips with a quasi period of 1.3 hr (Langmeier, Sztajno, and Trümper 1985). Furthermore Priedhorsky (1986) found a possible $222^{\mathrm{d}}.8$ period utilizing data of the *Vela 5* satellite.

The spectrum taken from the GSPC and the ME experiment during the *EXOSAT* verification phase was best-fitted by a Boltzmann-Wien type model plus a blackbody emission. It shows an iron K emission line at 6.47 $\pm$ 0.05 keV with an equivalent width of 109 $\pm$ 22 eV (White *et al.* 1986; Langmeier, Sztajno, and Trümper 1985). The source has not yet been optically identified. The discovery of type I X-ray bursts has been previously reported (Sztajno *et al.* 1986).

In this paper we report on a set of four *EXOSAT* observations of 4U 1705−44 during different intensity levels (from 0.7 to 8.3 $\times 10^{-9}$ ergs cm^{-2} s^{-1} in the 2–11 keV energy band). We report also on the discovery of type I X-ray bursts. In § II we give an overview of the observations with emphasis on the burst activity pattern. In § III we discuss the spectral properties of the persistent emission as well as the bursts. A discussion of the results follows in § IV.

II. OBSERVATIONS AND BURST PROPERTIES

The source 4U 1705−44 was observed four times with *EXOSAT*. The observation dates and the duration are listed in Table 1. In our analysis we utilized the data from the ME (Medium Energy) experiment (Turner, Smith, and Zimmermann 1981) and the GSPC (Gas Scintillation Proportional Counter) (Peacock *et al.* 1981) on board EXOSAT. Figure 1 shows the ME X-ray light curves in the 1–20 keV range. The data are normalized to counts s^{-1} half array^{-1} (four ME detectors). Note that the constant background was not subtracted. The scales in Figure 1*a*–*d* are the same, but the zero levels are suppressed.

Observation (*a*) (Fig. 1*a*) performed during the *EXOSAT* verification phase, has been presented elsewhere (Langmeier, Sztajno, and Trümper 1985). Quasi-regular intensity dips can be seen. No burst activity was observed. However, since the observation lasted only 8.5 hr, an irregular burst activity with a longer waiting time cannot be excluded.

During 24 hr of continuous *EXOSAT* monitoring on 1985 September 11, a total of 17 X-ray bursts were observed for the first time from 4U 1705−44 (Sztajno *et al.* 1985). Thirteen X-ray bursts occurred very regularly at intervals of about 2 hr (Fig. 1*b*). They show a 3–4 s rise time, a maximum lasting 4–6 s, and a long delay time of 100 s or more. Four out of the 17

TABLE 1

OBSERVATION SUMMARY

Obs. ID	Date	Start time (UT)	Duration (hours)	Intensity (ergs cm^{-2} s^{-1})	No. of Bursts
a	1983 Jul 30	2:50	8:21	10.7×10^{-9}	0
b	1985 Sep 11	9:30	27:19	1.3×10^{-9}	17
c	1985 Oct 3	17:47	16:43	2.3×10^{-9}	3
d	1986 Apr 7	8:20	16:40	1.8×10^{-9}	4

NOTE. Intensity in the 1 to 20 keV energy band.

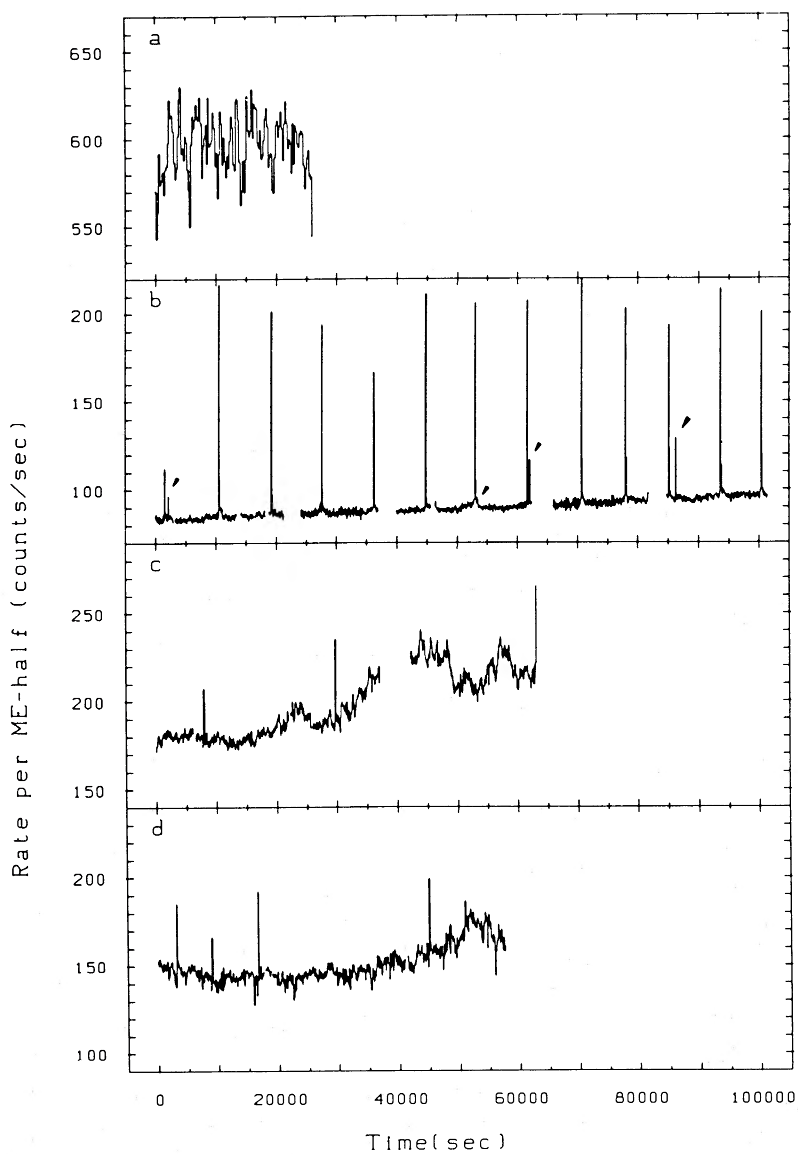

FIG. 1.—The 1 to 20 keV counting rate plotted as a function of time for the *EXOSAT* observations of 4U 1705−44. The data are not corrected for deadtime, and the constant background rate of ~40 counts per s is not subtracted. The arrows in (*b*) indicate the bursts with short waiting time.

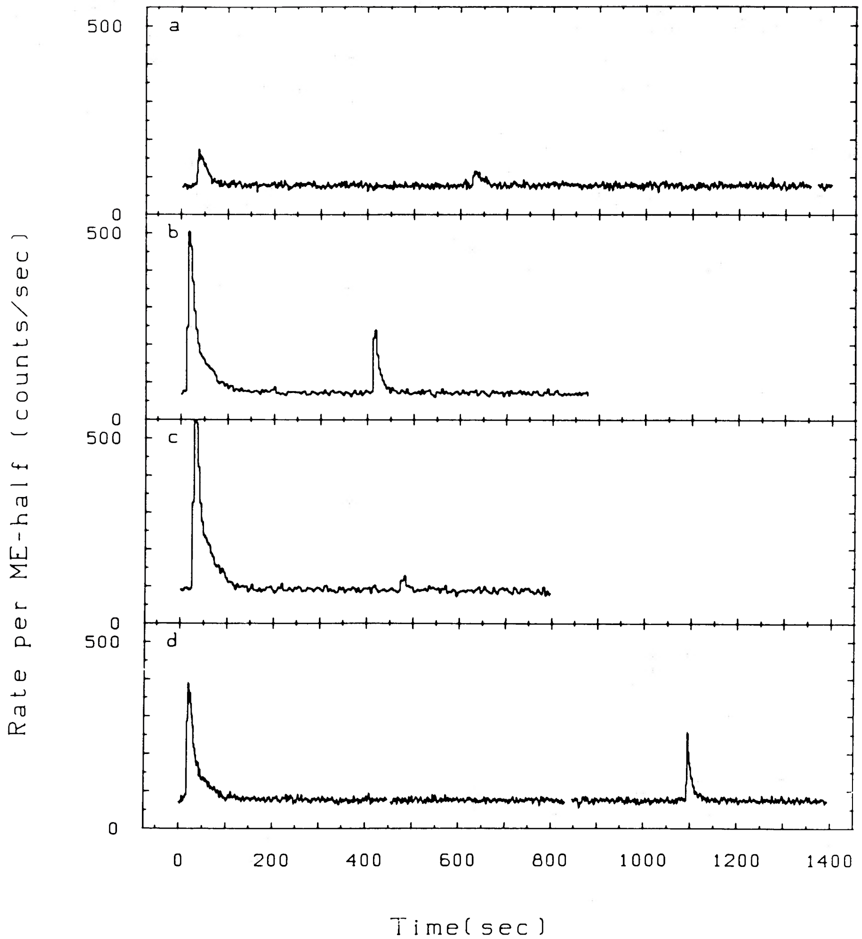

FIG. 2.—Four pairs of bursts with short waiting time intervals, observed on 1985 September 11. The 1 to 20 keV counting rate is plotted. The data are not corrected for deadtime, and the constant background rate is not subtracted.

bursts were detected with a waiting time of only 400, 450, 550, and 1100 s, respectively, after a main burst. They are marked with arrows in Figure 1*b*. Figure 2 shows the detailed structure of these "short waiting time" burst pairs. These bursts were always less energetic and had a much shorter decay time (~ 30 s) compared to the main bursts.

The next two observations (*c* and *d*) made in 1985 October and 1986 April show burst activity as well, but the mean burst frequency is lower ($0.2\ h^{-1}$) with waiting times ranging between 2 and 9 hours (Fig. 1*c*, *d*). The persistent flux is about a factor of 2 higher (2×10^{-9} ergs cm^{-2} s^{-1}) and the variability is stronger compared to the preceding observation. The bursts observed during these observations had a comparable peak flux of 13 to 18×10^{-9} ergs cm^{-2} s^{-1}, but the decay time of 25 s was significantly shorter. The decay time is comparable to that of the short waiting time bursts in (*a*). No short waiting times are observed. Observation (*d*), done in the last *EXOSAT* orbit, suffers from an unstable pointing. Variability seen in this observation should be taken with caution.

III. DATA ANALYSIS

We analyzed the persistent emission for all observations. Figure 3 shows the spectra of the observations marked by the observation ID. We made an attempt to fit all four spectra with the same emission model. Following White *et al.* (1986) we used a combination of a Boltzmann-Wien" type ($\sim E^{-\alpha} e^{E/kT}$) together with a blackbody spectrum and an iron emission line. In general the ME and the GSPC spectra were compatible for all observations; however, the GSPC has a higher sensitivity for line detection. Thus for the ME fits we fixed the energy and the width of the iron line as determined by the GSPC. Table 2 shows the fitted parameters and the calculated fluxes. Only the

TABLE 2

THE SPECTRAL PARAMETERS FOR THE BOLTZMANN-WIEN MODEL

Obs. ID	a	b	c	d
$N_H(10^{21}/cm^2)$	$14.2^{+3.}_{-5.}$	$19.3^{-1.0}_{+0.6}$	$13.3^{+0.9}_{-0.8}$	$7.4^{+0.6}_{-1.3}$
F_{BB}	4.1 ± 0.6	...	...	...
kT_{BB} (keV)	1.5 ± 0.10	...	...	...
Radius (km)	7.5 ± 1.5	...	...	...
F_{BW}	6.6 ± 1.2	1.38 ± 0.02	2.46 ± 0.02	1.58 ± 0.03
α..................	1.58 ± 0.3	1.49 ± 0.12	1.38 ± 0.11	1.18 ± 0.10
kT_{BW} (keV)	$12.6^{+226.}_{-6.4}$	$24.4 - {}^{+21.}_{5.}$	$6.5^{+0.9}_{-0.7}$	$5.7 - {}^{+0.7}_{0.5}$
E_{Line} (keV)[a]	6.48 ± 0.05	6.54 ± 0.3	6.18 ± 0.2	6.48 ± 0.3[b]
FWHM (keV)[a] ...	1.1 ± 0.3	1.2 ± 0.3	1.3 ± 0.3	1.3 ± 0.3[b]
Width (eV)[a]	109 ± 22	90 ± 35	230 ± 80	40 ± 30[c]
χ^2/d.o.f.	1.24	2.18	1.30	1.16
d.o.f................	23	27	27	27

NOTE: Fluxes in 10^{-9} ergs cm^{-2} s^{-1} (1–20 keV); iron line parameters for observation (*a*) taken from White *et al.* 1986.

[a] Values determined by GSPC.

[b] Fixed.

[c] Determined by ME because of insufficient GSPC background.

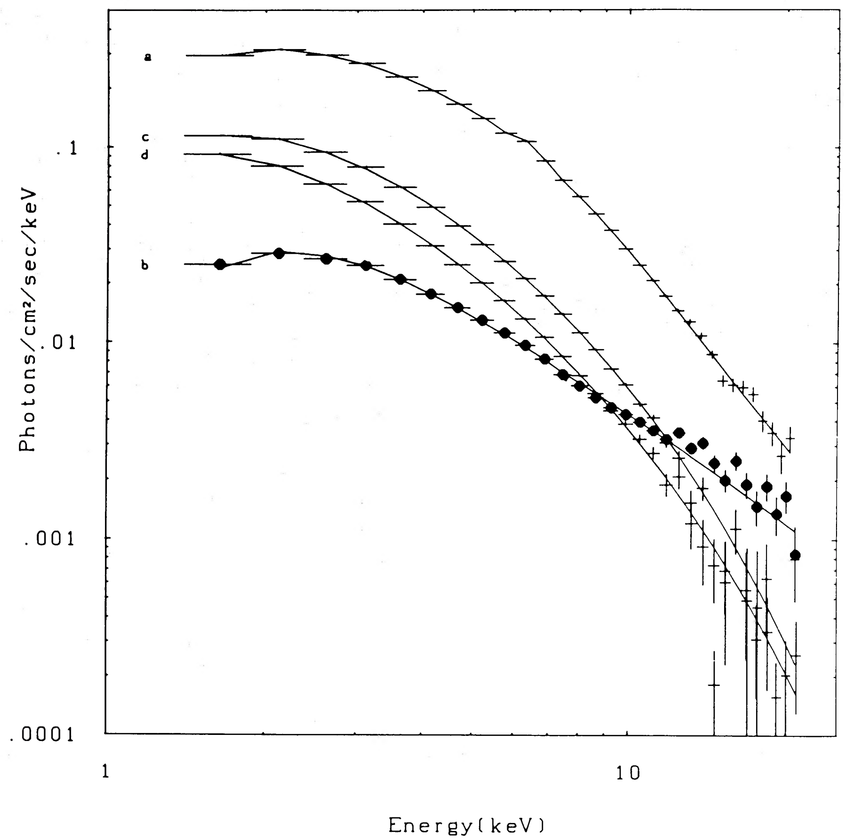

FIG. 3.—The photon spectrum for each of the four observations

high-state spectrum (*a*) requires the addition of a significant blackbody component. The blackbody emission radius, calculated for a distance of 10 kpc is 7.5 ± 1.5 km. During the high state observation 4U 1705−44 revealed a so-called "normal branch" behavior, a linear relation between the hardness of the energy spectrum and the intensity.

The spectra of the medium intensity level (*c*), (*d*) were well fitted by the Boltzmann-Wien component alone. The iron line parameters are again determined by the GSPC. The addition of a blackbody component was not required. Also in these observations a correlation between the intensity and the hardness of the energy spectrum was observed. The low state spectrum (*b*) is drastically harder than any of the other spectra. As can be seen in Figure 4 the flux density above ~10 keV is even larger than that of the medium intensity spectra. A fit with above spectral models yields only a lower limit for the Boltzmann-Wien temperature (see Table 2), suggesting that in our energy range the spectrum can be as well represented by a pure power law. Nevertheless for both models the spectral fits are not acceptable. They fail to model the high-energy part of the spectrum above ~7 keV. Inclusion of a high energy power law tail or a rather hot (~4 keV blackbody component into the spectral model yielded no significant improvement of χ^2.

The detailed analysis of 24 bursts would be beyond the scope of this paper; it will be presented elsewhere. As a representative sample we analyzed the spectra of the "short waiting time" burst pair of Figure 2*d* as well as the peak spectra of the first burst of observation (*c*) and (*d*), respectively. Figure 4 presents a comparison of the blackbody spectral analysis of the "main" X-ray burst (*dots*) and the secondary burst (*open circles*) observed 18 minutes after the main bursts (obs. *b*). The blackbody fit to the burst net counts (persistent emission subtracted) during the maximum gives a blackbody temperature of $kT = 2.3 \pm 0.1$ keV. In the burst decay the temperature decreases to $kT = 1.25 \pm 0.15$ keV, typical for type I X-ray bursts. The blackbody radii averaged over the burst and calculated for a spherical emitter in a 10 kpc distance are 7.5 ± 0.3 km for the main burst and 7.0 ± 0.3 for the second burst. It should be pointed out that for both bursts the blackbody radius remains the same within the errors. The values for the radii and temperatures are not corrected. Due to gravitational redshift one always observes a lower temperature (van Paradijs 1979; Goldman 1979) and therefore a larger radius. On the other hand Comptonization in the neutron star atmosphere shifts the peak of the emission to higher energies. The measured color temperature is always greater than the effective blackbody temperature (Czerny and Sztanjo 1983; London, Taam, and Howard 1984; Ebisuzaki, Hanawa, and Sugimoto 1983). The bolometric maximum peak flux of the main burst is about 14×10^{-9} ergs cm^{-2} s^{-1} assuming a blackbody spectrum, and the integrated energy over the entire burst is $2.8 \pm 0.1 \times 10^{-7}$ ergs cm^{-2} ($0.7 \pm 0.1 \times 10^{-7}$ ergs cm^{-2} second burst). The peak luminosity for a distance of 10 kpc is $L_{peak} = 1.7 \times 10^{38}$ ergs s^{-1}. The peak fluxes of the bursts remain approximately the same in all observations. For observation (*c*), burst 1, we calculated a peak flux of

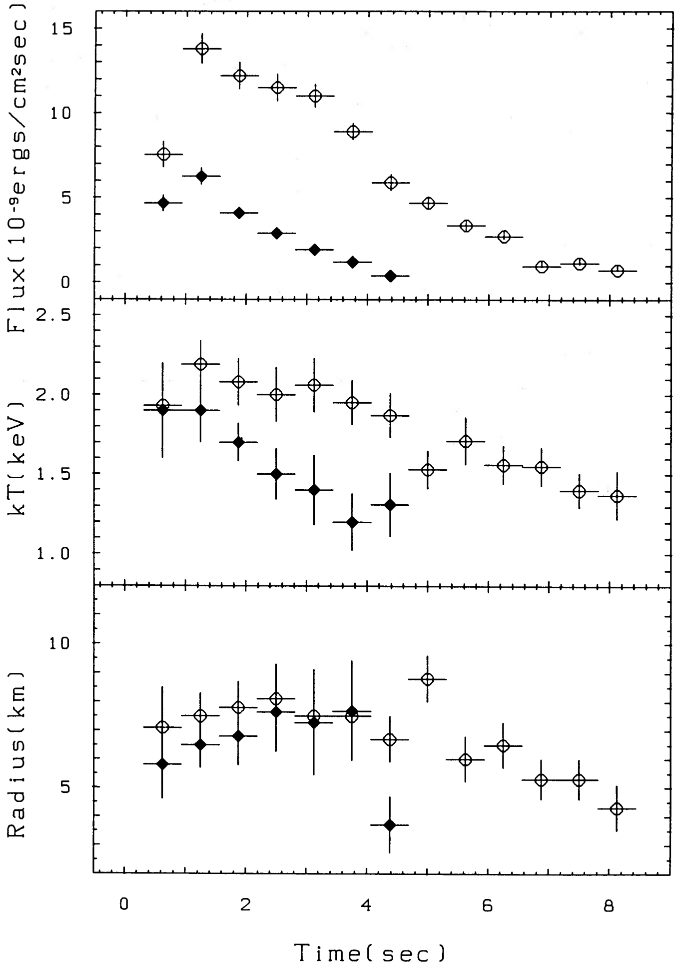

FIG. 4.—The temperature, radius, and flux history of the two consecutive bursts from Fig. 2*d*. The filled dots represent the data for the "short waiting time burst." The flux is bolometric corrected. The blackbody radius is calculated for a distance of 10 kpc.

$18.4 \pm 1.0 \times 10^{-9}$ ergs cm^{-2} s^{-1} and for the first burst in observation (*d*) a value of $13.1 \pm 1.0 \times 10^{-9}$ ergs cm^{-2} s^{-1} was derived.

IV. DISCUSSION

In our observations type I bursts from 4U 1705−44 were detected for the first time. At the lowest intensity level four "short waiting time bursts" were seen. Similar events with short recurrence intervals are reported for the transients EXO 0748−676 (Gottwald *et al.* 1986, 1987) and 4U 1608−52 (Murakami, *et al.* 1980) and for the steady sources 4U 1636−53 (Lewin *et al.* 1976) and 4U 1745−25 (Inoue *et al.* 1984). The short waiting time bursts cannot be understood in the context of classical thermonuclear flash models (e.g., Ayasli and Joss 1982). The recurrence time is too short to replenish fuel so that an additional energy reservoir must exist. Hanawa and Fujimoto (1984) predict that nuclear fuel can survive a burst in the outer layers of the neutron star. Based on that idea Fujimoto *et al.* (1987) suggest that convection and instabilities in the neutron star envelope transport unburned fuel and freshly accreted material inward to layers where it meets the conditions for thermonuclear runaways. The total released energy in the second burst is expected to be of the order of the amount of unburned fuel (cf. Gottwald *et al.* 1987). The second burst in Figure 3 emits 4 times less energy than the first burst. This agrees with former observations of short waiting time bursts where the integrated burst energy in the first burst always exceeded that in the second one (Gottwald *et al.* 1986; Matsuoka 1985). The calculated blackbody emission radii in the main burst and the second burst are identical, thus ruling out that nonspherical burning in different areas of the neutron star surface is responsible for the short waiting time events.

Burst theory predicts a dependence of the burst properties on the accretion rate $\dot{M}$ (e.g., Ayasli and Joss 1982); in particular, that with increasing $\dot{M}$ the recurrence time intervals should become shorter until, at very high $\dot{M}$, the burst activity will be suppressed. The observed correlation between burst frequency and the strength of the persistent emission is opposite to this prediction. It is similar to what was found in EXO 0748−676 (Gottwald *et al.* 1986). In addition, the shortening of the burst decay times with increasing persistent flux and the occurrence of short waiting time bursts only in the low-intensity state suggests that the bursting behavior of 4U 1705−44 resembles that of EXO 0748−676 (Gottwald *et al.* 1986).

The X-ray flux (1–20 keV) of 4U 1705−44 varied from 1.3 to 10.7×10^{-9} ergs cm^{-2} s^{-1} on a time scale of months. With an arbitrary phase the data are consistent with the $222^{d}.8$ period, proposed by Priedhorsky (1986). We observed a shortening in decay time with a decrease of the mean burst intervals, while the level of the persistent emission increased. At high accretion rates the burst activity is suppressed. We therefore conclude that the flux changes between our observations of 4U 1705−44 reflect real changes in the accretion rate.

Our spectrum of the maximum intensity state can be represented by a two-component model, a "Boltzmann-Wien" type spectrum together with a blackbody emission and an additional iron line. The emission radius calculated for this blackbody component is 7.5 km, the same value as the one for the burst emission radii. This supports the interpretation that the blackbody component originates close to the neutron star (White *et al.* 1986; Sztajno *et al.* 1985). Furthermore, the temperatures of the bursts in the decay part and the blackbody component of the persistent emission are similar. The flux observed in the maximum state is similar to the maximum burst peak flux. For an assumed distance to the galactic center of 10 kpc the maximum luminosity is $1.7 \pm 0.2 \times 10^{38}$ ergs s^{-1}, a value which is in the range of the hydrogen Eddington limit.

The change from the high to medium intensity is characterized by the disappearance of the blackbody component. As intensity goes down the spectrum becomes gradually softer. The N_H-value stays constant in the high and medium states at a value of 10^{22} atoms cm^{-2} expected for galactic center sources.

At a low-intensity level the spectrum becomes drastically harder. At the same time the hydrogen column density increase by a factor of ~ 2. This behavior is suggestive of a "phase transition" at the inner edge of the accretion disk from an optically thick to an optically thin state. There are several possibilities to explain the spectral hardening. One interpretation is that in the low state we directly observe a hot region close to the neutron star, which is obscured otherwise. This would imply that during the high states the high energy photons are Compton scattered to lower energies or, alternatively, a thick blown-up inner disk edge obscures the hot part of the system.

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