Evidence for crust cooling in the transiently accreting 11-Hz X-ray pulsar in the globular cluster Terzan 5

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ABSTRACT
The temporal heating and subsequent cooling of the crusts of transiently accreting neutron stars carries unique information about their structure and a variety of nuclear reaction processes. We report on a new Chandra Director’s Discretionary Time observation of the globular cluster Terzan 5, aimed to monitor the transiently accreting 11-Hz X-ray pulsar IGR J17480−2446 after the cessation of its recent 10-week long accretion outburst. During the observation, which was performed ≃125 d into quiescence, the source displays a thermal spectrum that fits to a neutron star atmosphere model with a temperature for an observer at infinity of $kT_\infty \approx 92$ eV. This is ≃10 per cent lower than that found ≃75 d earlier, yet ≃20 per cent higher than the quiescent base level measured prior to the recent outburst. This can be interpreted as cooling of the accretion-heated neutron star crust, and implies that crust cooling is observable after short accretion episodes. Comparison with neutron star thermal evolution simulations indicates that substantial heat must be released at shallow depth inside the neutron star, which is not accounted for in current nuclear heating models.

Key words: stars: neutron – pulsars: individual: CXOGClb J174804.8−244648 – pulsars: individual: IGR J17480−2446 – globular clusters: individual: Terzan 5 – X-rays: binaries.

1 INTRODUCTION
Neutron stars are the densest directly observable stellar objects in our Universe and constitute ideal astrophysical laboratories to study matter under extreme physical conditions. The outer layer of a neutron star, its crust, covers about one-tenth of the total stellar radius and consists of ions, electrons and neutrons. The structure and composition of the crust play an important role in the emission of gravitational waves and the evolution of the neutron star’s magnetic field (Brown & Bildsten 1998; Ushomirsky, Cutler & Bildsten 2000; Horowitz & Kadau 2009). Furthermore, studying the crusts of neutron stars allows the investigation of a variety of nuclear reaction processes (Haensel & Zdunik 1990, 2008; Gupta et al. 2007). The energy released in these reactions locally heats the crust, but is eventually conducted over the entire stellar body and radiated away via neutrinos emitted from the dense core, and via thermal X-ray radiation from the neutron star surface (Brown, Bildsten & Rutledge 1998; Rutledge et al. 2002). During quiescent episodes, the thermal X-ray radiation emerging from the hot neutron star can be detected with sensitive X-ray satellites.

Prior to the onset of an accretion phase, a neutron star is nearly isothermal and the surface radiation therefore offers a probe of the temperature of the stellar core (Colpi et al. 2001). Shortly after an accretion outburst, however, the thermal X-ray emission tracks the temperature of the heated crust (Ushomirsky & Rutledge 2001; Rutledge et al. 2002). As the crust cools and restores thermal equilibrium with the core, the thermal X-ray emission decreases and settles at a quiescent base level set by the core temperature (Rutledge et al. 2002). This thermal relaxation depends on the composition of the crust, which determines the conduction of heat towards the surface and the core, and on the details of the nuclear reactions, which set the magnitude and depth of the heat sources (Brown & Cumming 2009).

In the past decade, crust cooling has successfully been monitored for four transiently accreting neutron stars: KS 1731−260...
In 2010 December, ~10 weeks after its onset, the accretion activity ceased and the binary returned to quiescence (Degenaar & Wijnands 2011a). A Chandra observation obtained about 50 d later, in 2011 February, demonstrated that the quiescent thermal X-ray emission of J1748 was elevated above the base level measured from archival observations taken in 2003 and 2009, by approximately a factor of 4 (Degenaar & Wijnands 2011a,b). The associated rise in neutron star temperature (a factor of 1.4) can be interpreted as an accretion-heated crust, although two alternative explanations could be invoked (Degenaar & Wijnands 2011a). First, the neutron star possibly continues to accrete at a very slow rate, causing a variable quiescent flux. Secondly, the amount of hydrogen and helium left on the neutron star after an accretion phase determine the heat flux that is flowing from the stellar interior towards the surface. For a constant interior temperature, the quiescent thermal emission might therefore differ by a factor of a few due to changes in the envelope composition after an intervening outburst (Brown, Bildsten & Chang 2002). Both of these scenarios could also account for the enhanced surface temperature observed in 2011.

2 OBSERVATIONS, ANALYSIS AND RESULTS

2.1 A new Chandra observation of Terzan 5

To further investigate the cause of the elevated thermal X-ray emission detected from J1748 after its 10-week outburst, we obtained a new Chandra Director’s Discretionary Time observation of Terzan 5 on 2011 April 29–30 (obs ID 13252; Fig. 1). This is ~125 d into quiescence and ~75 d since the previous Chandra observation. The cluster was positioned on the back-illuminated S3 CCD at the nominal target position and the observation was read out in the FAINT timed data mode. We used the CIAO software tools (v. 4.3) for the reduction and extraction of data products, following standard analysis procedures. There were no occurrences of background flares during the observation, so that the final net exposure time on our target was 39.5 ks.

Using the task DMEXTRACT, we extracted source count rates and light curves from a circular region with a radius of 1 arcsec, centred at the best-known position of IGR J17480−2446 (Pooley et al. 2010). Corresponding background events were collected from a circular region with a radius of 40 arcsec, positioned on a source-free part of the CCD located 1.4 arcmin west of the cluster core. J1748 is detected at a net count rate of (3.7 ± 0.3) × 10⁻³ count s⁻¹ and a total of 146 source photons were collected during the observation. Source and background X-ray spectra were obtained using the meta-task SPECEXTRACT, which also generates the appropriate ancillary response files (arf) and redistribution matrix files (rmf). Using the IFOO tool GRPPHA, the spectral data were grouped into bins with a minimum number of 20 photons. The resulting background-corrected spectrum was modelled in the energy range of 0.5–10.0 keV using the software package XSPEC (v. 12.6; Arnaud 1996).

2.2 Quiescent spectra of IGR J17480−2446

Similar to previous observations (Degenaar & Wijnands 2011a,b), the X-ray spectrum of J1748 can be adequately fit by an absorbed thermal emission model and does not require the addition of any hard, non-thermal component (Fig. 2). Within XSPEC, we use the neutron star atmosphere model NSATMOS (Heinke et al. 2006a) to fit the thermal emission from the neutron star surface. In this model, we fix the mass and radius of the neutron star to $M = 1.4 M_\odot$ and $R = 10.5$ km, and we set the distance to the cluster to 4.5 kpc. As predicted by XSPEC, our data are well modelled by this model, which provides a good fit to the X-ray emission from J1748 (Fig. 2).
DISCUSSION

We analysed a new Chandra observation of Terzan 5, obtained \( \approx 125 \) d after the end of the accretion outburst of J1748. The quiescent X-ray spectrum of the source is soft and can be adequately fit by a neutron star atmosphere model NSATMOS with a temperature of \( kT^\infty = 92.1 \pm 3.1 \) eV. This is nearly 10 per cent lower than measured 75 d earlier in 2011 February (\( kT^\infty = 100.9 \pm 3.3 \) eV), yet over 20 per cent higher than the quiescent base level of the source detected in 2003 and 2009 (\( kT^\infty = 72.0 \pm 3.3 \) eV). The thermal X-ray emission and inferred neutron star temperature have thus decreased after the initial enhancement (Fig. 3).

To explain the elevated thermal emission observed in 2011 in terms of a different envelope composition left after the 2010 accretion phase, the neutron star temperature inferred from our new observation should have been similar to the previous measurement, since the composition of the layer would not change in absence of accretion (Brown et al. 2002). This is not consistent with our results. Continued accretion is thought to reveal itself through stochastic variability in the X-ray emission on both long (months/years) and short (seconds/days) time-scales, and/or via the presence of a hard, non-thermal emission component in the X-ray spectrum (Rutledge et al. 2001; Cackett et al. 2010b; Fridriksson et al. 2011). We find

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R = 10 \text{ km}, \quad \text{whereas the source distance is set to the current best estimate for Terzan 5: } D = 5.5 \text{ kpc (Ortolani et al. 2007). The normalization was frozen at the recommended value of 1, which implies that the radiation is emerging from the entire stellar surface. Our only free parameter for the NSATMOS model is thus} \, \kappa, \text{ which implies that the radiation is emerging from the entire stellar surface.}
\]

The solid lines indicate best fits to the neutron star atmosphere model NSATMOS.

The normalization was frozen at the recommended value of 1. We tied the hydrogen column density between the data sets, i.e. this fit parameter is required to be the same amongst the observations, whereas the neutron star temperature could vary freely for the different spectra. This approach resulted in a joint fit value of \( N_H = (2.0 \pm 0.3) \times 10^{22} \text{ cm}^{-2} \) and a reduced chi-square of \( \chi^2 = 0.77 \) for 21 degrees of freedom. Fig. 2 displays the X-ray spectra observed at the four epochs.

For each data set, we deduce the neutron star temperature as seen by an observer at infinity, \( kT^\infty \), and calculate the total unabsorbed model flux in the 0.5–10 keV energy range, \( F_{\text{unabs}} \). The model fits are then extrapolated to the 0.01–100 keV energy range to obtain an estimate of the total emitted bolometric flux, which is translated into a luminosity, \( L_{\text{bol}} \), by assuming that the source is located at a distance of \( D = 5.5 \) kpc (Ortolani et al. 2007). The results of our spectral analysis are summarized in Table 1, where all quoted errors refer to 90 per cent confidence levels. The evolution of the neutron star temperature as inferred from the spectral fits is plotted in Fig. 3.

### Table 1. Results from fitting the Chandra spectral data.

| Date            | \( kT^\infty \) (eV) | \( F_{\text{unabs}} \) (10\(^{-13}\) erg cm\(^{-2}\) s\(^{-1}\)) | \( L_{\text{bol}} \) (10\(^{33}\) erg s\(^{-1}\)) |
|-----------------|----------------------|-------------------------------------------------|----------------------------------|
| 2003-07-13/14   | 72.0 ± 3.3           | 1.64 ± 0.30                                     | 0.59 ± 0.11                      |
| 2009-07-14/15   | 100.9 ± 3.3          | 6.33 ± 0.83                                     | 2.29 ± 0.30                      |
| 2011-02-17      | 92.1 ± 3.1           | 4.39 ± 0.60                                     | 1.59 ± 0.21                      |
| 2011-04-29/30   | 100.9 ± 3.3          | 6.33 ± 0.83                                     | 2.29 ± 0.30                      |

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Crust cooling of the Terzan 5 X-ray pulsar L155

3.1 Crust cooling simulations of IGR J17480−2446

We employed the thermal evolution code of Brown & Cumming (2009), using all the basic physics ingredients and modelling approach described in that work, to simulate neutron star crust cooling curves for J1748 (Fig. 3). We assumed that the outburst had a duration of \( t_{\text{obs}} = 0.17 \) yr and that mass was accreted at a rate of \( \dot{M} = 2.0 \times 10^{17} \) g s\(^{-1}\), as inferred from X-ray observations (Degenaar & Wijnands 2011a). Furthermore, the temperature of the neutron star core was fixed at \( T = 7.0 \times 10^8 \) K, which matches the inferred value of the quiescent base level (Degenaar & Wijnands 2011b).

Using standard physics input, the crust temperature is too low and the slope of the cooling curve too flat to match the observations (dotted curve in Fig. 3). Motivated by recent theoretical conjectures (see Section 1), we also performed simulations with a heat source placed at shallow depth inside the neutron star and varied its strength, \( Q_{\text{extra}} \). We position this extra heat at a column depth of \( \rho g \sim 4.5 \times 10^{11} \) g cm\(^{-2}\), which roughly corresponds to a density \( \rho \approx 4 \times 10^{15} \) g cm\(^{-3}\). We found that the exact depth primarily affects the crust cooling curve at the time probed by the observations of J1748. This also implies that our \( \text{Chandra} \) observations cannot firmly constrain the depth of the additional heat release, although we can obtain some limits.

Assuming that the crust cooling curve of J1748 indeed follows a power-law decay with an index of \(-0.1\) (see above), we estimate that there is an inward-directed heat flux in the crust of \( F \sim 3 \times 10^{20} \) erg cm\(^{-2}\) s\(^{-1}\) (Brown & Cumming 2009, equation 12). At any given depth inside the neutron star, it takes a certain characteristic time for heat to diffuse to the surface. Therefore, at a given time there will be a certain depth at which the layer above has already thermally relaxed, while deeper layers are still hot and have not yet started to cool (Brown & Cumming 2009). The first \( \text{Chandra} \) observation of J1748 was obtained \( \leq 50 \) d after the end of the accretion outburst; this is the characteristic thermal time-scale for layers located at a column depth of \( \rho \approx 3 \times 10^{16} \) g cm\(^{-3}\). This is much shallower than the depth at which most crust nuclear reactions are thought to occur (Gupta et al. 2007; Haensel & Zdunik 2008). The heat flux is directed inwards, and it thus must be a source of heat exterior to the depth corresponding to the thermal time-scale of 50 d. This implies that there is a heat deposit at less than \( \pm 150 \) m inside the neutron star (Brown & Cumming 2009). This is much shallower than the depth at which most crust nuclear reactions are accounted for by existing nuclear physics calculations (Gupta et al. 2007; Haensel & Zdunik 2008; Horowitz et al. 2008).

3.2 Repercussions

The X-ray observations of J1748 obtained after its recent 10-week accretion outburst can be explained as cooling of the accretion-heated neutron star crust. However, regardless of the exact value of \( \dot{M} \), this requires a substantial source of heat located at shallow depth inside the neutron star that is not accounted for by existing nuclear physics calculations (Gupta et al. 2007; Haensel & Zdunik 2008; Horowitz et al. 2008). A shallow heat source has also been proven necessary to explain the crust cooling curve of at least one of the quasi-persistent LMXBs (MBX 1659−29; Brown & Cumming 2009). The presence of substantial heat sources in the outer crustal layers is important for the ignition of superbursts: the extra heat

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\(^1\) We note that if residual accretion occurs in quiescence, variations in the thermal emission could be due to a changing emission area (a hotspot at the magnetic pole) and may not necessarily imply a changing surface temperature. Given the data statistics, it would not be possible to make this distinction.
release raises the crust temperature and can thus compensate for the effect of a high thermal conductivity (Gupta et al. 2007; Brown & Cumming 2009).

Our work on J1748 suggests that the crust of a neutron star can become substantially heated during an accretion episode of only a few weeks, and that it is technically feasible to detect the subsequent crust cooling with existing, sensitive X-ray instruments. LMXBs in which the neutron star accretes for weeks or months are much more common than those that undergo extended accretion episodes of years. Future crust cooling studies can therefore draw from a larger sample of transiently accreting neutron stars. The most promising targets are neutron stars that have relatively low core temperatures, but exhibit bright accretion episodes, so that a substantial amount of matter is consumed and a considerable temperature gradient can develop in the crust (Brown et al. 1998). Transient Be/X-ray binaries, which harbour strongly magnetized neutron stars feeding of the matter expelled by their massive Be companions, can potentially also be included in future studies (Brown et al. 1998).

Studying a larger sample of crust cooling curves allows us to investigate whether the presence of strong, shallow heat sources is a common feature amongst transiently accreting neutron stars. In particular, observations performed within ∼1 month after the end of an accretion outburst can further constrain the magnitude and depth of such heat sources (Brown & Cumming 2009). The next challenge is then to identify the nature of this extra heat release.

Our crust cooling simulations suggest that IGR J17480−2446 continues to cool within the next year. New Chandra observations are planned to confirm this and to put further constraints on the shape of the crust cooling curve.

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