Optical and X-ray observations of the neutron star soft X-ray transient XTE J1709–267

P. G. Jonker,1⋆† D. K. Galloway,2 J. E. McClintock,1 M. Buxton,3 M. Garcia1 and S. Murray1
1Harvard–Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
2Massachusetts Institute of Technology, Center for Space Research, Cambridge, MA 02139, USA
3Department of Astronomy, Yale University, 260 Whitney Avenue, New Haven, CT 06520, USA

ABSTRACT
In this paper we report on the discovery of the optical counterpart to the neutron star soft X-ray transient (SXT) XTE J1709–267 at an $R$-band magnitude of $R = 20.5 \pm 0.1$ and $22.24 \pm 0.03$, in outburst and quiescence, respectively. We further report the detection of type I X-ray bursts in RXTE data obtained during an outburst of the source in 2002. These bursts show a precursor before the onset of the main burst event, reminiscent of photospheric radius expansion bursts. Sifting through the archival RXTE data for the burster 4U 1636–53, we found a nearly identical burst with precursor in 4U 1636–53. A comparison of this burst to true photospheric radius expansion bursts in 4U 1636–53 leads us to conclude that these bursts-with-precurser do not reach the Eddington limit. Nevertheless, from the burst properties we can derive that the distance to XTE J1709–267 is consistent with the distance of the Globular Cluster NGC 6293.

We further report on the analysis of a 22.7 ks observation of XTE J1709–267 obtained with the Chandra satellite when the source was in quiescence. We found that the source has a soft quiescent spectrum which can be fit well by an absorbed black body or neutron star atmosphere model. A power law contributes less than $\sim 20$ per cent to the 0.5–10 keV unabsorbed flux of $(1.0 \pm 0.3) \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$. This flux is only slightly lower than the flux measured right after the outburst in 2002. This is in contrast to the recent findings for MXB 1659–29, where the quiescent source flux decreased gradually by a factor of $\sim 7–9$ over a period of 18 months. Finally, we compared the fractional power–law contribution to the unabsorbed 0.5–10 keV luminosity for neutron star SXTs in quiescence for which the distance is well-known. We find that the power-law contribution is low only when the source quiescent luminosity is close to $\sim 1–2 \times 10^{33}$ erg s$^{-1}$. Both at higher and lower values the power–law contribution to the 0.5–10 keV luminosity increases. We discuss how models for the quiescent X-ray emission can explain these trends.

Key words: accretion, accretion discs – binaries: general – stars: individual: XTE J1709–267 – stars: individual: 4U 1636–53 – stars: neutron – X-rays: binaries.

1 INTRODUCTION
Low-mass X-ray binaries are binary systems in which a $\lesssim 1$-$M_\odot$ star transfers matter to a neutron star or a black hole. A large fraction of low-mass X-ray binaries are transients; these are called soft X-ray transients (SXTs). Although several of the neutron star systems were already detected in quiescence with Einstein, EXOSAT, ASCA and ROSAT (e.g. Petro et al. 1981; van Paradijs et al. 1987; Verbunt et al. 1994; Asai et al. 1998; Rutledge et al. 1999), detailed studies of these faint quiescent counterparts to neutron star transients have only become possible with Chandra and XMM–Newton (e.g. Wijnands et al. 2001; Rutledge et al. 2002).

Several mechanisms have been proposed to explain the observed X-ray luminosity and spectra of quiescent neutron star SXTs. Accretion may be ongoing at a low level producing a soft spectrum (Zampieri et al. 1995). Several authors have pointed out that the presence of a $\sim 10^9$ G magnetic field would have a large influence on the accretion flow. The onset of a propeller or pulsar wind mechanism (Illarionov & Sunyaev 1975; Stella, White & Rosner 1986; Campana & Stella 2000) has been proposed as an explanation of the...
hard power-law spectral component. Although detailed theoretical model calculations predicting the spectral shape are absent so far, Zhang, Yu & Zhang (1998) argue that in the propeller phase the spectrum will be hard. In addition to these two apparently mutually exclusive models, it is thought that a soft, thermal spectral component with a luminosity of typically $10^{32–33}$ erg s$^{-1}$ will be generated due to the fact that the neutron star crust and core are heated via pycnonuclear reactions in the crust during the accretion phase. The crust will thermally radiate in (soft) X-rays, cooling the neutron star (e.g. Brown, Bildsten & Rutledge 1998; Colpi et al. 2001; Ushomirsky & Rutledge 2001). In this model the observed quiescent luminosity can differ from outburst to outburst by a factor of 2–3 because the fraction of hydrogen and helium left in the atmosphere after an outburst will vary from outburst to outburst. This fraction influences the heat flux that flows from the core to the surface (Brown, Bildsten & Chang 2002). The quiescent luminosity is also likely to vary from source to source because the neutron star core and crust temperature depend on the mass accretion history of the source and the cooling rate may depend among other things on the neutron star mass. Using hydrogen neutron star atmosphere (NSA) models to fit the soft part of the quiescent spectrum, neutron star radii and temperatures can be determined. The observed values are in the range expected from neutron star theory. If it can be established that the quiescent emission is indeed due to the hot neutron star surface or core, these systems could provide a way to determine neutron star radii. Together with information about the neutron star spin—for example, obtained through burst oscillations (e.g. Strohmayer & Bildsten 2004) and/or pulsations observed during outburst (e.g. Wijnands 2004)—and mass (see Thorsett & Chakrabarty 1999), this provides important information about the behaviour of matter under physical conditions that are unattainable on Earth.

Recently, using the Chandra satellite we followed the neutron star SXT RX J170930.2–263927, also called XTE J1709–267, towards quiescence (Jonker et al. 2003). XTE J1709–267 was detected for the first time using ROSAT All-Sky Survey observations performed in 1990 (Voges et al. 1999). The source was also detected by ROSAT in 1992 (see Verbunt 2001; Jonker et al. 2003). Since then, the source has been detected with RXTE three times: in 1997 (Marshall et al. 1997), in 2002 (Jonker et al. 2003), and in 2004 (Markwardt & Swank 2004). During the 1997 outburst Cocchi et al. (1998) found type I bursts using the Wide Field Cameras on board the BeppoSAX satellite. Because the source is located only 9–10 arcmin away from the core of the globular cluster NGC 6293 it has been speculated that XTE J1709–267 is associated with NGC 6293 (Verbunt 2001; Jonker et al. 2003).

In this paper we present X-ray and optical observations of XTE J1709–267 in quiescence and outburst. A preliminary announcement of the optical observations has already been made in Jonker, Buxton & McClintock (2004a).

2 OBSERVATIONS AND ANALYSIS

2.1 Chandra

We have observed the neutron star SXT XTE J1709–267 during quiescence using the ACIS-I CCDs operated in the very faint mode on board the Chandra satellite (Weisskopf et al. 2002) for ~25 ks on 2003 May 12 (observation ID 3507). As a result of the short deadtime introduced by reading out the CCDs, the effective on-source time was 22.7 ks. The X-ray data were processed by the Chandra X-ray Center, but we reprocessed the data starting with the level 1 products in order to take full advantage of the newest available calibrations.

We used the CIAO software to reduce the data (version 3.0.2 and CALDB version 2.26). Events with ASCA grades of 1, 5, 7, cosmic rays, hot pixels, and events close to CCD node boundaries were rejected. We searched the data for periods of enhanced background radiation but none was present. Hence, all the data were used in our analysis.

We offset pointed the satellite with respect to the known accurate coordinates of XTE J1709–267 (see Jonker et al. 2003) in order to put some of the globular cluster NGC 6293 in the field of view. We detected >15 sources, but the coordinates of only one were consistent with those of XTE J1709–267 (the analysis of the other sources will be presented elsewhere). We detected 166 source counts in 22.7 ks. The spectrum of XTE J1709–267 was extracted from a circular region with a 5–arcsec radius centred on the source, where the background spectrum was extracted from a circular region with a radius of 5 arcsec located 50 arcsec east of the source (three background counts were detected in this region). We rebinned the spectrum such that each bin contained at least five counts per bin. Because of this low number of counts, we used the CASH statistic method in our spectral fitting to estimate the errors on the fitting parameters (Cash 1979). We only include photons with energies above 0.3 and below 10 keV in our spectral analysis because the ACIS timed exposure mode spectral response is not well calibrated outside that range. In order to validate the CASH statistics we did not subtract the background photons. These background photons all have energies above 3 keV.

We fit the spectra using the XSPEC package (version 11.3.0; Arnaud 1996). We fit the spectrum with an absorbed blackbody model and with an absorbed NSA model (Pavlov, Shibanov & Zavlin 1991; Zavlin, Pavlov & Shibanov 1996). We kept the absorption fixed at the value we found during outburst ($N_H = 4.4 	imes 10^{21}$ cm$^{-2}$; Jonker et al. 2003). The Galactic absorption, the NSA normalization, the mass and the radius of the neutron star were held fixed during the fit at $4.4 	imes 10^{21}$ cm$^{-2}$, $1/D^2 = 1.3 	imes 10^{-8}$ pc$^{-2}$ (for the distance, $D$, in pc, we took the value of the globular cluster 8.8 $\times$ 10$^3$ pc; see Section 2.2), 1.4 M$_\odot$ and 10 km, respectively. The best-fitting parameters are presented in Table 1. The reddening to the globular cluster NGC 6293 of $E(B – V) = 0.41$ implies a column density of $2.2 	imes 10^{21}$ cm$^{-2}$ assuming $A_V = 3.1 	imes E(B – V)$ and using the relation between $A_V$ and $N_H$ of Predehl & Schmitt (1995). We also fitted a NSA and a blackbody to the data with the $N_H$ fixed at $2.2 	imes 10^{21}$ cm$^{-2}$ (see Table 1). The best-fitting parameters are consistent within the 90 per cent confidence contours with those obtained using $N_H = 4.4 	imes 10^{21}$ cm$^{-2}$.

The flux in the last two bins is underestimated for both the blackbody (see Fig. 1) and the NSA model fits. This can (partially) be explained by the fact that we did not subtract the background. Had we subtracted the background as defined above, it would have reduced the count rate above 3 keV (three out of the 10 photons

| $N_H$ (cm$^{-2}$) | Model | BB radius in (d/10 kpc)$^2$ km | Temperature (keV) | Goodness (per cent) |
|-----------------|-------|-------------------------------|-------------------|---------------------|
| $4.4 \times 10^{21}$ | BB | 3.6 ± 1.2 | 0.24 ± 0.02 | 85 |
| $4.4 \times 10^{21}$ | NSA | – | 0.125 ± 0.002 | 57 |
| $2.2 \times 10^{21}$ | BB | 1.2 ± 0.4 | 0.28 ± 0.02 | 49 |
| $2.2 \times 10^{21}$ | NSA | – | 0.116 ± 0.002 | 82 |

$^a$Parameter fixed at this value.

Table 1. Best-fitting parameters of the quiescent spectrum of XTE J1709–267 (NSA stands for neutron star atmosphere and BB refers to blackbody). All quoted errors are at the 68 per cent confidence level.

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detected above 3 keV would have been labelled background photons). Additionally, a hard (power-law) spectral component could be present. A power-law spectral component with index 2 contributes less than 20 per cent to the unabsorbed flux in the 0.5–10 keV band. The absorbed 0.5–10 keV source flux for both models and both \( N_H \) values considered above was consistent with \( \sim (4.6 \pm 0.4) \times 10^{-14} \) erg cm\(^{-2}\) s\(^{-1}\), whereas the unabsorbed flux was \( \sim (1.0 \pm 0.3) \times 10^{-13} \) erg cm\(^{-2}\) s\(^{-1}\). Here the error is determined from the range in fluxes derived from the various models. For all models we performed a Monte Carlo simulation (using the GOODNESS command in XSPEC). We simulated 10\(^4\) spectra based on a Gaussian distribution of parameters centred on the best-fitting model parameters with a Gaussian width set by the 1\(\sigma\) errors on the fit parameters. The percentage of these simulations with the fit statistic less than that for the data is more than the fiducial 50 per cent mark for three of the four cases considered, but again this may be partially explained by the presence of background photons in the last two bins. The goodness percentages are given in Table 1.

Even though the fit results presented in Jonker et al. (2003) are still valid, we also refitted the spectra of the last three of the five 2002 Chandra observations of XTE J1709–267, i.e. those with IDs 3464, 3475 and 3492 presented by Jonker et al. (2003). We used a fit-function consisting of a blackbody plus a power-law component. For this we reprocessed the archival data with the newest calibration files available. The result of these spectral fits can be found in Table 2. These spectra were obtained while the source returned to quiescence after an outburst.

### 2.2 RXTE

We found three type I X-ray bursts in the RXTE proportional counter array (PCA) observations obtained during the outburst of the source in 2002. We analysed these bursts using FTOOLS 5.2; we present the results for the burst for which four of the five proportional counter units (PCUs) were operational (for the other two bursts only three PCUs were operational; the profile of these two bursts was similar to that of the burst discussed in detail here). The burst start-time is MJD 52304.17794(5) UTC; the last digit in between brackets denotes the uncertainty. The light curve of the burst is plotted in Fig. 2 (left panel). A precursor to the main burst event can clearly be seen. No burst oscillations were present in the range 50–2000 Hz in the 2.5–25 keV power spectrum with a 95 per cent confidence upper limit of 14 per cent.

Spectra of the burst in the energy range 2.5–25 keV were calculated. We subtracted the persistent emission averaged over 16 s starting 20 s before the burst onset. We fitted the resultant burst

### Table 2. Results of fits to spectra from XTE J1709–267 observations obtained immediately after an outburst in 2002 (observations with IDs 3464, 3475 and 3492) using a blackbody plus power-law spectral model (see also Jonker et al. 2003). All quoted errors are at the 68 per cent confidence level. \( N_H \) was kept fixed at a value of \( 4.4 \times 10^{21} \) cm\(^{-2}\) during the fits. On the last line we give the result for a spectral fit using to the combined data from observation IDs 3492 and 3407. BB denotes blackbody and PL power law.

| Obs. ID | MJD (UTC) | BB radius (d/10 kpc)\(^2\) | BB temp. keV | PL index | PL norm.\(^a\) photons keV\(^{-1}\) cm\(^{-2}\) s\(^{-1}\) | \( \chi^2/\text{d.o.f.} / \text{Goodness} \) | Unabs. flux (0.5–10 keV) \(\text{erg cm}^{-2} \text{s}^{-1}\) |
|--------|------------|------------------|-------------|--------|---------------------|------------------|------------------|
| 3464   | 52365.018  | 60±30            | 0.22±0.02   | 2.5±0.2| \(9 \pm 2\) \times 10\(^{-4}\) | 98/111           | 4.7 \times 10\(^{-12}\) |
| 3475   | 52374.727  | \((3^{+3}_{-2})\times 10^2\) | 0.13±0.02   | 2\(^b\) | \((8 \pm 2)\) \times 10\(^{-5}\) | 23/24            | 8.4 \times 10\(^{-13}\) |
| 3492   | 52387.898  | 6±4              | 0.26±0.03   | –      | –                   | 75%              | 2.4 \times 10\(^{-13}\) |
| 3492 & 3507 | 52771.322  | 7±3              | 0.22±0.02   | –      | –                   | 60%              | 1.7 \times 10\(^{-13}\) |

\(^{a}\)Power-law normalization at 1 keV.

\(^{b}\)Power-law index fixed at this value.
The neutron star SXT XTE J1709–267

Figure 2. Left panel: the type I X-ray burst detected in XTE J1709–267 with RXTE’s PCA on MJD 52304.17794 (UTC). Note the presence of a precursor event. The zeros in between the precursor and the main peak and before the precursor are the result of the subtraction of the persistent non-burst emission. Right panel: a type I X-ray burst with a similar precursor event detected in 4U 1636–53 with RXTE’s PCA on MJD 52333.988103. In both cases, PCUs 0234 were operational.

The burst properties with those of a nearly identical burst we found sifting through archival RXTE observations of the source 4U 1636–53. The findings for 4U 1636–53 are plotted in the right panels of Figs 2 and 3. The two bursts are remarkably similar to each other. However, for 4U 1636–53 photospheric radius expansion bursts are observed relatively often (see Fujimoto et al. 1988). The mean peak flux for the bright photospheric radius expansion bursts for 4U 1636–53 is $(7.2 \pm 0.7) \times 10^{-8} \text{erg cm}^{-2} \text{s}^{-1}$ (here the uncertainty is the standard deviation of the observed peak photospheric radius expansion burst flux distribution; Galloway et al., in preparation). With a value of $(5.8 \pm 0.1) \times 10^{-8} \text{erg cm}^{-2} \text{s}^{-1}$ the bolometric peak flux of the burst with precursor in 4U 1636–53 is significantly lower.

The burst from 4U 1636–53 reached a peak flux a factor of 1.25 smaller than the mean peak flux of the photospheric radius expansion bursts from that source. If we identify the latter as the Eddington limit, and multiply the peak flux of the burst from XTE J1709–267 by this factor we infer a distance of $10.1^{+3.2}_{-1.7} / 13.9^{+4.4}_{-2.3}$ kpc for the

Figure 3. Left panel: the evolution of the blackbody temperature (top) and radius (bottom) as a function of time since the burst start as determined from X-ray spectral fits of RXTE PCA data in the energy range from 2.5–25 keV for XTE J1709–267. Right panel: the same for the burst of 4U 1636–53.

spectra with an absorbed blackbody. The absorption was fixed at $N_H \sim 2 \times 10^{21} \text{cm}^{-2}$. This is consistent with the value derived for the globular cluster, although our results were consistent with being the same when we used $N_H \sim 4.4 \times 10^{21} \text{cm}^{-2}$; the RXTE data are not very sensitive to the exact value for $N_H$ as long as it is lower than a few times $10^{22} \text{cm}^{-2}$. The resultant blackbody radius and temperature for the burst spectra are presented in Fig. 3 (left panel). The bolometric peak flux $\sigma T^4 (R/d)^2$ we found was $(1.40 \pm 0.06) \times 10^{-8} \text{erg cm}^{-2} \text{s}^{-1}$.

Type I X-ray bursts with a precursor event have previously been identified with extreme cases of photospheric radius expansion, where the photospheric radius becomes so large and the blackbody temperature so small that the peak of the emission drops below the X-ray band (Lewin, van Paradijs & Taam 1993). However, from our spectral study of the burst we do not find evidence for a large increase in blackbody radius as is found for other photospheric radius expansion bursts with precursors. To investigate further whether this burst is in fact a photospheric radius expansion burst, we compare
source for an assumed Eddington limit of $2.0/3.8 \times 10^{38}$ erg s$^{-1}$ (see Kuulkers et al. 2003). The two values correspond approximately to hydrogen-rich and hydrogen-poor bursts, respectively. Of these distances, only the lower value is consistent with the suggestion made previously (Verbunt 2001; Jonker et al. 2003) that XTE J1709–267 is associated with the metal-poor globular cluster NGC 6293, because the distance to NGC 6293 is known to be $\sim 8.8$ kpc (see Harris 1996; according to Janes & Heasley 1991 the uncertainties in the cluster distance are considerable). If, as has been argued by several authors (cf. Tomsick et al. 1999b; Barret et al. 2000; Kuulkers et al. 2003), the flux reported from measurements made with the RXTE satellite are systematically too high by approximately 20 per cent, then the two distances we quote above are too small by a factor of $\sim 1.12$.

### 2.3 Optical observations

We observed the field of XTE J1709–267 for 900 s through an $R$-band filter with ANDICAM mounted on the 1.3-m telescope at CTIO.

**Figure 4.** Top panel: the 900-s $R$-band image obtained on 2004 March 26 with the ANDICAM instrument mounted on the 1.3-m telescope at CTIO. The optical counterpart to the neutron star SXT XTE J1709–267 is indicated with tick marks. The pixel scale is 0.369 arcsec pixel$^{-1}$. Bottom panel: the 20-min $R$-band image obtained on 2003 June 1 with the MAGIC instrument on the 6.5-m Magellan Clay telescope at Las Campanas. The photometric reference stars are indicated with a number. The proposed counterpart was detected in quiescence at $R \sim 22.2$. The image has been rebinned to a pixel scale of 0.138 arcsec pixel$^{-1}$. 

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We observed the neutron star SXT XTE J1709–267 on several occasions in outburst and quiescence in X-ray and optical. The brightening of a star from \( R = 22.24 \pm 0.03 \) in quiescence to \( R = 20.5 \pm 0.1 \) in outburst and its positional coincidence with the Chandra position for XTE J1709–267 provide convincing evidence that we have discovered the optical counterpart (Jonker et al. 2003a). Obviously, there is a small chance that the star found in quiescence is an interloper and not the true counterpart; spectroscopic observations of the proposed quiescent counterpart will test this. If we assume, however, that we also detected the optical counterpart in quiescence, the absolute magnitude, \( M_R \), for the counterpart would be \( M_R = 6.6–5.7 \), where we have assumed an R-band interstellar absorption, \( A_R \), of 0.92–1.84 mag, [for a distance of 8.8 kpc, from \( N_H = (2.2–4.4) \times 10^{21} \) cm \(^{-2} \), and from the relations between \( N_H \), \( A_V \) and \( A_R \) given by Rieke & Lebofsky (1985) and Predehl & Schmitt (1995)]. These \( M_R \) values are consistent with XTE J1709–267 being a low-mass X-ray binary with a late-type (K) dwarf companion.

The unabsorbed luminosity in the 0.5–10 keV X-ray band we find using Chandra observations of the source in quiescence is only slightly lower than the lowest luminosity measured by Jonker et al. (2003) (approximately a factor of 2; in that paper we gave the unabsorbed flux in the 0.1–10 keV and not the 0.5–10 keV band). So, the decay in luminosity in about 14 months is small (approximately a factor of 2). This is in contrast with the decay rate of the quasi-persistent source MXB 1659–29. Wijnands et al. (2004c) found that for this source the bolometric luminosity decreased by a factor of 7–9 in 18 months. Such a difference could be explained by the fact that MXB 1659–29 had been accreting steadily for several years before returning to quiescence. This extended period of steady accretion may have heated the neutron star crust to temperatures higher than that of the neutron star core, and after the outburst the crust cools down (Wijnands et al. 2004c). However, this difference could also reflect a difference between the quiescent mass accretion rates, although it is unclear why in some sources the mass accretion rate hits a minimum close after the outburst whereas in other neutron star STXs such as MXB 1659–29 the mass accretion rate keeps decreasing gradually.

Recently, we found (Jonker, Wijnands & van der Klis 2004c) that there seems to be an anticorrelation between the fractional power-law contribution to the 0.5–10 keV luminosity and the source luminosity in quiescence for quiescent luminosities lower than \( \sim 1.2 \times 10^{33} \) erg s \(^{-1} \) and a correlation between these two parameters for luminosities above this luminosity. In Fig. 5 we plot the power-law fractional contribution to the total 0.5–10 keV unabsorbed quiescent luminosity for several neutron star SXTs for which the distance is accurately known.\(^1\) To obtain the quiescent luminosities we use

\[ \text{Table 3. The magnitudes of six comparison stars, numbered as indicated in the bottom panel of Fig. 4, which have been used as photometric calibrators, the proposed counterpart (CP) and that of the star near (within 0.7 arcsec) the position of the proposed counterpart. The errors are formal fitting errors only; the estimated error in the zero-point is } \sim 0.1 \text{ mag.} \]

| Star      | R-band magnitude |
|-----------|------------------|
| 1         | 19.41 ± 0.02     |
| 2         | 20.26 ± 0.05     |
| 3         | 17.82 ± 0.01     |
| 4         | 20.35 ± 0.04     |
| 5         | 16.57 ± 0.01     |
| 6         | 20.47 ± 0.04     |
| CP        | 20.5 ± 0.1\(^a\)/22.24 ± 0.03\(^b\) |
| Nearby star| 21.56 ± 0.02   |

\(^a\)Value in outburst, corrected for the contribution of the nearby interloper.

\(^b\)Value in quiescence.
Figure 5. The fractional power-law contribution to the unabsorbed quiescent 0.5–10 keV luminosity for quiescent neutron stars. The points without positive error bars denote upper limits on the power-law fraction; for XTE J0929–314 there is a lower limit to the power-law contribution of 70 per cent. Data points for different sources are indicated with different symbols and/or colours. For Aql X–1, Cen X–4, MXB 1659–29, XTE J1709–267 and KS 1731–260 we have plotted more than one point because the quiescent source luminosity and power-law fraction of the quiescent luminosity was found to vary (for references, see text). These multiple data points of the same source have been connected with a (dashed) line. The Galactic cluster sources selected by Heinke et al. (2003) on the basis of their soft spectrum (the power-law contribution had to be less than 40 per cent for the sources to be selected) are indicated with a small circle.

To the high-luminosity side, the trend of increasing power-law fraction with luminosity is dominated by the data points of XTE J1709–267, which was followed by Chandra during its decay to quiescence after an outburst (Jonker et al. 2003; see also Table 2). We found that the power-law contribution to the 0.5–10 keV X-ray background is.

We took a distance of 5.3 ± 0.3 kpc for the globular cluster Ω Cen (Thompson et al. 2001), 10.3 ± 0.8 kpc for M80 (Brocato et al. 1996), 5.2 ± 0.3 kpc for 47 Tuc, 3.6 ± 0.3 kpc for NGC 6397 and 9.5 ± 0.9 kpc for M30 (all from Carretta et al. 2000).

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distances quoted in Jonker & Nelemans (2004) for the systems where photospheric radius expansion bursts have been observed. Because the photospheric radius expansion burst luminosity is thought to be close to 2.0 or 3.8 × 10^{38} erg s^{-1} (see Kuulkers et al. 2003) we use a range in quiescent luminosities to account for this ambiguity in source distance. In the case of XTE J1709–267 we took a distance range of 8–12 kpc. For the neutron star SXTs in the globular clusters Terzan 5 and NGC 6440, we took distances of 8.7 ± 3 and 8.5 ± 0.4 kpc, respectively (Cohn et al. 2002; Ortolani, Barbuy & Bica 1994). Finally, for Cen X–4 we use a distance of 1.2 kpc (Kuluzienski, Holt & Swank 1980; Chevalier et al. 1989; Barret, McClintock & Grindlay 1996). We do not take into account errors on the source quiescent luminosities due to errors on the measured source flux because these are typically smaller than the uncertainty in the burst chemical composition. When the error on the power-law contribution to the flux was not given in the literature, we assumed an error of 10 per cent. Finally, we included in the plot globular cluster sources which are thought to be quiescent neutron star SXTs on the basis of their soft spectrum (e.g. Verbunt, Elson & van Paradijs 1984). We used the sources and limits on the power-law component in the spectrum as found by Heinke et al. (2003).

To the high-luminosity side, the trend of increasing power-law fraction with luminosity is dominated by the data points of XTE J1709–267, which was followed by Chandra during its decay to quiescence after an outburst (Jonker et al. 2003; see also Table 2). We found that the power-law contribution to the 0.5–10 keV X-ray background is.
luminosity decreased from 72 per cent on MJD 52365.018, to 48 per cent on MJD 52374.727, to less than 19 per cent using the combined data from observations 3492 and 3507. The detailed study of Aql X–1 confirms the observed trend (Rutledge et al. 2002). However, the quiescent properties of the counterpart to the neutron star SXT EXO 1745–248 in the dense globular cluster core of Terzan 5 seemingly do not fit the correlation (Wijnands et al. 2004a). Perhaps the identified source is an interloper or perhaps the distance to Terzan 5 is much smaller than what is assumed (Ortolani, Barbay & Bica 1996 derived a distance of 5.6 kpc). Alternatively, the apparent correlation is spurious and Terzan 5 is the first source to fill in the gap. If the apparent smooth change in power-law contribution to the quiescent luminosity is real, it could mean that the nature of the power-law spectral component at high and low source luminosities is different.

Because we observed the power-law contribution in XTE J1709–267 to decrease when the source returned to quiescence after an outburst, it is conceivable that the power-law component at luminocities above ∼1–2 × 10^{33} erg s^{-1} finds its origin in residual accretion. It has been proposed that neutron star SXTs enter a propeller regime when the outburst decay rate steepens, impeding most if not all accretion (Campana et al. 1998). However, pulsations were still detected in SAX J1808.4–3658 after the alleged onset of the propeller mechanism (Psaltis & Chakrabarty 1999). Furthermore, steepening of the decay is also found in black hole candidate SXTs (e.g. Jonker et al. 2004b). Finally, the work of Cornellisse et al. (2002) shows that there is a class of burst sources which likely accrete at a low level. Deep observations a few hours after the detection of a type I burst in SAX J2224+5421 did not reveal a persistent source with a 2–10 keV upper limit of 1.3 × 10^{-13} erg cm^{-2} s^{-1} (Cornelisse et al. 2003), which for the distance of SAX J2224+5421 leads to an upper limit on the luminosity in that band of 7.4 × 10^{33} erg s^{-1}. Therefore, we think it is more likely that the origin of the power law at relatively high quiescent luminosities lies in residual accretion. If so, this can help explain the observed short-term neutron star temperature changes in Aql X–1 (Rutledge et al. 2002). These short-term temperature changes pose a problem for the cooling neutron star core/crust model. However, if residual accretion is ongoing the observed changes can, for instance, be explained as being the result of a different hydrogen and helium content in the atmosphere during the two observations caused by the residual accretion. Hence, the fact that this power-law component can be explained at least qualitatively in terms of residual accretion helps the cooling neutron star model as an explanation for the thermal component.

The origin of the power law on the low quiescent luminosities side of ∼1–2 × 10^{33} erg s^{-1} is still unclear. Because SAX J1808.4–3658 is known to have a sizable magnetic field, the power-law component could be explained as being due to a pulsar-wind mechanism (e.g. Stella et al. 1994; Burderi et al. 2003). However, this cannot explain the strong power-law components in the non-pulsating sources Cen X–4, SAX J1810.8–2609 and XTE J2123–058, although one must bear in mind that Cen X–4 and SAX J1810.8–2609 have not been observed with RXTE/PCA when the sources were in outburst (whereas XTE J2123–058 has been observed with RXTE/PCA in outburst (see Homan et al. 1999 and Tomsick et al. 1999a). A possible explanation for the apparent correlation between the fractional power-law contribution and the total 0.5–10 keV luminosity at low quiescent luminosities is that there is a power-law spectral component with a luminosity of ∼10^{32} erg s^{-1}. This power-law luminosity would then need to be approximately the same for all sources; the luminosity of the blackbody can differ between sources. In the cooling neutron star model, the luminosity of the thermal component depends on the time-averaged mass accretion rate and the neutron star mass (Brown et al. 1998; Colpi et al. 2001). A low blackbody luminosity could point at a low time-averaged mass accretion rate and/or a large neutron star mass allowing for enhanced core cooling (cf. Colpi et al. 2001). The nature of the power law and why it would have a luminosity close to ∼10^{32} erg s^{-1} in the 0.5–10 keV band is unclear.

Finally, we found a precursor to several type I X-ray bursts of XTE J1709–267. A similar burst with a precursor was found for the bursting atoll source 4U 1636–53. A precursor to the main burst event in relatively long bursts has been associated with photospheric radius expansion bursts (see Lewin et al. 1993). However, from a comparison of the burst properties of photospheric radius expansion bursts in 4U 1636–53 (Galloway et al., in preparation) with the properties of the burst with a precursor in 4U 1636–53 we conclude that these bursts with precursors in 4U 1636–53 and hence also in XTE J1709–267 are not photospheric radius expansion bursts. Perhaps these precursor events are related to bursts with multiple peaks observed in 4U 1636–53 (van Paradijs et al. 1986; Fujimoto et al. 1988).

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Cohn H. N., Lugger P. M., Grindlay J. E., Edmonds P. D., 2002, ApJ, 571, 818
Colpi M., Geppert U., Pau D., Possenti A., 2001, ApJ, 548, L175
Cornelisse R., Verbunt F., in’t Zand J. J. M., Kuulkers E., Heise J., 2002, A&A, 392, 931
Cornelisse R. et al., 2003, A&A, 405, 1033
Fujimoto M. Y., Sztajno M., Lewin W. H. G., van Paradijs J., 1988, A&A, 199, L9
Harris W. E., 1996, AJ, 112, 1487
Heinke C. O., Grindlay J. E., Lugger P. M., Cohn H. N., Edmonds P. D., Lloyd D. A., Cool A. M., 2003, ApJ, 598, 501
Homan J., Méndez M., Wijnands R., van der Klis M., van Paradijs J., 1999, ApJ, 513, L119
Illarionov A. F., Sunyaev R. A., 1975, A&A, 39, 185
in’t Zand J. J. M., van Kerkwijk M. H., Pooley D., Verbunt F., Wijnands R., Lewin W. H. G., 2004, ApJ, 563, L41
Jonker P. G., Nelemans G., 2004, MNRAS, in press (astro-ph/0407168; doi:10.1111/j.1365-2966.2004.08193.x)
Jonker P. G., Mendez M., Wijnands R., van der Klis M., 2003, A&A, 392, 931
Jonker P. G., Buxton M., McClintock J. E., 2004a, The Astronomer’s Telegram, 262, 1
Jonker P. G., Gallo E., Dhawan V., Rupen M., Fender R. P., Dubus G., 2004b, MNRAS, 351, 1359
Jonker P. G., Wijnands R., van der Klis M., 2004c, MNRAS, 349, 94
Kaluzienski L. J., Holt S. S., Swank J. H., 1980, ApJ, 241, 779
Kuulkers E., den Hartog P. R., in’t Zand J. J. M., Verbunt F. W. M., Harris W. E., Cocchi M., 2003, A&A, 399, 663
Lewin W. H. G., van Paradijs J., Taam R. E., 1993, Space Sci. Rev., 62, 223
Markwardt C. B., Swank J. H., 2004, The Astronomer’s Telegram, 255, 1
Marshall F. E., Swank J. H., Thomas B., Angelini L., Valinia A., Ebisawa K., 1997, IAU Circ, 6543, 2
Otrolani S., Barbuy B., Bica E., 1994, A&AS, 108, 653
Otrolani S., Barbuy B., Bica E., 1996, A&A, 308, 733
Pavlov G. G., Shibanov I. A., Zavlin V. E., 1991, MNRAS, 253, 193
Petri L., Canizares C., Kriss G., McClintock J., Remillard R., 1981, BAAS, 13, 901
Predehl P., Schmidt J. H. M. M., 1995, A&A, 293, 889
Psaltis D., Chakrabarty D., 1999, ApJ, 521, 332
Rieke G. H., Lebofsky M. J., 1985, ApJ, 288, 618
Rutledge R. E., Bildsten L., Brown E. F., Pavlov G. G., Zavlin V. E., 1999, ApJ, 514, 945
Rutledge R. E., Bildsten L., Brown E. F., Pavlov G. G., Zavlin V. E., 2001, ApJ, 551, 921
Rutledge R. E., Bildsten L., Brown E. F., Pavlov G. G., Zavlin V. E., 2002, ApJ, 577, 346
Stella L., White N. E., Rosner R., 1986, ApJ, 308, 669
Stella L., Campana S., Colpi M., Mereghetti S., Tavani M., 1994, ApJ, 423, L47
Stetson P. B., 1987, PASP, 99, 191
Strohmayer T. E., Bildsten L., 2004, in Lewin W. H. G., van der Klis M., eds, Cambridge Astrophys. Ser., X-ray Binaries, Cambridge Univ. Press, Cambridge, in press
Thompson I. B., Kaluzny J., Pych W., Burley G., Krzeminski W., Paczyński B., Persson S. E., Preston G. W., 2001, AJ, 121, 3089
Thorsett S. E., Chakrabarty D., 1999, ApJ, 512, 288
Tomicka J. A., Halpern J. P., Kemp J., Kaaret P., 1999a, ApJ, 521, 341
Tomicka J. A., Kaaret P., Kroeger R. A., Remillard R. A., 1999b, ApJ, 512, 892
Tomicka J. A., Gelino D. M., Halpern J. P., Kaaret P. 2004, ApJ, 610, 933
Ushomirsky G., Rutledge R. E., 2001, MNRAS, 325, 1157
van Paradijs J., Szatmey L., Lewin W. H. G., Trumper J., Vacca W. D., van der Klis M., 1986, MNRAS, 221, 617
van Paradijs J., Verbunt F., Shafer R. A., Arnaud K. A., 1987, A&A, 182, 47
Verbunt F., 2001, A&A, 368, 137
Verbunt F., Elson R., van Paradijs J., 1984, MNRAS, 209, 899
Verbunt F., Belloni T., Johnston H. M., van der Klis M., Lewin W. H. G., 1994, A&A, 285, 903
Voges W. et al., 1999, A&A, 349, 389
Weisskopf M. C., Brinkman B., Canizares C., Garmire G., Murray S., Van Speybroeck L. P., 2002, PASP, 114, 1
Wijnands R., 2004, in Kaaret P., Lamb F. K., Swank J. H., eds, AIP Conf. Proc. Vol. 714, X-ray Timing 2003: Rossi and Beyond. Am. Inst. Phys., Melville, NY, p. 209
Wijnands R., Miller J. M., Markwardt C., Lewin W. H. G., van der Klis M., 2001, ApJ, 560, L159
Wijnands R., Guainazzi M., van der Klis M., Méndez M., 2002, ApJ, 573, L45
Wijnands R., Heinke C. O., Pooley D., Edmonds P., Lewin W. H. G., Grindlay J. E., Jonker P. G., Miller J. M. 2004a, ApJ, submitted
Wijnands R., Homan J., Heinke C. O., Miller J. M., Lewin W. H. G. 2004b, ApJ, submitted
Wijnands R., Homan J., Miller J. M., Lewin W. H. G., 2004c, ApJ, submitted
Wijnands R., Homan J., Miller J. M., Lewin W. H. G., 2004c, ApJ, 606, L61
Zampieri L., Turolla R., Zane S., Treves A., 1995, ApJ, 439, 849
Zavlin V. E., Pavlov G. G., Shibanov Y. A., 1996, A&A, 315, 141
Zhang S. N., Yu W., Zhang W., 1998, ApJ, 494, L71

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