Variable quiescent state for the neutron-star X-ray transient SAX J1750.8-2900: not such a hot neutron star after all?

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ABSTRACT
We monitored the neutron star low-mass X-ray binary SAX J1750.8−2900 after the end of its 2015/2016 outburst using the X-ray Telescope (XRT) aboard Swift to detect possible post-outburst ‘rebrightenings’, similar to those seen after its 2008 outburst. We did not detect any rebrightening behaviour, suggesting that the physical mechanism behind the rebrightening events is not always active after each outburst of the source. Any model attempting to explain these rebrightenings should thus be able to reproduce the different outburst profiles of the source at different times. Surprisingly, our Swift/XRT observations were unable to detect the source, contrary to previous Swift/XRT observations in quiescence. We determined a temperature upper limit of \( \leq 10^6 \) eV, much colder than the post 2008 outburst value of \( \sim 145 \) eV. We also report on an archival Chandra observation of the source after its 2011 outburst and found a temperature of \( \sim 126 \) eV. These different temperatures, including the non-detection very close after the end of the 2015/2016 outburst, are difficult to explain in any model assuming we observe the cooling emission from a neutron star core or an accretion-heated crust. We discuss our observations in the context of a change in envelope (the outer \( \sim 100 \) m of the crust) composition and (possibly in combination with) a cooling crust. Both hypotheses cannot explain our results unless potentially unrealistic assumptions are made. Irrespective of what causes the temperature variability, it is clear that the neutron star in SAX J1750.8−2900 may not be as hot as previously assumed.

Key words: stars: neutron – X-rays: binaries – X-rays: individual: SAX J1750.8−2900 – accretion, accretion disks

1 INTRODUCTION

Low-mass X-ray binaries (LMXBs) consist of a neutron star or black hole having a sub-solar donor star. This companion star facilitates accretion onto the primary by overflowing its Roche lobe. Most systems are not accreting persistently but only during outbursts which have typical X-ray luminosities of \( L_X \approx 10^{35} \) – \( 10^{39} \) erg s\(^{-1}\). The outburst episodes are separated by long periods of quiescence in which the X-ray luminosity is very low (\( L_X \sim 10^{30} \) – \( 10^{34} \) erg s\(^{-1}\)). During the outbursts, the accretion rate onto the compact object varies strongly. Commonly, these outbursts are explained by the disk instability model (see Lasota 2001, for a review), although many uncertainties remain. Several systems show post-outburst ‘rebrightenings’\(^1\) that may appear multiple times at low luminosities (\( 10^{32} \)–\( 10^{36} \) erg s\(^{-1}\)), lasting for days to tens of days. Among these systems are both neutron star and black hole transients. Furthermore, they are also observed in transiently accreting white dwarfs (during so-called dwarf novae), suggesting that the production mechanism is related to the general behaviour of accretion flows and not connected to a specific type of accretor (see Patruno et al. 2009, for a discussion). These rebrightenings cannot be explained within the disk instability model in a straightforward manner (e.g., Lasota 2001; Patruno et al. 2009; Kotko et al. 2012).

For LMXBs having neutron stars (NSs), the accreted material during an outburst compresses the surface and results in crust heating by processes such as electron capture, pycnonuclear reactions, and neutron emission (e.g., Haensel & Zdunik 1990, 2008; Steiner 2012). This results in the crust being heated out of equilibrium with the core. Once in quiescence this heated crust cools to reinstate thermal equilibrium with the core. Thus, any heating and cooling observed in this scenario is indicative of a change in the crust temperature. The core does not show any significant temperature evolution over these time scales. Monitoring the cooling evolution of an accretion-heated crust can help us understand the physics of the neutron star crust (e.g., Rutledge et al. 2002; Brown & Cumming 2009; Page & Reddy 2013). So far ten NS LMXBs that potentially exhibit crust cooling have been studied (see e.g., Wijnands et al. 2001, Degenaar et al. 2017, Parikh et al. 2017b; see Wijnands et al. 2017 for a review).

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¹ ‘Rebrightenings’ have also been referred to as ‘mini outbursts’, ‘echo outbursts’, and ‘reflares’ in the literature (Osaki et al. 2001; Csák et al. 2005; Patruno et al. 2016)
SAX J1750.8–2900 (hereafter SAX J1750) was first detected by BeppoSAX in 1997 (Natalucci et al. 1999). The source showed several type-I thermonuclear bursts demonstrating the primary to be a NS. Some of the type-I bursts showed photospheric radius expansions from which an upper limit on the distance was calculated to be $6.79 \pm 0.14$ kpc (assuming H-poor burning; Kaaret et al. 2002; Galloway et al. 2008). Kaaret et al. (2002) observed nearly coherent oscillations from the source during its type-I bursts, revealing the spin of the neutron star to be $\sim 601$ Hz. Since its first detection, four more outbursts have been observed—the longer outbursts (duration of $\sim 400$ d) in 2001, 2008, and 2015/2016 (Kaaret et al. 2002; Markwardt & Swank 2008; Sanchez-Fernandez et al. 2015, Figure 2); and a shorter outburst ($\sim 30$ d) in 2011 (Fiocchi et al. 2011; Natalucci et al. 2011).

The source has been studied in quiescence after its 2008 and 2011 outbursts. After its 2008 outburst, SAX J1750 did not go straight into quiescence but it showed a period of rebrightenings that lasted for $\sim 200$ d (Lowell et al. 2012, see also Allen et al. 2015). The source was found truly in quiescence during an XMM-Newton observation taken $\sim 400$ d after the full outburst with a relatively high surface temperature of $\sim 148$ eV, resulting in the speculation that it might host the hottest known NS in a LMXB$^2$ (Lowell et al. 2012). Wijnands & Degenaar (2013) studied the source $\sim 350$ d after the 2011 outburst when it showed a brief accretion flare in its quiescent state. The pre-flare quiescent level they found was in agreement with that found after the 2008 outburst by Lowell et al. (2012).

2 OBSERVATIONS AND DATA ANALYSIS

We monitored SAX J1750, using the X-ray telescope (XRT; Burrows et al. 2005) on board Swift, after the end of its 2015/2016 outburst to investigate if the source also exhibited rebrightenings after this recent outburst. Surprisingly, we found that the source was not detected at all, and so no rebrightenings were observed. The upper limits (on the luminosity and inferred surface temperature, see Section 3.2.2) determined for these observations was below those determined previously by XMM-Newton and earlier Swift/XRT observations when the source was in quiescence (Lowell et al. 2012; Wijnands & Degenaar 2013). To compare our new results with these earlier findings and to ensure uniform analysis we reanalysed the archival quiescent XMM-Newton and Swift/XRT data. In addition, to study further variability in quiescence we searched the XMM-Newton, Swift/XRT, and Chandra archives for additional observations of the source. We found one extra Chandra observation (performed in 2013) when the source was in quiescence. We also analyse this observation in our paper. We use the Swift/Burst Alert Telescope (BAT; Barthelmy et al. 2005) and the Rossi X-ray Timing Explorer/Proportional Counting Array (RXTE/PCA; Jahoda et al. 2006) to track the luminosity evolution of the source over time.

2.1 Swift/BAT and RXTE/PCA

We use the data from the Swift/BAT and the RXTE/PCA instruments to track the long-term outburst variability of SAX J1750 in the 15 – 50 keV and 2 – 60 keV range, respectively. We downloaded the Swift/BAT data for SAX J1750 from the BAT online archive$^3$ (Krimm et al. 2013). The RXTE/PCA data was taken from the RXTE Galactic Center Observation archive, compiled by Craig Markwardt$^4$ (Swank & Markwardt 2001). The Swift/BAT data were rebinned with a bin size of 10 d.

2.2 XMM-Newton

XMM-Newton was used to observe SAX J1750 on 2010 April 7 (observation ID [ObsID]: 0603850201) using all three EPIC instruments – MOS1, MOS2, and pn, operated in window mode. The data were downloaded from the XMM-Newton archive$^3$. We did not use the RGS and OM data because the source was too faint to be studied using these instruments. The ~ 3 ksec raw data were reprocessed using the Science Analysis System (SAS; version 14.0) with emproc and epproc. The light curve of the data were checked for background flaring at high energies, > 10 keV for the MOS and between 10 – 12 keV for the pn. Data with count rates (in these energy ranges) above 0.2 counts s$^{-1}$ and 0.5 counts s$^{-1}$ were removed from the MOS and pn data, respectively. The final exposure time of the MOS1, MOS2, and pn was 19.6 ksec, 19.6 ksec, and 16.2 ksec, respectively. Circular source extraction regions of radius 20 arcsec and 25 arcsec were used for the MOS and pn, respectively. All instruments suffered from contamination by stray light due to a nearby bright source outside the field of view. This can be seen in Figure 1 which shows the field of view around SAX J1750. The figure also shows another nearby source in the field of view – 2RXP J175029.3–285954 (Jonker et al. 2011). A stripe of stray light was seen crossing the source position, as observed by all three cameras. The background regions were circular regions of radius 25 arcsec.

\[^{2}\] It was assumed that the crust and core were in equilibrium at the time of this XMM-Newton observation.

\[^{3}\] http://swift.gsfc.nasa.gov/results/transients/

\[^{4}\] https://asd.gsfc.nasa.gov/Craig.Markwardt//galscan/html/SAXJ1750.8-2900.html

\[^{5}\] http://nxsadata.esac.esa.int/nxsa-web/#search

Figure 1. The image of the field near SAX J1750.8–2900 (indicated by the dashed circle of radius 25 arcsec) as obtained using the EPIC-MOS1 instrument on board XMM-Newton. The source located to the upper left is 2RXP J175029.3–285954. The stray light contamination seen in the figure is caused by another nearby bright source (outside the field of view).
2.3 Swift/XRT
All the Swift/XRT observations of SAX J1750, up to October 2016, were used to create a light curve. The data were downloaded from the HEASARC archive\(^6\). The raw data were processed with xrtpipeline using HEASOFT (version 6.17). The XSELECT (version 2.4c) program was used for obtaining the light curve using a circular source region with a radius of 50 arcsec and an annulus having an inner radius of 250 arcsec and an outer radius of 350 arcsec as the background region. Neither of the regions include the nearby source 2RXP J175029.3−285954. No type-I thermonuclear bursts were detected in any of the XRT data. None of the Window Timing (WT) mode data were piled-up but some Photon Counting (PC) mode data (7 observations) were piled-up. This was corrected for by removing the data located in the inner source region (the exact radius of the exclusion region was calculated according to the online thread\(^7\)).

Out of all the XRT observations, we can identify two sets of quiescent observations – one after the 2011 outburst and one after the 2015/2016 outburst. All these data were collected using the PC mode. We have stacked the data after each outburst to obtain constraints on the observed effective surface temperature and luminosity. Interval 1 (post 2011 outburst; see Table 1 of Allen et al. 2015) ranges from 2012 Feb 14 (ObsID: 0031174024) to 2012 Mar 6 (ObsID: 0031174028). A flare was detected on 2012 Mar 17 and 20 (ObsID: 0031174030 and ObsID: 0031174031; Wijnands & Degenaar 2013) and these data have been excluded in the determination of the quiescent level. Studying the source images of the observations taken after the flare reveals that for all but one of these observations the source was near the edge of the CCD. The observation that was centred on the source (Obs ID: 0031174032) had an exposure of 1 ks and only provided a non-constraining upper limit. Thus, we also did not use the post-flare observations to determine the quiescent level of SAX J1750. The observations that were obtained after the 2015/2016 outburst are combined as Interval 2 (see Table 1). The observations making up each interval were stacked to create two combined event files, one for each of the two intervals.

The source was not detected in Interval 2 and a spectrum could not be extracted. Instead we simulated a spectra with a circular region of radius 25 arcsec for the source. For the background, regions comprising of three circular regions having a radius of 25 arcsec each were used. The background regions were chosen to ensure that the nearby source 2RXP J175029.3−285954 (Fig. 1) was not included. The Swift/XRT data do not show any evidence of contamination from the nearby bright source (that lies outside the field of view) which results in stray light in the XMM-Newton data (see Section 2.2). The sizes of the source and background regions used here are smaller than those used to create the light curve (see first paragraph of this section) as all the quiescent data are observed in the PC mode and do not have many photons (≈ 0 – 20). The stacked exposure map was created using ximage. The resulting spectrum were grouped to have a minimum of 2 counts per bin using grppha. The ancillary response files were generated using xrtmkarf and the appropriate rmf files were used\(^8\).

2.4 Chandra
SAX J1750 was observed using Chandra on 2013 April 29 for 25 ksec in the faint mode with the ACIS-S array. We downloaded the data (obsID: 14651) from the Chandra Data Archive\(^9\) and used CIAO (version 4.8) to analyse it. The Chandra data were examined for possible background flaring by studying the light curve from the background region (all parts of the detector except the source region). No background flaring was present for the Chandra observation of SAX J1750, so we used the entire exposure time of 25 ksec for our spectral analysis.

A circular source region of radius 2 arcsec was used for light curve and spectrum extraction. A background consisting of four circular regions, each having a radius of 10 arcsec, was used. The background regions were placed on the same CCD as that of the source and avoid the bright source in the field of view (2RXP J175029.3−285954; see Fig. 1). There was no evidence of contamination by stray light from the nearby source outside the field of view (see Section 2.2). The spectrum was extracted using specextract and rebinned using grppha to have at least 5 photons per bin. We used the auxiliary response file created by specextract for which the point-source aperture correction has been applied.

3 RESULTS
3.1 Outburst Properties
The Swift/BAT and RXTE/PCA light curves of SAX J1750 (Fig. 2, first and second panel) show the 2008, 2011, and 2015/2016 outbursts. A close up of the 2008 outburst (including the rebrightenings) is also shown in Figure 3, lower panel (PCA data) and Figure 4, upper panel (BAT data). In Figure 3, the 2011 outburst is visible as a slight rise in count rate around MJD 55700 when the source became visible again after the Sun time constraint window ended. Likely, most of the 2011 outburst occurred at the time of the Sun constraint window. The total observed outburst duration, post the Sun constraint window, was ~ 20 d which indicates a lower limit on the length of the outburst. The upper limit on the length of the 2011 outburst is ~ 110 d (the ~ 20 d of the observed outburst plus the ~ 90 d the source was in the Sun constraint window). The brightest reported luminosity during this outburst was \(L_X \approx 10^{36} \text{ erg s}^{-1}\) (Natalucci et al. 2011).

Sanchez-Fernandez et al. (2015) reported the initial detection of the 2015/2016 outburst of SAX J1750 on MJD 57278. The PCA also observed the 2001 outburst of the source and the light curve of this outburst is shown in Figure 3 (upper panel). In this figure a smaller outburst ~ 1000 d after the end of the 2001 outburst can be seen. This outburst has not yet been reported. We shall refer to it as the 2004 outburst. As can be seen from Figure 3 and Figure 4 the

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\(^6\) http://heasarc.gsfc.nasa.gov/cgi-bin/W3Browse/swift.pl
\(^7\) http://www.swift.ac.uk/analysis/xrt/pileup.php
\(^8\) Interval 1 : swxpcto126_20110101v014.rmf
Interval 2 : swxpcto126_20130101v014.rmf
\(^9\) http://cda.harvard.edu/chaser/
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Figure 2. The top three panels show the light curve of SAX J1750 obtained using Swift/BAT (15 – 50 keV, binsize = 10 d), RXTE/PCA (2 – 60 keV, binsize = 1 d), and Swift/XRT (0.5 – 10 keV), respectively. The vertical red and blue lines in the top panel indicate the times of the XMM-Newton observation and the Chandra observation, respectively. The green arrow in the XRT light curve (middle panel) indicates the time when the flare reported by Wijnands & Degenaar (2013) occurred. The bottom two panels show the observed effective temperature and luminosity evolution of the source in quiescence.

2001, 2008, and 2015/2016 outbursts seem to have ended in ∼ 300 – 400 d.

The background subtracted and pile-up corrected Swift/XRT light curve of all observations of SAX J1750 is shown in Figure 2 (middle panel). The 2008 outburst has been previously studied by Lowell et al. (2012) and Allen et al. (2015). The 2015/2016 outburst of SAX J1750 was not well covered with only one observation. During our Swift/XRT monitoring campaign after the 2015/2016 outburst, we obtained data using six pointings in August 2016 for a total of ∼ 5 ksec (see Table 1 for the log of the observations). Surprisingly, we did not detect the source, indicating that during our observations the source did not show any rebrightening events. To confirm the source would not exhibit such a rebrightening event in a later phase after the outburst and to get better upper limits in case the source was once again not detected, we obtained another ∼ 4 ksec XRT observation in October 2016. During this observation we, once again, did not detect the source. In Section 3.2.2, we discuss these observations further when we determine luminosity and temperature upper limits.

Table 1. Log of the Swift/XRT observations of SAX J1750 after the end of its 2015/2016 outburst, forming Interval 2. The upper limits on the count rate are determined for a 95% confidence level using the prescription by Gehrels (1986).

| Date       | Observation ID | Exposure Time (ksec) | Count Rate (0.5 – 10 keV) (10^-3 c s^-1) |
|------------|----------------|----------------------|------------------------------------------|
| 2016/08/03 | 00031174033    | 0.9                  | <3.2                                     |
| 09         | 00031174035    | 0.3                  | <1.2                                     |
| 18         | 00031174037    | 1.0                  | <3.1                                     |
| 22         | 00031174038    | 0.9                  | <3.5                                     |
| 24         | 00031174039    | 1.3                  | <2.4                                     |
| 30         | 00031174040    | 0.5                  | <6.1                                     |
| 2016/10/12 | 00031174041    | 3.7                  | <0.8                                     |
| Total      | 4.8            |                      | <0.6                                     |
| 2016/10/12 | 00031174041    | 3.7                  | <0.8                                     |
| Total      | 8.5            |                      | <0.4                                     |

Figure 3. The RXTE/PCA light curves (2 – 60 keV, binsize = 1 d) of the 2001 and 2004 outbursts (top panel), and the 2008 and 2011 outbursts (bottom panel) of SAX J1750. The zero point for the time axis of the top panel is MJD 51940 and for the bottom panel MJD 54460.
of activity at lower luminosity. However, in both the 2001 and 2008 outburst the main outburst lasted for ~ 200 d and the secondary lower luminosity behaviour for an additional ~ 200 d.

The peak of the 2015/2016 outburst was followed by a Sun constraint window (Fig. 4, bottom panel). It is reasonable to assume that the outburst behaviour followed a gradual decay during this period. After this window the source stayed active for another ~ 200 d. We did not detect any post-outburst rebrightenings after the end of the 2015/2016 outburst during our Swift/XRT observations. It is possible that we could have missed the rebrightenings because we only have a limited number of Swift/XRT observations but these rebrightenings seem to last a long time (~ 200 d as shown by the 2008 outburst). Thus, if the rebrightening behaviour after each outburst has a similar time scale we can exclude the occurrence of rebrightenings after the 2015/2016 outburst. It is unknown what causes the source to sometimes experience a regular outburst and sometimes show rebrightening. Furthermore, considering the full length of the outbursts (main outburst and rebrightenings) the 2001, 2008, and 2015/2016 outbursts are comparable, lasting ~ 300–400 d (see Fig. 2, 3, and 4). The 2001 and 2015/2016 outbursts are more similar to each other compared to the 2008 outburst. They do not experience distinct rebrightenings although their profiles have different shapes – the main peak of the 2001 outburst is followed by a period of low luminosity before transitioning to quiescence whereas the 2015/2016 outburst does not show this and gradually transitions to quiescence.

The 2004 and 2011 outburst started ~ 1300 and ~ 1100 d after the 2001 and 2008 outburst, respectively. Both quiescent periods (~ 1300 and ~ 1100 d) were similar and they were both short outbursts lasting ~ 60 d. Therefore, the source seems to show two different types of outbursts – long (2001, 2008, and 2015/2016; ~ 400 d) and short outbursts (2004 and 2011; ~ 60 d). The source also exhibited a short outburst (~ 20 d) in 1997 (see Fig. 2 of Natalucci et al. 1999). About 12 days into this outburst the luminosity decreased (by factor ~ 30) briefly for ~ 5 d before increasing again (by a factor of ~ 4, as observed by the BeppoSAX Wide Field Cameras [2 – 30 keV]; Jager et al. 1997).

### 3.2 Quiescent Temperatures and Luminosities

Here we present the results of the analysis of SAX J1750 in quiescence. All spectra obtained using the different instruments have been fitted using XSPEC. We model the equivalent hydrogen column density $N_H$ with tfabs, using VERN cross-sections (Verner et al. 1996) and WILDF abundances (Wilms et al. 2000) for all spectra. W-statistics (background subtracted Cash statistics; Wachter et al. 1979) were used throughout due to the low number of counts per bin for the spectra from the different instruments. The 0.5 – 10 keV energy range will be considered throughout. All reported fluxes and luminosities correspond to the unabsorbed ones. The errors are given for the 90 per cent confidence range.

#### 3.2.1 XMM-Newton

When we fit the spectra using an absorbed power-law model, the obtained photon index ($\Gamma = 6.0^{+1.7}_{-1.1}$) was very soft (with an $N_H = 7.7^{+2.4}_{-1.8} \times 10^{22}$ cm$^{-2}$). Due to the softness of the spectra we decided to fit a neutron star atmosphere model (nsatmos; used for NSs with weak magnetic fields; Heinke et al. 2006) to the spectra. We assumed a neutron star mass and radius of 1.4$M_\odot$ and 10 km, at a distance of 6.79 kpc. The entire surface of the neutron star

![Figure 4. A zoom in of the Swift/BAT light curve (15 – 50 keV, binsize = 10 d) of SAX J1750 of its 2008 (top panel) and 2015/2016 (bottom panel) outbursts. The zero point for the time axis for the 2008 outburst is MJD 54460 and for the 2015/2016 outburst MJD 57200. The red vertical lines in both panels indicate the times of the Swift/XRT observations.](image)

| MJD (days) | Instrument | Observation ID | $kT_{\text{eff}}$ (eV) | Luminosity (erg s$^{-1}$) (10$^{33}$, 0.5 – 10 keV) |
|-----------|------------|----------------|------------------------|--------------------------------------------------|
| 55293.5   | XMM-Newton | 0063850201      | 144.9$^{+2.3}_{-1.9}$  | 8.0 ± 0.8                                         |
| 56031.7   | Swift/XRT  | Interval 1      | 130.6$^{+1.5}_{-1.0}$  | 5.2 ± 2.1                                         |
| 56411.8   | Chandra    | 14651          | 126.2$^{+3.2}_{-3.3}$  | 4.2 ± 0.7                                         |
| 57624.0   | Swift/XRT  | Interval 2      | ≤ 100                  | ≤ 2.2                                             |

*These values were obtained using a fixed $N_H = 5.7 \times 10^{22}$ cm$^{-2}$ for all the spectra.

*The unabsorbed luminosity was calculated using a distance of 6.79 kpc.

*This interval ranges from 2012 Feb 4 (ObsID: 0031174024) to 2012 Mar 6 (ObsID: 0031174028).

*The ObsIDs for this interval are shown in Table 1.

We examined the Swift/BAT and RXTE/PCA data (when available) of all the other outbursts of SAX J1750. A Sun constraint window occurred during many of its outbursts. We are unable to know how SAX J1750 behaved at these times and so the complete profiles of these outbursts are not known. The 2008 outburst shows clear rebrightenings (see Fig. 2; see also Lowell et al. 2012; Allen et al. 2015). In the case of the 2001 outburst, the source does not appear to have transitioned fully to quiescence but showed a phase
The observed effective surface temperature we simulated a spectrum using \texttt{fakeit} in \texttt{XSPEC}. The simulation used the \texttt{arf} of the stacked observations in Interval 2 and the appropriate response matrix file (swiftPC012s6_20130101v014.rmf). For the simulated spectrum, we employed an \texttt{nsatmos} model with parameters consistent with those we have used so far, such as those for mass, radius, normalization, distance, and \( N_\text{H} \). We then adjusted the \texttt{nsatmos} temperature such that the model predicted count rate within \texttt{XSPEC} matched our calculated count rate upper limits. Using this method, the upper limit on the temperature was determined to be \( T < 106 \) eV and the upper limit on the flux was \( F_X < 4.0 \times 10^{-13} \) erg cm\(^{-2}\) s\(^{-1}\) (see Table 2 for the luminosity upper limit).

### 3.2.3 Chandra

We fit the \textit{Chandra} spectrum with an \texttt{nsatmos} model and observed an effective temperature of \( kT_{\text{eff}} = 129.9^{+5.3}_{-5.7} \) eV with a column density value (consistent with that from our \textit{XMM-Newton} analysis) of \( N_\text{H} = (6.3 \pm 0.8) \times 10^{22} \) cm\(^{-2}\). When fixing the column density to the value determined using \textit{XMM-Newton}, we obtained a \( kT_{\text{eff}} = 126.2^{+3.3}_{-2.2} \) eV, and a flux of \( F_X = 7.6^{+1.3}_{-1.2} \times 10^{-13} \) erg cm\(^{-2}\) s\(^{-1}\). The inferred luminosity was \( L_X = (4.2 \pm 0.7) \times 10^{33} \) erg s\(^{-1}\) (see also Table 2). The spectrum is shown in Figure 5. We added a power-law component to the model to determine if it was necessary and refitted the spectrum. We found that this additional component was not required to improve the fit. We determined the upper limit on the flux contribution from this component to be \( \sim 10 \) per cent (assuming a photon index of 1.5).

### 4 DISCUSSION

We studied the end of outburst behaviour of SAX J1750 after several outbursts (see Section 4.1) as well as the quiescent properties of the source (see Section 4.2).

#### 4.1 Outburst variability

Several dwarf novae and transient LMXBs (both neutron star and black hole ones) show post-outburst rebrightenings. The NS LMXB SAX J1808.4–3658 likely showed such rebrightenings after all its outbursts (Patruno et al. 2016). SAX J1750 previously showed a post-outburst rebrightening after its 2008 outburst (Lowell et al. 2012; Allen et al. 2015). We requested \textit{Swift}/XRT observations of SAX J1750 at the end of its 2015/2016 outburst to determine if post-outburst rebrightenings are also a recurrent feature in SAX J1750, however, we found that it is not the case for this source.

The behaviour of SAX J1750 during different outbursts differs significantly from each other. Some outburst are relatively short (\( \lesssim 1 \) month) while other outburst last > 1 yr. In addition, at least one long outburst (2008) showed an episode of rebrightening while for the last long outburst (2015/2016) of the source such rebrightenings were not observed. The reason(s) for this different outburst behaviour is not understand but any model explaining the outburst behaviour of this source has to take these outburst variations into account. We note that many other X-ray transients show quite a variety of outburst profiles so SAX J1750 is not unusual in its behaviour (e.g., neutron star sources such as Aql X–1 and 4U 1608–52, and black hole source such as 4U 1630–47 and GX 339–4; Lei et al. 2014; Capitanio et al. 2015; Clavel et al. 2016; Waterhouse et al. 2016). Furthermore, Wijnands & Degenaar (2013) reported a flare...
during their Swift/XRT observations after the 2011 outburst, increasing the complexity of the accretion behaviour of this source. Similar flares have been seen for other sources as well (e.g., Aql X-1, Coti Zelati et al. 2014; see Wijnands & Degenaar 2013 for an in depth discussion). The flaring behaviour also needs to be accounted for in a model attempting to explain the accretion variability in SAX J1750.

### 4.2 SAX J1750 in quiescence

SAX J1750 was observed in quiescence after 3 outbursts – after the 2008 outburst using XMM-Newton, after the 2011 outburst using Swift/XRT and Chandra, and after the 2015/2016 outburst once again using Swift/XRT. These are all the known outbursts of this source since 2008. However, if accretion activity occurred in one of the Sun constraint windows or was not at a high enough level to be picked up by BAT then it could have been missed and might complicate the discussion. For our discussion we assume that no undetected activity occurred.

Our quiescent data can be well fit by a thermal component model, without the need of a power-law component. This thermal emission likely comes from the neutron star surface caused by a cooling emission from a hot neutron star of low level accretion of matter onto the surface. The latter indeed could potentially produce an entirely thermal spectrum (see e.g., Zampieri et al. 1995) and the quiescent variations we see can then be explained by fluctuations in the residual accretion rate. However, recently it has been suggested that low level accretion onto a neutron star in quiescence not only produces a soft component but also a hard component (e.g., Chakrabarty et al. 2014; D'Angelo et al. 2015; Wijnands et al. 2015) that is roughly equal in strength in the 0.5 – 10 keV range compared to the soft component (see discussion in Wijnands et al. 2015). If true, the absence of the power-law component in our spectra would indicate that we do not see low-level accretion but indeed cooling emission from the surface. In the remainder of the discussion we will consider our observations in the context of this assumption.

#### 4.2.1 Do we see crust heating and cooling during our observations?

The XMM-Newton observation taken ∼ 400 d after the end of the 2008 outburst (and rebrightenings) indicated an observed effective neutron star temperature $kT_{\text{eff}}$ of $\sim 145 \pm 2.5$ eV, consistent with the results of Lowell et al. (2012). They proposed that at the time of the observation the crust and core were in equilibrium. From the very high surface temperature, they also inferred that SAX J1750 may harbour the hottest known NS in a LMXB. Wijnands & Degenaar (2013) also observed SAX J1750 in quiescence, ∼ 350 d after the end of the small 2011 outburst, using Swift/XRT. We analysed the pre-flare data to determine the quiescent crust temperature of SAX J1750. We found a $kT_{\text{eff}}$ of $\sim 131 \pm 12$ eV, consistent with the results of Wijnands & Degenaar (2013) and consistent with the value seen by Lowell et al. (2012). This further supported the hypothesis that SAX J1750 may host the hottest known NS in a LMXB as after a different outburst the source was still at a similar temperature to that after the 2008 outburst (although we note that the very large error bars on these post 2011 data are not very constraining).

At the time of publication by Lowell et al. (2012) it was generally assumed that short outbursts (of only a few months) could not heat a NS crust significantly out of equilibrium with the core. And therefore, this study assumed crust-core equilibrium when interpreting their results. Since then several sources have shown that in fact such short outbursts can still heat the crust significantly out of equilibrium with the core (Degenaar et al. 2013, 2015; Waterhouse et al. 2016; Parikh et al. 2017b). The dominant source of this heating is postulated to be located at a shallow depth in the crust. This is different from the deep crustal heating reactions which will still contribute to crustal heating during such short outbursts but not dominate it. The origin of this shallow heat source is unknown but has been observed for many sources. Typically it contributes up to ∼ 2 MeV per accreted nucleon of heat (Brown & Cumming 2009; Degenaar et al. 2011, 2014). Therefore, it is possible that for the XMM-Newton and post 2011 outburst Swift/XRT observations we still observed a heated crust rather than the crust in equilibrium with the core. If so, this temperature may not be directly related to the core temperature (see discussion below) and we cannot conclude that SAX J1750 is the hottest known NS LMXB. We further discuss the possibility of SAX J1750 hosting the hottest NS in Section 4.2.2.

To further study the quiescent behaviour of this source we searched the various satellite archives. We found a Chandra observation of the source taken ∼ 800 d after the end of the short 2011 outburst and we found a $kT_{\text{eff}}$ of $\sim 126 \pm 3$ eV. If no undetected accretion activity in between the Interval 1 Swift/XRT observations and the Chandra observation, this Chandra observation was taken further into quiescence after the end of the 2011 outburst compared to the Interval 1 Swift/XRT observations and could be indicative of a cooling crust. However, due to the large error bars on these Swift/XRT data we are unable to get an exclusive interpretation. The crust at the time of the Chandra observation could be at the same level, or lower, or even higher than at the time of the Swift/XRT observation. Therefore, we do not discuss the Swift/XRT data from Interval 1 further in context with the XMM-Newton and Chandra data because of its large error bars.

The XMM-Newton observation was taken ∼ 400 d after a long, bright 2008 outburst and may show a heated NS crust. Unfortunately, no follow up observations are present in the same quiescent period to check for crust cooling. The Chandra observation was taken further into quiescence, ∼ 800 d after the shorter 2011 outburst. The brightness of this outburst is not known due to limitations introduced by the Sun constraint window. The Chandra observation indicates a lower effective observed temperature compared to the XMM-Newton observation potentially indicating a cooling crust (although the short 2011 outburst may have reheated the crust to some degree).

SAX J1750 experienced another relatively long, bright outburst in 2015/2016. When using Swift/XRT to observe SAX J1750 after this outburst we did not detect the source. These observations were done very close after the estimated end of outburst (∼ 50 d after the end). From these observations we obtained an upper limit on the observed effective temperature of $\lesssim 106$ eV. This upper limit is significantly lower than previously obtained quiescent temperatures. However, it is not trivial to explain this low quiescent temperature. One of the explanations of such a relatively low temperature upper limit so soon after the end of outburst would be that the crust of the neutron star was not heated during the preceding accretion outburst. Similar behaviour has been observed for MAXI J0556–332, which experienced three outbursts. Modelling the quiescent evolution for this source indicated that the outbursts (having different profiles) need different magnitudes of shallow heating to explain the post-outburst cooling trends (Homan et al. 2014; Deibel et al. 2015; Parikh et al. 2017a). In particular, the cooling curve after outburst two of MAXI J0556–332 can be modelled without any shallow heating. A similar effect might be at work in SAX J1750, although it remains unclear what causes this difference in the amount of heat generated by the shallow heating process during the different
4.2.2 The hottest NS in SAX J1750

The Chandra and the 2016 Swift/XRT observations show the NS in SAX J1750 to be at temperatures much lower than \( \sim 145 \text{ eV} \) based on which Lowell et al. (2012) proposed it to be the hottest known NS LMXB. Can it still be the hottest known NS LMXB? If the various different temperatures can be explained only by a change in the chemical composition of the envelope it could still be the hottest known NS LMXB. Although it seems unlikely that the envelope composition after the three outbursts changes in a manner such that we always observe a decreasing temperature. Alternatively, if these different temperatures are the result of a cooling NS crust SAX J1750 will not host the hottest NS in a LMXB.

In addition, one must also consider the effect of the envelope composition on the other quiescent NS LMXBs. Ideally one has to compare NS LMXBs in quiescence which have the same envelope composition. This is of course not possible because it is difficult to determine the composition, introducing another uncertainty in the models (see Han & Steiner 2017). These other NS LMXBs may be hotter than SAX J1750 but if their envelopes have heavier elements the observed effective temperature would be lower than if they had a pure light element envelope. We must take this uncertainty into account when discussing the possibility of the hottest NS LMXB and at all other times when conclusions are being drawn based on the absolute value of the observed effective temperature. This will also affect the conclusions that can be inferred when creating the quiescent luminosity versus the long-term average accretion rate diagram commonly used in quiescent NS LMXBs studies to infer NS core properties (e.g., Heinke et al. 2010; see also Han & Steiner 2017 for such a comparison).

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