X-ray bursts at extreme mass accretion rates from GX 17+2

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Abstract. We report on ten X-ray bursts originating from GX 17+2 in data obtained with the RXTE/PCA in 1996–2000. Three bursts were short in duration (~10 s), whereas the others lasted for ~6–25 min. All bursts showed spectral softening during their decay. No evidence for high-frequency (>100 Hz) oscillations at any phase of the bursts is seen. Also no correlations of the burst properties with respect to the persistent X-ray spectral properties are seen, suggesting no correlation with inferred persistent mass accretion rate. The presence of short bursts in GX 17+2 and other bright X-ray sources, i.e. Cyg X-2, GX 3+1 and GX 13+1, as well as the absence of bursts in the bright X-ray sources Sco X-1, GX 5–1, GX 340+0, GX 349+2, GX 9+1 and GX 9+9 is not accounted for in the current X-ray bursts theories at the high mass accretion rates encountered in these sources.

We find that the if we model burst spectra after subtraction of the pre/post burst emission, we obtain satisfactory results, but that two-component spectral fits to the total burst emission result in bad spectral fits whenever there is a black-body component present in the persistent emission. We conclude that the black-body contribution from the persistent emission is also present during the burst. This implies that in contrast to previous suggestions the persistent black-body emission does not arise from the same site as the burst emission. The black-body component of the persistent emission is consistent with arising in an expanded boundary layer, as indicated by recent theoretical work.

Five of the long bursts showed evidence for radius expansion of the neutron star photosphere (independent of the spectral analysis method used), presumably due to the burst luminosity reaching the Eddington value. When the burst luminosity is close to the Eddington value, slight deviations from pure black-body radiation are seen below ~10 keV. Similar deviations have been seen during (long) X-ray bursts from other X-ray bursters; they can not be explained by spectral hardening models.

The total persistent flux just before and after the radius expansion bursts is inferred to be a factor 2–3 higher than the net peak flux of the burst. If both the burst and persistent emission are radiated isotropically, this would imply that the persistent emission is a factor of 2–3 higher than the Eddington luminosity. This is unlikely and we suggest that the persistent luminosity is close to the Eddington luminosity and that the burst emission is (highly) anisotropic (ξ~2). Using the fact that the net burst peak fluxes equal the Eddington limit, applying standard burst parameters (1.4 M⊙ neutron star, cosmic composition, electron scattering opacity appropriate for high temperatures), and taking into account gravitational redshift and spectral hardening, we derive a distance to GX 17+2 of ~8 kpc. The uncertainty in this value is up to ~30%.

Key words. accretion, accretion disks | binaries: close | stars: individual (GX 17+2) | stars: neutron | X-rays: bursts

1. Introduction

X-ray bursts were discovered in 1975 from the source 4U 1820–30 (Grindlay & Heise 1975; Grindlay et al. 1976).

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It was realized soon thereafter that these were thermonuclear runaway events on the surface of neutron stars (Woosley & Taam 1976; Maraschi & Cavaliere 1977). Another kind of X-ray bursts was found (together with the above type of bursts) from MXB 1730–355 (later re-
ferred to as the Rapid Burster), which were suggested to be due to accretion instabilities. The former and latter kind of bursts were then dubbed type I and type II, respectively (Hoffman et al. 1978a).

The main characteristics of type I bursts (for a review see Lewin et al. 1993) are: sudden and short (~1 s) increase in the X-ray flux, exponential decay light curve, duration of the order of seconds to minutes, softening during the decay (attributed to cooling of the neutron star surface), (net) burst spectra reasonably well described by blackbody emission from a compact object with ~10 km radius and temperature of ~1–2 keV, and integrated net burst luminosities ranging from ~10^{39} to 10^{40} erg. When the luminosity during the burst reaches the Eddington limit, the neutron star photosphere expands. Since L_{\text{Edd}} \propto R^2 T^4, when the radius of the photosphere, R, expands, the effective temperature, T, drops, with the burst luminosity, L, being constant (modulo gravitational redshift effects with changing R) at the Eddington limit, L_{\text{Edd}}. Bursts during their radius expansion/contraction phase are therefore recognizable by an increase in the inferred radius with a simultaneous decrease in the observed temperature, while the observed flux stays relatively constant. The observations of type I X-ray bursts may in principle provide direct observational information about the structure of a neutron star, i.e. its equation of state (EOS), which can be used to compare with theoretical approaches (see Lewin et al. 1993, and references therein).

Type I X-ray burst theory basically predicts three different regimes in mass accretion rate (\dot{M}) for unstable burning (Fujimoto et al. 1981, Fushiki & Lamb 1987; see also Bildsten 1998, 2000, Schatz et al. 1999, and references therein; note that values of critical \dot{M} depend on metallicity, and on assumed core temperature and mass of the neutron star):

1) low accretion rates; 10^{-14} M_{\odot} \text{yr}^{-1} \lesssim \dot{M} \lesssim 2 \times 10^{-10} M_{\odot} \text{yr}^{-1}; mixed H/He burning triggered by thermally unstable H ignition
2) intermediate accretion rates; 2 \times 10^{-10} M_{\odot} \text{yr}^{-1} \lesssim \dot{M} \lesssim 4-11 \times 10^{-10} M_{\odot} \text{yr}^{-1}; pure He shell ignition after steady H burning
3) high accretion rates; 4-11 \times 10^{-10} M_{\odot} \text{yr}^{-1} \lesssim \dot{M} \lesssim 2 \times 10^{-8} M_{\odot} \text{yr}^{-1}; mixed H/He burning triggered by thermally unstable He ignition

H and He are burning stably in a mixed H/He environment for very low and very high values of \dot{M}, i.e. \dot{M} below ~10^{-14} M_{\odot} \text{yr}^{-1} and above ~2 \times 10^{-8} M_{\odot} \text{yr}^{-1} (close to the critical Eddington \dot{M}). During pure helium flashes the fuel is burned rapidly, and such bursts therefore last only 5–10 s. This gives rise to a large energy release in a short time, which causes the bursts often to reach the Eddington limit, leading to photospheric radius expansion. Bursts with unstable mixed H/He burning release their energies on a longer, ~100 s, timescale, due to the long series of \beta decays in the rp-process (see e.g. Bildsten 1998, 2000).

The Z sources (Hasinger & van der Klis 1989) are a group of sources inferred to persistently accrete near the Eddington limit. In a colour-colour diagram they trace out a Z-like shape, with the three limbs of the Z (historically) referred to as the horizontal branch (HB), normal branch (NB) and flaring branch (FB), from top to bottom. \dot{M} is inferred to increase from sub-Eddington at the HB, near-Eddington at the NB to super-Eddington at the FB (e.g. Hasinger 1987; Lamb 1989; Hasinger et al. 1990). According to the burning regimes outlined above these sources should exhibit long (\gtrsim 100 s) type I X-ray bursts, at least on the HB and NB. However, of the Z sources, only GX 17+2 and Cyg X-2 show (infrequent) bursts (Kahn & Grindlay 1984; Tawara et al. 1984c; Sztajno et al. 1986; Kuulkers et al. 1995, 1997; Wijnands et al. 1997; Smail 1998), indicating that most of the material is burning stably. This is in contrast to the above theoretical expectations for high \dot{M}. Moreover, the bursts in Cyg X-2 are short (~\sim 5 s), whereas GX 17+2 shows both short (~\sim 10 s) and long (~\gtrsim 100 s) bursts. One of the bursts of Cyg X-2 showed a radius expansion phase (Smale 1998); this burst clearly bears all the characteristics of a He flash (regime 2), whereas the neutron star is inferred to accrete at near-Eddington rates. The short duration bursts in GX 17+2 also hint to a He flash origin, whereas the long duration bursts hint to unstable mixed H/He burning (presumably at high accretion rates, regime 3 as defined above; see also van Paradijs et al. 1988). In general, one finds no correlation of the burst properties with position in the Z, although the number of bursts investigated for GX 17+2 was limited (Kuulkers et al. 1995, 1997).

The Proportional Counter Array (PCA) onboard the Rossi X-ray Timing Explorer (RXTE) combines high throughput using a large collecting area (maximum of ~6500 cm^2) with the ability to label counts down to a time resolution of \mu s. This is ideal to study short events like X-ray bursts, especially during the crucial first stage, i.e. the start of the burst. Analysis of X-ray bursts in sources with inferred persistent (relatively) high mass accretion rates (\gtrsim 0.2 M_{\text{Edd}}) observed with the RXTE/PCA were presented for one burst seen with Cyg X-2 (Smale 1998) and one seen in GX 3+1 (Kuulkers & van der Klis 2000). Such studies may provide us more insight in the properties of X-ray bursts which occur at these extreme mass accretion rates. In this paper we present the first account of ten X-ray bursts from GX 17+2 observed by the RXTE/PCA during the period 1996–2000. For an account of the X-ray timing and spectral properties of GX 17+2 using the same data set we refer to Homan et al. (2001).

2. Observations and Analysis

The PCA (2–60 keV; Bradt et al. 1993) onboard RXTE observed GX 17+2 various times during the mission. Up to now a total of 657 ksec of useful data has been obtained. A log of these observations is given in Table 1. During the observations in 1996–1998 all five proportional counter units (PCUs) were active, whereas in 1999 and 2000 only
three units were active. The high voltage settings of the PCUs have been altered three times during the mission (so-called gain changes), which modified the response of the detectors. These changes therefore mark four periods, called gain epochs. The observations were done in two standard modes: one with relatively high spectral resolution (129 energy bands covering the 249 channels over the whole PCA energy band) every 16 sec, i.e. STANDARD 2 mode, the other having no spectral information providing the intensity in the whole PCA energy band at a moderate time resolution of 0.125 s, i.e. STANDARD 1 mode. Additional data were obtained in various high time resolution (≤2 ms) observation modes within a specific energy band with either low spectral resolution (B-modes or E-modes) or no spectral resolution (SB-modes). The B-, E- and SB-modes used here combined the information from all layers of all active PCUs together.

For the spectral analysis of the persistent emission we used the STANDARD 2 data. We accumulated data stretches of 96 s just before the burst, and the same after the burst, combining the PCUs which were operating. In order to study the spectral properties of the bursts we used two approaches. Spectra during the bursts were determined every 0.25 sec for ~20 s after the start of the burst. For the short bursts this includes the whole burst. In 1996 a B- and E-mode were available, giving 16 and 64 energy bands, covering channels 0–49 and 50–249, at 2 ms and 125 μs, respectively. For the observations in 1998 and 1999, two SB-modes covering channels 0–13 and 14–17 at 125 μs, and an E-mode giving 64 energy bands covering channels 18–249 at 16 μs time resolution. During the long bursts we also used the STANDARD 2 data to create spectra at 16 s intervals, for evaluating the remainder of these bursts. Since no high time resolution spectral data were available during the 1997 observations (only 4 SB-modes covering the total PCA energy range), only the STANDARD 2 data were used to study the spectral properties of the burst from this observation. All spectra were corrected for background and dead-time using the procedures supplied by the RXTE Guest Observer Facility. A systematic uncertainty of 1% in the count rate spectra was taken into account. For our spectral fits we confined ourselves to the energy range of 3–20 keV, which is best calibrated. The hydrogen column density, N\textsubscript{H}, towards GX 17+2 was fixed to that found by the Einstein SSS and MPC measurements (2 x 10\textsuperscript{22} atoms cm\textsuperscript{-2}, Christian & Swank 1997; see also Di Salvo et al. 2000). In all cases we included a Gaussian line (see Di Salvo et al. 2000) fixed at 6.7 keV, with a fixed line width of 0.1 keV. 1σ confidence errors were determined using Δχ\textsuperscript{2} = 1.

Large amplitude, high coherence brightness oscillations have been observed during various type I X-ray bursts in other low-mass X-ray binaries (LMXBs; see e.g. Strohmayer 1998, 2000). In all our bursts from GX 17+2 we searched for the presence of such burst oscillations. Using the high time resolution modes we performed Fast Fourier Transforms (FFTs) to produce power spectra with a Nyquist frequency of 2048 Hz. This was done in the total energy band (2–60 keV) and in a high energy band ranging from ~8 keV to ~20 keV. For the 1996 observations, however, the high time resolution mode only covered the 13.5–60 keV range; the 2–60 keV FFTs provided a Nyquist frequency of 256 Hz. The lengths of the data segments for which the FFTs were performed were either 0.25 s or 2 s. To increase the sensitivity for cases where burst oscillations are only present for a period of time comparable or shorter than the length of the FFT, we oversampled the data by factors of 2 and 8, respectively, by taking the start time of the next data segment to be 0.125 s and 0.25 s later than that of the previous one, instead of 0.25 s and 2 s.

3. Results

3.1. Temporal behaviour

Inspection of all the light curves of the data of GX 17+2 obtained so far yielded a total of ten X-ray bursts (designated b1, b2, ..., b10). Table 2 gives the start times of the bursts, together with the gain epoch in which the observations were done and the number of active PCUs. We also give some basic properties, i.e. the duration of the bursts as estimated by eye using the light curves in the total PCA energy band and/or the hardness (ratio of count rates in two energy bands) curves, the rise time of the burst as determined in two ways (see below), and the exponential

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Table 1. RXTE observation log of GX 17+2

<table>
<thead>
<tr>
<th>Year</th>
<th>Start (UT)</th>
<th>End (UT)</th>
<th>t\text sub{exp} \textsuperscript{a} (ksec)</th>
<th># of bursts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td>feb 07</td>
<td>feb 09</td>
<td>56</td>
<td>1</td>
</tr>
<tr>
<td>1997</td>
<td>feb 02</td>
<td>feb 07</td>
<td>59</td>
<td>1</td>
</tr>
<tr>
<td>1997</td>
<td>apr 01</td>
<td>apr 04</td>
<td>35</td>
<td>0</td>
</tr>
<tr>
<td>1997</td>
<td>jul 27</td>
<td>jul 28</td>
<td>43</td>
<td>0</td>
</tr>
<tr>
<td>1998</td>
<td>aug 07</td>
<td>aug 08</td>
<td>71</td>
<td>1</td>
</tr>
<tr>
<td>1998</td>
<td>nov 18</td>
<td>nov 20</td>
<td>86</td>
<td>2</td>
</tr>
<tr>
<td>1999</td>
<td>oct 03</td>
<td>oct 12</td>
<td>298</td>
<td>5</td>
</tr>
<tr>
<td>2000</td>
<td>mar 31</td>
<td>mar 31</td>
<td>7</td>
<td>0</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Between Feb 2–27, 1997 observations every 3–6 days.

\textsuperscript{b} Total effective exposure time.

Table 2. Bursts in GX 17+2

<table>
<thead>
<tr>
<th>Burst</th>
<th>Start Time (UT)</th>
<th>E&lt;sub&gt;a&lt;/sub&gt;</th>
<th>PCUs&lt;sup&gt;c&lt;/sup&gt;</th>
<th>t&lt;sub&gt;dur&lt;/sub&gt;&lt;sup&gt;a&lt;/sup&gt;</th>
<th>t&lt;sub&gt;rise&lt;/sub&gt;&lt;sup&gt;d&lt;/sup&gt;</th>
<th>t&lt;sub&gt;f&lt;/sub&gt;&lt;sup&gt;e&lt;/sup&gt;</th>
<th>t&lt;sub&gt;exp&lt;/sub&gt;&lt;sup&gt;f&lt;/sup&gt;</th>
<th>(\chi^2_{\text{red}}/\text{dof}&lt;sup&gt;i&lt;/sup&gt;</th>
<th>Branch&lt;sup&gt;h&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>b1</td>
<td>1996 feb 08</td>
<td>16:17:12</td>
<td>1</td>
<td>10</td>
<td>1.22 ± 0.05</td>
<td>0.35 ± 0.05</td>
<td>1.83 ± 0.08</td>
<td>1.1/130</td>
<td>mNB</td>
</tr>
<tr>
<td>b2</td>
<td>1997 feb 08</td>
<td>02:36:34</td>
<td>3</td>
<td>5</td>
<td>1.19 ± 0.08</td>
<td>1.03 ± 0.08</td>
<td>248 ± 1.4</td>
<td>2.5/49</td>
<td>mNB</td>
</tr>
<tr>
<td>b3</td>
<td>1998 aug 13</td>
<td>03:15:50</td>
<td>3</td>
<td>5</td>
<td>0.53 ± 0.09</td>
<td>0.27 ± 0.09</td>
<td>2.55 ± 0.24</td>
<td>1.0/131</td>
<td>INB</td>
</tr>
<tr>
<td>b4</td>
<td>1998 nov 18</td>
<td>08:51:26</td>
<td>3</td>
<td>5</td>
<td>1.34 ± 0.04</td>
<td>0.61 ± 0.04</td>
<td>197 ± 2</td>
<td>3.7/147</td>
<td>SV</td>
</tr>
<tr>
<td>b5</td>
<td>1998 nov 18</td>
<td>14:37:30</td>
<td>3</td>
<td>5</td>
<td>0.41 ± 0.04</td>
<td>0.54 ± 0.04</td>
<td>2.06 ± 0.13</td>
<td>1.1/85</td>
<td>mNB</td>
</tr>
<tr>
<td>b6</td>
<td>1999 oct 03</td>
<td>15:36:32</td>
<td>4</td>
<td>3 (2,2,3)</td>
<td>1600 ± 0.4</td>
<td>0.19 ± 0.04</td>
<td>274 ± 3</td>
<td>2.0/242</td>
<td>HBB</td>
</tr>
<tr>
<td>b7</td>
<td>1999 oct 05</td>
<td>23:41:43</td>
<td>4</td>
<td>3 (2,2,4)</td>
<td>500 ± 0.56</td>
<td>0.30 ± 0.03</td>
<td>77.3 ± 1.2</td>
<td>1.9/104</td>
<td>uNB</td>
</tr>
<tr>
<td>b8</td>
<td>1999 oct 06</td>
<td>11:10:33</td>
<td>4</td>
<td>3 (2,2,3)</td>
<td>500 ± 1.66</td>
<td>0.13 ± 0.02</td>
<td>70.2 ± 1.4</td>
<td>1.2/57</td>
<td>HBB</td>
</tr>
<tr>
<td>b9</td>
<td>1999 oct 09</td>
<td>12:34:24</td>
<td>4</td>
<td>3 (2,2,3)</td>
<td>500 ± 0.13</td>
<td>0.16 ± 0.02</td>
<td>76.4 ± 1.5</td>
<td>3.1/66</td>
<td>uNB</td>
</tr>
<tr>
<td>b10</td>
<td>1999 oct 10</td>
<td>09:10:47</td>
<td>4</td>
<td>3 (2,2,3)</td>
<td>700 ± 0.72</td>
<td>0.20 ± 0.04</td>
<td>115 ± 3</td>
<td>3.7/57</td>
<td>INB</td>
</tr>
</tbody>
</table>

<sup>a</sup> Burst designation used in text.
<sup>b</sup> RXTE gain epoch of the observation.
<sup>c</sup> Numbers of active PCUs; if <5 the PCU unit numbers are given between brackets.
<sup>d</sup> Approximate total burst duration in sec.
<sup>e</sup> Time (sec) for the count rate to rise from 25% to 90% of the net-peak burst rate.
<sup>f</sup> Duration of fast rise phase in sec, see text.
<sup>g</sup> Exponential decay time in sec.
<sup>h</sup> Goodness of the exponential fit to the decay part of the burst light curve.

<sup>i</sup> Source position in the Z just before the burst (see also Fig. 14); u, m, and l stand for upper, middle and lower, respectively. SV means ‘soft’ vertex, i.e. the NB/FB vertex.

decay time as determined from a fit to the (exponential) decay part of the Standard 1 light curves, together with its goodness of fit expressed in terms of \(\chi^2_{\text{red}}\). We note that the estimates of the durations are rather arbitrary, but robust methods such as the so-called T90 measurements<sup>2</sup> for duration as used for \(\gamma\)-ray bursts (see Kosht et al. 1996, and references therein) can not be applied, especially to the longer bursts, since the persistent emission varies on the same time scale (or even faster) as the burst itself, see e.g. Fig. 1. The rise time of the bursts was determined as follows. We constructed light curves in the full PCA energy band with a time resolution of 1/32 sec. We defined \(t_{\text{rise}}\) as the time for the burst to increase from 25% to 90% of the net peak burst rate (see e.g. Muno et al. 2000; van Straaten et al. 2001). A detailed look at the light curves revealed that the rise of bursts b1–b4, b8 and b10 consisted of a rapid rise phase and a subsequent slower rise phase to maximum. In bursts b5–b7 and b9 the count rate rapidly increased to maximum, with no subsequent slower rise. This causes \(t_{\text{rise}}\) to be distributed around two values (0.13–0.72 sec for b5–b7, b9 and 1.19–1.66 sec for b1–b4, b8, b10). We therefore also fitted the pre-burst phase, fast rise phase (and slow rise phase) with a constant level and one (or two) linear functions, respectively, using the Standard 1 light curves. We find that the fast rise time, i.e. the total duration of the fast rise phase, \(t_{\text{f}}\), is between 0.1 and 0.6 sec (see Table 2). In the fits to the (exponential) decay portion of the light curves for the three short bursts we used the Standard 1 light curves, while for the longer bursts we rebinned these data to a time resolution of 5 sec. For some of the long bursts an exponential does not describe the decay very well; this is probably due to the short term variations in the persistent emission. For burst 9 and burst 10 we fitted only the initial decay (first few 100 s), since including the whole burst increased the decay time and worsened the fit, due also to the long-term decay of the persistent emission after these bursts.

Three bursts were rather short, \(~10\,\text{s}\) (b1, b3, b5), whereas the other bursts are long, \(~500–1600\,\text{s}\) (b2, b4, b6–b10). In Fig. 2 we show the light curves of the 3 short bursts, at low (<7 keV) and high (>7 keV) energies, with the corresponding hardness (ratio of the count rates in the high and low energy band) curves, all at a time resolution of 0.125 s. All three bursts show a fast rise (typically less than 0.5 s) and an exponential decay with an exponential decay time of \(~2\,\text{s}\) (see Table 2). As the bursts decay, the hardness decreases, corresponding to softening of the burst emission. The main difference between the three bursts is the fact that the peak of burst b3 is about 25% lower than the other two bursts; it looks like a ‘failed’ burst. It also has two peaks, as if some new unstable burning occurred, \(~5\,\text{s}\) after the start of the burst.

In Figs. 3 and 4 we show the light curves at low and high energies of the long bursts, i.e. b2, b4, b6 and b7–b10, respectively, together with the corresponding hardness curves, all at a time resolution of 2 s. In Figs. 5 and 6 we focus on the start of these bursts, all at a time resolution of 0.125 s. Again the rise times are very short (also typically less than 0.5 s), but the decay times are much longer, with exponential decay times in the range \(~70–280\,\text{s}\) (see Table 2). The burst emission clearly becomes softer as the burst decays. Apart from the fact that the hard burst emission decays faster than the soft burst emission (i.e. spectral softening), there are more pronounced differences between the light curves of the two energy
Fig. 1. Standard 1 light curve of the GX 17+2 observations during October 10, 1999, at a time resolution of 5 s. Time zero corresponds to 05:39:27 (UTC). No corrections for background bands. In Figs. 3 and 4 one sees that all the low energy light curves show a kind of spike at the start of the decay. These spikes last for a few seconds in most cases; however, for burst b6 it seems to last ~15 s (with an exponential decay time of 9±2 s). At high energies no such spikes occur (except for burst b10); instead they have more flattened peaks, with durations ranging from tens of seconds to ~200 s. Burst b6 is the nicest example of this. Zooming in on the start of these long bursts, it becomes clear that the rise is somewhat slower at high energies with respect to low energies (causing the hardening of the emission during the start of the burst). Also, in bursts b4 and b6–b9 very short (<0.5 s) spikes occur during the rise in the high energy light curve, which again are especially evident in burst b6 (two spikes!). This causes the hardness to drop on the same time scale in some of these bursts. Later we will show that this corresponds to fast radius expansion/contraction episodes.

3.2. Spectral behaviour

3.2.1. Persistent emission

The persistent emission just before the bursts b6 and b7 can be satisfactorily ($\chi^2_{\text{red}}=0.7–1.2$ for 35 degrees of freedom [dof]) described by an absorbed cut-off power-law component (including a Gaussian line, see Sect. 2). Similar results are obtained for the persistent emission after the bursts. For the persistent emission before and after the remainder of the bursts this is not a satisfactory model ($\chi^2_{\text{red}}$ ranges from 1.4 for 35 dof [b8] to 5.5 for 42 dof [b3]). Instead, an additional component is necessary to improve the fits. We chose a black body, as is generally used when modeling the X-ray spectra of bright LMXBs (e.g. White et al. 1986; Christian & Swank 1997; Church & Balucinska-Church 2001). Note that more complicated models are necessary to describe the spectra of GX 17+2 with better energy resolution and broader energy range (e.g. Di Salvo et al. 2000). However, our approach is sufficient for this paper. The spectral fit results are given in Table 3. The error in the persistent flux is derived as follows. We changed each free parameter to their maximum and minimum value constrained by their 1σ error, while leaving the other parameters fixed at their best value. Then the error is defined as half the interval between the lowest and highest flux obtained. This procedure was verified by performing Monte Carlo simulations: we varied each spectral parameter assuming they are normally distributed, using the 1σ-errors. The resulting persistent flux (2–10 keV) was consistent with also being normally distributed, but slightly skewed to higher luminosities. The persistent flux just before and after the bursts during the various observations varied between 1.7–2.2×10$^{-8}$ erg s$^{-1}$ cm$^{-2}$ (2–10 keV). For bursts b6 and b7 we determined single parameter 90% confidence upper limits (using $\chi^2=2.71$) on the black-body contribution, by including a black-body component in the spectral fits, and fixing the black-body temperature to its mean value derived for the persistent spectra of the other bursts, i.e. kT$_{\text{bb}}=1.14$ keV. The black-body component contribution to the persistent emission varied between <2% (burst b7) up to 34% (burst b2) in the 2–10 keV band (see Table 3).

3.2.2. Persistent emission during the bursts?

Usually it is assumed that the persistent emission is not influenced by the burst and that one can, therefore, study the burst by subtracting the persistent emission from the total source emission. This is referred to as the ‘standard’ burst spectral analysis (see e.g. van Paradijs & Lewin 1986; Sztajno et al. 1986). However, whenever the neutron star photosphere contributes significantly to the persistent emission, this approach may not be correct, since the burst emission may originate from the same region (van Paradijs & Lewin 1986). If not taken into account, the spectral fits to the net burst spectra may contain systematic errors in the observed black-body temperature, T$_{\text{bb}}$ (also referred to as the colour temperature, T$_{\text{col}}$, see e.g. Lewin et al. 1993), and apparent black-body radius, R$_{\text{bb}}$, especially near the end of the burst when the net burst flux is low and when T$_{\text{bb}}$ would relate to the persistent black-body temperature and be independent of the net burst flux. The result would be that R$_{\text{bb}}$ artificially decreases. One would predict that in this case of incorrect subtraction of the persistent emission, the net burst spectrum does not have a black-body energy distribution.
Van Paradijs & Lewin (1986) proposed to model the total source spectrum by performing two-component spectral fits, using a black-body component and a non-black-body component. During the burst the non black-body component is fixed to that found in the persistent emission, and the black-body component is left free. In this way, it should include all emission from the neutron star photosphere. The underlying idea is that the non black-body component arises from the accretion process, and is not influenced by the X-ray burst.

GX 17+2 is a bright X-ray source with presumably a hot neutron star contribution to the persistent emission. Since the source is bright, the peak net burst flux relative to the persistent flux is rather low, as compared to most other burst sources. It is therefore an excellent source to study the above described effects (Sztajno et al. 1986). The black-body component contributed \( \sim 40\% \) to the persistent emission just before the two bursts observed by EXOSAT. Using the ‘standard’ burst spectral analysis Sztajno et al. (1986) found relatively high black-body temperatures (\( kT_{bb} \sim 2-3 \text{ keV} \)) and relatively small apparent black body radii (\( R_{bb} \sim 3-5 \text{ km} \), assuming isotropic radiation and a distance of 10 kpc) during their short (\( \sim 10 \text{ s} \)) burst. Moreover, during their long (>5 min)
same as Fig. 2, but at a time resolution of 2 s, for the last four bursts observed in 1999 Oct (b7–b10). The low and high energy ranges are 2–7.5 keV and 7.5–18.8 keV, respectively.

Table 3. Persistent emission spectral parameters $^a$

<table>
<thead>
<tr>
<th>burst</th>
<th>$F_{\text{pers}}$ (2–10 keV)</th>
<th>$kT_{\text{bb}}$ (keV)</th>
<th>$R_{\text{bb}}$ (km)</th>
<th>$\Gamma$</th>
<th>$E_{\text{cut}}$ (keV)</th>
<th>$\text{norm.}^b$</th>
<th>$\text{gnorm.}^f$</th>
<th>$\chi^2$/dof</th>
<th>%bb$^g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>b1</td>
<td>1.7±0.2</td>
<td>1.15±0.06</td>
<td>14.1±1.5</td>
<td>1.0±0.1</td>
<td>4.5±0.2</td>
<td>3.8±0.4</td>
<td>0.013±0.002</td>
<td>0.89/47</td>
<td>18</td>
</tr>
<tr>
<td>b2</td>
<td>1.7±0.2</td>
<td>1.13±0.03</td>
<td>19.2±1.5</td>
<td>0.9±0.1</td>
<td>4.2±0.2</td>
<td>2.6±0.4</td>
<td>0.013±0.002</td>
<td>0.58/40</td>
<td>32</td>
</tr>
<tr>
<td>b3</td>
<td>1.7±0.2</td>
<td>1.10±0.04</td>
<td>20.3±1.8</td>
<td>0.7±0.1</td>
<td>4.0±0.2</td>
<td>2.3±0.4</td>
<td>0.014±0.002</td>
<td>0.85/40</td>
<td>31</td>
</tr>
<tr>
<td>b4</td>
<td>2.0±0.3</td>
<td>1.16±0.05</td>
<td>17.5±1.7</td>
<td>0.9±0.1</td>
<td>4.5±0.2</td>
<td>3.2±0.4</td>
<td>0.010±0.002</td>
<td>0.59/40</td>
<td>25</td>
</tr>
<tr>
<td>b5</td>
<td>2.0±0.1</td>
<td>—</td>
<td>—</td>
<td>1.0±0.03</td>
<td>5.1±0.1</td>
<td>4.8±0.1</td>
<td>0.012±0.002</td>
<td>0.71/35</td>
<td>&lt;7$^h$</td>
</tr>
<tr>
<td>b6</td>
<td>2.2±0.1</td>
<td>—</td>
<td>—</td>
<td>1.17±0.03</td>
<td>4.6±0.1</td>
<td>7.0±0.2</td>
<td>0.015±0.002</td>
<td>1.22/35</td>
<td>&lt;2$^h$</td>
</tr>
<tr>
<td>b7</td>
<td>2.0±0.3</td>
<td>1.08±0.13</td>
<td>11.0±4.3</td>
<td>1.0±0.1</td>
<td>5.3±0.3</td>
<td>3.8±0.5</td>
<td>0.011±0.002</td>
<td>1.13/33</td>
<td>7</td>
</tr>
<tr>
<td>b8</td>
<td>2.0±0.3</td>
<td>1.26±0.08</td>
<td>11.6±1.5</td>
<td>1.0±0.1</td>
<td>4.9±0.3</td>
<td>4.3±0.4</td>
<td>0.010±0.003</td>
<td>0.87/33</td>
<td>16</td>
</tr>
<tr>
<td>b9</td>
<td>1.7±0.2</td>
<td>1.18±0.05</td>
<td>15.1±1.4</td>
<td>1.1±0.1</td>
<td>4.5±0.3</td>
<td>3.7±0.5</td>
<td>0.011±0.002</td>
<td>1.16/33</td>
<td>24</td>
</tr>
</tbody>
</table>

$a$ $N_{\text{H}}$ was fixed to $2\times10^{22}$ atoms cm$^{-2}$, see text.

$b$ Unabsorbed persistent flux in $10^{-8}$ erg s$^{-1}$ cm$^{-2}$.

c Black-body radius at 10 kpc.

d Power-law photon index.

e Power-law normalization in photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ at 1 keV.

$f$ Normalization in photons cm$^{-2}$ s$^{-1}$ in the line modeled by a Gaussian fixed at 6.7 keV and width ($\sigma$) of 0.1 keV.

g Black-body emission contribution to the total persistent flux in % (2–10 keV).

$^h$ 90% confidence upper limit, using $kT_{\text{bb}}=1.14$ keV, see text.

burst $kT_{\text{bb}}$ showed only a small change from $\sim2.1$ keV at the peak of the burst to $\sim1.7$ keV near the end of the burst, with an accompanying decrease in $R_{\text{bb}}$ from $\sim7$ km to $\sim4$ km. Their fits were, however, satisfactory, with $\chi^2_{\text{red}}$ of 0.6–1.2.$^3$ Sztajno et al. (1986) therefore applied the two-component spectral fit method and found that the resulting black-body temperatures during the short burst were now in the range normally encountered for type I X-ray bursts and that the systematic decrease in $R_{\text{bb}}$ had disappeared. The $\chi^2_{\text{red}}$ values of the spectral fits were between 0.6 and 1.3, except for one fit, for which they found 1.6, i.e. slightly worse than the ‘standard’ spectral analysis. They attributed the slightly higher values of $\chi^2_{\text{red}}$ to the smaller relative error in the total burst data with respect to the net-burst data where the persistent emission was subtracted. Note that Sztajno et al. (1986) found now a slight increase in $R_{\text{bb}}$, apparently anti-correlated with $T_{\text{bb}}$. They thought this to be due to the non-Planckian shape of the spectrum of a hot neutron star (van Paradijs 1982; see Titarchuk 1994; Madej 1997, and references therein; see, however, Sect. 5.2).

Guided by the results of Sztajno et al. (1986), we started our burst spectral fits by performing two-
component fits to the total source spectra, using a black body and a non black-body component. The parameters of the non black-body component, i.e. the absorbed cut-off power law and Gaussian line, were fixed to the values found for the persistent emission before the burst, see Table 3. We find that the two-component burst spectral fits to the 16s spectra provided satisfactory results for bursts b6 and b7, for which the persistent emission did not contain a significant contribution from the black-body component ($\chi^2_{\text{red}} \lesssim 3$ for 37 dof [burst b6]; average $\chi^2_{\text{red}}$ of $\sim 1$ for 37 dof). However, the 16s spectral fits were bad whenever the persistent emission spectra contained a black-body component; the fits became worse as the persistent black-body contribution became stronger (for the first $\sim 100$ s after the start of the burst: $\chi^2_{\text{red}}$/dof$\approx 1.5$–3/37 [burst b8], $\chi^2_{\text{red}}$/dof$\approx 2.5$–8/37 [burst b9], $\chi^2_{\text{red}}$/dof$\approx 5$–10/37 [burst b10], $\chi^2_{\text{red}}$/dof$\approx 20$–24/44 [burst b4], $\chi^2_{\text{red}}$/dof$\approx 22$–25/44 [burst b2]). The resultant $\chi^2_{\text{red}}$ values were the worst near the peak of these bursts. An example of the parameter values and the goodness of fit during the burst is shown for burst b4 in the left panel of Fig. 7, for which the persistent emission had a black-body contribution of $31\%$ ($2$–$10$ keV). An example of a total burst spectrum and the result of the two-component fit is shown in the left panel of Fig. 9 for burst b2. The $\chi^2_{\text{red}}$/dof values for burst b4 decrease from $\approx 24$/44 at the beginning of the burst to $\approx 2$/44 near the end of the burst. A similar trend in goodness of fit is seen for the 0.25 s burst spectral fits: average $\chi^2_{\text{red}}$ of $\sim 2$ for 18 dof during the first $\sim$10 s of e.g. burst b4 and an average $\chi^2_{\text{red}}$ of $\sim 1$ for 16 dof during the first $\sim$10 s of e.g. burst b6 (see the left panel and the two most right panels of Fig. 7). The $\chi^2_{\text{red}}$ values for 0.25 s spectral fits were (much) lower than those for the 16s spectral fits, due to the (much) lower signal to noise and lower spectral resolution of the 0.25 s spectra. Note that the high values of $\chi^2_{\text{red}}$ for the 16s spectra are not due to fast spectral variations within the time the spectra are accumulated. This only applies to spectra which include the first few seconds of the bursts, where spectral changes are fast due to the short radius expansion and initial contraction phase. Halfway the decline of burst b4 $R_b$ seems to increase again; this also applies to the other long bursts (except burst b6), and to the short bursts (e.g. burst b1: second panel from the left of Fig. 7).
This is similar to that seen by Sztajno et al. (1986), but their fits seemed less bad (see above). We attribute their seemingly better fits due to the much lower signal to noise of their EXOSAT/ME data.

If we compare the mean bolometric black-body flux during the first 10s after the peak, \( F_{bb,peak} \), of bursts b4 and b6 in Fig. 7, it is clear that \( F_{bb,peak} \) for burst b4 is higher than that for burst b6. The difference is \( 0.63(\pm0.12) \times 10^{-8} \text{erg s}^{-1} \text{cm}^{-2} \) (for the error in \( F_{bb,peak} \) we used the rms variation in the bolometric black-body fluxes). This is virtually the same as the bolometric black body contribution in the persistent emission, \( F_{bb,pers} \), before burst b4 (indicated by the dotted lines in the top panels for burst b4 in Fig. 7): \( F_{bb,pers} = 0.65(\pm0.05) \times 10^{-8} \text{erg s}^{-1} \text{cm}^{-2} \). We determined \( F_{bb,peak} \) and \( F_{bb,pers} \) for all the bursts to see if this effect is seen in other bursts as well. For the short bursts we used the highest observed black body flux, while for burst b2 we used the first 16s measurement after the start of the burst. The result is displayed in Fig. 8 (top panel). Indeed, \( F_{bb,peak} \) differs between the bursts and is clearly correlated with \( F_{bb,pers} \) (except for burst b3). Such a relation can be expected if \( F_{bb,peak} \) is close to a certain upper limit (presumably the Eddington limit) and includes a (certain fraction) of the persistent emission. Indeed, we can reasonably fit the data points to the function \( F_{bb,peak} = F_{bb,pers} + C \) (excluding bursts b2 and b3; burst b2 did not cover the first 10s after the peak of the burst, while burst b3 was weak with respect to the other bursts). The resulting goodness of fit is \( \chi^2_{red} = 1.96 \) for 7 dof. We find \( C = (1.31 \pm 0.03) \times 10^{-8} \text{erg s}^{-1} \text{cm}^{-2} \); this is close to the values of \( F_{bb,peak} \) for bursts b6 and b7 which had no significant black-body contribution in the preceding persistent emission. In Fig. 8 we have also indicated whether a burst was a radius expansion event (see next Section). It can be seen that some of the bursts with no radius expansion/contraction phase have higher values of \( F_{bb,peak} \) than most of the radius expansion bursts. Theoretically, during the radius expansion/contraction phases the flux should equal the Eddington limit. Therefore, the (peak) fluxes observed for different radius expansion bursts should have similar values, whereas for bursts with no radius expansion/contraction phase they should be either similar or smaller. This is certainly not the case.

To summarize, we find that the method proposed by Van Paradijs & Lewin (1986) and applied by Sztajno et al. (1986) to the bursts observed by EXOSAT does not work for our bursts observed with the RXTE/PCA. The two-component spectral fits give bad results whenever there is a black-body contribution to the persistent emission.
Moreover, the total burst peak fluxes, $F_{bb,peak}$, are different from burst to burst and depend on the amount of the black-body contribution to the persistent emission, $F_{bb,pers}$. This is not what one would expect if during some of the bursts a limit is reached (presumably the Eddington limit). We conclude that the persistent black-body emission does not disappear during the burst. An example is displayed in the right panel of Fig. 9. We show again the first 16 s spectrum during burst b2 plus now the results of a three-component fit, i.e. two black bodies and a cut-off power-law (all subjected to interstellar absorption). The parameters of the cut-off power law and one black-body component have been fixed to that found for the persistent emission, so that the fit does have the same number of dof as that in the left panel. Clearly, the fit has improved considerably. This result means that all of the persistent emission is decoupled from the burst, and that thus the ‘standard’ spectral analysis should work for our bursts. This is the subject of the next subsection.

3.2.3. ‘Standard’ spectral analysis: net burst emission

When modeling the net burst spectra (i.e. spectra obtained after subtraction of the persistent emission from the total source spectrum) by a black body, the spectral fits are almost all satisfactory (average $\chi^2_{red}$ values of $\sim$1). The fit results are shown for the 3 short bursts in Figs. 10 (b1, b3, b5) and for the 7 long bursts in Figs. 11 (b2, b4, b7–b10) and 12 (left panel; b6). For the long bursts we used a logarithmic time scale, to emphasize the start of the bursts, where changes in the parameters are most rapid.

The fits are, while much improved overall, still not optimal during the peaks of the long bursts b4, b6 and b10 ($\chi^2_{red}$=2–3 with $44 \, [b4]$ or $37 \, [b6,b10]$ dof for the spectral fits to the 16 s spectra). In Fig. 13 we show the average net burst spectrum during the flat top part of burst b6 excluding the radius expansion and initial contraction phase (see below), i.e. 27–187 s after the start of the burst. $T_{bb}$ and $R_{bb,10}$ do not change much during this interval.

Clearly, deviations occur below $\sim$10 keV, i.e. a drop in intensity below $\sim$5.5 keV, while there is an excess between $\sim$5.5–8 keV. These deviations are much larger than the calibration uncertainties.

In the short bursts $T_{bb}$ decreases during the decay, indicating the cooling of the neutron star, as already noted from the hardness curves. There are some slight variations in the apparent black-body radius (at 10 kpc), $R_{bb,10}$, and $T_{bb}$ during the first few seconds. However, considering the behaviour of the net burst black-body flux, $F_{bb,net}$, they do not show the correlations that would be expected for radius expansion events, i.e. an increase in $R_{bb,10}$ with a simultaneous drop in $T_{bb}$ and a (nearly) constant $F_{bb,net}$.

The long bursts all show more or less the same behaviour (note again that for burst b2 we have no short time scale spectral information, see first left panel of Fig. 11). After a fast increase ($\Delta \leq 0.5$ s) to maximum, $F_{bb,net}$ remains constant ($1.4-1.7 \times 10^{-8}$ erg s$^{-1}$ cm$^{-2}$ for the various bursts) for 50–200 s, and then decays exponentially. The duration of this flat-topped phase is similar to that seen in the light curve at high energies (see middle panels of Figs. 3 and 4). During the first part $T_{bb}$ increases, then it levels off, to decrease again when $F_{bb,net}$ decreases.

$R_{bb,10}$ is $\sim$5 km during the decay of the burst, until $F_{bb,net}$ drops below typically $0.2 \times 10^{-8}$ erg s$^{-1}$ cm$^{-2}$. Then $R_{bb,10}$ decreases again. Note that this latter behaviour resembles the systematic effects described by van Paradijs & Lewin (1986) near the end of the burst, when the persistent emission becomes important with respect to the net burst emission (see previous Section). However, we have argued above that the persistent black-body emission is decoupled from the burst black-body emission. We note that this behaviour is probably not due to the fact that we assumed a constant persistent component during the bursts, while in fact the persistent component may vary on the same time scale of the burst or faster (see Sect. 3.1). One would then expect that in some bursts $R_{bb}$ would de-
The most dramatic changes in the spectral parameters can be seen during the first few seconds of the long bursts, however: while there is a short dip in $R_{\text{bb}}$ near the start of the burst, $R_{\text{bb,10}}$ shows values which are up to a factor of $\sim 6$ larger than those found later on (although this is less clear for burst b10, see rightmost panel of Fig. 11). This is typical of radius expansion/contraction episodes, as described in Sect. 1. Burst b6 shows this behaviour clearest and may have had even two of such episodes within one second (Fig. 12, left panel). The expansion to maximum radius takes place in less than $0.5\,\text{s}$, while the initial contraction phases are quite long: it takes between 5 and 20 s from maximum expansion back to close to the neutron star surface.

In the bottom panel of Fig. 8 we show the (average) net burst peak fluxes, $F_{\text{bb,net,peak}}$, determined in the same way as in the previous subsection for $F_{\text{bb,peak}}$, but now for the net-burst emission. Most of the net burst peak fluxes are all in the same range. For the radius expansion bursts (bursts b4, b6–b9; see below) this is as expected if the Eddington limit is reached. Note that $F_{\text{bb,peak}} \approx F_{\text{bb,net,peak}}$ for bursts b6 and b7, as is expected if there is no black-body contribution to the persistent emission. We conclude that the values reached for $F_{\text{bb,net,peak}}$ during the radius expansion/contraction phase is a measure of the Eddington limit observed at Earth. The maximum values of $F_{\text{bb,net}}$ during burst b1, b2, b5 and b10 is more or less similar to the maximum flux reached for the radius expansion bursts. These bursts did not have (clear) radius expansion/contraction phases (although we note here again that for burst b2 we did not have high time spectral resolution).

Radius expansion events are most conveniently displayed in a flux-temperature diagram (where temperature increases from right to left, analogous to HR-diagrams). Our best example, burst b6, is displayed this way in the right-hand panel of Fig. 12. In this diagram the radius expansion/contraction phase and the subsequent cooling of the neutron star are clearly distinguished by two separate tracks (see e.g. Lewin et al. 1993). The data points distributed along a horizontal line in the upper part of the diagram (i.e. nearly constant $F_{\text{bb,net}}$ of $1.2-1.3 \times 10^{-8}\,\text{erg s}^{-1}\text{cm}^{-2}$) represent the expansion/contraction phase. The data points distributed along a diagonal line from the upper left to the lower right part of the diagram are from the cooling phase of the burst. We note that the data point in between the two tracks is from the very first rise phase. Comparing both panels of Fig. 12 it seems that the burst spends a long time near the vertex of both tracks, about $150\,\text{s}$, where $F_{\text{bb,net}} \approx 1.2 \times 10^{-8}\,\text{erg s}^{-1}\text{cm}^{-2}$ and $kT_{\text{bb}} \approx 2.65\,\text{keV}$. The first part ($F_{\text{bb,net}} \approx 0.4 \times 10^{-8}\,\text{erg s}^{-1}\text{cm}^{-2}$) of the cooling track is well described ($\chi^2_{\text{red}} = 0.6$ for 9 dof) by a straight line with a slope of $4.14 \pm 0.15$ (dotted line in Fig. 12), i.e. $F_{\text{bb,net}}$ is consistent with being proportional to $T_{\text{bb}}^4$, as expected if the neutron star photosphere radiates as a black-body during the cooling phase with a constant effective area. Below $F_{\text{bb,net}} \approx 0.4 \times 10^{-8}\,\text{erg s}^{-1}\text{cm}^{-2}$ the data points start to deviate from this relation. The flux-temperature diagrams for the other long bursts are more or less consistent with the behaviour of burst b6, although the exact locations of the vertices between

![Fig. 9. Left panel: At the top the first 16 s observed spectrum after the start of burst b2 is displayed. A two-component fit is shown, i.e. a single black-body and cut-off power-law (both subjected to interstellar absorption). The parameters of the cut-off power-law component are fixed to the values derived for the persistent emission. At the bottom the residuals after subtracting the best model from the observed spectrum is displayed. The fit is clearly bad ($\chi^2_{\text{red}}$/dof=24.2/44). Right panel: At the top the same first 16 s spectrum at the beginning of burst b2 is displayed. Now a three-component fit is shown, i.e. two black-body components and one cut-off power-law component (both subjected to interstellar absorption). The cut-off power-law and one black-body component parameters are fixed to the values derived for the persistent emission. At the bottom the residuals after subtracting the best model from the observed spectrum is displayed. The fit has clearly improved ($\chi^2_{\text{red}}$/dof=1.8/44).]
may be slightly underestimated due to the finite width of the burst duration, \( F_{\text{net}} \), by summing up the observed net burst fluxes, \( F_{\text{net}} \), how fast the flux varies in time. Evidently, the spectral fit models as shown in Table 3) and the average persistent flux \( F_{\text{bb}}^\text{net} \) approximated by integrating the persistent flux between 0.01 and 100 keV using the apparent black-body radius, \( R_{\text{bb},10} \) at 10 kpc, and goodness of fit expressed in reduced \( \chi^2 \). The number of dof is 22 for burst b1 and 18 for bursts b3 and b5.

the radius expansion/contraction phase and the cooling phase differ slightly \((kT_{\text{bb}}=2.3-2.6\text{keV}, F_{\text{bb},\text{net}}=1.2-1.35\times10^{-8}\text{erg s}^{-1}\text{cm}^{-2})\). The early parts of the cooling phases for the other long bursts are in most cases also consistent with black-body cooling, although the flux level at which they start to deviate from \( F_{\text{bb},\text{net}}\times T_{\text{bb}}^4 \) varies from burst to burst \((\sim1\times10^{-8}\text{erg s}^{-1}\text{cm}^{-2} \text{for burst b4). The slope becomes somewhat steeper below these fluxes for all bursts.\)}

3.2.4. Burst parameters

Using the burst X-ray spectral fits we can determine for each burst the maximum net bolometric black-body flux, \( F_{\text{bb,\text{max}}} \), and the total burst fluence \( \int F_{\text{bb},\text{net}} dt \). These can be used to derive the burst parameters \( \gamma = F_{\text{bb,\text{max}}} / F_{\text{bb},\text{net}} \), where \( F_{\text{bb,\text{max}}} \) is the bolometric persistent flux \( \text{i.e. persistent black-body component plus cut-off power-law component} \) approximated by integrating the persistent flux between 0.01 and 100 keV using the spectral fit models as shown in Table 3) and the average burst duration, \( \tau = \int F_{\text{bb},\text{net}} dt \). Note that \( F_{\text{bb,\text{max}}} \) may be slightly underestimated due to the finite width of the time bins. The magnitude of this effect depends on how fast the flux varies in time. \( F_{\text{bb,\text{net}}} \) has been determined by summing up the observed net burst fluxes, \( F_{\text{bb,\text{net}}} \), per time bin from the start of the burst to the estimated end of the burst. Since \( F_{\text{bb,\text{net}}} \) decays exponentially it finishes in principle only at infinite times. To compensate for this we fit the decay with an exponential and determine the ‘rest’ fluence by integrating from the estimated end of the burst up to infinity. Note that this ‘rest’ fluence is large only for burst b2, which was interrupted during its decay (see leftmost panel of Fig. 3). For the burst parameter \( \alpha \) (ratio of the average persistent flux to the time-averaged flux emitted in the bursts, \( \alpha = F_{\text{bb,\text{net}}}/(E_{\text{bb}}/\Delta t) \)), where \( \Delta t \) is the time since the previous burst) we can only give lower limits, since the source is not observed during South Atlantic Anomaly passages and earth occultations. For burst b5 we have, however, also assumed that between bursts b4 and b5 no other bursts occurred \((\Delta t=5.77\text{hr})\). Note that when we derive \( \alpha \) we assume that between bursts the persistent luminosity is constant. Since GX 17+2 is a highly variable source \( \text{see e.g. Fig. 1) this is not strictly valid. The burst parameters can be found in Table 4. \)

### 3.3. Burst position in the Z

The colour-colour diagram (CD) of the data from the three different RXTE gain epochs is shown in Fig. 14, together with the source positions just before the burst (see also Table 2). To determine the position of the source in the CD at the time of the burst, we calculated the soft and hard colour values from 64 s intervals just before a burst. The three short bursts all occurred when the source was in the lower part of the NB. Among the long bursts, two occurred in the lower part of the HB, four in the NB, and one close to the NB/FB vertex. During the observations in 1996-2000 GX 17+2 spent about 28% of its time in the HB, 44% of its time in the NB, and 28% in the FB. It thus seems that the NB is overpopulated, whereas the FB is underpopulated with bursts \( \text{i.e. none occurred). However, by assuming that bursts have an equal chance to occur at each instant independent of branch, this result is not very significant \( \text{probability of 4% seeing 7 out of 10 bursts in the NB, and 7% of seeing none out of 10 bursts in the FB). Our conclusion does not change much if we include the EXOSAT/ME results reported by Kuulkers et al. (1997), i.e. during their total of 260 ksec of observing time GX 17+2 spent 11% of its time in the HB, 66% in the NB and 23% in the FB, with 3 bursts occurring in the NB and 1 in the (lower part of) the FB. This leads to total probabilities of 7% seeing 10 out of 14 bursts in the NB, and 6% seeing only 1 out of 14 bursts in the FB. \)

### 4. Search for burst oscillations

Following the method described by Leahy et al. (1983; see also Vaughan et al. 1994) we defined a 99% confidence level above which powers are regarded to be due to a real signal. This level depends on the number of trials, which basically is the number of independent frequency bins that are examined. In our search this number is \( \sim2\times10^7 \) which leads to a trigger level of 42.8 in the Leahy et al. (1983) nor-
Fig. 11. Spectral fit results for the net burst emission of bursts b2, b4 and b7–b10 plotted on a logarithmic time scale; from top to bottom: bolometric black-body flux, $F_{\text{bb,net}}$, in $10^{-8}$ erg s$^{-1}$ cm$^{-2}$, black-body temperature, $kT_{\text{bb}}$, apparent black-body radius, $R_{\text{bb,10}}$, at 10 kpc, and goodness of fit expressed in reduced $\chi^2$. The filled circles and open squares represent the fit results of the 0.25 s and 16 s spectra, respectively. The data have been logarithmically rebinned for clarity. For the 0.25 s spectral fits the number of dof is 18 for burst b4 and 16 for bursts b7–b10. For the 16 s spectral fits the number of dof is 44 for bursts b2 and b4, and 37 for bursts b7–b10.

malization. This level was never reached, indicating that no coherent oscillations were detected in any of the bursts. We inspected the frequencies of the highest observed powers. The powers occurred at apparently random frequencies, consistent with the idea that they are due to random fluctuations.

Since no powers were found above the trigger level, only upper limits to the strength of possible burst oscillations can be given (see van der Klis 1989; Vaughan et al. 1994). We used the (maximum) observed powers to determine a 99% confidence upper limit to a true signal power. These upper limit powers were then converted into the full amplitude of an assumed sinusoidal signal, which is given by:

$$A = 1.61 \sqrt{\frac{P}{N}} \left[ \text{sinc} \left( \frac{\pi \nu}{2 \nu_{\text{Nyq}}} \right) \right]^{-1},$$

where $P$ is the (upper limit) signal power (Vaughan et al. 1994; Groth 1975), $N$ the number of photons used in the FFT, $\nu$ the frequency at which the power was found, and $\nu_{\text{Nyq}}$ the Nyquist frequency. Table 5 gives the upper limits on $A$ for all bursts — each burst was divided into four parts: 5 s before the rise, the rise, the peak, and decay (= end of peak + 2$t_{\exp}$). Note that $A$ is a factor $\sqrt{2}$ larger than the rms amplitude that is often quoted.

The values of the upper limits are not very constraining. Only those obtained from the 2 s FFTs in the 2–60 keV band are well below the strongest values observed in some of the atoll sources (see e.g. Strohmayer 1998, 2000a).

5. Discussion

5.1. X-ray burst properties

Of the ten X-ray bursts from GX 17+2 seen so far with the RXTE/PCA, three are rather short (>10 s), whereas the other seven have durations of ~6–25 min. They all show evidence for cooling of the neutron star photosphere during the (exponential) decay, confirming previous results. The burst durations found are in the range seen previously (Kahn & Grindlay 1984; Tawara et al. 1984c; Sztajno et
al. 1986; Kuulkers et al. 1997). Using the time resolved X-ray spectral fits (see Sect. 5.2) we determined typical burst parameters, i.e. burst fluence, $\tau$ (a characterisation of the burst decay time), $\gamma$ (indicating the net brightness of the burst with respect to the persistent level) and $\alpha$ (comparison between total net burst flux and total persistent flux in between bursts). Since not all these parameters were given for GX 17+2 bursts observed previously, we (re-)determined these values from the information given in the various papers. This is explained in Appendix A and the results are given in Table A.1. Again, our values for the burst parameters for both the short and long bursts are comparable to those for the bursts observed previously. Since observations with RXTE are interrupted by either SAA passages or Earth occultations, and the fact that the length of each ‘continuous’ observation was limited (~hours) we could not determine the separation in time between bursts. One of our short bursts occurred, however, ~5.8 hr after a long burst. So far this is the shortest recurrence time encountered for bursts in GX 17+2. Our lower limits on $\alpha$ are rather low. However, from the bursts observed previously, it is found that $\alpha$ always exceeds ~1000. This means that most of the accreted material is being burned continuously. The fluences of the bursts from GX 17+2 are either ~$5.5 \times 10^{38}$ erg cm$^{-2}$ (short bursts) or $140 - 670 \times 10^{38}$ erg cm$^{-2}$ (long bursts). At a distance of 10 kpc (but see Sect. 5.3) these correspond to total energies of $6.5 \times 10^{38}$ erg and $2 - 8 \times 10^{40}$ erg, respectively, within the range seen for type I bursts (see e.g. Lewin et al. 1993).

One short burst was rather faint, with a peak intensity which was a factor of ~0.8 lower than for the other bursts, and displayed two peaks in the light and bolometric flux curves. This burst resembles the (relatively) weak double-peaked bursts seen from 4U 1636−53 (Sztajno et al. 1985; Fujimoto et al. 1988). Such bursts are clearly not radius expansion/contraction events, but are instead thought to be due to the mixing of fresh material into the unstably burning layer; such mixing may be caused by shear instabilities in the outer envelope of the neutron star (Fujimoto et al. 1988).

We show for the first time that almost all of the long bursts of GX 17+2 have episodes of radius expansion and contraction of the neutron star photosphere. The expansion and initial contraction all occur during the first
Table 4. Burst parameters

<table>
<thead>
<tr>
<th>burst</th>
<th>$F_{\text{b, max}}^a$</th>
<th>$E_b^b$</th>
<th>$\tau$ (s)</th>
<th>$\gamma$</th>
<th>$\alpha$</th>
</tr>
</thead>
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<tr>
<td>b1</td>
<td>1.59±0.06</td>
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<td>3.39±0.14</td>
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<td>271±11</td>
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<td>396±22</td>
<td>2.3±0.1</td>
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<td>102±5</td>
<td>1.9±0.2</td>
<td>≥20</td>
</tr>
</tbody>
</table>

- $^a$ Peak net-burst black-body flux in $10^{-8}$ erg s$^{-1}$ cm$^{-2}$.
- $^b$ Burst fluence in $10^{-8}$ erg cm$^{-2}$.
- $^c$ Using the 16 s spectral fit results.
- $^d$ Assuming that between burst b4 and b5 no other bursts occurred.

Table 5. Upper limits on burst oscillations

<table>
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<tr>
<th>burst</th>
<th>$\phi^a$</th>
<th>upper limits on fractional amplitude $^b$</th>
<th>burst</th>
<th>$\phi^a$</th>
<th>upper limits on fractional amplitude $^b$</th>
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<td>0.48</td>
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</table>

- $^a$ Phase of burst profile: b=before burst, r=rise, p=peak, d=decay.
- $^b$ 99% confidence upper limits in the 50-2000 Hz frequency range.
- $^c$ Assuming that between burst b4 and b5 no other bursts occurred.

few seconds of the bursts. However, the final contraction phase lasts from ~20 s up to ~180 s. During the expansion/contraction phase the net burst flux remains constant, presumably at the Eddington value. Long contraction phases might be caused by long phases of unstable hydrogen burning, whose time scale is limited by $\beta$-decays, up to ~100 s after the burst has started (see e.g. Bildsten 1998, 2000, and references therein). The maximum apparent radius, $R_{\text{bb}}$, reached during the expansion episodes is ~30 km (at 10 kpc). Corrected for gravitational redshift effects and spectral hardening (see Appendix B), the maximum photospheric radius $R_{\text{bb}}$ (as measured by a local observer) is probably ~90–125 km. We do not see evidence for a change in the cut-off power-law component above ~10 keV up to these radii. This suggests that either the environment in between the neutron star surface and expanded photosphere at ~90–125 km is involved in producing the high-energy radiation but was not affected, or the inner disk and corona which presumably produce the high-energy radiation do not extend down to the neutron star. A possibility is that the magnetospheric radius extends out to at least these radii, disrupting the disk.
Fig. 13. Top panel: Average observed net burst (i.e. total source minus persistent emission) spectrum during the flat top of burst b6, i.e. from 27 to 187 s after the start of the burst. A black-body fit is shown ($kT_{bb}=2.658\pm0.015$ keV, $R_{bb,10}=4.65\pm0.06$ km, $\chi^2_{red}=2.4$ for 37 dof). Bottom panel: Residuals after subtracting the best fit black-body model from the observed spectrum.

Fig. 14. Colour-colour diagrams of the RXTE/PCA observations of GX 17+2 (after Homan et al. 2001). The left, middle and right panels refer to the observations done during RXTE gain epochs 1, 3 and 4, respectively. The soft colour is defined as the count rate ratio in the 4.7–7.1 keV to the 2.9–4.7 keV energy bands for the epoch 1 data, in the 4.8–7.3 keV to the 3.0–4.8 keV energy bands for the epoch 3 data, and in the 4.6–7.1 keV to the 2.9–4.6 keV energy bands for the epoch 4 data. The hard colour is defined as the count rate ratio in the 10.6–19.8 keV to the 7.1–10.6 keV energy bands for the epoch 1 data, in the 10.5–19.7 keV to the 7.3–10.5 keV energy bands for the epoch 3 data, and in the 10.5–19.6 keV to the 7.1–10.5 keV energy bands for the epoch 4 data. Each point represents an average of 16 s. We have indicated the position of the source during 64 s intervals just before a burst (indicated by b1, b2, ..., b10, in chronological order), and the three limbs of the Z (HB, NB, FB). Since the HB is not clearly distinguishable from the NB in this figure, we have indicated the approximate HB/NB vertex by a line.
sion just before the long bursts in other sources is \(\sim 1\%\) of the Eddington value, i.e. a factor of \(\sim 100\) lower than in GX 17+2 (see also Sect. 5.4).

We note that even longer X-ray bursts do exist, which last for several hours (Cornelisse et al. 2000, Strohmayer 2000b, Wijnands 2001, Kuulkers 2001). Their recurrence time is much longer than normal type I bursts (\(\gtrsim 7.5\) days, Cornelisse et al. 2001; \(\lesssim 4.8\) yrs, Wijnands 2001), and they seem to occur at persistent luminosities which are a factor of \(\sim 0.1\)–\(0.2\) of the Eddington limit.

### 5.2. Black-body spectral fits

#### 5.2.1. Decoupled persistent and burst emission

It has previously been pointed out (van Paradijs & Lewin 1986; see also Sztajno et al. 1986) that, if the persistent emission before the burst contains a spectral component which originates from the same regions as the burst emission, this should be taken into account in the spectral analysis of X-ray bursts. This is especially the case when the neutron star is accreting matter at high rates such as thought to be the case in Z sources, making the neutron star hot and radiate soft (black-body) emission. ‘Standard’ X-ray burst spectral analyses (modeling the net-burst emission by black-body radiation) then results in systematic errors in the spectral parameters, especially during the end of the burst when the net-burst luminosity is small. It was therefore suggested to model the total burst emission using a two-component approach, i.e. with a soft component (usually a black body) and a hard component (fixed at the parameters found for the persistent emission). The former component is thought to contain all emission from the neutron star photosphere, while the latter component is assumed to be from the accretion disk and not affected by the prompt burst. However, we find that using this two-component spectral fitting approach does not give satisfactorily results (i.e. we get bad fits). Instead, the ‘standard’ burst analysis, which assumes the persistent emission continues unchanged, gives satisfactory results.

This result suggests that the persistent emission is unaffected during the burst and that the persistent blackbody component (which is not always present) does not arise from the same region as the burst emission, contrary to what was previously assumed. We find that during the initial exponential decay phase the neutron star photosphere shows pure black-body cooling, both for the short and long bursts. During that stage the apparent black-body radius stays constant at 5–6 km (at 10 kpc). Comparing these radii with the apparent radii of the black-body component of the persistent emission (if present) indicates that the persistent black-body component originates from a larger area than of the burst emission. The inner part of the accretion disk or an expanded boundary layer (see below) are the most obvious sites for this persistent soft component. A recent study of X-ray spectra from LMXBs with luminosities spanning several orders of magnitude has shown that the persistent blackbody emission likely does not arise in (part of) the accretion disk (Church & Balucinska-Church 2001). Instead, a detailed study of the structure and emission from accretion disk boundary layers around neutron stars (Popham & Sunyaev 2001) has shown that at very high accretion rates (near Eddington values) the boundary layer expands radially, with radial extents larger than one stellar radius. Moreover, at these high rates the expected emission from the boundary layer has a spectrum that strongly resembles black-body spectra. The fact that we see black-body emission in the persistent spectra with apparent radii which are larger (factor \(\sim 2\)–\(3\)) than the neutron star (see also Church & Balucinska-Church 2001) is in line with this. Still, one would expect that such a boundary layer would be affected by the bursts (see Popham & Sunyaev 2001), of which we do not see clear evidence from our spectral fits (see also previous Section). We note, however, that Homan et al. (2001), who studied the properties of the NB and FB quasi-periodic oscillations (NB/FB QPO or NBO/FBO) during bursts b4 and b10, found that during the bursts the absolute amplitude of these QPOs decreased significantly. This suggests that the inner accretion flow is affected by the increase in the radiation from the neutron star, contrary to what our spectral results indicate. Apparently the QPO mechanism of the NBO/FBO is much more sensitive to the radiation field than the bulk flow of matter itself. This is in accordance with models for NBO/FBO (Fortner et al. 1989), which require a delicate balance between the radiation field and the accretion flow, that might easily be disrupted during X-ray bursts.

#### 5.2.2. Deviations from black-body emission

The emission from a (hot) neutron star is not expected to be a perfect black-body (van Paradijs 1982; London et al. 1984, 1986; see also Titarchuk 1994; Madej 1997, and references therein). This results in a systematic difference between the effective temperature (as would be measured on Earth), \(T_{\text{eff,\infty}}\), and the temperature as obtained from the spectral fits (also referred to as ‘colour’ temperature), \(T_{\text{bb}}\). In general, the deviations from a Planckian distribution will depend on several parameters, such as temperature, elemental abundance, neutron star mass and radius. The hardening factor, \(T_{\text{bb}}/T_{\text{eff,\infty}}\), has been determined through numerical calculations by various people and its value is typically around 1.7. When the burst luminosity approaches the Eddington limit the deviations from a black-body become larger, and so does the spectral hardening (\(T_{\text{bb}}/T_{\text{eff,\infty}} < 2\), Babul & Paczyński 1987; Titarchuk 1988). During extreme radius expansion phases, however, this trend may break down and \(T_{\text{bb}}/T_{\text{eff,\infty}} < 1\) (Titarchuk 1994). Attempts have been made to determine the spectral hardening from the observed cooling tracks, but are still rather uncertain (e.g. Penninx et al. 1989). As a result, the interpretation of X-ray bursts spectra has
remained uncertain and constraints on the mass-radius relationship for neutron stars elusive.

During the radius expansion/contraction phase blackbody emission does not provide a good description of our observed net-burst spectra, leaving a slight excess in emission between ~5.5–10 keV and lack of emission between ~3–5.5 keV (Fig. 11). Such systematic deviations have been observed before, especially during the radius expansion/contraction phases. For example, spectra obtained with the Large Area Counter (LAC) onboard Ginga during the long burst of 4U 2129+11 (van Paradijs et al. 1990) show remarkably similar deviations at the same energies as we see in GX 17+2. The persistent mass accretion rate in 4U 2129+11 is inferred to be a factor of ~100 lower than for GX 17+2; this indicates that the radiation properties of the photospheres are the same when they are radiating near the Eddington luminosity, which is independent of the persistent mass accretion rate. As noted by van Paradijs et al. (1990), the ‘bumpiness’ of the residuals point to the presence of relatively narrow-band spectral features, rather than the residuals being due to broad-band spectral hardening at Eddington luminosities.

From our ‘standard’ spectral analysis, we find that the apparent black-body radii decrease near end of the decay. This was also inferred from the EXOSAT/ME observations of GX 17+2 (Sztajno et al. 1986), and has been seen in other sources as well (e.g. Chevalier & Ilovaisky 1990). If this were due a real decrease in the burst emitting area one might expect to see burst oscillations due to the spinning neutron star. We do not see evidence for this. If the expanded boundary layer reacts to its changing environment on the same time scale as the burst itself then variations in this layer’s structure could also play a role here.

The observed behaviour resembles the systematic effects described by van Paradijs & Lewin (1986), which occurs near the end of the bursts in the presence of a persistent hot neutron star component. However, we have argued that the persistent black body component does not contribute to the burst emission, so this is not a viable explanation. Sztajno et al. (1986) argued that this effect also can not be due to spectral hardening, since that would lead to an apparent radius increase with decreasing T$_{bb}$. Their argument was based on the assumption that the spectral hardening decreases with decreasing temperatures (and therefore decreasing burst luminosity), see also Sztajno et al. (1985). However, later model calculations have shown that in fact spectral hardening increases again whenever the burst luminosity drops below a certain value (L$_{bb}$<0.2L$_{Edd}$, e.g. London et al. 1986, Ebisuzaki 1987). For an assumed constant size of the emission region during the cooling stage (presumably the whole neutron star surface), the apparent radii will then become smaller as T$_{bb}$ decreases, consistent with what is observed.

5.2.3. The radius expansion/contraction track

The observed net burst flux remains rather constant during the radius expansion/contraction phases (F$_{bb,net}$ ~1.24×10$^{-8}$ erg s$^{-1}$ cm$^{-2}$ for burst b6, with a reduced $\chi^2$ of 1.4 for 29 dof, excluding the highest flux point). However, for a constant composition and constant (an)isotropy of the radiation, one would expects to see a slight increase in the observed bolometric burst flux with increasing photosphere radius, since the gravitational redshift decreases (see e.g. Lewin et al. 1993). In Fig. 15, we zoom in on the observed radius expansion/contraction phase of burst b6 (note that for F$_{bb,net}$ and T$_{bb}$ we now use a linear scale). Overdrawn is an example of the expected relation between bolometric burst flux and the photospheric radius (continuous line), for ‘standard’ values of $M_\text{ms}=1.4M_\odot$, $X=0.73$, T$_{bb}$/T$_{\text{eff},\infty}=1.7$, and high-temperature electron scattering opacity, see Appendix B for details. The curve was normalized so as to give the observed values of F$_{bb,net}$ and T$_{bb}$ at touch down (at the leftmost point of the radius expansion/contraction track). In practice this is analogous to solving for the distance and the photospheric radius R at touch down (see Appendix B). Taking the generally used low-temperature electron scattering opacity (but keeping the other parameters at their ‘standard’ values, see above) makes the disagreement even larger (dash-dot-dot-dotted line in Fig. 15). There are three ways to flatten the radius expansion/contraction track, or, equivalently, to reduce the gravitational redshift corrections. The most obvious one is to lower the mass of the neutron star; the expected track (dash-dotted line) for $M_\text{ms}=0.5M_\odot$ is given. However, such a low-mass neutron star is in not in line with the observed and expected masses for neutron stars (see e.g. Thorsett & Chakrabarty 1999). A second option is to lower the hydrogen content of the burning material (shown by the dashed line for X=0). However, the long contraction phase is typical for unstable mixed H/He-burning (see Sect. 5.4) and not expected for unstable pure He-burning. Moreover, the distance derived at touch down is then rather high (d=15.2 kpc for X=0, see also Appendix B). Finally, increasing the hardening factor to T$_{bb}$/T$_{\text{eff},\infty}=2$, also flattens the expected track (dotted line in Fig. 15). This may be the most realistic option, since spectral hardening values of ~2 are inferred for burst luminosities near the Eddington limit (Babul & Paczyński 1987; but see Titarchuk 1994, where T$_{bb}$/T$_{\text{eff},\infty}<1$ at very large photospheric radii). We note that the effects of an expanded boundary layer, as discussed in the previous Section, may also be of importance here. However, at present it is uncertain how to take this into account.

5.3. The distance to GX 17+2 and the persistent emission

Assuming that during the expansion and contraction phase the net-burst luminosity equals the Eddington luminosity we are able to estimate the distance to GX 17+2.
As noted before (Lewin et al. 1993; see also recent discussions of parameters, see text. The radius of the photosphere, $R$, presumably equals the radius of the neutron star surface. We find values of $R > 12 - 20 \text{ km}$, where the range arises from the different assumptions in deriving these radii (see Appendix B). These are slightly higher than the ‘canonical’ value for the neutron star radius of 10 km.

One can also use the radius expansion events to get an idea of the strength of the persistent luminosity in Eddington units, without the knowledge of the distance to the source, mass of the neutron star, etc. However, for long events we find that the total persistent emission before/after the burst is a factor of 2–3 larger than the net-burst emission during expansion/contraction phase. If indeed the maximum net-burst flux equals the Eddington flux, then this would imply that the persistent flux is 2–3 times the Eddington flux. From the models characterising the behaviour of Z sources it is inferred that on the HB, NB and FB, the mass accretion rates (and therefore luminosity) are just below, at or just above Eddington values, respectively (e.g. Hasinger 1987; Lamb 1989; Hasinger et al. 1990). The only way out is that the (net) burst emission is (highly) anisotropic with respect to the persistent emission. Since the true luminosity values should be more or less comparable, one thus infers an anisotropy factor of ~2 for the (net) burst emission. This cannot be ascribed to localized emission on the neutron star (see also Section 5.4), but might be due to part of the burst emission being hidden behind a puffed-up inner accretion disk.

In the case of highly anisotropic burst emission ($\xi \sim 2$) the distance estimate to GX 17+2 is reduced to ~8 kpc (see Appendix B). This estimate is comparable to that derived for other similar X-ray sources (e.g. Christian & Swank 1997; Schulz 1999). We note that anisotropic burst emission may also explain the apparent inconsistency in the distance to Cyg X-2 from a radius expansion burst, i.e. ~11.6 kpc (Smale 1998; for a 1.9 $M_\odot$ neutron star, peak photospheric radius of 26 km, cosmic abundances, low temperature opacity, no spectral hardening; see also Appendix B), and that derived from optical measurements, i.e. 7.2 kpc (Orosz & Kuulkers 1999). However, for Cyg X-2 the persistent flux before the burst was derived to be of the same order as the net peak burst flux.

5.4. X-ray bursts and (extreme) mass accretion rates

We found no significant correlation between the burst parameters and the position of the source in the Z-track at the time of the bursts, i.e. both long and short bursts may occur at similar mass accretion rates. We find that no X-ray bursts occurred when the source was on the FB, despite considerable coverage compared to the other branches of the Z. However, this result is not sufficiently significant to exclude the possibility that bursts occur on the FB as frequently as elsewhere. We do note that the absence of bursts on the FB is consistent with theoretical expectations (see Sect. 1; e.g. Bildsten 1998, 2000), as the mass accretion rate on the FB is thought to be super-Eddington (e.g. Hasinger 1987; Lamb 1989; Hasinger et al. 1990).

At near-Eddington accretion rates, long bursts are expected from X-ray burst theory (see Sect. 1; see also van Paradijs et al. 1988). These are thought to be due to mixed H/He burning, triggered by thermally unstable He igni-
tion. The fast rise and the short radius expansion part of the long bursts resemble pure helium flashes which last on the order of 5–10 s, although in the case of GX 17+2 the recurrence times of these bursts are on the order of a day instead of the expected hours for typical pure helium flashes. This flash triggers the long phase of unstable mixed H/He burning. Our analysis gives the first example of the existence of such long bursts at high (near-Eddington) accretion rates. However, GX 17+2 also displays short (~10 s) bursts, which are not expected at high accretion rates. Similarly, Cyg X-2, also accreting at near-Eddington values, displays rather short bursts (~5 s). Such short bursts are only expected for accretion rates which are a factor of 20–100 lower.

Since it is not the global mass accretion rate that matters, but the mass accretion rate per unit area (e.g. Marshall 1982; see also Bildsten 2000), it might be that at different times the area which accumulates most of the accreted matter differs, giving rise to short and long bursts. However, if the areas are relatively small, pulsations are expected due to the neutron star rotation (unless the accreted matter is distributed symmetrically along the rotation axis, such as in an equatorial belt). We do not see any evidence for this.

The properties of X-ray bursts depend not only on the mass accretion rate (per unit area), but also on the temperature of the neutron star envelope and composition of the accreted material (e.g. Fushiki & Lamb 1987; Taam et al. 1996; see also Bildsten 1998, 2000; Lamb 2000). At high accretion rates and high envelope temperatures the combined He flash and mixed H/He burning occurs; however at high accretion rates and low envelope temperatures only He flashes may occur (see Lamb 2000). The difference in envelope temperature at different times may indeed explain the occurrence of the two types of bursts, and it would be worthwhile to explore this further. It is not clear, however, how such different envelope temperatures could be reached at very similar accretion rates. The composition of the accreted material is not expected to change much, since fresh matter arrives at high rates.

The situation at high mass accretion rates becomes even more confused when one considers the other Z sources (Sco X-1, GX 5–1, GX 340+0, GX 349+2, Cyg X-2) as well as the bright ‘GX atoll’ sources (GX 3+1, GX 13+1, GX 9+1, GX 9+9). The latter are thought to accrete with rates around 10% of the Eddington mass accretion rate (Psaltis & Lamb 1998; see also Kuulkers & van der Klis 2000). For those sources, only short (~10–15 s duration) bursts are seen (infrequently) in GX 3+1 (Makishima et al. 1983; Asai et al. 1993; Molkov et al. 1999; Kuulkers & van der Klis 2000) and GX 13+1 (Matsuba et al. 1995) and no bursts have been reported for GX 9+1 and GX 9+9, despite ample observing times.

The X-ray spectral and fast timing properties of the other five canonical Z sources are very similar to those of GX 17+2 (see Hasinger & van der Klis 1989; van der Klis 2000), and thus one would infer comparable mass accretion rates (but see Homan et al. 2001). Of the five of these sources, however, only Cyg X-2 shows X-ray bursts, which are typical He flashes, whereas the others do not burst at all (despite ample observing times). Since at very high accretion rates no bursts are expected one would then naively infer that the average mass accretion rate is different, i.e. higher, in the four non-bursting Z sources with respect to the two bursting Z sources. But this would imply that the correlated X-ray spectral and fast timing properties are not a function of the inferred mass accretion rate, See van der Klis (2001) for a possible way in which the correlated properties could vary in response to changes in the mass accretion rate without being a function of it. Also, note that differences in mass accretion rate per unit area may be of importance here, as was already suggested by Kuulkers et al. (1997) to explain the properties of quasi-periodic oscillations occurring on the HB and upper parts of the NB, and the presence of bursts in GX 17+2. On the other hand, since the envelope temperatures and composition also influence the bursting properties, they may be of importance too (e.g. Taam et al. 1996). Future modelling may provide more insight in the processes involved.

6. Conclusions

We found ten X-ray bursts in all data on GX 17+2 obtained with the RXTE/PCA to date. Three had a short duration (~10 s), while the others had durations ranging from ~6 to 25 min. All the bursts showed spectral softening during the decay, suggestive of cooling of the neutron star. No evidence for high-frequency (>100 Hz) oscillations at any phase of the bursts is seen. We also find no evidence for correlations of the burst properties with respect to the source position near the time of the burst in the colour-colour diagram (presumably a function of the mass accretion rate). The long bursts are consistent with being due to mixed H/He burning, triggered by thermally unstable He ignition, as is expected to occur at the inferred persistent mass accretion rates we encounter in GX 17+2, i.e. near-Eddington rates. However, the presence of short bursts in GX 17+2, as well as short bursts in another persistently bright LMXB, Cyg X-2, and no bursts in the other four similar LMXBs (Sco X-1, GX 5–1, GX 340+0 and GX 349+2), is not accounted for in the current X-ray burst theories. Note that this also holds for the bright ‘GX atoll’ sources (GX 3+1, GX 13+1, GX 9+1 and GX 9+9), which are thought to accrete near one tenth of the Eddington rate. Of these four atoll sources, only GX 3+1 and GX 13+1 infrequently show short (~10 s) X-ray bursts, whereas GX 9+1 and GX 9+9 have not been seen to burst at all.

We found that two-component spectral fits to the total burst emission, as has been suggested previously, do not give satisfactory results whenever the persistent emission before and/or after the burst contains a black-body contribution. On the other hand, the ‘standard’ spectral fit analysis, in which burst spectra after modeled by black-body radiation after subtraction of the persistent emission before and/or after the burst, does provide satisfactory
results. This means that whenever there is a black-body contribution in the persistent emission before and/or after the burst, it is probably also present during the burst (i.e. the burst black-body emission appears on top of the persistent black-body emission). This implies that the black-body component often seen in the persistent emission does not arise at the same site as the burst emission. We find evidence that the region of the persistent black-body emission is larger than that of the burst emission, which indicates that it probably originates in an expanded boundary layer, as recent modeling indicates.

Five of the long bursts showed evidence for an expanding photosphere during the first seconds of the burst, presumably due to the burst luminosity reaching Eddington values. The contraction phase differs in duration between the bursts, the longest being ~3 min. The net burst fluxes reached during the radius expansion/contraction phase are all more or less similar, which is indicative of the Eddington limit as observed at earth.

The total persistent flux just before the burst is inferred to be a factor 2-3 higher than the net burst flux during the radius expansion/contraction phase. If in both cases the emission is isotropic, this would imply that the persistent emission is a factor of 2-3 higher than the Eddington luminosity. We suggest that the burst emission is (highly) anisotropic. Since (theoretically) both the persistent luminosity in GX 17+2 and the (net) burst luminosity during the expansion/contraction phase are thought to have near Eddington values we then derive an anisotropy factor of ~2 for the burst emission.

When the burst luminosity is close to Eddington values, deviations from pure black-body radiation are evident below 10 keV. Similar deviations have been seen during other (long) X-ray bursts in other low-mass X-ray binaries, and can not be explained by spectral hardening. Assuming that the black-body approximation is, nevertheless, valid, and assuming that the net burst peak fluxes during the radius expansion/contraction phase equals the Eddington limit as seen on Earth, and assuming an anisotropy factor of ~2, we estimate the distance to GX 17+2, taking into account gravitational redshift effects and spectral hardening. For 'standard' parameters ($M_{ns}$=1.4 $M_{\odot}$, cosmic composition) we derive a distance ~8kpc. We estimate the systematic uncertainties on our derived distances to be up to ~30%.

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Appendix A: X-ray bursts from GX 17+2 observed with other instruments

X-ray bursts from GX 17+2 have been previously seen with the Monitor Proportional Counter (MPC) onboard the Einstein Observatory (Kahn & Grindlay 1984), the second Fine Modulation Collimator (FMC-2) onboard Hakucho (Tawara et al. 1984c) and the Medium Energy (ME) experiment onboard EXOSAT (Sztajno et al. 1986; Kuulkers et al. 1997). Not all the bursts parameters as tabulated in Table 4 for the bursts seen with the RXTE/PCA have been given by these authors. In order to compare our bursts in more detail with the other observed bursts we decided to extract the parameters from the information given in these papers. Since the X-ray energy ranges in which the different instruments operate are comparable and the fact that most of the (burst) emission is radiated in these energy bands, such a comparison is feasible. In the next subsections we describe how the parameters were determined for the different bursts.

A.1. MPC/Einstein

Kahn & Grindlay (1984, see also Kahn et al. 1981) observed a burst from GX 17+2 in 1980 with the MPC onboard Einstein, with a decay time of \( \sim 7.5 \) s. From their background subtracted count rate profiles in the 1.4–14.4 keV energy band (their figure 1) we determined the values for \( \gamma \) and \( \tau \). The value of \( \gamma \) is consistent with what is inferred using the quoted net peak and persistent count rate of 0.15 and 0.56 Crab (\( \sim 2 \) keV), respectively, by Kahn et al. (1981). The persistent flux before the burst was given as \( 1.56 \pm 0.02 \times 10^{-8} \text{erg cm}^{-2} \text{s}^{-1} \) (1–20 keV). Kahn & Grindlay (1984) report a maximum peak flux of 9.1 \( \times 10^{-8} \text{erg cm}^{-2} \text{s}^{-1} \) (1–20 keV), however, no error is given (only a \( \pm \) sign). It is not clear whether there is a typo involved or not. Moreover, this peak flux is much higher than that observed for the other bursts. An averaged net spectrum over the burst profile (first 7.68 s) was modeled as black-body emission. Values of \( 3.8 \lesssim T_{bb} \lesssim 9.3 \) keV.
The burst was observed ∼57 min later (Kahn et al. 1981; note that no observation time is given by Kahn & Grindlay 1984). Using this and the observed rate just before the burst we determined an upper limit on α.

### A.2. FMC-2/Hakucho

Four bursts (two in 1981 and two in 1982; denoted A–D) were found, originating from GX 17+2, during pointed observations with the FMC-2 onboard Hakucho (Tawara et al. 1984c). They had e-folding decay times of ∼100 (B, C) or ∼300 s (A, D). For each burst Tawara et al. (1984c) tabulated the net peak, net total (=fluence) and persistent flux in FMC-2 cts s$^{-1}$ in the 1–22 keV band. From this they calculated γ. Using this information we calculated τ and verified γ. Tawara et al. (1984c) also provided the total integrated energy flux (= total fluence) of the two bursts in 1981 and the two bursts in 1982, together with the integrated persistent fluxes over 40 hr and 50 hr, respectively. Note that it is not clear if the fluence and persistent flux are both given for the 1–22 keV energy band, and whether the persistent fluxes are corrected for interstellar absorption or not. From this it was estimated that α was of the order of 1000. Since the net fluence in counts of all bursts individually are given, we can determine the individual fluence in energy flux. Also, the (mean) persistent flux during the two observations can be determined.

And black-body emission area, $A_{bb}$, of 0.56 $\lesssim A_{bb} \lesssim 3.2 \times 10^{12}$ cm$^2$ (at 10 kpc) were found. This, in principle, may give us a handle on the observed fluence. However, this gives us a value of $E_b$ of $\sim 161 \times 10^{-6}$ erg cm$^{-2}$ (using $T_{bb} \sim 6.55$ and $A_{bb} \sim 1.88 \times 10^{12}$ cm$^2$), which is also much larger than observed for the other short bursts. We, therefore, do not quote the peak flux and burst fluence in Table A.1. Using the Einstein database maintained at HEASARC$^4$ we found the start of the simultaneous HRI observation as being March 29, 1980, 00:48:06 (UTC). The burst was observed ∼57 min later (Kahn et al. 1981; note that no observation time is given by Kahn & Grindlay 1984). Using this and the observed rate just before the burst we determined an upper limit on α.

Moreover, assuming that between bursts A and B, which occurred 12.5 hr after each other, no other bursts occur, we give a more exact value for α in this case (assuming a constant persistent flux). For the others we just assume the given value of 1000. We also give an estimate of the peak net burst fluence, from the observed values of $F_{pers}$ and γ.

### A.3. ME/EXOSAT

Two bursts were found in the EXOSAT/ME observations taken in 1984 and 1985 with durations of ∼10 s and over 5 min (Sztajno et al. 1986; denoted as burst I and II by Kuulkers et al. 1997). The persistent flux (2–10 keV) before a burst was determined from the spectral fits using a bremsstrahlung plus a black-body component, subjected to interstellar absorption. The values for the bremsstrahlung parameters and $N_H$ were given in the text, whereas the black-body results were indicated in their figures 4 and 5. The spectral fit results to the net burst emission are shown in their figures 2 and 3, from which we determined the bolometric maximum net peak fluence and the fluence. To determine the ‘rest’ fluence, we used the same approach as mentioned in Sect. 3.2.4, and fitted an exponential to the burst flux decay. In the case of burst I we have only 3 values; we therefore assumed that at infinity the burst flux decays to zero, while the exponential start time was set to the start of the burst. Since the spectral time resolution is not sufficient, we determined the burst parameters γ and τ from the observed raw (i.e. not dead-time corrected) count rate profiles (1–20 keV) given in their figure 1. We corrected the light curves for the ‘variable’ dead time (van der Klis 1989), as appropriate for the EXOSAT High Energy Resolution (HER) modes (see e.g. Kuulkers 1995). Sztajno et al. (1986) noted that in both bursts the maximum flux is ∼40% above the persistent level, indicating γ∼2.5, in rough agreement with our estimates. Using the start time of the two observations

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$^4$ See http://heasarc.gsfc.nasa.gov/.
during which the bursts occurred, as given by Kuulkers et al. (1997), and assuming that the persistent flux was constant, we were able to determine lower limits on $\alpha$. Note that Sztajno et al. (1986) gave rough upper limits of $\sim 10000$ and $\sim 500$, for burst I and II, respectively, which are more or less consistent with our determined values.

For the two bursts (denoted as burst III and IV) observed in 1986 discussed by Kuulkers et al. (1997) we only estimated $\gamma$ and $\tau$ from the observed (dead-time and background corrected) count rate profiles in the 1–20 keV band as displayed in their figure 7. $\tau$ is determined using the integrated net burst count rate profile and peak count rate. No spectral information is available for the persistent or burst emission in order to determine $F_{bb,max}$, $F_b$ and $\alpha$, although they note that $\alpha$ is probably larger than $\sim 1000$ for the second burst, if no bursts occurred in between the two bursts. However, if we naively assume that the persistent count rate is constant between bursts, and that between the start of the 1986 EXOSAT observation and the first burst, and between the two bursts, no other burst occurred, we can still get a crude estimate of (the lower limit on) the value of $\alpha$.

Appendix B: Distance estimate and gravitational redshift effect

Most of the distances derived from radius expansion bursts in the literature are solely based on the observed fluxes at maximum expansion, $F_{bb,max}$, and assuming this equals the (non-relativistic) Eddington luminosity, $L_{Edd,non-rel}$, from a source at distance $d$. Here one uses $L_{Edd,non-rel} = 4\pi GM_{ns}/\kappa$, where $c$ is the speed of light, $G$ the gravitational constant, $M_{ns}$ the mass of the neutron star and $\kappa$ the electron scattering opacity. Then the distance may be estimated as:

$$d = \left( \frac{L_{Edd,non-rel}}{4\pi F_{bb,max}} \right)^{1/2},$$

(B.1)

where $\xi$ is the anisotropy factor (for isotropic radiation $\xi = 1$). However, when the photosphere remains rather close to the neutron star, gravitational redshift effects become important (due to relativistic time dilation, see e.g. Lewin et al. 1993). The distance derived using Eq. B.1 is in fact only valid for values of the photosphere radius, $R > R_{ns}$ (see below). For $R > R_{ns}$ Eq. B.1 in principle only provides an upper limit on $d$.

The (relativistic) Eddington luminosity for an observer near the neutron star is given by:

$$L_{Edd} = \left( \frac{4\pi GM_{ns}/\kappa}{c} \right) \left[ 1 - 2GM_{ns}/(Rc^2) \right]^{-1/2}.$$  

(B.2)

For an observer at Earth, Eq. B.2 becomes, taking into gravitational redshift effects:

$$L_{Edd,\infty} = L_{Edd} \left[ 1 - 2GM_{ns}/(Rc^2) \right] = L_{Edd} \left[ 1 - R_g/R \right],$$

where $R_g$ is the Schwarzschild radius ($R \geq 1.5R_g$; see Lewin et al. 1993). Also the effective black-body temperature measured at Earth, $T_{eff,\infty}$, is affected by the gravitational potential:

$$T_{eff,\infty} = T_{eff} \left[ 1 - R_g/R \right]^{1/2},$$

(B.4)

where $T_{eff}$ is the effective black-body temperature near the neutron star. Assuming that the source radiates as a black-body, we know that:

$$L_{Edd} = 4\pi R^2 \sigma T_{eff}^4.$$  

(B.5)

For $L_{Edd,\infty}$ we also have:

$$L_{Edd,\infty} = 4\pi d^2 \xi F_{Edd,\infty}.$$  

(B.6)

where $F_{Edd,\infty}$ is the Eddington flux received at Earth.

Eqs. B.3 and B.4 are strictly valid only for non-rotating stars, but it is still approximately correct for stars with rotation periods of a few milliseconds. $F_{Edd,\infty}$ is set equal to the observed net-burst fluxes, $F_{bb,net}$, during the radius expansion/contraction phase. As noticed in Sect. 5.2, it is not easy to infer $T_{eff,\infty}$ from our observed values of $T_{bb}$. We therefore fixed the hardening factor, $T_{bb}/T_{eff}$, to different values in order to assess its effect. We also assume certain values for $M_{ns}$ and $\alpha$, and are then left with five equations (B.2–B.6) and five unknown variables ($L_{Edd}$, $L_{Edd,\infty}$, $T_{eff}$, $R$ and $d$); this enables us to derive a distance estimate. First, one can eliminate $L_{Edd}$ and $T_{eff}$ by combining Eqs. B.2, B.4 and B.5, and one gets the following equality (for $R \geq 1.5R_g$):

$$\frac{cGM_{ns}}{\kappa \sigma T_{eff,\infty}^4} = R^2 \left( \frac{R}{R_g} \right)^{3/2}.$$  

(B.7)

Since this equation can not be solved easily in an analytic way, we solved for $R$ numerically. Using $R$ we can then determine $L_{Edd,\infty}$ (Eq. B.3), which in turn can be used to determine the distance, $d$ (Eq. B.6).

In the low-temperature limit the electron scattering opacity, $\kappa$, is given by $\kappa = 0.2(1 + X) \text{cm}^2 \text{g}^{-1}$, where $X$ is the hydrogen fraction (by mass) of the photospheric matter (see e.g. Lewin et al. 1993). Note that for cosmic compositions $X = 0.73$. At very high temperatures (i.e. probably near the peak of bursts), however, the scattering electrons become relativistic and $\kappa$ may instead be approximated by (in the low-density limit)

$$\kappa = \kappa_0[1 + (kT/39.2 \text{ keV})^{0.86}]^{-1},$$

where $\kappa_0$ is same as for the low-temperature limit (Paczynski 1983). It is not entirely clear how $kT$ relates to our observed values of $kT_{bb}$, but one may assume $kT = kT_{bb}$ (e.g. van Paradijs et al. 1990). We use the high temperature electron scattering opacity in our calculations. The estimated distances differ by a factor of $\sim 1.05$ with respect to the estimates when taking the electron scattering opacity in the low-temperature limit (see also Table B.2).

The above described procedure for estimating the distance was followed using the values for $F_{bb,net}$ and $T_{bb}$ for each of the spectral fits to the 0.25s and 16s spectra in the radius expansion/contraction phase. When we assume no spectral hardening, i.e. $T_{eff,\infty} = T_{bb}$, and ‘standard’
parameters ($M_{ns}=1.4M_\odot$, $X=0.73$) no solutions can be found for those spectra having $kT_{bb} \gtrsim 1.75$ keV, i.e. only at the largest expansion radii do we have solutions (see also Table B.2). The highest observed values of $kT_{bb}$ during the radius expansion/contraction phase give the strongest constraints on the spectral hardening factor. This is at the moment of ‘touch-down’, i.e. at the vertex of the horizontal track and diagonal track in the flux versus temperature diagram. This locus is well defined for our long bursts observed in GX 17+2. Using the loci of the radius expansion bursts b4, b6–b9, we find that the minimum value of the (constant) hardening factor is between 1.34 (burst b4) and 1.52 (burst b6). The distance and radius $R$ as inferred at the loci both increase for increasing spectral hardening (e.g. for burst b6, the distance increases by a factor $\sim 1.1$, while $R$ increases by a factor of $\sim 2$ when the spectral hardening factor increases from 1.6 to 2).

In Table B.1 the results for ‘standard’ burst parameters can be seen, i.e. $M_{ns} = 1.4M_\odot$, cosmic composition of the photospheric matter, isotropic radiation ($\xi=1$), as well as taking $T_{bb}/T_{eff,\infty}=1.7$ and using the electron scattering opacity appropriate for high temperatures. We show the distance as derived by including gravitational redshift effects ($d_{rel}$) and not including these effects ($d_{non-rel}$, i.e. using Eq. B.1). The errors are set equal to the observed variances in the derived distances.

By relaxing the assumptions of standard burst parameters (i.e. varying $M_{ns}$, $X$ and $\xi$ individually within reasonable limits, while keeping the others at the ‘standard’ values) one can get an estimate of the systematic uncertainties involved (see e.g. also Kuulkers & van der Klis 2000). The results are shown in Table B.2 for burst b6, which is the longest burst of our sample. We show the results assuming a neutron star mass of $M_{ns} = 2M_\odot$, in the range required in models for explaining the kHz QPO in neutron star LMXBs (see e.g. Stella et al. 1999; Stella 2000; Lamb & Miller 2001), and close to the dynamical neutron mass estimate of Cyg X-2 using optical spectroscopy/photometry, $M_{ns} = 1.78\pm0.23$ (Orosz & Kuulkers 1999). Note that the distance derived is rather high (Table B.2). We also made the assumption that the photospheric composition is hydrogen-poor (i.e. $X=0$), as has been argued to be the case during radius expansion (see Sugimoto et al. 1984). However, the contraction phase of long bursts are typical of unstable mixed hydrogen/helium burning (see Sect. 5.4), which suggests that this is not a reasonable assumption. Also, the persistent mass accretion rate is inferred to be high, making it plausible that the photosphere will be continuously supplied with new hydrogen matter. Moreover, the distances derived are rather high (see Table B.2). We changed the anisotropy factor between the reasonable values $0.5 \lesssim \xi \lesssim 2$ (see van Paradijs & Lewin 1987; Lewin et al. 1993). Finally, we compared the distance values derived using values for $\kappa$ valid for low temperatures. The results shown in Table B.2 suggests that the systematic uncertainties on the derived distance are up to $\sim 30%$.

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5 Note that the gravitational redshift corrected distance estimates by Smale (1998: Cyg X-2), Kuulkers & van der Klis (2000: GX 3+1) and Kaptein et al. (2000: 1RXS J171824.2–402934) are derived using $T_{eff,\infty}=T_{bb}$ and $R=R_{bb}$, thus only using Eqs. B.2, B.3 and B.6.
### Table B.1. Distance ($d$ in kpc) and radius at touch down from radius expansion bursts$^a$

<table>
<thead>
<tr>
<th>burst</th>
<th>0.25 s spectra</th>
<th>16 s spectra</th>
<th>$R_{td}^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$d_{non-rel}^c$</td>
<td>$d_{rel}^c$</td>
<td>$d_{non-rel}^c$</td>
</tr>
<tr>
<td>b4</td>
<td>84 11.4±0.3 10.8±0.3 4 11.6±0.3 10.9±0.3</td>
<td>18.3</td>
<td></td>
</tr>
<tr>
<td>b6</td>
<td>83 12.1±0.5 11.4±0.5 6 12.2±0.1 11.1±0.1</td>
<td>12.8</td>
<td></td>
</tr>
<tr>
<td>b7</td>
<td>94 12.9±0.6 12.0±0.5 2 12.7±0.2 11.8±0.1</td>
<td>16.7</td>
<td></td>
</tr>
<tr>
<td>b8</td>
<td>93 12.3±0.6 11.5±0.5 2 12.1±0.1 11.2±0.1</td>
<td>14.4</td>
<td></td>
</tr>
<tr>
<td>b9</td>
<td>82 12.4±0.5 11.5±0.5 1 12.1 11.1</td>
<td>14.9</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>12.2±0.2 11.4±0.2</td>
<td>12.1±0.1 11.2±0.1</td>
<td>15.4±1.0</td>
</tr>
</tbody>
</table>

$^a$ For the parameters used we refer to the text.
$^b$ Black-body radius $R$ at touch down for a local observer (see text).
$^c$ Number of spectra in the expansion/contraction phase.
$^d$ Not taking into account gravitational redshift effects.
$^e$ Taking into account gravitational redshift effects.

### Table B.2. Distance ($d$ in kpc) and radius at touch down for burst b6 using different assumptions$^a$

<table>
<thead>
<tr>
<th>parameter$^a$</th>
<th>0.25 s spectra</th>
<th>16 s spectra</th>
<th>$R_{td}^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$d_{non-rel}^c$</td>
<td>$d_{rel}^d$</td>
<td>$d_{non-rel}^c$</td>
</tr>
<tr>
<td>standard$^f$</td>
<td>12.1±0.5 11.4±0.5</td>
<td>12.2±0.1 11.1±0.1</td>
<td>12.8</td>
</tr>
<tr>
<td>$M_{ns}=2.0, M_\odot$</td>
<td>14.4±0.6 13.5±0.6</td>
<td>14.6±0.1 12.7±0.2</td>
<td>13.0</td>
</tr>
<tr>
<td>$X=0$</td>
<td>15.9±0.7 15.3±0.6</td>
<td>16.1±0.1 15.1±0.1</td>
<td>18.9</td>
</tr>
<tr>
<td>low-T $\kappa$</td>
<td>11.6±0.5 11.0±0.5</td>
<td>11.7±0.1 10.6±0.1</td>
<td>11.8</td>
</tr>
<tr>
<td>$\xi=2$</td>
<td>8.5±0.3 8.1±0.3</td>
<td>8.6±0.1 7.9±0.1</td>
<td>12.8</td>
</tr>
<tr>
<td>$\xi=0.5$</td>
<td>17.1±0.7 16.2±0.7</td>
<td>17.3±0.1 15.8±0.1</td>
<td>12.8</td>
</tr>
<tr>
<td>$T_{bb}/T_{e,\infty}=2$</td>
<td>12.1±0.5 11.7±0.5</td>
<td>12.2±0.1 11.6±0.1</td>
<td>19.9</td>
</tr>
<tr>
<td>$T_{bb}/T_{e,\infty}=1^f$</td>
<td>12.1±0.5 (83) 10.5±0.7 (9)</td>
<td>12.2±0.1 (6)</td>
<td>—</td>
</tr>
</tbody>
</table>

$^a$ See text for details.
$^b$ Black-body radius $R$ at touch down for a local observer (see text).
$^c$ Not taking into account gravitational redshift effects.
$^d$ Taking into account gravitational redshift effects.
$^e$ $M_{ns}=1.4\, M_\odot$, $X=0.73$, $T_{bb}/T_{e,\infty}=1.7$, high-T $\kappa$, $\xi=1$.
$^f$ Between brackets the number of spectra taken into account are given.