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EXOSAT OBSERVATIONS OF DOUBLE-PEAKED BURSTS WITH RADIUS EXPANSION FROM 4U/MXB 1820−30

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ABSTRACT

We have seen 4U/MXB 1820−30 emitting X-ray bursts for the first time since 1976. Our *EXOSAT* observation spanned 20 hr on 1985 August 19/20. This burst source is important, because its location in the globular cluster NGC 6624 allows its distance to be reliably estimated (6.4 ± 0.6 kpc). We observed seven double-peaked bursts, which recurred with almost equal time intervals of 3.2 hr. The persistent flux varied by only 10% on time scales of 60 minutes. The ratio α of the total persistent energy emitted before a burst to the total energy released by a burst varied between 125 and 155. The burst spectra were fitted to a blackbody model. The inferred blackbody radius showed large variations, increasing from 10 to 200 km within the first 0.25–1.5 s, accompanied by a decrease in spectral temperature from 1.2 to 0.4 keV. After correction for spectral hardening effects in the neutron star atmosphere, the inferred source radius during burst decay was constant at ~ 10 km. We interpret this constant radius as the size of the neutron star. During the radius expansion phase, the luminosity remained constant at a mean value of 2.5×10^{38} ergs s^{-1}, which is consistent with the helium Eddington limit for a 10 km, 1.4 $M_\odot$ neutron star (assuming a distance of 6.4 kpc).

Subject headings: clusters: globular — stars: individual — stars: neutron — X-rays: binaries — X-rays: bursts

I. INTRODUCTION

The X-ray source 4U/MXB 1820−30 in the globular cluster NGC 6624 was among the first from which X-ray bursts were discovered (Grindlay and Gursky 1976; Grindlay *et al.* 1976). During these early observations the source changed from a low state to a high state over 4 days. At the same time, the burst interval decreased from ~ 3.4 to 2.2 hr, and then the burst activity stopped (Clark *et al.* 1977). Subsequent observations have always found the source in a high state with no bursts detected (Stella, Kahn, and Grindlay 1984, and references therein). This was the first evidence that the properties of X-ray bursts are dependent on the level of the persistent emission. In the thermonuclear flash model such a dependence is expected, because of the temperature dependence of helium fusion reactions (Ayasli and Joss 1982). At the highest accretion rates found in X-ray binaries ($> 10^{18}$ g s^{-1}), the temperature of the neutron star envelope should be high enough to sustain steady helium burning. The cessation of bursting activity from 4U/MXB 1820−30 as the persistent flux increased has been ascribed to the commencement of stable helium burning.

In this framework, X-ray burst luminosities should not exceed the Eddington limit; excess luminosity above the limit goes into expanding the surface layers of the neutron star, rather than radiation (Wallace, Woosley, and Weaver 1982; Paczyński 1983; Ebisuzaki, Hanawa, and Sugimoto 1983). However, many bursts with "super" Eddington luminosities have been reported (Grindlay *et al.* 1980; van Paradijs 1981; Inoue *et al.* 1981). If it is assumed that the Eddington limit cannot be exceeded (Ebisuzaki, Hanawa, and Sugimoto 1983 suggest that the relevant Eddington limit is that of a helium-rich envelope), then the mean distance to the burst sources which are concentrated near the Galactic center must be 6–7 kpc, less than the generally accepted 10 kpc (Ebisuzaki, Hanawa, and Sugimoto 1984; for a discussion of the Galactic center distance see Shuter 1983). Because of the location of 4U/MXB 1820−30 in the globular cluster NGC 6624, this X-ray burst source has a good distance estimate of 6.4 ± 0.6 kpc (see Vacca, Lewin, and van Paradijs 1986, and references therein). A detailed analysis of five bursts detected by *SAS 3* (Clark *et al.* 1977) has been given by Vacca, Lewin, and van Paradijs (1986). Fitting blackbody spectra to two energy bands, they find atmospheric radius expansion during the burst rise, followed by contraction during burst decay, as well as average peak luminosities of 2.1×10^{38} ergs s^{-1}, consistent with the helium Eddington limit.

Priedhorsky and Terrell (1984) have reported a possible 176 day modulation of the X-ray flux from 4U/MXB 1820−30 involving persistent emission variations by a factor of 2. To study this further, a series of *EXOSAT* observations was scheduled at various phases around the 176 day cycle. The first observation, made on 1985 August 19/20, was close to, but not at, the time of predicted minimum (1985 July 28) and found the source faint and bursting for the first time since 1976. These new *EXOSAT* data represent a major improvement in the quality of the burst data obtained from this source. In this paper we present a detailed analysis of seven bursts recorded during this 20 hr observation.

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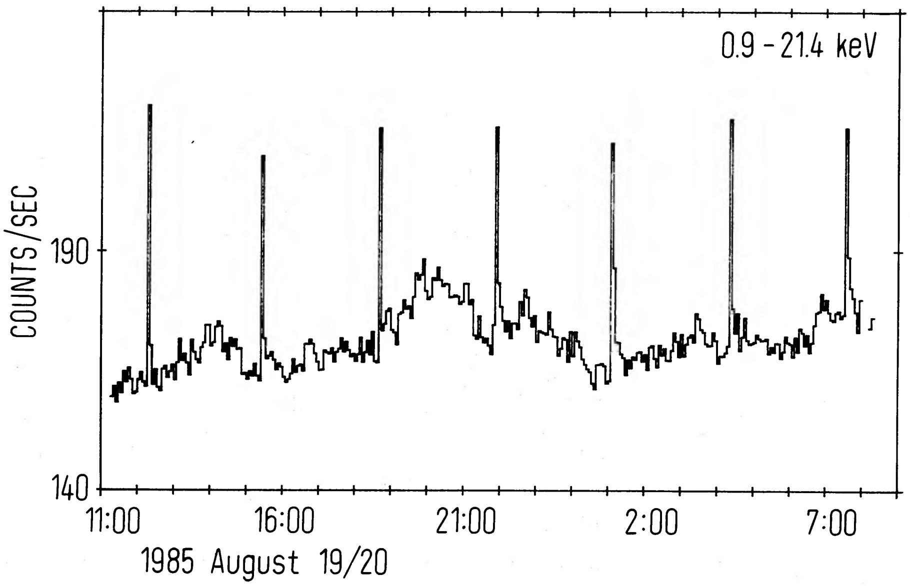

FIG. 1.—Background-subtracted 0.9–21.4 keV light curve of 4U/MXB 1820−30 from 1985 August 19/20. Count rate in counts s^{-1} per half detector array. The peak intensity of the bursts is smeared out by the limited time resolution of this figure (4 minutes).

II. THE OBSERVATION

The 20 hr continuous *EXOSAT* observation of 4U/MXB 1820−30 was made on 1985 August 19/20 starting at 11:16 UT. Data were obtained from the eight argon detectors of the medium energy experiment (ME; Turner, Smith, and Zimmermann 1981) in the energy range 1–15 keV. Counts were binned into 64 pulse height analyser channels with a time resolution of 0.5 s during the first part (8 hr), and 0.25 s during the last part of the observation. The ME experiment was operated with all eight detectors pointed on-source (except in the first 3.5 hr, in which one-half the detector array was offset by $\sim 2°$ to monitor the background). Background data were obtained from the 4 hr of slew time prior to and after the observation. One ME detector failed at 01:04 UT on August 20, leaving the ME experiment with seven working detectors.

III. RESULTS

In Figure 1 the background-corrected light curve for the whole observation is shown. The count rate is in units of counts per second per half detector array. The seven bursts (the narrow spikes in Fig. 1) are spaced at nearly equal intervals of 193 minutes, with a scatter of only ± 3 minutes (see Table 1). The persistent emission was 180 counts s^{-1} per half on average and varied by $\pm 10\%$ on time scales of 1 hr but showed no long-term trends.

Background-subtracted spectra were accumulated for each interburst interval, with data up to 15 minutes after the beginning of the burst excluded. Single-component models failed to give a good fit to the data, with typical reduced χ^2 of 15. The persistent emission could be well fitted by a two-component model comprising either (*a*) a power law with an exponential cutoff of the form $E^{-\gamma} \exp(-E/kT)$ and a blackbody spectrum (χ_r^2 of 1.2–1.7), or (*b*) a power law together with a blackbody spectrum (χ_r^2 of 0.9–1.2). In case (*a*) the best-fitting values of γ and kT were 0.85 ± 0.08 and 8.0 ± 0.5 keV respectively (all errors are 1 σ standard deviations). The blackbody component has a temperature of 0.36 ± 0.02 keV and contributes 16% to the total persistent flux in the energy band 0.1–20 keV. This leads to a blackbody radius of 38 km for an assumed distance of 6.4 kpc. In case (*b*) $\gamma = 2.2 \pm 0.3$ and the blackbody temperature is 2.2 ± 0.4 keV, with an equivalent blackbody radius of 1.5 km. In this model the blackbody contributes 30% to the total persistent emission. The absorption, also a free parameter, was in both cases consistent with the column density determined from 21 cm H I line absorption observations, which is 1.4×10^{21} H cm^{-2}. The flux in the 0.1–20 keV band

TABLE 1

PROPERTIES OF THE SEVEN BURSTS FROM 4U/MXB 1820−30

Burst Onset[a] (UT)	t_w (s)	f_{total}(0.1–20 keV) (10^{-7} ergs cm^{-2})	α	$R_{a,max}$ (km)	$t_{r,max}$ (s)
1985 Aug 19 12:16:23	...	3.39 ± 0.18	140 ± 14[b]	71	1.0–1.5
1985 Aug 19 15:26:51.5	11429	3.61 ± 0.17	132 ± 10	140	0.5–1.0
1985 Aug 19 18:42:52	11761	3.27 ± 0.14	156 ± 9	121	0.5–1.0
1985 Aug 19 21:55:28.5	11557	3.72 ± 0.14	147 ± 8	199	0.25–0.75
1985 Aug 20 01:07:46.5	11538	3.36 ± 0.16	152 ± 8	211	0.25–0.5
1985 Aug 20 04:23:19.25	11733	3.36 ± 0.18	144 ± 11	189	0.25–0.5
1985 Aug 20 07:33:25.75	11407	3.66 ± 0.13	124 ± 8	157	0.75–1.0

[a] Time resolution: first three bursts, 0.5 s; last four bursts, 0.25 s.
[b] Value obtained from mean recurrence interval of bursts.

was 4.3×10^{-9} ergs cm^{-2} s^{-1}, giving a persistent luminosity of 2×10^{37} ergs cm^{-2} s^{-1} for a distance of 6.4 kpc.

Figure 2 shows the light curves for bursts 1 and 5 in three different energy bands. All seven bursts show a double-peaked structure at energies above 6 keV, whereas below 6 keV the light curves are single-peaked. Such structure was previously seen in bursts from other sources (Hoffman, Cominsky, and Lewin 1980). The first peak is most prominent in bursts 1 and 7; in bursts 2–6 it is a narrow spike before the main peak, which resembles reported precursors to bursts (Lewin, Vacca, and Basinska 1984; Tawara *et al.* 1984).

Pulse height data were used to study the spectral evolution of all seven bursts. The persistent emission from intervals before and after each burst was subtracted. The bursts were sufficiently strong that we could utilize the full time resolution (0.5 s for the first three bursts and 0.25 s for the last four bursts) for the first 6 s of each burst. In the burst decay the accumulation time was increased to 10 s. To determine fluxes we have fitted our data to a blackbody spectrum with normalization I_0, spectral temperature kT_{spec}, and absorption N_H, as free parameters.

During the first 3 s of each burst the spectra were not always very well fitted by a Planck function with χ^2 values as large as 5 per degree of freedom ($\chi_r^2 = 5$). These spectra were better fitted by thermal bremsstrahlung and power-law models ($\chi_r^2 =$ 1–2.5). The best fits were obtained for a two-blackbody component model ($\chi_r^2 = 0.8$–1.5) with the two temperatures differing by 1.2 keV and bracketing the temperature of the single-blackbody model. This difference is much larger than the change of temperature within an integration, which is typically 0.1 keV (cf. Fig. 3). Spectra later in the burst give good fits to a Planck function, with χ_r^2 between 1 and 1.5. No narrow spectral features are visible during any part of the bursts. The absorption N_H during the bursts is consistent with the values found for the persistent emission. We used the best-fitting parameters of the blackbody fits to obtain the flux at the source in the 0.1–20 keV energy band and adopted the distance of 6.4 kpc from Vacca, Lewin, and van Paradijs (1986) to derive the luminosity L_a and apparent blackbody radii R_a. We have not corrected for relativistic effects.

In Figure 3 we plot the time evolution of spectral temperature and luminosity for all seven bursts. As can be seen in the figure, the bursts were very similar; their time histories can be overlaid with little scatter. For the first 3 s, the luminosity was nearly steady at a mean level of 2.5×10^{38} ergs s^{-1}. In the first 4 s the temperature passed from 1.8 keV through a minimum of ~ 0.4 keV to a maximum of 3 keV. Over the following 30 s the temperature decayed to 1.2 keV. Figure 4 shows the apparent radius and luminosity as a function of spectral temperature. The arrows indicate the direction of time evolution. The maximum radius expansion was reached between 0.25 and 1.5 s after the burst onset (see Table 1).

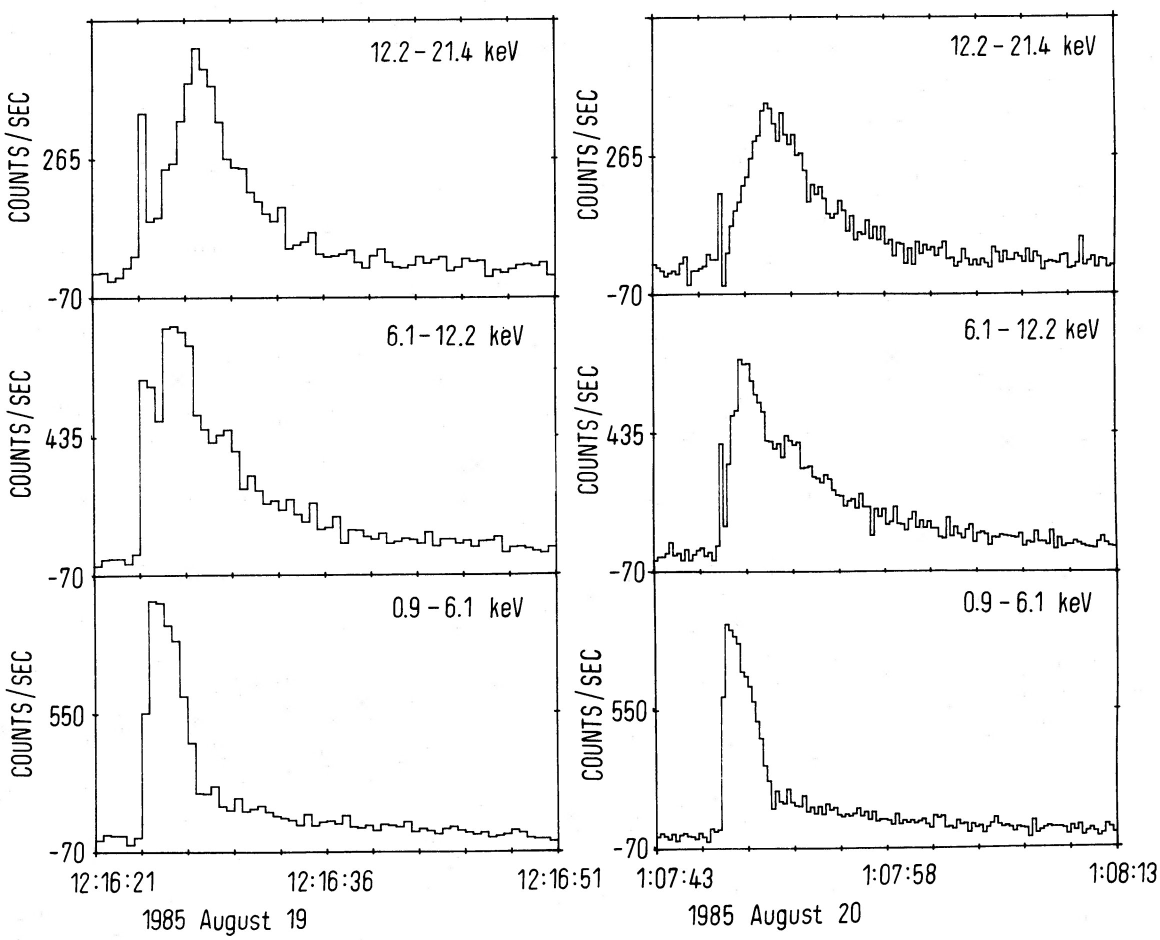

FIG. 2.—Light curves of bursts 1 (*left*) and 5 (*right*) in three different energy bands. All bursts are double-peaked above 6 keV.

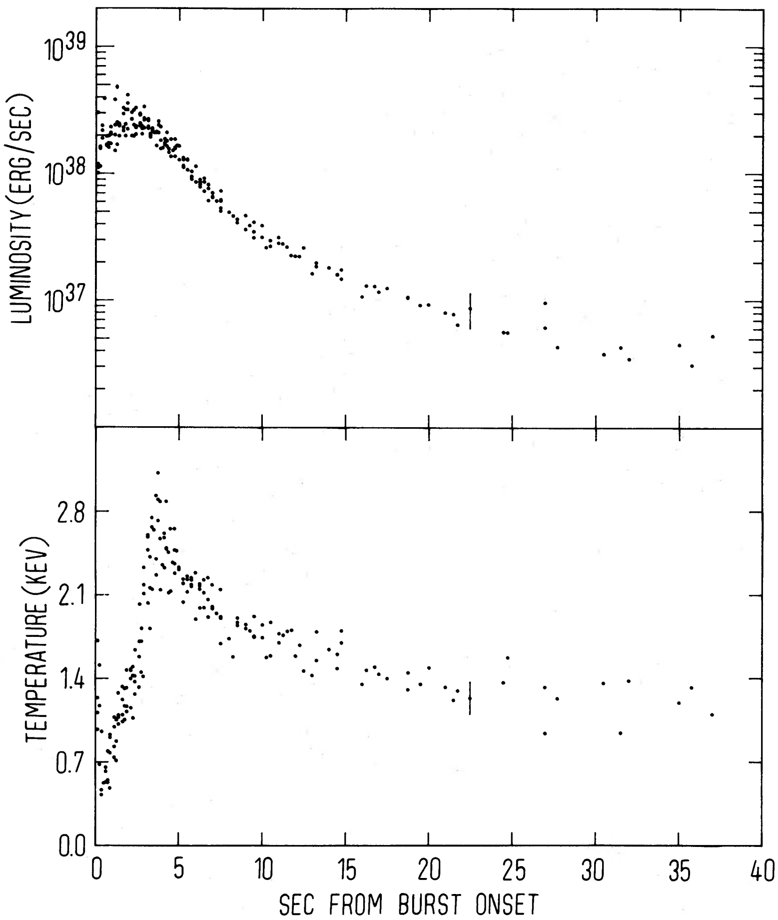

FIG. 3.—(*bottom*) Spectral evolution of the seven recorded bursts. The spectral temperature goes from 1.8 keV through a minimum at ~0.4 keV to a maximum of 3 keV, then decays. (*top*) The 0.1–20 keV luminosities derived from the blackbody fits, assuming a distance of 6.4 kpc. The error bars are standard deviations (1 σ).

During the burst decay the radius remained constant at 4.5 km as the temperature decreased.

We have also fitted a two-component model to background-subtracted spectra that include the persistent emission during one burst (cf. Sztajno *et al.* 1986). The variation in the spectral temperature of the blackbody component was the same as that obtained before, during the first 10 s of the burst. Following this the temperature remained constant at 1.7 keV during the burst decay and then increased to 2.2 keV 5 minutes after the burst had finished.

The ratio α of the total persistent energy before a burst to the total energy emitted in the burst was around 140 for the last six bursts. No obvious correlation with persistent flux is visible (the persistent emission varied little during the observation). The effective burst duration, i.e., the ratio of the total energy released in a burst to the peak luminosity, ranged from 4.5 to 6.5 s, similar to that found from other sources where radius expansion is seen (e.g., Gottwald *et al.* 1986).

IV. DISCUSSION

All seven bursts showed expansion of the neutron star atmosphere, associated with a decrease in spectral temperature. The radius peaks at 200 km, then contracts as the spectral temperature increases to its peak of 3 keV. Following this, the burst decays via a temperature decrease at an approximately constant radius of 4.5 km. Vacca, Lewin, and van Paradijs (1986) reported radius expansion up to a maximum radius of only 50 km. This difference compared to our results probably comes from the better time resolution of the *EXOSAT* data; during the first three bursts, when the time resolution is worse, the maximum radius is a factor of 2 lower (see Table 1). According to neutron star atmosphere models (London, Taam, and Howard 1984, 1986; Foster, Ross, and Fabian 1986), the spectral temperature measured at high luminosities is higher than the effective temperature $T_{\rm eff}$, because the radiation source function is reduced by electron scattering (London, Taam, and Howard 1984). The spectral hardening factor $T_{\rm spec}/T_{\rm eff}$ is ~1.4 for $T_{\rm spec} = 1.5$–2.8 keV, as observed in the constant-radius, cooling phase of the burst (London, Taam, and Howard 1986). Hence the derived blackbody radii are underestimated by at least a factor of 2, as $r_{\rm true}/r_{\rm apparent} \propto (T_{\rm spec}/T_{\rm eff})^2$. The true radius is thus ~10 km, consistent with current neutron star models.

Spectral fits to the persistent emission require the presence of a blackbody component plus a second component. Two possible combinations of two-component models were found to give an acceptable fit to the data. In one case the blackbody temperature was 0.36 keV with a radius of 38 km. This radius is a factor of 4 larger than that found in the cooling tail of the burst, and so is unlikely to be residual emission from the heated surface of the neutron star (cf. White *et al.* 1986; van Paradijs and Lewin 1986; Sztajno *et al.* 1986). It could originate from the inner edge of the gas pressure–dominated accretion disk, with the other harder component from Compton

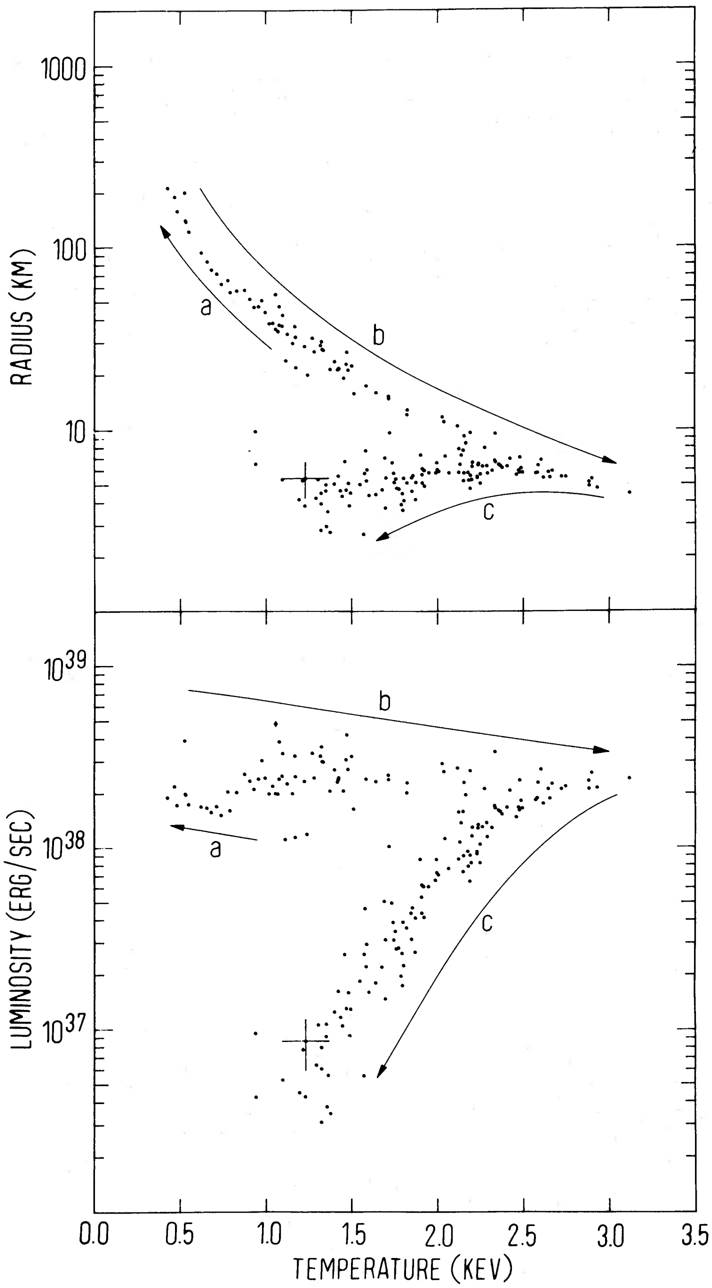

FIG. 4.—Apparent blackbody radius and luminosity as a function of spectral temperature. The bursts show radius expansion up to 200 km, with nearly constant luminosity, during the onset phase. The arrows indicate the time direction.

scattering in the inner radiation-dominated disk. In the other solution the blackbody temperature of 2.2 keV is much higher and similar to that found from other more luminous low-mass X-ray binaries (cf. White *et al.* 1986). In this case the blackbody radius is 1.5 km, much smaller than that found in the burst decay but perhaps consistent with that expected from a boundary layer between an accretion disk and the neutron star. (If the blackbody emission originated from a polar cap of the neutron star, a strong magnetic field on the order of 10^{12} G would be required, which we regard as unlikely.)

The burst luminosity shows a flat-topped maximum during the radius expansion phase. Individual luminosity measurements during this phase range from 1.5×10^{38} to 4×10^{38} ergs s^{-1}. We attribute much of this scatter to uncertainties in the poor fits during the first 3 s of the bursts. These poor fits may result from deviations from a blackbody spectrum caused by radiation transfer effects in the dramatically distended neutron star atmosphere (cf. London, Taam, and Howard 1986). The average peak luminosity during the onset phase (~ 3 s) ranges between 2.0×10^{38} and 2.8×10^{38} ergs s^{-1} for the individual bursts (burst 1 had the lowest value) and was 2.5×10^{38} ergs s^{-1} for all seven bursts together. For a 10 km radius neutron star with a mass of 1.4 $M_\odot$ the Eddington luminosity, as observed by a distant observer, is 1.35×10^{38}, 1.59×10^{38}, and 2.7×10^{38} ergs s^{-1} for a hydrogen-rich envelope, an envelope with solar abundance, and a helium-rich envelope respectively (see, e.g., Marshall 1982). The α-value and the fast development of the bursts in 4U/MXB 1820−30 suggest that helium is the major constituent in these thermonuclear flashes (Taam 1980; Fujimoto, Hanawa, and Miyaji 1981).

Our average peak luminosity agrees well with that reported by Vacca, Lewin, and van Paradijs 1986 (2.1×10^{38} ergs s^{-1}) and is consistent with the helium Eddington limit. This confirms theoretical expectations that no X-ray burst should exceed the Eddington limit, and that bursts that show strong radius expansion should be at the Eddington limit (Ebisuzaki, Hanawa, and Sugimoto 1983; Taam 1982; Wallace, Woosley, and Weaver 1982; Paczyński 1983). If all burst sources have peak luminosities less than or equal to the Eddington limit and are isotropically distributed around the Galactic center, the distance to the Galactic center must be ~ 6 kpc, much lower than the generally accepted value of 10 kpc (Shuter 1983). One can escape this uncomfortable result if super-Eddington luminosities are possible. Our result, that the Eddington limit holds for a source with a well-determined distance, makes that escape route more unlikely.

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