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CHALLENGE TO HEATING AND COOLING MODELS?*

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CONTINUED NEUTRON STAR CRUST COOLING OF THE 11 Hz X-RAY PULSAR IN TERZAN 5: A CHALLENGE TO HEATING AND COOLING MODELS?

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ABSTRACT

The transient neutron star low-mass X-ray binary and 11 Hz X-ray pulsar IGR J17480–2446 in the globular cluster Terzan 5 exhibited an 11 week accretion outburst in 2010. *Chandra* observations performed within five months after the end of the outburst revealed evidence that the crust of the neutron star became substantially heated during the accretion episode and was subsequently cooling in quiescence. This provides the rare opportunity to probe the structure and composition of the crust. Here, we report on new *Chandra* observations of Terzan 5 that extend the monitoring to $\simeq 2.2$ yr into quiescence. We find that the thermal flux and neutron star temperature have continued to decrease, but remain significantly above the values that were measured before the 2010 accretion phase. This suggests that the crust has not thermally relaxed yet, and may continue to cool. Such behavior is difficult to explain within our current understanding of heating and cooling of transiently accreting neutron stars. Alternatively, the quiescent emission may have settled at a higher observed equilibrium level (for the same interior temperature), in which case the neutron star crust may have fully cooled.

Key words: pulsars: general – pulsars: individual (IGR J17480-2446) – stars: neutron – X-rays: binaries

1. INTRODUCTION

Studying the thermal evolution of neutron stars is a promising avenue to gain insight into their structure and composition. These compact stellar remnants are born hot in supernova explosions, but quickly cool as their thermal energy is drained via neutrino emission from their dense interior and thermal photons radiated from their surface. When residing in low-mass X-ray binaries (LMXBs), neutron stars accrete matter from a late-type companion star that overflows its Roche lobe. The accretion of matter can re-heat the neutron star and drastically impact its thermal evolution.

Accretion causes the original crust of a neutron star (built of cold, catalyzed matter; Shapiro & Teukolsky 1986) to become replaced by one formed by the processed material. An accreted crust is out of nuclear equilibrium and represents a reservoir of energy as it provides a site for non-equilibrium processes that generate heat (e.g., Sato 1979; Haensel & Zdunik 1990a, 1990b; Steiner 2012). Compression of the crust by ongoing accretion induces a chain of nuclear reactions that produce heat at a rate that is proportional to the mass-accretion rate. In the outer crustal layers, electron captures generate on the order of $\simeq 0.01$ MeV per accreted nucleon (e.g., Gupta et al. 2007; Estradé et al. 2011). However, most heat is produced in pycnonuclear fusion reactions that occur deep within the crust and release $\simeq 1.5$ MeV nucleon⁻¹ (e.g., Haensel & Zdunik 1990b; Yakovlev et al. 2006; Horowitz et al. 2008). The structure and composition of the crust play an important role in the heat generation.

In transient LMXBs, a neutron star is typically accreting actively only for a few months at a time. Such accretion outbursts

are interleaved by quiescent episodes, generally lasting for years or decades, during which accretion onto the neutron star is strongly reduced or completely halted. During these quiescent intervals, the accretion-heated crust cools as the gained energy is thermally conducted toward the stellar core and surface (e.g., Ushomirsky & Rutledge 2001; Rutledge et al. 2002b). As the crust thermally relaxes, it eventually settles at a stable level that is determined by the core temperature, which evolves on a much longer time scale ($\simeq 10^4$ yr; e.g., Colpi et al. 2001). The cooling rate is sensitive to the heat capacity and thermal transport properties of the crust, and hence to its structure and composition.

Multi-epoch observations of four neutron star LMXBs following long (> 1 yr) accretion outbursts have revealed a steady decrease in thermal X-ray emission on a time scale of years (e.g., Wijnands et al. 2002, 2004; Cackett et al. 2008, 2010a; Degenaar et al. 2011b; Díaz Trigo et al. 2011; Fridriksson et al. 2011). These observations can successfully be modeled as cooling of an accretion-heated neutron star crust and have provided valuable insights into the properties of these layers (Rutledge et al. 2002b; Shternin et al. 2007; Brown & Cumming 2009; Page & Reddy 2013). These four so-called quasi-persistent LMXBs served as prime targets because their prolonged accretion phases were expected to severely heat the crust so that the subsequent cooling would become detectable. However, shorter outbursts can potentially also cause significant crustal heating (Brown et al. 1998).

IGR J17480–2446 is a neutron star LMXB that contains an 11 Hz X-ray pulsar and a $\simeq 0.8 M_{\odot}$ companion star (Strohmayer et al. 2010; Testa et al. 2012). The source is located in the dense core of the globular cluster Terzan 5, which lies at an estimated distance of $D \simeq 5.5$ kpc (Ortolani et al.

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Table 1
New *Chandra*/ACIS-S Observations of Terzan 5

Obs ID	Date	Exposure Time (ks)	Count Rate (10^{-3} counts s^{-1})
13705	2011 Sep 5	13.9	3.41 ± 0.50
14339	2011 Sep 8	34.1	3.06 ± 0.30
13706	2012 May 13	46.5	2.60 ± 0.24
14475	2012 Sep 17/18	30.5	2.92 ± 0.31
14476	2012 Oct 28	28.6	2.42 ± 0.29
14477	2013 Feb 5	28.6	1.76 ± 0.25
14625	2013 Feb 22	49.2	2.07 ± 0.21
15615	2013 Feb 24	84.2	1.90 ± 0.15

Notes. The count rates of IGR J17480–2446 are given for the 0.3–10 keV energy range. Quoted uncertainties are at the 1σ level of confidence.

2007). IGR J17480–2446 was identified as a transient X-ray source when it entered an accretion outburst in 2010 October (Bordas et al. 2010; Pooley et al. 2010). It remained active for $\simeq 11$ weeks at an estimated average bolometric luminosity of $L_X \simeq 6 \times 10^{37}$ erg s^{-1} (Linares et al. 2012), before it returned to quiescence in 2010 December (Degenaar & Wijnands 2011a).

Chandra observations obtained in 2011 February, $\simeq 50$ days after the end of the outburst, revealed that the quiescent X-ray emission of IGR J17480–2446 was elevated compared to the level measured from archival observations taken in 2003 and 2009 (Degenaar & Wijnands 2011a, 2011b). A new observation obtained $\simeq 75$ days later, in 2011 April, revealed that the thermal emission had decreased but still remained above the 2003/2009 level. By invoking the presence of a strong, additional heat source in the outer crustal layers, it was proposed that the crust became significantly heated during the accretion phase and was subsequently cooling in quiescence (Degenaar et al. 2011a). In this work we present new X-ray observations of Terzan 5 that support this hypothesis.

2. OBSERVATIONS, DATA ANALYSIS AND RESULTS

Between 2011 September and 2013 February, six new *Chandra*/ACIS observations were performed of Terzan 5 at times when no bright X-ray transients were active (Table 1). These can be used to further study the thermal evolution of the 11 Hz X-ray pulsar. All observations were performed in the “faint” timed data mode with the globular cluster positioned on the S3 chip. A 1/4 sub-array was used for the observations with IDs 14475–77, whereas all others were carried out in full frame mode. All observations were free from background flares. We reduced and analyzed the data using the CIAO tools version 4.5 and CALDB version 4.5.5.

We extracted source events from IGR J17480–2446 by using a circular region with a radius of $1''$. As a background reference we used a source-free circular region with a radius of $40''$ that was positioned $\simeq 1/4$ west of the cluster core. Count rates were extracted using DMEXTRACT, whereas spectra and the associated response files were created using SPECEXTRACT. We grouped the spectral data to contain a minimum of 15 photons per bin using GRPPHA, and performed spectral fits in the 0.5–10 keV range using XSPEC version 12.7 (Arnaud 1996). All uncertainties quoted in the text and presented in plots and tables are at the 1σ level of confidence.

The 2011 September observation was split into two exposures that were taken within three days (Obs IDs 13705 and 14339; Table 1). IGR J17480–2446 is detected at similar count rates in both observations and we did not find any significant spectral

differences when analyzing the two data sets separately. We therefore summed the two spectra and weighted response files using the task COMBINE.SPECTRA to improve the statistics. Likewise, we combined the three exposures that were taken in 2013 February within an interval of 19 days (Obs IDs 14477, 14625, and 15615; Table 1).

2.1. Spectral Analysis

We fit all data sets simultaneously to study the thermal evolution of the neutron star. To ensure a homogenous analysis, we include the *Chandra* observations performed in 2003 and 2009 (i.e., before the 2010 accretion outburst; Obs IDs 3798 and 10059), as well as those obtained in 2011 February and April (Obs IDs 13225 and 13252). For details on those observations, we refer to Degenaar & Wijnands (2011a, 2011b) and Degenaar et al. (2011a).

Previous studies showed that the quiescent spectra of IGR J17480–2446 were fitted well with a thermal emission model (Degenaar & Wijnands 2011a, 2011b; Degenaar et al. 2011a). We use the neutron star atmosphere model NSATMOS of Heinke et al. (2006a), for which we fix the mass and radius of the neutron star at $M = 1.4 M_\odot$ and $R = 10$ km, the source distance at $D = 5.5$ kpc, and the normalization at unity (which implies that the entire neutron star is radiating). As such, the only free fit parameter for this model is the neutron star effective temperature kT . Since it is common in the literature to quote the temperature as seen by a distant observer, we convert the fitted temperatures to $kT^\infty = kT/(1+z)$, where $1+z = (1 - R_s/R)^{-1/2} = 1.31$ is the gravitational redshift factor for our choice of M and R (with $R_s = 2GM/c^2$ being the Schwarzschild radius, G the gravitational constant, and c the speed of light).

In all spectral fits we account for interstellar absorption by including the TBABS model (Wilms et al. 2000) with the VERN cross sections (Verner et al. 1996) and WILM abundances (Wilms et al. 2000). We tie the hydrogen column density between the different observations, i.e., this parameter is assumed to be constant at all epochs (for a justification, see Miller et al. 2009). The NSATMOS model fits were extrapolated to the 0.01–100 keV range to obtain an estimate of the (unabsorbed) thermal bolometric flux. The results of our spectral analysis are summarized in Table 2.

Fitting all quiescent spectral data simultaneously yields a good fit with a reduced chi-squared value of $\chi_\nu^2 = 0.89$ for 61 degrees of freedom (dof) and a p -value of $P_\chi = 0.72$.¹⁰ The obtained hydrogen column density, $N_H = (1.98 \pm 0.07) \times 10^{22}$ cm $^{-2}$, is consistent with the average value found for the 16 brightest X-ray point sources in the cluster (Heinke et al. 2006b), and the values obtained in previous quiescent studies of IGR J17480–2446 (Degenaar & Wijnands 2011a, 2011b; Degenaar et al. 2011a).

The obtained temperatures show a gradual decrease from $kT^\infty \simeq 100$ to $\simeq 83$ eV over the $\simeq 2.2$ yr time span covered by the observations. These values are higher than those measured from pre-outburst data obtained in 2003/2009 ($kT^\infty \simeq 74$ eV). The inferred 0.5–10 keV thermal luminosity decreases from $L_X \simeq 1.5 \times 10^{33}$ to $\simeq 6.3 \times 10^{32}$ erg s^{-1} , but remains above the pre-outburst level of $L_X \simeq 3.6 \times 10^{32}$ erg s^{-1} . The estimated bolometric flux is on average a factor $\simeq 1.6$ higher than the flux measured in the 0.5–10 keV band (Table 2). The temperatures

¹⁰ The p -value associated with the test statistic represents the probability that deviations between the model and the data are due to chance alone. Generally, the model is rejected when $P_\chi \lesssim 0.05$.

Table 2
Results from Analysis of the Spectral Data

Epoch	MJD	kT^∞ (eV)	F_X (10^{-13} erg cm $^{-2}$ s $^{-1}$)	F_{bol}	L_X (10^{32} erg s $^{-1}$)	L_{bol}
2003/2009	52833.5/55027.5	73.6 ± 1.6	1.00 ± 0.12	1.78 ± 0.20	3.62 ± 0.43	6.44 ± 0.72
2011 Feb	55609	99.7 ± 1.6	4.19 ± 0.33	6.02 ± 0.41	15.2 ± 1.2	21.8 ± 1.5
2011 Apr	55680.5	91.5 ± 1.5	2.81 ± 0.23	4.26 ± 0.29	10.2 ± 0.8	15.4 ± 1.0
2011 Sep	55810.5	89.2 ± 1.5	2.50 ± 0.19	3.86 ± 0.25	9.05 ± 0.69	14.0 ± 0.9
2012 May	56060	84.8 ± 1.5	1.97 ± 0.19	3.15 ± 0.23	7.13 ± 0.69	11.4 ± 0.8
2012 Sep	56187.5	88.5 ± 1.9	2.40 ± 0.24	3.73 ± 0.32	8.69 ± 0.87	13.5 ± 1.2
2012 Oct	56228	84.6 ± 2.0	1.94 ± 0.23	3.11 ± 0.32	7.02 ± 0.83	11.3 ± 1.2
2013 Feb	56340	82.8 ± 1.2	1.75 ± 0.12	2.86 ± 0.17	6.33 ± 0.43	10.4 ± 0.6

Notes. F_X and F_{bol} represent the unabsorbed fluxes in the 0.5–10 keV and 0.01–100 keV bands, respectively. L_X and L_{bol} give the corresponding luminosities for a distance of $D = 5.5$ kpc. For the spectral fits, the neutron star mass and radius were fixed at $M = 1.4 M_\odot$ and $R = 10$ km, and a distance of $D = 5.5$ kpc was assumed. The hydrogen column density was tied between the different data sets, yielding $N_{\text{H}} = (1.98 \pm 0.07) \times 10^{22}$ cm $^{-2}$. Quoted uncertainties are at the 1σ level of confidence.

and fluxes obtained for the 2003/2009 and 2011 February/April data are consistent with the values reported in previous work (Degenaar & Wijnands 2011a, 2011b; Degenaar et al. 2011a).

We note that the *NSATMOS* model assumes that the magnetic field has a negligible effect on the emerging spectrum, which is justified for $B \lesssim 10^9$ G (Heinke et al. 2006a). However, this may not be valid for IGR J17480–2446, as it has an estimated magnetic field of $B \simeq 10^9$ – 10^{10} G (Cavecchi et al. 2011; Miller et al. 2011; Papitto et al. 2011). Magnetized neutron star atmosphere models, however, only allow for much higher field strengths of $B \geq 10^{12}$ G. We briefly explored one such model (NSA; Zavlin et al. 1996), adopting $B = 10^{12}$ G. This did not yield an acceptable fit to the combined data set ($\chi^2_{\nu} = 1.71$ for 88 dof, $P_\chi = 3.6 \times 10^{-5}$). However, since we compare relative fluxes and temperatures, the observed decrease should be robust and not caused by any model uncertainties (nor by systematic uncertainties such as the source distance).

2.2. Constraints on a Hard Emission Tail

The quiescent spectra are soft and well-fitted with a thermal emission model. Previous analysis of the 2003/2009 and 2011 February/April data showed that any possible non-thermal emission tail, which is often seen in the spectra of quiescent neutron star LMXBs, could contribute at most $\simeq 20\%$ to the total unabsorbed 0.5–10 keV flux (Degenaar & Wijnands 2011a, 2011b; Degenaar et al. 2011a). We examined the possible presence of a hard spectral component by adding a power-law component (PEGPWRLW) to the thermal model fits.

We first investigated the 2013 February data set, because it had the longest exposure time and the highest sensitivity. The *NSATMOS* model provides an adequate fit ($\chi^2_{\nu} = 1.25$ for 18 dof and $P_\chi = 0.21$), but it can be seen in Figure 1 that the flux in the last energy bin is underestimated. Adding a power-law component results in $\chi^2_{\nu} = 0.89$ for 16 dof and $P_\chi = 0.59$. The photon index is not well constrained ($\Gamma < 5.7$), but the best-fit value of $\Gamma = 3.3$ is much softer than typically found for the quiescent spectra of neutron star LMXBs ($\Gamma \simeq 1.5$ – 2). Given the limited quality of the spectral data, this is probably because the power law attempts to fit part of the thermal emission. This suggests that there is no significant power-law component present in the spectrum.

If we include a power-law component when fitting all data sets simultaneously, we again obtain a very soft index with large errors ($\Gamma = 3.6^{+0.7}_{-1.3}$; yielding $\chi^2_{\nu} = 0.67$ for 52 dof and $P_\chi = 0.97$). To place limits on the power-law contribution we fixed

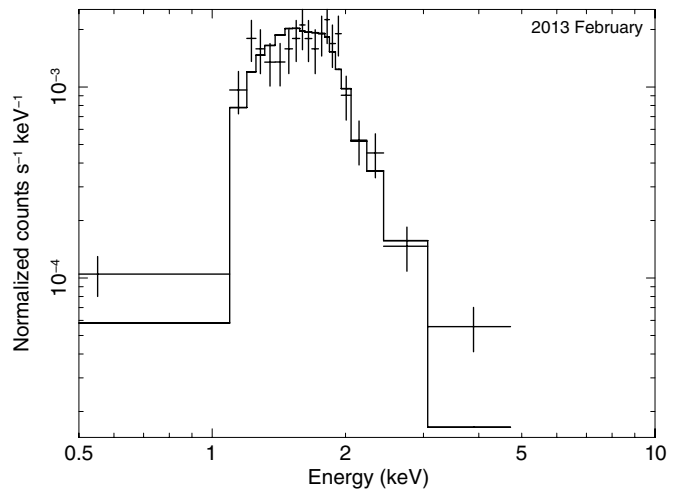


Figure 1. Combined X-ray spectrum of the three observations performed in 2013 February (Obs IDs 14477, 14625, and 15615). The solid line represents a fit using an absorbed neutron star atmosphere model.

the index to $\Gamma = 2.0$. For this fit the fractional contribution of the hard tail to the unabsorbed 0.5–10 keV varies (non-monotonically) between 3% and 22% for the different data sets ($\chi^2_{\nu} = 0.68$ for 53 dof and $P_\chi = 0.96$). We consider these upper limits.

2.3. The Crust Cooling Curve

Figure 2 displays the evolution of the temperature of the neutron star following the 2010 accretion outburst. The thermal emission follows a steady and smooth decay.¹¹ This supports the hypothesis that the crust became significantly heated during the accretion phase and is cooling in quiescence.

To characterize the shape of the crust cooling curve and allow for a comparison with other sources, we fit the temperature curve with an exponential decay function of the form $y(t) = ae^{-(t-t_0)/\tau} + b$, and a power-law decay of the form $y(t) = a(t-t_0)^{-\alpha} + b$. Here, a is a normalization constant, b a constant offset that represents the quiescent base level, τ the e-folding time, α the decay index, and t_0 the start time of the cooling curve (assumed to be 2010 December 26, MJD 55556; Degenaar & Wijnands 2011b).

¹¹ The apparent enhancement in the 2012 September data (Obs ID 14475) is only at the $\simeq 1\sigma$ level and hence not significant (see also Tables 1 and 2).

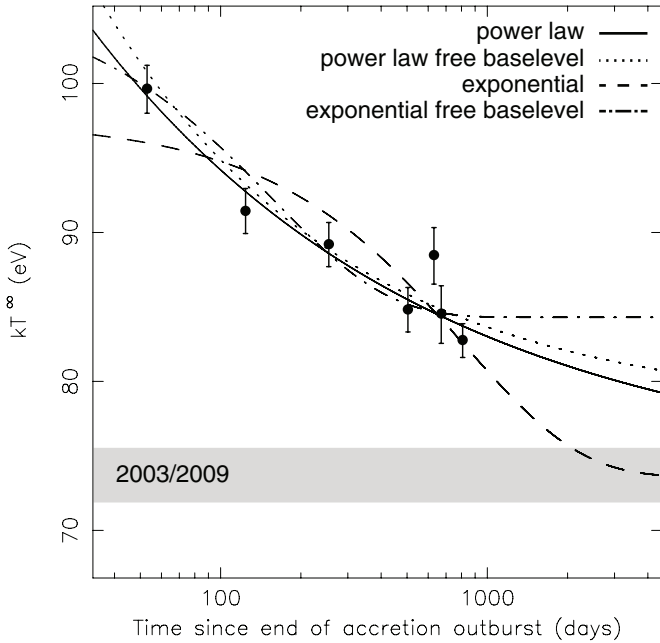


Figure 2. Evolution of the neutron star temperature after the 2010 outburst along with decay fits. The solid and dashed lines represents fits to a power law and exponential decay that go down to the level detected in 2003/2009 (gray shaded area), respectively. The dotted (power law) and dash-dotted (exponential) lines are decay fits with the quiescent base level left as a free parameter. The end of the outburst was assumed to be 2010 December 26 (MJD 55556; Degenaar & Wijnands 2011b). Error bars represent 1σ confidence intervals.

First exploring the exponential decay, we find that fixing the quiescent base level to the temperature inferred from the 2003/2009 data (i.e., $b = 73.6$ eV) results in a poor fit (dashed line in Figure 2). If we instead allow this parameter to vary (i.e., assuming that the quiescent base level can differ between outbursts; see Section 3.3), a better fit is obtained that yields a base level of $b = 84.3 \pm 1.4$ eV (dash-dotted curve in Figure 2; Table 3). This is close to the value obtained from the 2013 February data ($kT^\infty = 82.8 \pm 1.2$ eV) and suggests that the crust cooling curve may have (nearly) leveled off.

We obtain better fits by using a power-law decay function. Assuming a fixed base level of $b = 73.6$ eV yields an acceptable fit (solid curve in Figure 2; Table 3). When including the base level as a fit parameter, we obtain $b = 77.3 \pm 1.0$ eV. This is significantly lower than our most recent measurement of 2013 February (Table 2). If the power-law fit is a correct description of the temperature evolution, it would therefore be indicative of continued cooling of the crust.

The crust cooling curves of other sources have been fit to a power-law decay without a constant offset (Cackett et al. 2008, 2010a; Degenaar et al. 2011b; Fridriksson et al. 2011). To allow for a direct comparison of the decay index of IGR J17480–2446, we therefore also report a fit without including a base level (i.e., assuming $b = 0$; Table 3).

3. DISCUSSION

We use new *Chandra* observations of the globular cluster Terzan 5 to further study the quiescent emission of the 11 Hz X-ray pulsar IGR J17480–2446. The new data cover a time span of $\simeq 250$ –800 days since the cessation of its 2010 October–December accretion phase. We combine these with two earlier observations obtained $\simeq 50$ and $\simeq 125$ days

Table 3
Decay Fits to the Quiescent Light Curve

Fit Parameter (unit)	Value
Exponential decay, base level fixed	
Normalization, a (eV)	23.8 ± 1.3
Decay time, τ (days)	825 ± 107
Constant offset, b (eV)	73.6 fixed
χ^2_ν (dof)	3.08 (5)
P_χ	0.01
Exponential decay, base level free	
Normalization, a (eV)	21.6 ± 4.0
Decay time, τ (days)	157 ± 62
Constant offset, b (eV)	84.3 ± 1.4
χ^2_ν (dof)	1.84 (4)
P_χ	0.12
Power-law decay, base level fixed	
Normalization, a (eV)	98.6 ± 18.7
Decay index, α	0.34 ± 0.04
Constant offset, b (eV)	73.6 fixed
χ^2_ν (dof)	1.21 (5)
P_χ	0.30
Power-law decay, base level free	
Normalization, a (eV)	147.9 ± 12.7
Decay index, α	0.47 ± 0.05
Constant offset, b (eV)	77.3 ± 1.0
χ^2_ν (dof)	1.20 (4)
P_χ	0.31
Power-law decay, no constant offset	
Normalization, a (eV)	124.8 ± 4.8
Decay index, α	0.06 ± 0.01
Constant offset, b (eV)	0 fix
χ^2_ν (dof)	1.43 (5)
P_χ	0.21

Notes. The quiescent data was fit to an exponential decay of the form $y(t) = a e^{-(t-t_0)/\tau} + b$, and a power-law decay shaped as $y(t) = a(t - t_0)^{-\alpha} + b$. The power-law fit without constant offset is included to allow for a direct comparison with other sources. The start of the cooling curve, t_0 was set to 2010 December 26 (MJD 55556; Degenaar & Wijnands 2011b). Quoted uncertainties are at the 1σ level of confidence.

post-outburst. The source intensity is observed to decay smoothly over the 2.2 yr time span covered by the observations.

Fitting the spectral data with a neutron star atmosphere model suggests that the neutron star temperature steadily decreased by $\simeq 20\%$ from $kT^\infty \simeq 100$ to $\simeq 83$ eV. The inferred 0.5–10 keV luminosity decreased by a factor of $\simeq 2.5$ from $L_X \simeq 1.5 \times 10^{33}$ to $\simeq 6.3 \times 10^{32}$ erg s $^{-1}$. The quiescent spectra of IGR J17480–2446 are described well by a thermal model and there is no indication for the presence of a significant hard emission tail. By including a power-law spectral component to the thermal model fits, we found that it must always contribute $\lesssim 22\%$ to the total unabsorbed 0.5–10 keV flux.

The temperature determined from our most recent observations (2013 February) is higher than that measured in 2003/2009 at the $\simeq 5\sigma$ level of confidence (Figure 2). Likewise, the thermal flux remains a factor of $\simeq 2$ above the pre-outburst level (Table 2). If the source were to return to the 2003/2009 level, this suggests that the neutron star crust is still hot and needs to cool further.

3.1. Comparison with Other Sources and Model Calculations

The observed steady decrease in neutron star temperature provides strong support for the hypothesis that the crust was substantially heated during the 2010 accretion outburst and is currently cooling in quiescence. Such crustal cooling has previously been reported for four other neutron star LMXBs: KS 1731–260, MXB 1659–29, EXO 0748–676, and XTE J1701–462 (Wijnands et al. 2002, 2004; Cackett et al. 2008, 2010a; Degenaar et al. 2009, 2011b; Díaz Trigo et al. 2011; Fridriksson et al. 2010, 2011). All four experienced prolonged outbursts lasting $\simeq 1.5$ to $\simeq 25$ yr, and show a continuous decrease in their quiescent thermal emission on a time scale of years. IGR J17480–2446 is the first regular transient LMXB (i.e., with an outburst length of weeks to a few months) showing strong evidence for crustal cooling.¹²

It is instructive to compare the observed crust cooling curve with that of the quasi-persistent sources. Fitting the current data to a power-law decay without a constant offset results in a decay index of $\alpha = 0.06 \pm 0.01$. Comparable values of $\alpha \simeq 0.03$ – 0.07 were obtained for EXO 0748–676 and XTE J1701–462 (Degenaar et al. 2011b; Fridriksson et al. 2011), whereas the decay indices of KS 1731–260 and MXB 1659–29 are higher ($\alpha \simeq 0.13$ and $\simeq 0.33$, respectively; Cackett et al. 2008, 2010a). If the crust cooling curves of the quasi-persistent sources are instead fitted with an exponential decay, this leads to e-folding time scales of $\tau \simeq 200$ – 500 days (Cackett et al. 2008, 2010a; Degenaar et al. 2011b; Fridriksson et al. 2011). For IGR J17480–2446 we obtain $\tau \simeq 825$ days, assuming that it returns to its 2003/2009 level, although this decay fit does not match the data well. Nevertheless, we can conclude that despite that it was accreting for a significantly shorter time (by a factor $\gtrsim 10$), the crust cooling curve is not strikingly different from that of the other four.

It is remarkable that the crust cooling curve of IGR J17480–2446 is rather similar to that of the quasi-persistent LMXBs and that the crust is still hot $\simeq 2.2$ yr after the end of its outburst. Its much shorter outburst length of $\simeq 11$ weeks (a factor of $\gtrsim 10$ shorter than the others) should have caused significantly less heating, resulting in more rapid cooling (e.g., Page & Reddy 2013). This is illustrated by Figure 3, where we compare the updated crust cooling curve with the model calculations presented in Degenaar et al. (2011a), which were based on the first two data points.

In order to reach the observed high temperature at early times (within $\simeq 125$ days after the outburst) an additional source of heat was needed at shallow depth in the crust (at a column density of $P/g \lesssim 10^{14}$ g cm⁻², corresponding to a matter density of $\rho \lesssim 3 \times 10^{10}$ g cm⁻³; Degenaar et al. 2011a). It is interesting to note that in an independent study, Linares et al. (2012) found that the unusual thermonuclear X-ray burst activity of IGR J17480–2446 might require additional energy release in the outer layers of the neutron star. The origin of such an additional heat source is currently unclear (i.e., it is not accounted for by standard nuclear heating models; see the discussion in Degenaar et al. 2013), but it was also invoked to explain the crust cooling curves of KS 1731–260 and MXB 1659–29 (Brown & Cumming 2009). A recent observation of the neutron star LMXB XTE J1709–267 taken very shortly after an outburst also suggested

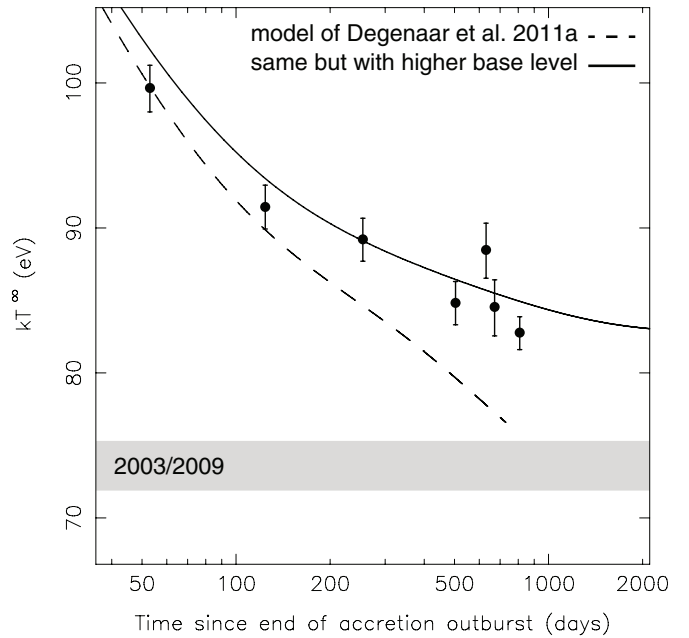


Figure 3. Evolution of the neutron star temperature after the 2010 outburst compared to model calculations. The dashed line shows the model presented by Degenaar et al. (2011a), which was based on the first two data points. It included an extra crustal heat source of 1.0 MeV per accreted nucleon placed at a depth of $P/g = 4.5 \times 10^{11}$ g cm⁻² ($\rho \simeq 4 \times 10^8$ g cm⁻³) to match the temperature at early times. The solid curve shows the same model, but for a higher base temperature of $kT^\infty = 84$ eV (compared to $kT^\infty = 72$ eV for the dashed curve; see Degenaar et al. 2011a for details).

the presence of a substantial heat source located in the outer crustal layers, although for that source any effects of possible ongoing accretion cannot be excluded (Degenaar et al. 2013).

It is clear from Figure 3 that the preliminary calculations presented in Degenaar et al. (2011a) do not match the new data points: the observed temperatures at later times are systematically higher than the model prediction. Possible ways to keep the neutron star hot for a longer time are to impose a lower thermal conductivity or a larger specific heat (Rutledge et al. 2002b; Shternin et al. 2007; Brown & Cumming 2009; Page & Reddy 2013). However, this could possibly make it more difficult to get the neutron star hot at early times, and would imply that the crust properties are different from that of the quasi-persistent neutron stars. It might therefore not be straightforward to explain our observations with standard heating and cooling models.

3.2. Unusual Crust Properties?

It is worth considering whether the neutron star in IGR J17480–2446 may have unusual crust properties that can influence its thermal evolution. Apart from the short outburst, another feature that sets this source apart from the quasi-persistent LMXBs is that it showed X-ray pulsations (at 11 Hz) during outburst. This has three implications. Firstly, the neutron star likely has a higher magnetic field than the other four sources ($B \simeq 10^9$ – 10^{10} G; Cavecchi et al. 2011; Miller et al. 2011; Papitto et al. 2011). A high magnetic field can strongly affect the thermal evolution of neutron stars, although this is thought to become effective only at much higher field strengths of $B \gtrsim 10^{12}$ G (e.g., Aguilera et al. 2008; Pons et al. 2009; Cooper & Kaplan 2010). Therefore, the magnetic field is not expected to be a source of influence in IGR J17480–2446.

Second, with a spin period of 11 Hz, the neutron star in IGR J17480–2446 is rotating much slower than those in KS

¹² Quiescent monitoring observations of another two sources recently commenced: MAXI J0556–332, which was active for $\simeq 1.5$ yr in 2011–2012, and Swift J174805.3–244637 in Terzan 5, which was active for $\simeq 2$ months in 2012. Data acquisition and analysis are in progress, but preliminary results reveal evidence for crustal cooling in both sources.

1731–260, MXB 1659–29, and EXO 0748–676, which have spin periods of ≈ 524 , 567, and 552 Hz, respectively (as inferred from the detection of oscillations during thermonuclear X-ray bursts; Smith et al. 1997; Wijnands et al. 2001; Galloway et al. 2010, the spin period of XTE J1701–462 is not known). It was found by Linares et al. (2012), that the relatively low spin frequency of IGR J17480–2446 has a profound effect on its thermonuclear X-ray bursting behavior (which are ignited in the surface layers of the neutron star). Rotation can also affect the structure of the crust and hence its heating and cooling properties (e.g., Haensel et al. 2008). However, the effect of rotation on the crust equation of state is thought to become prominent only at high frequencies of $\gtrsim 1000$ Hz and may therefore not be a source of influence for IGR J17480–2446 and the other crust cooling neutron stars.

Thirdly, the fact that IGR J17480–2446 harbors an 11 Hz pulsar indicates that the binary may have an unusual accretion history and started its Roche lobe overflow phase relatively recently ($\lesssim 10^7$ yr ago; Patruno et al. 2012). It was noted by Wijnands et al. (2013) that in such a young LMXB the neutron star might have a different crust composition. Accretion can replace the outer layers of the crust on a time scale of $\approx 10^5/M_9$ yr, and the innermost crustal layers after $\approx 10^7/M_9$ yr (where M_9 is the time-averaged mass-accretion rate of the binary in units of $10^{-9} M_\odot \text{yr}^{-1}$; Chamel & Haensel 2008). For an estimated long-term averaged accretion rate of $\approx 10^{-11}$ – $10^{-10} M_\odot \text{yr}^{-1}$ (Wijnands et al. 2013), the time needed to replace the crust in IGR J17480–2446 would thus be $\approx 10^6$ – 10^7 yr for the outer layers, and $\approx 10^8$ – 10^9 yr for the inner ones. It is therefore conceivable that (part of) the crust is still composed of the original, catalyzed matter. This could markedly impact its thermal and transport properties.

3.3. Alternative Explanations

There are alternative explanations that could possibly account for our observations. It is possible that matter continues to accrete onto the neutron star in quiescence. There is evidence for such low-level accretion in some neutron star LMXBs (e.g., Rutledge et al. 2002a; Campana & Stella 2003; Cackett et al. 2010b). The resulting spectrum may be thermal and difficult to distinguish from that of a cooling neutron star (Zampieri et al. 1995; Soria et al. 2011). Although little is understood about the physics of such a residual accretion flow, it is generally assumed that it would involve stochastic variability (on time scales of seconds to years) and the presence of a strong non-thermal emission component. Instead, the quiescent data of IGR J17480–2446 show a very smooth decay and any possible hard spectral component can only contribute $\lesssim 22\%$ to the total unabsorbed 0.5–10 keV flux. There are therefore no obvious indications that low-level accretion is occurring.

As an accretion-heated crust cools, it eventually settles at a base level that is determined by the temperature of the core. Since the core temperature does not change appreciably in between different outbursts (e.g., Brown et al. 1998; Colpi et al. 2001; Ushomirsky & Rutledge 2001), the temperature of IGR J17480–2446 would thus be expected to return to the level measured before the outburst in 2003/2009. However, it has been proposed that the heat flux flowing from the stellar interior to the surface is determined by the amount of hydrogen and helium that is left on the surface after the end of an outburst, and that this may change from one accretion phase to another (Brown et al. 2002). As a result, the observed thermal emission after different outbursts may differ by a factor of a few while the interior temperature is the same.

The quiescent light curve of IGR J17480–2446 can be described by an exponential decay that levels off to a temperature of $kT^\infty = 84.3 \pm 1.4$ eV. This is similar to the values determined from our last four observations (2012 May till 2013 February). This could suggest that the crust has already cooled, with a characteristic time scale of $\tau = 157 \pm 62$ days. This is shorter than the decay times measured for the quasi-persistent sources and hence points to faster cooling, as would be expected for a shorter outburst length (e.g., Page & Reddy 2013). Although a detailed theoretical modeling is beyond the scope of this paper, we briefly explored the effects of a higher base level on the crust cooling curve. The solid line in Figure 3 shows the cooling trajectory using the same physics input as the dashed curve (for details, see Degenaar et al. 2011a), but with a higher quiescent base level of $kT^\infty = 84$ eV. Such a model can better reproduce the shape of the observed cooling curve and could account for the higher temperatures at late times.

To conclude, it is possible that the quiescent emission of IGR J17480–2446 has settled at a higher observed equilibrium level and that the neutron star crust has (nearly) cooled. In this case, the thermal flux and inferred neutron star temperature is not expected to change appreciably any more until a new outburst occurs (unless low-level accretion onto the neutron star occurs in quiescence, which would likely cause non-monotonic variability in the quiescent flux). However, the current data are better fit by a power-law decay, which is suggestive of continued cooling. If the temperature of the neutron star is indeed observed to decrease further, this could possibly challenge our current understanding of heating and cooling of transiently accreting neutron stars. Continued monitoring of Terzan 5 with *Chandra* to further study the flux evolution of IGR J17480–2446 can discriminate between the different possibilities.

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