Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

Mon. Not. R. Astron. Soc. **422,** 581–589 (2012) doi:10.1111/j.1365-2966.2012.20636.x

Strong X-ray variability in the quiescent state of the neutron star low-mass X-ray binary EXO 1745−248

N. Degenaar[1,2]⋆† and R. Wijnands[1]

[1]*Astronomical Institute 'Anton Pannekoek', University of Amsterdam, Postbus 94249, 1090 GE Amsterdam, the Netherlands*
[2]*Department of Astronomy, University of Michigan, 500 Church Street, Ann Arbor, MI 48109-1042, USA*

Accepted 2012 January 25. Received 2012 January 25; in original form 2011 August 4

ABSTRACT

The transient neutron star low-mass X-ray binary EXO 1745−248, located in the globular cluster Terzan 5, was detected during its quiescent state with *Chandra* in 2003. The source displayed a 0.5–10 keV quiescent X-ray luminosity of $L_{\mathrm{q}} \sim 10^{33}\,(D/5.5\,\mathrm{kpc})^2\,\mathrm{erg\,s^{-1}}$, which was completely dominated by hard non-thermal emission. This is at odds with other non-pulsating neutron stars that typically show detectable soft thermal emission at such quiescent luminosities. Here we use three additional *Chandra* observations, performed in 2009 and 2011, to further study the quiescent properties of EXO 1745−248. We find that the power-law intensity varies considerably up to a factor of ∼3 within hours and by about one order of magnitude between the different epochs. We discuss the implications of the observed change in quiescent flux for the interpretation of the hard power-law emission. We constrain the neutron star surface temperature as seen by a distant observer to $kT^{\infty} \lesssim 42$ eV and the thermal bolometric luminosity to $L_{\mathrm{q,bol}}^{\mathrm{th}} \lesssim 7 \times 10^{31}\,(D/5.5\,\mathrm{kpc})^2\,\mathrm{erg\,s^{-1}}$. This confirms that EXO 1745−248 harbours a relatively cold neutron star and suggests that, for example, enhanced cooling mechanisms are operating in the stellar core or that the binary on average resides in quiescence for hundreds of years.

Key words: accretion, accretion discs – stars: neutron – globular clusters: individual: Terzan 5 – X-rays: binaries – X-rays: individual: EXO 1745–248.

1 INTRODUCTION

Low-mass X-ray binaries (LMXBs) are binary star systems that are composed of a compact primary (a neutron star or a black hole) that accretes the outer gaseous layers of a (sub-)solar-mass companion star. Neutron star primaries can reveal themselves by showing coherent X-ray pulsations when the accretion flow is funnelled on to the magnetic poles of the neutron star, or by displaying type I X-ray bursts caused by unstable thermonuclear burning of the accreted matter on the surface of the neutron star.

Many neutron star LMXBs are transient and alternate active accretion outbursts with long episodes of quiescence. Whereas outbursts typically last only a few weeks and generate 0.5–10 keV X-ray luminosities of $L_{\mathrm{X}} \sim 10^{36}$–$10^{38}\,\mathrm{erg\,s^{-1}}$ (e.g. Chen, Shrader & Livio 1997), the quiescent phase may extend to many decades and is characterized by a much lower quiescent luminosity of $L_{\mathrm{q}} \sim 10^{31}$–$10^{33}\,\mathrm{erg\,s^{-1}}$ (0.5–10 keV; Heinke et al. 2009). The cause of the quiescent X-ray emission has been subject of debate (e.g. Campana 2003). Spectrally, one can distinguish a soft thermal component at energies below ∼2 keV, and a hard non-thermal emission tail that dominates the quiescent X-ray spectrum above ∼2–3 keV.

The soft quiescent spectral component is generally interpreted as heat being radiated from the surface of the cooling neutron star (Brown, Bildsten & Rutledge 1998; Colpi et al. 2001). As such, the quiescent thermal emission provides a measure of the neutron star's interior temperature. However, low-level accretion on to the surface of the neutron star might also produce a thermal X-ray spectrum (Zampieri et al. 1995). The hard non-thermal emission is usually modelled as a simple power law with a photon index of Γ ∼1–2, and its fractional contribution to the total 0.5–10 keV flux may vary anywhere from 0 to 100 per cent (Jonker et al. 2004b). It has been attributed e.g. to shock emission generated in the interaction of a residual accretion flow with the magnetic field of the neutron star, or the re-activation of a radio pulsar in quiescence (Campana et al. 1998). It remains an unanswered question if, and how, the two spectral components are related.

⋆E-mail: degenaar@umich.edu
†Hubble Fellow.

1.1 EXO 1745−248 in Terzan 5

Terzan 5 is a globular cluster located in the bulge of our Galaxy at an estimated distance of $D = 5.5$ kpc (Ortolani et al. 2007).[1] This cluster has a particularly high stellar density, which is thought to cause a high rate of dynamical star encounters and the formation of compact binary systems (e.g. Pooley et al. 2003). Apart from a large number of millisecond radio pulsars (Ransom et al. 2005) and faint X-ray point sources that may be quiescent LMXBs or cataclysmic variables (Heinke et al. 2006b), Terzan 5 also contains two confirmed transiently accreting neutron stars.

Already in 1980, a number of type I X-ray bursts were detected from the direction of the cluster, which testified the presence of an active neutron star LMXB (Makishima et al. 1981). Subsequent X-ray activity was observed from Terzan 5 in 1984, 1990, 1991, 2000, 2002, 2010 and most recently in 2011 (Table 1 and references therein). While the detections in 1984, 1990 and 1991 concern single observations and hence only snapshots of the activity, the most recent four outbursts have been covered by several X-ray instruments, e.g. by the All-Sky Monitor (ASM) on-board *RXTE* (Fig. 1).

Multiple type I X-ray bursts were detected during the 2000 and 2010 outbursts, while a superburst (i.e. a very energetic thermonuclear burst that lasts for several hours) was observed in 2011. This thus evidences active accretion on to a neutron star in 2000, 2010 and 2011 (Galloway, Özel & Psaltis 2008; Altamirano et al. 2011b; Linares et al. 2011; Mihara et al. 2011; Motta et al. 2011). High spatial resolution *Chandra* observations have revealed that these three outbursts involved two different transient neutron star LMXBs (cf. Heinke et al. 2003; Pooley et al. 2010, 2011).

Historically, the source that was active in 2000 and 2011 is referred to as EXO 1745−248, whereas the recently discovered 2010 transient has been dubbed IGR J17480−2446.[2] In addition to exhibiting type I X-ray bursts, the latter also displays 11-Hz X-ray pulsations (Strohmayer et al. 2010; Papitto et al. 2011). The two transient neutron star LMXBs have a spatial separation of merely ∼5 arcsec (see Fig. 2). Hence, apart from *Chandra*, none of the present and past X-ray missions provides sufficient angular resolution to spatially resolve them. It is thus unclear which of the two transient neutron star LMXBs was causing the outbursts that occurred in 1980, 1984, 1990, 1991 and 2002. Moreover, 50 distinct low-luminosity X-ray point sources have been identified within the half-mass radius of Terzan 5 (0.83 arcmin; Heinke et al. 2006b), so the possibility of additional active transient sources causing these historic outbursts cannot be ruled out.

Terzan 5 has been observed with *Chandra* on several occasions when no bright transients were active (Table 2). These observations can be addressed to investigate the two neutron star LMXBs during quiescence. The quiescent properties of the 2010 transient, IGR J17480−2446, are the subject of a recent ongoing study (Degenaar & Wijnands 2011a,b; Degenaar, Brown & Wijnands 2011b). The quiescent emission spectrum of the 2000/2011 transient, EXO 1745−248, was studied by Wijnands et al. (2005) using a *Chandra* observation obtained in 2003. At that time, the source was displaying a 0.5–10 keV luminosity of $L_{\rm q} \sim 10^{33}$ erg s^{-1}, which is not unusual for neutron star LMXBs in quiescence (e.g. Heinke et al. 2009). Unlike other non-pulsating neutron star LMXBs, however, the quiescent X-ray spectrum of EXO 1745−248 was found to be completely dominated by a hard emission component, with no indications of thermal radiation (Wijnands et al. 2005). Although a non-thermal component is often seen for neutron star LMXBs in quiescence (e.g. Jonker et al. 2004b), typically thermal emission can be detected as well.

The lack of detectable quiescent thermal emission places strong constraints on the properties of the neutron star core (Jonker, Wijnands & van der Klis 2004a; Tomsick, Gelino & Kaaret 2005; Wijnands et al. 2005; Jonker et al. 2007; Heinke et al. 2009). These neutron stars must be cold, suggesting that their interior may be efficiently cooled through neutrino emissions (see also Section 4.1). Such neutron stars are expected to be relatively massive, because larger central densities are thought to lead to a higher rate of neutrino cooling (Lattimer & Prakash 2004; Yakovlev & Pethick 2004). In this work, we discuss three additional *Chandra* observations of Terzan 5, carried out in 2009 and 2011, to further investigate the quiescent properties of EXO 1745−248.

2 *Chandra* OBSERVATIONS OF Terzan 5

We use four *Chandra* observations of Terzan 5, spread between 2003 and 2011, to study any possible spectral and temporal variability in the quiescent emission of EXO 1745−248. Details of the individual observations can be found in Table 2 and references therein. All four were carried out in the faint data mode, with the nominal frame time of 3.2 s and the target positioned on the S3 chip. Data reduction was carried out using the CIAO tools (v. 4.3) and following standard *Chandra* analysis threads.[3] The 2003 and 2009 data were reprocessed using the task ACIS_PROCESS_EVENTS to benefit from the most recent calibration. Episodes of high background were removed from the 2003 data, which resulted in a net exposure time of 31.2 ks. No background flares were present during the 2009 and 2011 observations, so the full exposure time was used in the analysis.

EXO 1745−248 is clearly detected in the dense core of the cluster in 2003 and 2009 (Fig. 2, left). We used a circular region with a 1.5 arcsec radius to extract source events, and one with a radius of 40 arcsec positioned on a source-free part of the CCD ∼1.4 arcmin west of the cluster core as a background reference. We extracted count rates and light curves using the tool DMEXTRACT, while the meta-task SPECEXTRACT was used to obtain spectra and to generate the ancillary response files (arf) and redistribution matrix files (rmf). The spectral data were grouped into bins with a minimum of 15 photons using the tool GRPPHA and fitted using the software package XSPEC (v. 12.7). To take into account the interstellar neutral hydrogen absorption along the line of sight, we include the PHABS model in all our spectral fits using the default XSPEC abundances and cross-sections. Throughout this paper we assume a distance of $D = 5.5$ kpc towards EXO 1745−248 when converting X-ray fluxes into luminosities. All quoted errors correspond to 90 per cent confidence levels.

Whereas EXO 1745−248 was one of the brightest sources in Terzan 5 during the 2003 and 2009 observations, the source had considerably faded in 2011 (Fig. 2). Although the source is not clearly visible in the 2011 data sets, there appears to be an excess of photons present at the source position. To verify this, we employed the wavelet-detection algorithm PWDETECT

[1] Throughout this paper we assume a distance of $D = 5.5$ kpc for Terzan 5 and EXO 1745−248.

[2] In the study of Heinke et al. (2006b), EXO 1745−248 is denoted as CX3 and IGR J17480−2446 as CX25.

[3] http://cxc.harvard.edu/ciao/threads/index.html

Table 1. Historic activity from Terzan 5.

Year	Satellite(s)	L_X (erg s^{-1})	$L_{X,peak}$ (erg s^{-1})	t_{ob} (d)	Comments	Ref.
1980	*Hakucho*	$\lesssim 3 \times 10^{36}$	–	>16	Type I X-ray bursts	1,2
1984	*EXOSAT*	$\sim 3 \times 10^{37}$	–	–		3
1990	*ROSAT* (PSPC)	$\sim 3 \times 10^{35}$	–	–		4
1991	*ROSAT* (HRI)	$\sim 3 \times 10^{34}$	–	–		5
2000	*RXTE*, *Chandra*	$\sim 2 \times 10^{37}$	$\sim 6 \times 10^{37}$	~ 100	Type I X-ray bursts, dipping	6,7,8
2002	*RXTE*	$\sim 2 \times 10^{37}$	$\sim 4 \times 10^{37}$	~ 30		8,9
2010	*Integral*, *RXTE*, *Swift*, *Chandra*	$\sim 2 \times 10^{37}$	$\sim 7 \times 10^{37}$	~ 80	Type I X-ray bursts, 11-Hz pulsations	10–15
2011	*MAXI*, *RXTE*, *Swift*, *Chandra*	$\sim 3 \times 10^{36}$	$\sim 9 \times 10^{36}$	~ 20	Superburst	16–19

Note. L_X represents the (average) 0.5–10 keV luminosity and t_{ob} reflects any available constraints on the outburst duration. We calculated L_X from fluxes reported in the literature or using publicly available *RXTE*/ASM or *MAXI* data. For the conversion to the 0.5–10 keV energy band we use PIMMS (v. 4.4) by assuming a fiducial spectrum with $N_H = 1 \times 10^{22}$ cm^{-2} and $\Gamma = 1.5$, and we adopt a distance of $D = 5.5$ kpc. When possible we also give the 0.5–10 keV peak luminosity, $L_{X,peak}$. References: (1) Makishima et al. (1981); (2) Inoue et al. (1984); (3) Warwick et al. (1988); (4) Verbunt et al. (1995); (5) Johnston, Verbunt & Hasinger (1995); (6) Markwardt & Swank (2000); (7) Heinke et al. (2003); (8) Altamirano et al., in preparation; (9) Wijnands, Homan & Remillard (2002b); (10) Bordas et al. (2010); (11) Papitto et al. (2011); (12) Miller et al. (2011); (13) Motta et al. (2011); (14) Linares, Chakrabarty & van der Klis (2011); (15) Degenaar & Wijnands (2011b); (16) Altamirano et al. (2011a); (17) Altamirano et al. (2011b); (18) Mihara et al. (2011) and (19) Pooley et al. (2011).

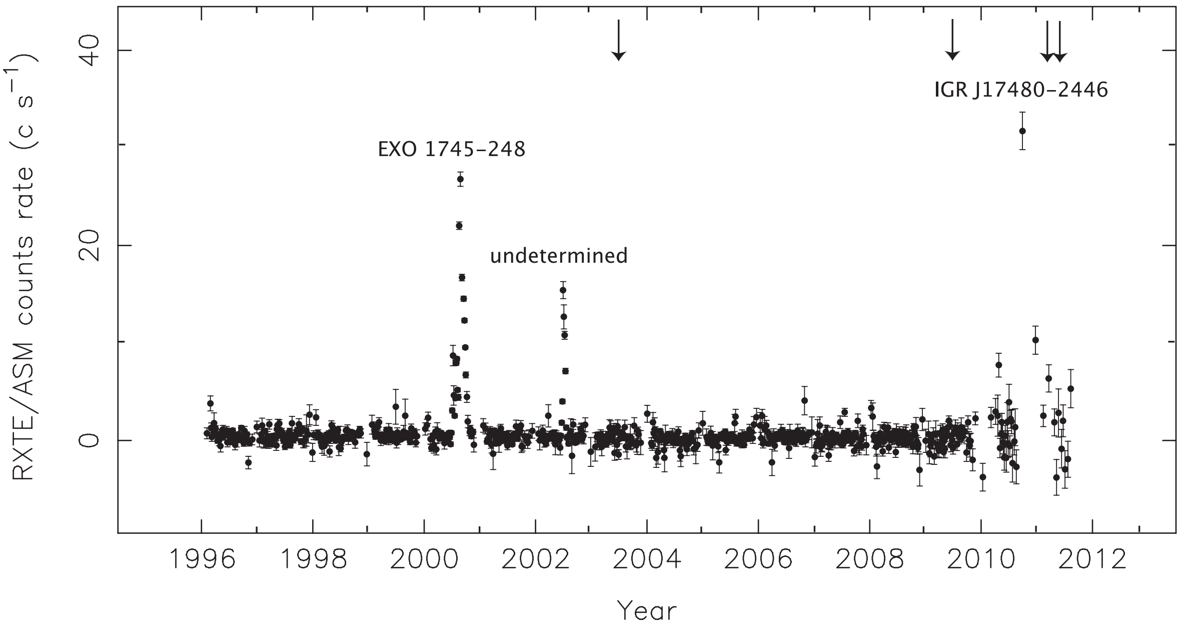

Figure 1. *RXTE*/ASM 5-d-averaged light curve of Terzan 5, illustrating three different outbursts that were recorded in the past 15 years (1.5–12 keV). Arrows indicate *Chandra* observations that were performed when no bright X-ray transients were active (Table 2). We note that the most recent outburst that was detected in 2011 October and November (EXO 1745−248) was not covered by the *RXTE*/ASM.

(Damiani et al. 1997a,b), which has been found to be particularly effective in detecting faint sources located close to brighter objects and hence it is a very useful tool for globular clusters (e.g. Heinke et al. 2006b). We performed standard PWDETECT runs on the ACIS-S3 chip with wavelet sizes varying from 0.5 to 2.0 arcsec.[4] This suggests that EXO 1745−248 was weakly detected during both 2011 observations (see Section 3.2). We extracted count rates and spectra using the tools DMEXTRACT and SPECEXTRACT, respectively. We combined the 2011 spectral data using the CIAO task COMBINE_SPECTRA to improve the statistics.

[4] See http://www.astropa.unipa.it/progetti_ricerca/PWDetect.

3 EXO 1745−248 IN QUIESCENCE

3.1 The 2003/2009 data: spectra and variability

The 2003 *Chandra* observation ofTerzan 5 was used by Wijnands et al. (2005) to study the quiescent properties of EXO 1745−248. At that time the source was detected at a mean count rate of $(0.71 \pm 0.05) \times 10^{-2}$ counts s^{-1} and displaying significant variability in the light curve (0.5–10 keV). The quiescent spectrum was found to be hard and absent of a thermal emission component. The data could be best described by a single absorbed power law model with a hydrogen column density $N_H = (1.4 \pm 0.5) \times 10^{22}$ cm^{-2} and a spectral index of $\Gamma = 1.8 \pm 0.5$. Wijnands et al. (2005) concluded

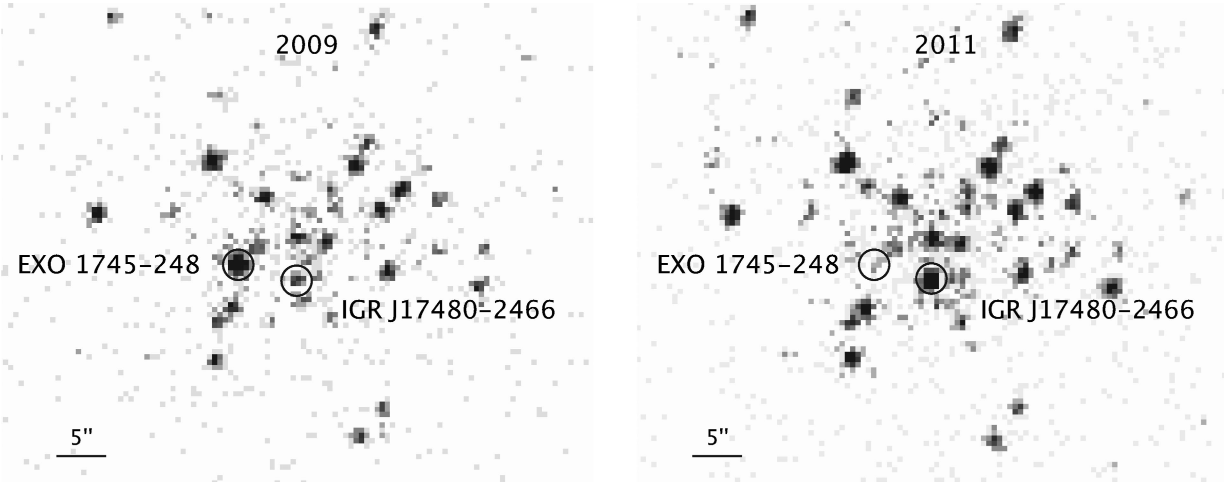

Figure 2. *Chandra*/ACIS images obtained in 2009 and 2011 (0.5–5 keV). For the 2011 image, we summed the two individual exposures of February and April (Table 2). The locations of the two known transient neutron star LMXBs are indicated by circles of 1.5 arcsec radii.

Table 2. *Chandra* observations of EXO 1745−248 in quiescence.

Date (yyyy-mm-dd)	Obs ID	$t_{\rm exp}$ (ks)	Net count rate (counts s^{-1})	Ref.
2003-07-13/14	3798	39.5	7.1×10^{-3}	1,2,3
2009-07-14/15	10 059	36.4	1.1×10^{-2}	3
2011-02-17	13 225	29.7	4.0×10^{-4}	4
2011-04-29/30	13 252	39.5	3.8×10^{-4}	5

Note. After correcting for background flares, the exposure time of the 2003 observation is $t_{\rm exp}$ = 31.2 ks. The quoted net source count rates are for the 0.5–10 keV band. Observation details can be found in the references: (1) Heinke et al. (2006b); (2) Wijnands et al. (2005); (3) Degenaar & Wijnands (2011a); (4) Degenaar & Wijnands (2011b) and (5) Degenaar et al. (2011b).

that any possible thermal emission component contributed at most ∼10 per cent to the unabsorbed 0.5–10 keV flux of $F_{\rm X} = 2.2^{+0.7}_{-0.3} \times 10^{-13}$ erg cm^{-2} s^{-1}. An upper limit on the neutron star temperature as seen by an observer at infinity of $kT^{\infty} \lesssim 80$ eV was inferred. We reprocessed and refitted the 2003 data in this work and obtained similar results as found previously (see Table 3).

During the 2009 observation EXO 1745−248 was detected at an average count rate of $(1.09 \pm 0.06) \times 10^{-2}$ counts s^{-1} (0.5–10 keV). The count rate light curve, shown in Fig. 3, reveals considerable variation by a factor of ∼3 on a time-scale of hours. We fitted the 2009 spectral data using a variety of models. Similar to the results for the 2003 observation, we find that a thermal emission model does not provide a good description of the data. We first tried a neutron star atmosphere model, which is often used to describe the X-ray spectra of quiescent neutron star LMXBs. Using the model NSATMOS (Heinke et al. 2006a) we explored fits by either fixing several parameters or leaving these free to float. All trials resulted in a reduced χ^2 value of $\chi^2_{\nu} > 6$; hence, no acceptable fit could be obtained.

A simple blackbody can describe the data, but returns unrealistic model parameters: $N_{\rm H} < 0.3 \times 10^{22}$ cm^{-2}, a temperature $kT = 1.4 \pm 0.2$ keV and an emitting radius $R = 0.04^{+0.6}_{-0.04}$ km (for D = 5.5 kpc), yielding $\chi^2_{\nu} = 1.1$ for 21 degrees of freedom (d.o.f.). The obtained hydrogen column density is well below that inferred for the 2000 outburst and 2003 quiescent data of EXO 1745−248 ($N_{\rm H} \sim 1.5 \times 10^{22}$ cm^{-2}; Heinke et al. 2003; Wijnands et al. 2005), as well as the average value found for the X-ray sources in Terzan 5 ($N_{\rm H} \sim 1.9 \times 10^{22}$ cm^{-2}; Heinke et al. 2006b). Furthermore, the temperature and emitting radius would be highly unusual for a (non-pulsating) thermally emitting neutron star in quiescence (e.g. Rutledge et al. 1999). We thus conclude that this model does not correctly describe the data.

Fitting the 2009 spectral data with a simple absorbed power law yields $N_{\rm H} = (1.1 \pm 0.3) \times 10^{22}$ cm^{-2} and $\Gamma = 1.3 \pm 0.3$ ($\chi^2_{\nu} = 1.3$ for 22 d.o.f.). The resulting 0.5–10 keV unabsorbed flux is $F_{\rm X} = (2.7 \pm 0.2) \times 10^{-13}$ erg cm^{-2} s^{-1} (see Table 3). To constrain any thermal emission component, we add an NSATMOS model with a canonical neutron star mass and radius of $M_{\rm NS} = 1.4\,{\rm M}_{\odot}$ and $R_{\rm NS} = 10$ km, a source distance of $D = 5.5$ kpc and a normalization of unity. The only free fit parameter for this model component is the neutron star temperature. Addition of this model component does not improve the fit ($\chi^2_{\nu} = 1.3$ for 21 d.o.f.). Since the spectral data do not require the inclusion of a thermal component, we consider the obtained neutron star temperature and thermal flux as upper limits to their true values. As such we find that the thermal component contributes $\lesssim$42 per cent to the total 0.5–10 keV unabsorbed flux and we obtain a neutron star temperature of $kT^{\infty} \lesssim 85$ eV. By extrapolating the NSATMOS model fit to an energy range of 0.01–100 keV, we estimate a thermal bolometric luminosity of $L^{\rm th}_{\rm q,bol} \lesssim 1 \times 10^{33}$ erg s^{-1}. This is comparable to the results for the 2003 observation (see Table 3).

The 0.5–10 keV unabsorbed flux inferred from the 2009 spectral data is higher than observed in 2003. This suggests that the source intensity may be variable on a time-scale of years, although the two measurements are consistent within the 90 per cent confidence errors (see Table 3). To further investigate whether there are intensity or spectral variations between 2003 and 2009, we fitted the two data sets simultaneously to an absorbed power law model. When all spectral parameters are forced to be the same (i.e. assuming that there are no spectral differences between the two data sets), we obtain $N_{\rm H} = (1.3 \pm 0.3) \times 10^{22}$ cm^{-2} and $\Gamma = 1.6 \pm 0.3$ for $\chi^2_{\nu} = 1.3$ (38 d.o.f.). Enabling the power-law normalization to vary between the two epochs (i.e. allowing only the intensity to change) provides a better fit that yields $N_{\rm H} = (1.2 \pm 0.3) \times 10^{22}$ cm^{-2} and $\Gamma = 1.5 \pm 0.3$ for $\chi^2_{\nu} = 1.0$ (36 d.o.f.). This model fit is shown in

Table 3. Results from spectral fitting.

Year	$N_{\rm H}$ (10^{22} cm^{-2})	Γ	$kT_{\rm eff}^{\infty}$ (eV)	χ^2_ν/cstat (d.o.f.)	$F_{\rm X}$ (10^{-13} erg cm^{-2} s^{-1})	$L_{\rm q}$ (10^{32} erg s^{-1})	$L_{\rm q,bol}^{\rm th}$	Thermal fraction
				Individual fits: PHABS(POWERLAW)				
2003	1.4 ± 0.5	1.9 ± 0.5		0.2 (13)	$2.2^{+0.6}_{-0.3}$	$8.0^{+2.5}_{-1.1}$		
2009	1.1 ± 0.3	1.3 ± 0.3		1.3 (22)	2.7 ± 0.2	9.8 ± 0.7		
2011	1.2 fix	1.5 fix		44 (33)	0.11 ± 0.04	0.4 ± 0.2		
				Individual fits: PHABS(POWERLAW+NSATMOS)				
2003	1.7 ± 0.7	1.9 ± 0.5	$\lesssim$89	0.2 (12)	$2.8^{+1.7}_{-1.0}$	10^{+4}_{-6}	$\lesssim$14	$\lesssim$55 per cent
2009	1.5 ± 0.6	1.3 ± 0.3	$\lesssim$85	1.3 (21)	3.6 ± 1.1	13 ± 4	$\lesssim$12	$\lesssim$42 per cent
2011	1.2 fix	1.5 fix	$\lesssim$42	44 (32)	0.11 ± 0.05	0.4 ± 0.2	$\lesssim$0.7	$\lesssim$34 per cent
				Simultaneous fit: PHABS(POWERLAW), all parameters tied				
2003	1.3 ± 0.3	1.6 ± 0.3		1.3 (38)	2.3 ± 0.2	8.3 ± 0.7		
2009								
				Simultaneous fit: PHABS(POWERLAW), $N_{\rm H}$ and Γ tied				
2003	1.2 ± 0.3	1.5 ± 0.3		1.0 (37)	2.0 ± 0.2	7.2 ± 0.7		
2009					2.7 ± 0.2	9.8 ± 0.7		
				Simultaneous fit: PHABS(POWERLAW), Γ tied				
2003	1.1 ± 0.3	1.5 ± 0.3		1.0 (36)	1.9 ± 0.2	6.9 ± 0.7		
2009	1.3 ± 0.3				2.8 ± 0.2	10 ± 1		
				Simultaneous fit: PHABS(POWERLAW), $N_{\rm H}$ tied				
2003	1.2 ± 0.3	1.7 ± 0.3		0.9 (36)	2.0 ± 0.3	7.2 ± 1.1		
2009		1.4 ± 0.3			2.8 ± 0.2	10 ± 1		

Note. All quoted errors refer to 90 per cent confidence levels. The 2011 data were fitted using *W*-statistics (an adapted version of Cash's statistics that allows for background subtraction), while we employed χ^2 statistics for the 2003 and 2009 data. $F_{\rm X}$ gives the total unabsorbed model flux in the 0.5–10 keV band and $L_{\rm q}$ represents the corresponding luminosity assuming $D = 5.5$ kpc. For the model fits that include a thermal component (NSATMOS) we give the thermal bolometric luminosity ($L_{\rm q,bol}^{\rm th}$) and the fractional contribution of the thermal component to the total unabsorbed 0.5–10 keV flux (last column).

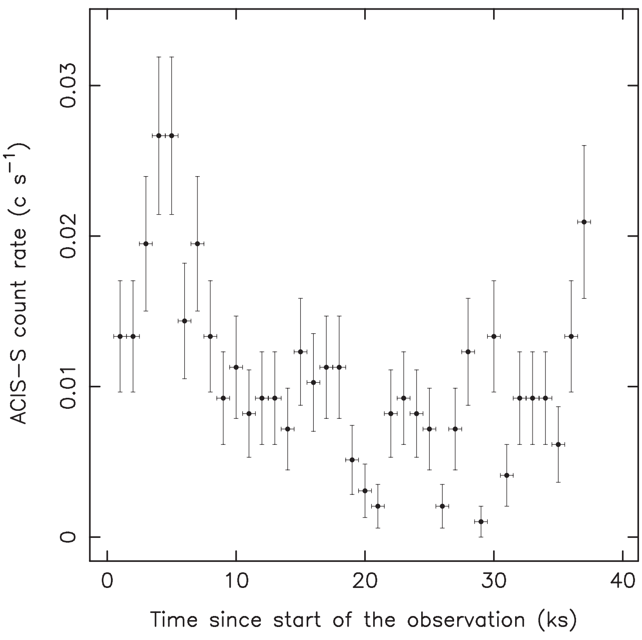

Figure 3. X-ray count rate light curve of EXO 1745−248 obtained from the 2009 *Chandra* observation of Terzan 5, covering the energy range of 0.5–10 keV and using a bin time of 1000 s.

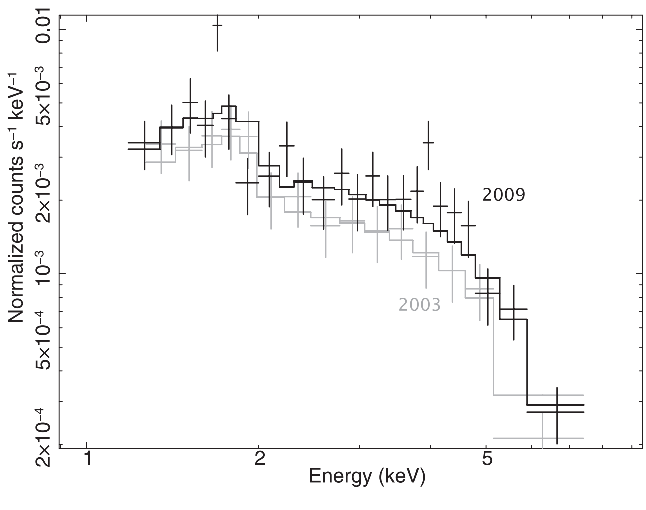

Figure 4. *Chandra*/ACIS spectra of EXO 1745−248 as observed in 2003 (bottom, grey) and 2009 (top, black). The solid lines represent the best-fitting results for an absorbed power law model with the hydrogen column density and spectral index fixed between the two epochs, while the power-law normalization is variable.

Fig. 4. An *F*-test suggests that there is a 1 per cent probability of achieving this level of improvement by chance. The inferred 0.5–10 keV unabsorbed fluxes are $F_{\rm X} = (2.0 \pm 0.2) \times 10^{-13}$ and $(2.7 \pm 0.2) \times 10^{-13}$ erg cm^{-2} s^{-1} for the 2003 and 2009 data, respectively. This suggests that the source intensity changed by ∼30 per cent between the two epochs.

We next allowed the spectral shape to vary between 2003 and 2009. The 2000 outburst light curve of EXO 1745−248 displayed X-ray dips (Markwardt et al. 2000). Such behaviour has been seen in some LMXBs and is thought to result from obscuration of the central X-ray source, e.g. by the outer edge of the accretion disc (e.g. Boirin et al. 2005). As a result, the absorption column density along the line of sight may be variable. We therefore fitted the quiescent data of EXO 1745−248 with the power-law spectral index fixed between the two epochs, while the hydrogen column density was allowed to vary. The results from this fit suggest that the X-ray spectrum was possibly more absorbed in 2009, although the fit values obtained for the two epochs are consistent within the errors (see Table 3). Keeping the hydrogen column density fixed and instead allowing the power-law index to vary yields a harder spectral index for the 2009 data, although within the errors the value is consistent with the 2003 result (Table 3).

The spectral analysis is inconclusive as to whether or not the spectral shape changed between the 2003 and 2009 data sets. We therefore carried out a colour–intensity study. For the present purpose we choose two different energy bands of 0.5–2.5 and 2.5–10 keV. We determine the ratio of *Chandra*/ACIS-S counts in the two bands (2.5–10 and 0.5–2.5 keV) and compare this to the intensity in the full energy band (0.5–10 keV). The results are displayed in Fig. 5. The model-independent colour–intensity study suggests that the X-ray emission was harder and brighter in 2009 when compared to the 2003 data. For completeness we included the 2011 observations (discussed below), but due to the large statistical uncertainties we cannot draw any conclusions about possible changes in the spectral shape compared to the other two epochs (Fig. 5).

3.2 The 2011 data: flux estimates and constraints

Using PWDETECT we obtain a tentative detection with a statistical significance of 3.5σ at the position of EXO 1745−248 for both 2011 observations. In the 2011 February observation there are 11 photons detected within a 1.25-arcsec circular region centred on the source position. Placing three regions of similar dimensions at source-free locations near the cluster core suggests that $\sim$5 photons are expected from the background. Applying the prescription for low number statistics of Gehrels (1986), we infer that 12 net photons are detected at 90 per cent confidence level. This implies a count rate of $\sim 4.0 \times 10^{-4}$ counts s^{-1} (0.5–10 keV).

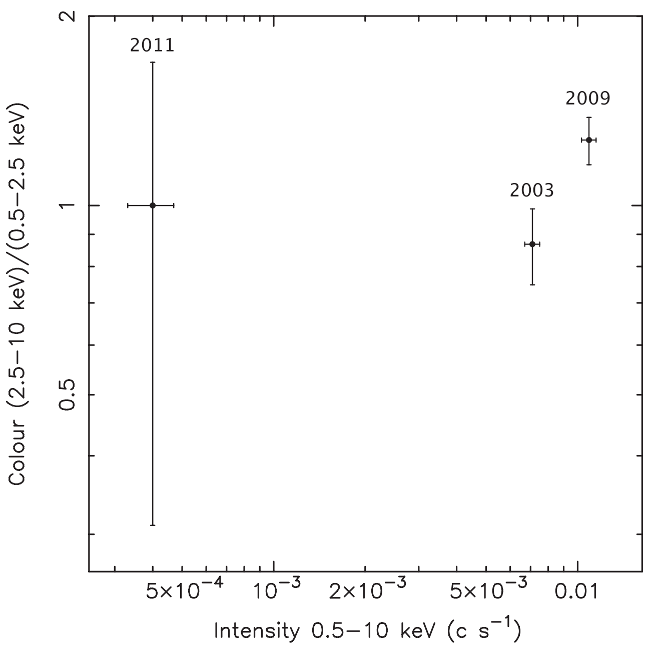

Figure 5. Observed *Chandra*/ACIS-S intensity versus colour of EXO 1745−248 during three different quiescent epochs.

In 2011 April there are 13 photons detected at the location of EXO 1745−248, whereas eight are collected from our selected background regions. Using Gehrels (1986), we find that a total of 15 net photons are detected at 90 per cent confidence level, implying a count rate of $\sim 3.8 \times 10^{-4}$ counts s^{-1}. It is possible that the excess of photons is due to a statistical fluctuation in the background or a different, overlapping X-ray source. In this case, these count rates can be regarded as upper limits on the intensity of EXO 1745−248.

Although the low number of photons does not allow detailed spectral analysis, we can obtain some estimates on the X-ray flux that corresponds to these count rates. We group the combined (background-corrected) 2011 spectrum to a minimum of one photon per bin and fit it in XSPEC using *W*-statistics (an adapted version of Cash's statistics that allows for background subtraction; Wachter, Leach & Kellogg 1979).

Assuming that the observed decrease in intensity was completely due to a lower power-law normalization, i.e. adopting the average spectral shape inferred from the 2003 and 2009 data of $N_{\rm H} = 1.2 \times 10^{22}$ cm^{-2} and $\Gamma = 1.5$ (Table 3), we obtain a 0.5–10 keV flux of $F_{\rm X} \sim 1.1 \times 10^{-14}$ erg cm^{-2} s^{-1} for the 2011 data (cstat = 44 for 33 d.o.f.). This translates into a luminosity of $L_{\rm q} \sim 4 \times 10^{31}$ erg s^{-1}, which would indicate a drop in intensity by a factor of $\sim$20–25 compared to the 2003 and 2009 observations.

Given the hints of spectral variability between the 2003 and 2009 data sets (Section 3.1), it may be more likely that the power-law index and/or hydrogen column density was different in 2011. For a realistic range in spectral parameters of $N_{\rm H} = (0.5-2.0) \times 10^{22}$ cm^{-2} and $\Gamma = 1$–3, we find a 0.5–10 keV flux range of $F_{\rm X} \sim (0.5-3.4) \times 10^{-14}$ erg cm^{-2} s^{-1} for the 2011 data, or a luminosity of $L_{\rm q} \sim (2-12) \times 10^{31}$ erg s^{-1}. We thus conclude that the power-law flux varied at least by a factor of $\sim$6. If the excess of photons seen during the 2011 observations is not related to the source, however, these estimates represent upper limits and hence the flux variation can be as large as a factor of $\gtrsim$50.

To investigate whether the 2011 data can put further constrains on the thermal quiescent emission, we added an NSATMOS component to the power-law fit for $N_{\rm H} = 1.2 \times 10^{22}$ cm^{-2} and $\Gamma = 1.5$. As for the 2003 and 2009 data, we assume $M_{\rm NS} = 1.4\,{\rm M}_{\odot}$, $R_{\rm NS} = 10$ km, $D = 5.5$ kpc and a thermal model normalization of unity. This way, we obtain an upper limit on the neutron star temperature of $kT^{\infty} \lesssim 42$ eV (cstat = 44 for 32 d.o.f.). The corresponding constraint on the thermal bolometric luminosity, obtained by extrapolating the model fit to the 0.01–100 keV energy range, is $L^{\rm th}_{\rm q,bol} \lesssim 7 \times 10^{31}$ erg s^{-1}. The estimates for the 2011 observations are consistent with the constraints obtained from analysis of the 2003 and 2009 spectral data (Section 3.1).

4 DISCUSSION

We use four *Chandra* observations of the globular cluster Terzan 5 to study the quiescent spectral and variability properties of the transient neutron star LMXB EXO 1745−248, which was active in 2000 and 2011. The observations were carried out in 2003, 2009 and 2011. No intervening accretion outbursts have been observed from the cluster during this epoch.

In 2003, EXO 1745−248 is detected at a 0.5–10 keV luminosity of $L_{\rm q} \sim 8 \times 10^{32}$ erg s^{-1}, while its intensity was $\sim$30 per cent higher 6 years later in 2009 ($L_{\rm q} \sim 1 \times 10^{33}$ erg s^{-1}). Apart from flux variations between the two epochs, the source count rate varies up to a factor of $\sim$3 during the individual observations, i.e. on a time-scale of hours. On both occasions, the X-ray spectrum is best described by a simple absorbed power law model. The source spectrum is thus dominated by hard, non-thermal emission and lacks the thermal emission component that is seen for many (non-pulsating) neutron star LMXBs at such quiescent luminosities. This implies that all observed variability can be ascribed to the hard spectral component. Our spectral fits suggest that a higher power-law normalization alone can account for the increased flux observed in 2009 compared to 2003. However, a colour–intensity study indicates that the X-ray spectrum likely changed between the two epochs, being spectrally harder in 2009 than in 2003.

While EXO 1745−248 is one of the brightest sources in Terzan 5 during the 2003 and 2009 observations, we find only a small (3.5σ) excess of photons at the source location during the two observations carried out in 2011. For these tentative detections we estimate a 0.5–10 keV luminosity of $L_{\rm q} \sim 4 \times 10^{31}$ erg s^{-1}. If the excess of photons seen during the 2011 observations is not related to the source, this should be considered an upper limit. We conclude that compared to 2003 and 2009, the power-law flux had faded at least by a factor of $\sim$6 in 2011, but possibly as much as a factor of $\gtrsim$50.

By adding a neutron star atmosphere model NSATMOS to the power-law spectral fit of the 2011 data, we constrain the neutron star temperature to $kT^{\infty} \lesssim 42$ eV and the thermal bolometric luminosity to $L_{\rm q,bol}^{\rm th} \lesssim 7 \times 10^{31}$ erg s^{-1}. These results are consistent with the constraints inferred from the absence of thermal emission during the 2003 and 2009 data sets (Table 3; see also Wijnands et al. 2005).

4.1 Constraints on the thermal emission

Whereas neutron stars cool primarily via neutrino emissions from their dense cores and via photon radiation from the stellar surface, episodes of mass accretion cause heating of the neutron star. Accretion of matter induces a chain of nuclear reactions that deposit heat deep inside the neutron star crust, which is thermally conducted over the entire stellar body. In $\sim 10^4$ yr, a neutron star reaches a thermal steady state in which heating due to the accretion of matter is balanced by cooling via neutrino emission from the stellar core and photon radiation from the surface (Brown et al. 1998; Colpi et al. 2001).

According to the minimal cooling paradigm, there is an unescapable rate of neutrino emissions that carries away energy and cools the neutron star (Page et al. 2004; Page, Geppert & Weber 2006). If a neutron star is particularly massive, however, its large central density might open up the threshold for more efficient neutrino emission processes that enhance the cooling rate (Yakovlev & Pethick 2004). Such neutron stars are therefore expected to be relatively cold. In principle, measurements of the thermal surface radiation can constrain the rate of neutrino emissions (i.e. standard/slow versus enhanced) from the neutron star core (Yakovlev, Levenfish & Haensel 2003; Heinke et al. 2009).

For slow neutrino cooling, deep crustal heating should provide an incandescent surface emission that is set by the time-averaged mass-accretion rate of the neutron star as $L_{\rm q,bol}^{\rm th} = \langle \dot{M}_{\rm long} \rangle Q_{\rm nuc}/m_{\rm u}$ (e.g. Brown et al. 1998; Colpi et al. 2001). Here, $Q_{\rm nuc} \sim 2$ MeV is the nuclear energy deposited in the crust per accreted nucleon (e.g. Haensel & Zdunik 2008), $m_{\rm u} = 1.66 \times 10^{-24}$ g is the atomic mass unit and $\langle \dot{M}_{\rm long} \rangle$ is the long-term mass-accretion rate of the system averaged over $\sim 10^4$ yr. If the thermal luminosity is found to be much fainter, this is indicative of a relatively massive neutron star that undergoes enhanced neutrino cooling in its interior. We can estimate the thermal quiescent luminosity expected from deep crustal heating for EXO 1745−248, and compare this with our observational constraints.

Heinke et al. (2003) estimate a bolometric accretion luminosity of $L_{\rm acc} \sim 3 \times 10^{37}$ erg s^{-1} by analysing *Chandra* and *RXTE* data obtained during the 2000 outburst of EXO 1745−248. For a bolometric accretion luminosity given by $L_{\rm acc} = (GM_{\rm NS}/R_{\rm NS})\langle \dot{M}_{\rm ob} \rangle$, we can estimate that the mass-accretion rate during the 2000 outburst was thus $\langle \dot{M}_{\rm ob} \rangle \sim 2 \times 10^{17}$ g s^{-1} or $\sim 3 \times 10^{-9}$ M$_{\odot}$ yr^{-1} (assuming a canonical neutron star with $M_{\rm NS} = 1.4$ M$_{\odot}$ and $R_{\rm NS} = 10$ km). The time-averaged mass-accretion rate of the neutron star ($\langle \dot{M}_{\rm long} \rangle$) may be approximated by multiplying the average outburst accretion rate ($\langle \dot{M}_{\rm ob} \rangle$) with the duty cycle of the binary, i.e. the ratio of the outburst duration and the recurrence time. The recurrence time of EXO 1745−248 is not well constrained, but the historic activity of Terzan 5 provides some rough estimates.

In the past 30 years eight distinct outbursts have been observed from the cluster, of which two could be ascribed to EXO 1745−248 with certainty (2000 and 2011; see Table 1). If this is representative for the long-term accretion history of the source, the recurrence time of the system would be $\sim$11 yr. For a typical outburst duration of $\sim$2 months (0.17 yr) the implied duty cycle would be $\sim$1 per cent. This yields a time-averaged mass-accretion rate of $\langle \dot{M}_{\rm long} \rangle \sim 2 \times 10^{15}$ g s^{-1} ($\sim 3 \times 10^{-11}$ M$_{\odot}$ yr^{-1}). For these estimates, deep crustal heating should generate a quiescent bolometric luminosity of $L_{\rm q,bol}^{\rm th} \sim 4 \times 10^{33}$ erg s^{-1}. This value would increase if more than two of the Terzan 5 outbursts were due to activity of EXO 1745−248.

The above crude estimate suggests that the quiescent thermal luminosity expected to arise from deep crustal heating is within a factor of a few of the upper limits inferred from the 2003 and 2009 *Chandra* data sets ($L_{\rm q,bol}^{\rm th} \lesssim 1 \times 10^{33}$ erg s^{-1}; Section 3.1), but a factor of $\gtrsim$60 higher than the constraints we obtain from analysis of 2011 quiescent data ($L_{\rm q,bol}^{\rm th} \lesssim 7 \times 10^{31}$ erg s^{-1}; Section 3.2). If the low luminosity observed in 2011 is intrinsic to the source and not caused by temporary obscuration of the X-ray emission (see Section 4.2), the neutron star is thus colder than expected for a duty cycle of 1 per cent. This might imply that the source on average has a longer recurrence time and that the behaviour seen in the past 30 years is not representative for its long-term activity. When slow neutrino emission processes are operating in the core, a thermal bolometric quiescent luminosity of $L_{\rm q,bol}^{\rm th} \lesssim 7 \times 10^{31}$ erg s^{-1} would require a time-averaged mass-accretion rate of $\langle \dot{M}_{\rm long} \rangle \lesssim 4 \times 10^{13}$ g s^{-1} ($\lesssim 6 \times 10^{-13}$ M$_{\odot}$ yr^{-1}). If the observed 2000 outburst is typical for the long-term accretion history of EXO 1745−248, its duty cycle would need to be $\lesssim$0.02 per cent, meaning that the source should reside $\gtrsim$900 yr in quiescence in between subsequent outbursts.

Alternatively, the neutron star in EXO 1745−248 might undergo enhanced core cooling, as was previously proposed by Wijnands et al. (2005). The same conclusion was drawn for the other transient neutron star LMXB in Terzan 5, IGR J17480−2446, based on its quiescent thermal luminosity (Degenaar & Wijnands 2011a). This would suggest that at least one of the two neutron star LMXBs undergoes enhanced core cooling or that both have a long recurrence time. The latter scenario would imply that other historic outbursts of Terzan 5 were likely caused by one or more additional transient sources.

4.2 Quiescent variability

Investigation of the four observations discussed in this work reveals that the quiescent emission of EXO 1745−248 varies both on short and long time-scales. We can summarize our observations as follows. During the 2003 and 2009 observations the source intensity changed by a factor of a few on a time-scale of hours. The X-ray flux varied by ∼30 per cent between 2003 and 2009, i.e. over a time-scale of 6 years, whereas the power-law flux had decreased by a factor of $\gtrsim$6 (and depending on the spectral parameters possibly as much as a factor of $\gtrsim$50) in the 19 months separating the 2009 and first 2011 observation. There is no evidence for variability between the two 2011 observations, which were separated by ∼2 months. It is of note that the source entered a new accretion outburst five months later in 2011 October (Altamirano et al. 2011a). Several (weakly magnetized) transient neutron star LMXBs have been found to exhibit changes in their quiescent luminosity and this variability has been interpreted in different ways.

For a group of five sources, KS 1731−260 (Wijnands et al. 2002a; Cackett et al. 2010b), MXB 1659−29 (Wijnands et al. 2004; Cackett et al. 2008), XTE J1701−462 (Fridriksson et al. 2010, 2011), EXO 0748−676 (Degenaar et al. 2009, 2011a; Díaz Trigo et al. 2011) and IGR J17480−2446 (the other LMXB in Terzan 5; Degenaar et al. 2011b), a gradual decrease in thermal X-ray emission, extending to many years, is observed after the end of an accretion outburst. This variability has been ascribed to cooling of the neutron star crust that was heated due to the accretion of matter (e.g. Rutledge et al. 2002b). For one of these sources, XTE J1701−462, episodes of increased thermal emission were found superimposed on the decaying trend. These involved a correlated increase in the contribution of the power-law spectral component and have therefore been attributed to temporal low-level accretion on to the neutron star surface (Fridriksson et al. 2010, 2011). Neutron star crust cooling cannot be invoked as an explanation for the quiescent variability of EXO 1745−248, since its quiescent emission spectrum is fully dominated by hard non-thermal emission.

Both Aql X-1 and Cen X-4 have been extensively studied in quiescence, using observations spanning decades, which has revealed intensity variations occurring on time-scales of minutes to years (Rutledge et al. 1999, 2002a; Campana & Stella 2003; Campana et al. 2004; Cackett et al. 2010a, 2011). For Cen X-4, a recent study showed that both spectral components need to be variable to explain the observed intensity variations (Cackett et al. 2010a). In particular, it was found that the ratio of the power law to thermal flux remained approximately constant, while the total flux changed by a factor of $\gtrsim$4. This suggests a direct connection between the two spectral components and led to the interpretation of residual accretion acting in quiescence (Cackett et al. 2010a). Studies of Aql X-1 were not conclusive about which of the spectral components was underlying the observed variability. Both accretion on to the neutron star surface with a variable mass-inflow rate and the variable interaction between the pulsar relativistic wind and matter outflowing from the companion star were suggested to explain the observed variability (Rutledge et al. 1999, 2001, 2002a; Campana & Stella 2003; Cackett et al. 2011).

The accreting millisecond X-ray pulsars NGC 6440 X-1 and SAX J1808.4−3658 both displayed quiescent flux variations by a factor of $\lesssim$2 that could be entirely attributed to the power-law spectral component (Cackett et al. 2005; Campana, Stella & Kennea 2008; Heinke et al. 2009). The behaviour of EXO 1745−248 is thus perhaps most reminiscent of these two neutron stars, although its variation in power-law flux appears to be stronger (up to a factor of $\gtrsim$6). It is of note that some transient LMXBs harbouring a black hole primary exhibit X-ray intensity variations in their quiescent state that are of similar magnitude as observed for EXO 1745−248 (Kong et al. 2002; Hynes et al. 2004). These systems display pure power-law spectra in quiescence, without any thermal emission component. The mechanism underlying the variations in power-law flux seen in black hole LMXBs might also produce the observed variations in the neutron star systems. This would necessarily imply, however, that the power-law emission cannot be related to any distinctive properties of a neutron star, such as a solid surface and a magnetic field.

Accretion is known to cause considerable variability on long time-scales, driving the outburst and quiescence cycles of transient LMXBs, as well as on short time-scales during outburst episodes. Continued low-level accretion therefore seems to be an attractive explanation for the observed variability of EXO 1745−248. The source might have been accreting at 0.5–10 keV luminosities of $L_q \sim (8-10)\times10^{32}$ erg s^{-1} when it was observed in 2003 and 2009, while its true quiescent luminosity (i.e. the emission level when all accretion activity has ceased) is lower and possibly represented by the 2011 observations ($L_q \sim 4 \times 10^{31}$ erg s^{-1}, 0.5–10 keV). However, it may not be straightforward to explain the large and relatively rapid drop in X-ray intensity that occurred between 2009 and 2011 within this framework. This would require a strong reduction of the accretion flow in the 19 months separating the two observations, while it had restored again only ∼5 months later when the source exhibited a new accretion outburst (2011 late-October; Altamirano et al. 2011a).

Possibly, the non-thermal X-ray emission was not intrinsically reduced but rather obscured during the 2011 observations. EXO 1745−248 displayed prominent dipping activity during the first ∼50 d of its 2000 outburst (Markwardt et al. 2000). During the dips the X-ray intensity was reduced by a factor of a few, indicating that the central X-ray source was temporarily obscured, although the dips disappeared and did not return in the second half of the outburst (Altamirano et al., in preparation). The same process may cause obscuration of the X-ray emission in quiescence. For example, the occurrence of a new outburst of EXO 1745−248 in late-2011 indicates that there was likely a (cold) accretion disc present during the 2011 quiescence observations (which were separated by ∼75 d; see Table 2) that may have partly blocked the central X-ray source and hence caused the faded X-ray emission compared to the 2003 and 2009 data.

Our colour–intensity study and spectral analysis suggest that the hydrogen column density may have varied between the 2003 and 2009 observations, which could lend support to the presence of a varying obscuring medium in quiescence. This interpretation would require the power-law emission to be produced close to the central X-ray source. An origin at the shock front between the pulsar wind and matter flowing out from the companion star would then be less likely than accretion of matter on to the neutron star's magnetic field or surface. We note that, depending on the exact spectral parameters, the decrease in quiescent power-law flux might be as large as a factor of $\gtrsim$50 (Section 3.2), which would be much stronger than the intensity variations seen during the dipping activity in the 2000 outburst of EXO 1745−248.

EXO 1745−248 adds to the (growing) list of neutron star LMXBs that show considerable X-ray variability during quiescence. New *Chandra* observations of Terzan 5 have been planned for the coming year. These allow us to further study the quiescent properties of EXO 1745−248 and can potentially shed more light on the nature of its strong quiescent X-ray variability.

ACKNOWLEDGMENTS

This work was supported by the Netherlands Research School for Astronomy (NOVA). ND is supported by NASA through Hubble

Postdoctoral Fellowship grant number HST-HF-51287.01-A from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Incorporated, under NASA contract NAS5-26555. RW acknowledges support from a European Research Council (ERC) starting grant. This work made use of the *Chandra* public data archive, *MAXI* data provided by RIKEN, JAXA and MAXI team, as well as results provided by the ASM/*RXTE* teams at MIT and at the *RXTE* SOF and GOF at NASA's GSFC. The authors are grateful to the anonymous referee for thoughtful comments that helped improve this paper.

REFERENCES

Altamirano D., Degenaar N., Heinke C. O., Homan J., Pooley D., Sivakoff G. R., Wijnands R., 2011a, Astron. Telegram, 3714
Altamirano D., Degenaar N., Heinke C. O., Homan J., Pooley D., Sivakoff G. R., Wijnands R., 2011b, Astron. Telegram, 3720
Boirin L., Méndez M., Díaz Trigo M., Parmar A. N., Kaastra J. S., 2005, A&A, 436, 195
Bordas P. et al., 2010, Astron. Telegram, 2919
Brown E. F., Bildsten L., Rutledge R. E., 1998, ApJ, 504, L95
Cackett E. M. et al., 2005, ApJ, 620, 922
Cackett E. M., Wijnands R., Miller J. M., Brown E. F., Degenaar N., 2008, ApJ, 687, L87
Cackett E. M., Brown E. F., Miller J. M., Wijnands R., 2010a, ApJ, 720, 1325
Cackett E. M., Brown E. F., Cumming A., Degenaar N., Miller J. M., Wijnands R., 2010b, ApJ, 722, L137
Cackett E. M., Fridriksson J. K., Homan J., Miller J. M., Wijnands R., 2011, MNRAS, 414, 3006
Campana S., 2003, preprint (astro-ph/0311212)
Campana S., Stella L., 2003, ApJ, 597, 474
Campana S., Colpi M., Mereghetti S., Stella L., Tavani M., 1998, A&AR, 8, 279
Campana S., Israel G. L., Stella L., Gastaldello F., Mereghetti S., 2004, ApJ, 601, 474
Campana S., Stella L., Kennea J. A., 2008, ApJ, 684, L99
Chen W., Shrader C. R., Livio M., 1997, ApJ, 491, 312
Colpi M., Geppert U., Page D., Possenti A., 2001, ApJ, 548, L175
Damiani F., Maggio A., Micela G., Sciortino S., 1997a, ApJ, 483, 350
Damiani F., Maggio A., Micela G., Sciortino S., 1997b, ApJ, 483, 370
Degenaar N., Wijnands R., 2011a, MNRAS, 412, L68
Degenaar N., Wijnands R., 2011b, MNRAS, 414, L50
Degenaar N. et al., 2009, MNRAS, 396, L26
Degenaar N. et al., 2011a, MNRAS, 412, 1409
Degenaar N., Brown E. F., Wijnands R., 2011b, MNRAS, 418, L152
Díaz Trigo M., Boirin L., Costantini E., Méndez M., Parmar A., 2011, A&A, 528, 150
Fridriksson J. K. et al., 2010, ApJ, 714, 270
Fridriksson J. K. et al., 2011, ApJ, 736, 162
Galloway D. K., Özel F., Psaltis D., 2008, MNRAS, 387, 268
Gehrels N., 1986, ApJ, 303, 336
Haensel P., Zdunik J. L., 2008, A&A, 480, 459
Heinke C. O., Edmonds P. D., Grindlay J. E., Lloyd D. A., Cohn H. N., Lugger P. M., 2003, ApJ, 590, 809
Heinke C. O., Rybicki G. B., Narayan R., Grindlay J. E., 2006a, ApJ, 644, 1090
Heinke C. O., Wijnands R., Cohn H. N., Lugger P. M., Grindlay J. E., Pooley D., Lewin W. H. G., 2006b, ApJ, 651, 1098
Heinke C. O., Jonker P. G., Wijnands R., Deloye C. J., Taam R. E., 2009, ApJ, 691, 1035
Hynes R. I. et al., 2004, ApJ, 611, L125
Inoue H. et al., 1984, PASJ, 36, 855
Johnston H. M., Verbunt F., Hasinger G., 1995, A&A, 298, L21
Jonker P. G., Wijnands R., van der Klis M., 2004a, MNRAS, 349, 94
Jonker P. G., Galloway D. K., McClintock J. E., Buxton M., Garcia M., Murray S., 2004b, MNRAS, 354, 666
Jonker P. G., Steeghs D., Chakrabarty D., Juett A. M., 2007, ApJ, 665, L147
Kong A. K. H., McClintock J. E., Garcia M. R., Murray S. S., Barret D., 2002, ApJ, 570, 277
Lattimer J. M., Prakash M., 2004, Sci, 304, 536
Linares M., Chakrabarty D., van der Klis M., 2011, ApJ, 733, L17
Makishima K. et al., 1981, ApJ, 247, L23
Markwardt C. B., Swank J. H., 2000, IAU Circ., 7454, 1
Markwardt C. B., Strohmayer T. E., Swank J. H., Zhang W., 2000, IAU Circ., 7482, 2
Mihara T. et al., 2011, Astron. Telegram, 3729
Miller J. M., Maitra D., Cackett E. M., Bhattacharyya S., Strohmayer T. E., 2011, ApJ, 731, L7
Motta S. et al., 2011, MNRAS, 414, 1508
Ortolani S., Barbuy B., Bica E., Zoccali M., Renzini A., 2007, A&A, 470, 1043
Page D., Lattimer J. M., Prakash M., Steiner A. W., 2004, ApJS, 155, 623
Page D., Geppert U., Weber F., 2006, Nuclear Phys. A, 777, 497
Papitto A., D'Aì A., Motta S., Riggio A., Burderi L., di Salvo T., Belloni T., Iaria R., 2011, A&A, 526, L3
Pooley D. et al., 2003, ApJ, 591, L131
Pooley D., Homan J., Heinke C., Linares M., Altamirano D., Lewin W., 2010, Astron. Telegram, 2974
Pooley D., Homan J., Altamirano D., Degenaar N., Heinke C. O., Lewin W., Sivakoff G. R., Wijnands R., 2011, Astron. Telegram, 3743
Ransom S. M., Hessels J. W. T., Stairs I. H., Freire P. C. C., Camilo F., Kaspi V. M., Kaplan D. L., 2005, Sci, 307, 892
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, 559, 1054
Rutledge R. E., Bildsten L., Brown E. F., Pavlov G. G., Zavlin V. E., 2002a, ApJ, 577, 346
Rutledge R. E., Bildsten L., Brown E. F., Pavlov G. G., Zavlin V. E., Ushomirsky G., 2002b, ApJ, 580, 413
Strohmayer T. E., Markwardt C. B., Pereira D., Smith E. A., 2010, Astron. Telegram, 2929
Tomsick J. A., Gelino D. M., Kaaret P., 2005, ApJ, 635, 1233
Verbunt F., Bunk W., Hasinger G., Johnston H. M., 1995, A&A, 300, 732
Wachter K., Leach R., Kellogg E., 1979, ApJ, 230, 274
Warwick R. S., Norton A. J., Turner M. J. L., Watson M. G., Willingale R., 1988, MNRAS, 232, 551
Wijnands R., Guainazzi M., van der Klis M., Méndez M., 2002a, ApJ, 573, L45
Wijnands R., Homan J., Remillard R., 2002b, Astron. Telegram, 101
Wijnands R., Homan J., Miller J. M., Lewin W. H. G., 2004, ApJ, 606, L61
Wijnands R., Heinke C. O., Pooley D., Edmonds P. D., Lewin W. H. G., Grindlay J. E., Jonker P. G., Miller J. M., 2005, ApJ, 618, 883
Yakovlev D. G., Pethick C. J., 2004, ARA&A, 42, 169
Yakovlev D. G., Levenfish K. P., Haensel P., 2003, A&A, 407, 265
Zampieri L., Turolla R., Zane S., Treves A., 1995, ApJ, 439, 849

This paper has been typeset from a TEX/LATEX file prepared by the author.