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A low-level accretion flare during the quiescent state of the neutron-star X-ray transient SAX J1750.8−2900

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ABSTRACT

We report on a series of *Swift*/X-ray telescope observations, performed between 2012 February and 22 March, during the quiescent state of the neutron-star X-ray binary SAX J1750.8−2900. In these observations, the source was either just detected or undetected, depending on the exposure length (which ranged from ∼0.3 to ∼3.8 ks). The upper limits for the non-detections were consistent with the detected luminosities (when fitting a thermal model to the spectrum) of $\sim 10^{34}$ erg s^{-1} (0.5–10 keV). This level is consistent with what has been measured previously for this source in quiescence. However, on March 17 the source was found to have an order of magnitude larger count rate. When fitting the flare spectrum with an absorbed power-law model, we obtained a flare luminosity of (3–4) $\times\, 10^{34}$ erg s^{-1} (0.5–10 keV). Follow-up *Swift* observations showed that this flare lasted <16 d. This event was very likely due to a brief episode of low-level accretion on to the neutron star and provides further evidence that the quiescent state of neutron-star X-ray transients might not be as quiet as is generally assumed. The detection of this low-level accretion flare raises the question whether the quiescent emission of the source (outside the flare) could also be due to residual accretion, albeit continuous instead of episodic. However, we provide arguments which would suggest that the lowest intensity level might instead represent the cooling of the accretion-heated neutron star.

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

1 INTRODUCTION

In neutron-star low-mass X-ray binaries (LMXBs), a neutron star is accreting mass from a donor with a mass lower (often much lower) than the mass of the neutron star. The mass transfer occurs because the donor star fills its Roche lobe. Most systems (the X-ray transients) are only occasionally visible during short X-ray outbursts (with X-ray luminosities from $\sim 10^{34}$ erg s^{-1} up to a few times 10^{38} erg s^{-1}) but most of the time the sources are in their dormant, quiescent state (during which they have X-ray luminosities of typically 10^{32}–10^{34} erg s^{-1}). In this state, many systems have an X-ray spectrum that is dominated by a soft thermal component with a typical blackbody temperature of ∼0.1–0.3 keV. Often a non-thermal component is present as well which can be described by a power law with a photon index of ∼1–2 (see e.g. Campana et al. 1998). In some sources, this non-thermal component dominates the 0.5–10 keV X-ray spectrum, and no thermal emission can significantly be detected (e.g. Campana et al. 2005; Wijnands et al. 2005a,b; Heinke et al. 2009; Degenaar, Patruno & Wijnands 2012).

The origin of the non-thermal component is not understood, and it has been speculated that the neutron-star magnetic field plays an important role in the production of this spectral component (see e.g. Campana et al. 1998; Degenaar et al. 2012 for reviews). The thermal component very likely arises from the surface of the neutron star. This component could represent the cooling emission of the neutron-star core which is heated in outburst due to pycnonuclear reactions deep in the neutron-star crust (Brown, Bildsten & Rutledge 1998). If true, then the quiescent thermal flux (which is related to the core temperature) and the long-term time-averaged accretion rate (representing the amount of heating in the crust) should be positively correlated. It has been found that most systems have cores which are too cold to be explained by standard core cooling processes, and enhanced neutrino emission processes are needed in the core to cool them down (e.g. Brown et al. 1998; Yakovlev & Pethick 2004; Heinke et al. 2009; Wijnands, Degenaar & Page 2013); only a few systems can be described accurately with standard core cooling (e.g. Rutledge et al. 1999, 2000; Degenaar et al. 2011; Wijnands et al. 2013). Enhanced core cooling is thought to occur for neutron stars that are relatively massive or are composed of exotic matter (e.g. Colpi et al. 2001; Lattimer & Prakash 2001; Page et al. 2004).

Alternatively, the soft thermal component could be due to low-level residual accretion down to the neutron-star surface. When the

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matter falls on to the neutron star, it emits radiation with a thermal-like spectrum which is nearly indistinguishable (i.e. when taking into account the often very low number of photons detected) from the thermal spectrum expected from the cooling of the neutron stars (Zampieri et al. 1995; Soria et al. 2011). If this scenario occurs, those systems would be excellent targets to search for gravitational redshifted lines due to heavy elements which are accreted on to the neutron-star surface (Bildsten, Salpeter & Wasserman 1992; Brown et al. 1998). If no accretion occurs, those elements sink very quickly into the crust and only hydrogen remains at the top which does not have lines in the soft X-ray band.

Clearly, it is important to determine whether the thermal quiescent emission is due to residual accretion or due to core cooling. However, this is not very straightforward to determine. One way to distinguish residual accretion from cooling as the dominant source of the thermal emission is to search for variability of the quiescent emission since core cooling is expected to be much more stable in time than the expected stochastic variations in the residual accretion rate. Therefore, variability of the thermal component would be clear evidence that residual accretion might be occurring in the system. We note that crust cooling from a heated neutron-star crust due to long episodes of accretion could also produce detectable variability in quiescence (e.g. Wijnands et al. 2002, 2004; Cackett et al. 2008, 2010; Degenaar et al. 2011; Fridriksson et al. 2011), but typically this is expected to be a smooth decay (e.g. Rutledge et al. 2002; Shternin et al. 2007; Brown & Cumming 2009; Page & Reddy 2012).

Here we report clear evidence for a short, very faint accretion episode in the neutron-star X-ray transient SAX J1750.8−2900 during its quiescent phase using observations performed with the X-ray telescope (XRT) aboard *Swift*. SAX J1750.8−2900 was discovered by Natalucci et al. (1999) using the *BeppoSAX* satellite. The detection of type I X-ray burst demonstrated the presence of a neutron-star accretor and allows for a distance estimate of ∼6.8 kpc (Galloway et al. 2008). After its discovery outburst, the source exhibited several more outbursts (e.g. Kaaret et al. 2002; Linares et al. 2008; Markwardt & Swank 2008), with the last, relatively faint (with a peak luminosity of $\sim 10^{36}$ erg s^{-1}), outburst occurring in 2011 February (Fiocchi et al. 2011; Natalucci et al. 2011). It is unclear how long this 2011 outburst lasted, but the source light curve obtained through the Galactic bulge scan programme[1] (Swank & Markwardt 2001) using the Proportional Counter Array (PCA) aboard the *Rossi X-ray Timing Explorer* (*RXTE*) satellite suggests that the outburst lasted at most until the end of February/early March 2011. No outbursts have been reported from the source since this 2011 outburst.

2 OBSERVATIONS AND RESULTS

SAX J1750.8−2900 was observed with *Swift*/XRT between 2012 February 14 and March 17 during a series of observations spaced by one to two weeks (see Table 1 for a log of the observations). All data were obtained in photon counting mode. Typically the source intensity was near the detection limit, with the source either being undetected or showing a small excess of photons (depending on exposure time; see Table 1). On March 17, however, we noticed a large enhancement in the source count rate. We obtained two extra observations within the following week to study the decay of this flare.

[1] The *RXTE*/PCA Galactic bulge scan light curves (Swank & Markwardt 2001) can be found at http://asd.gsfc.nasa.gov/Craig.Markwardt//galscan/main.html.

Table 1. Log of the *Swift*/XRT observations.

Observation ID	Date (2012)	Exposure time (ks)	Count rate (counts s^{-1})
31174024	14 Feb.	3.8	$(1.5 \pm 0.6) \times 10^{-3}$
31174025	26 Feb.	2.6	$<1.8 \times 10^{-3}$
31174026	29 Feb.	0.3	$<1.2 \times 10^{-2}$
31174027	3 Mar.	3.2	$(1.6 \pm 0.7) \times 10^{-3}$
31174028	6 Mar.	2.8	$<1.7 \times 10^{-3}$
31174030	17 Mar.	3.1	$(1.9 \pm 0.2) \times 10^{-2}$
31174031	20 Mar.	1.0	$(5.2 \pm 2.1) \times 10^{-3}$
31174032	22 Mar.	1.0	$<2.0 \times 10^{-3}$

Note. Quoted count rates are background corrected and for the full XRT energy range (0.3–10 keV).

We used the *Swift* data analysis tools incorporated in HEASOFT version 6.11. We processed all data using the tool *xrtpipeline*. We used the tool *Xselect* to extract images, light curves and spectra. A circular region with a radius of 10 pixels was used to extract source events and three circular regions with radii of 10 pixels to extract the background data. We created exposure maps for each observation and used these when creating light curves and spectra.

The source was detected (albeit sometimes barely) when the observations were sufficiently long (>3 ks) and during the two flare observations (Obs. IDs 31174030 and 31174031 in Table 1). For the non-detections during the shorter observations, we determined upper limits on the count rate (95 per cent confidence level) using the prescription of Gehrels (1986). We also co-added all pre-flare data (i.e. excluding the three last observations listed in Table 1, which concern the observation in which the flare was discovered and the two follow-up observations): the source is clearly detected in this combined data set at a count rate of $(9.1 \pm 2.8) \times 10^{-4}$ counts s^{-1}.

The light curve of the flare episode is shown in Fig. 1. The source clearly exhibited a flare on March 17, with a count rate a factor of ∼10 above the quiescent level (see also Table 1). The

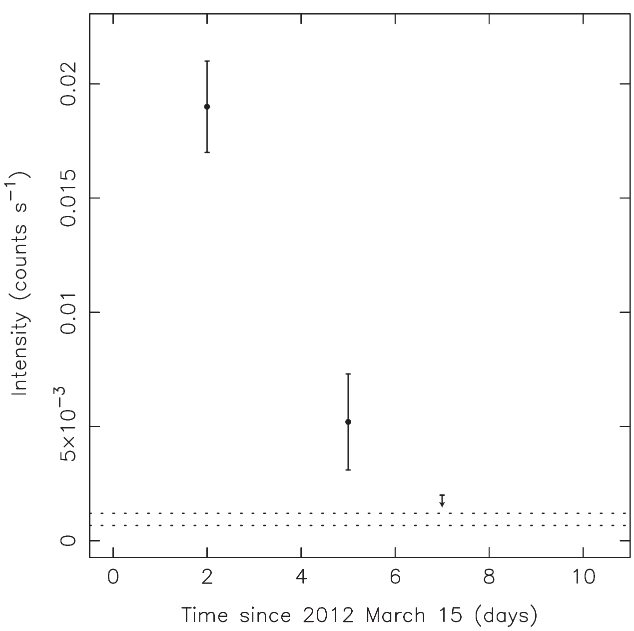

Figure 1. *Swift*/XRT count rate curve (0.3–10 keV) of the flare episode. The dotted lines indicate the quiescent count rate observed during the pre-flare observations. The count rate upper limit obtained during the last observation is for the 95 per cent confidence level.

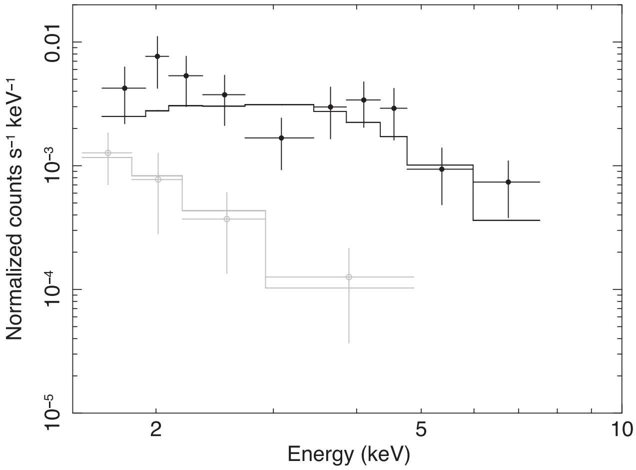

Figure 2. *Swift*/XRT spectra of the peak of the flare (black; Obs. IDs 31174030 and 31174031) and the combined quiescent data (grey; all other observations; see Table 1).

data obtained on March 20 show that the source intensity was still enhanced compared to the pre-flare level by a factor of ∼5, but on March 22 the count rate was consistent with the source being back in quiescence. Since the last observation just before the flare occurred on March 6, we can constrain the flare duration between 5 and 16 d.

We extracted the spectra of the flare observations (Obs. IDs 31174030 and 31174031; Table 1), as well as the combined quiescent data set (all observations except Obs. IDs 31174030 and 31174031). The obtained spectra were grouped to a minimum of 5 photons per bin. Although this is not sufficient to formally allow us to use the χ^2 minimization technique to fit the spectra, we have found previously (e.g. Wijnands & Wang 2002; Armas Padilla et al. 2013a) that this method can still be used accurately even with so few photons per spectral bin (we note that when using the W-statistics, we obtained consistent results). We created ancillary response files (using exposure maps) and used the response matrix files (v.13) from the calibration data base (CALDB). The spectra were fitted in the range 0.5–10 keV using XSPEC. The errors on the fit parameters are for 90 per cent confidence levels. The quiescent and flare spectra are shown in Fig. 2.

Despite that the source was clearly detected both during the flare and in the combined quiescent data set, the extracted spectral data were of insufficient quality to fit complex models. We therefore fixed the column density $N_{\rm H}$ in order to investigate the spectral shape. The $N_{\rm H}$ for SAX J1750.8−2900 is not well constrained, so here we use values of 4×10^{22} and 6×10^{22} cm^{-1} which were obtained by analysing *XMM–Newton* quiescent spectral data of the source (Lowell et al. 2012). The assumed column density did not significantly impact the obtained spectral parameters (see Table 2).

The flare spectrum could be fitted with an absorbed power-law model (PHABS*POWERLAW), yielding a reduced chi-squared value of $\chi^2_\nu = 1.3$ for 8 degrees of freedom (dof). The obtained photon index was relatively high (2.4–2.8) albeit with large errors (1.3–1.6). The inferred flux during the flare was $\sim 10^{-12}$ erg s^{-1}, and the unabsorbed flux was $\sim(5\text{–}8) \times 10^{-12}$ erg s^{-1} (both 0.5–10 keV). The large range in the latter is due to the range in assumed $N_{\rm H}$. This demonstrates that when the absorption is high and not well constrained, extrapolating a power-law model to low energies (<2 keV) results in large uncertainties in the unabsorbed fluxes. Using these fluxes, we obtain a source luminosity during the flare of $\sim(3\text{–}4) \times 10^{34}$ erg s^{-1} for a distance of 6.8 kpc.

A power-law model could also describe the quiescent spectrum satisfactorily but the resulting photon index was very large (>6), suggesting that a thermal model is more appropriate. To allow for a direct comparison with the quiescent spectrum observed with *XMM–Newton*, we follow Lowell et al. (2012) and fit the XRT spectrum with a blackbody model (BBODYRAD) with $N_{\rm H} = 4 \times 10^{22}$ cm^{-2} fixed, and a neutron-star atmosphere model (NSATMOS; Heinke et al. 2006) with $N_{\rm H} = 6 \times 10^{22}$ cm^{-2} fixed. Both give acceptable fits with $\chi^2_\nu = 0.5$ (2 dof) and 1.0 (3 dof) for the blackbody and NSATMOS model, respectively.[2] The obtained blackbody temperature is 0.3 ± 0.2 keV, and the temperature for the NSATMOS model is 0.15 ± 0.02 keV. For both assumed column densities and both spectral models, the 0.5–10 keV absorbed flux is $\sim 6 \times 10^{-14}$ erg s^{-1}, and the unabsorbed flux is $\sim(1.2 - 1.6) \times 10^{-12}$ erg s^{-1}. The resulting 0.5–10 keV luminosities are $(6\text{–}9) \times 10^{33}$ erg s^{-1} (for a distance of 6.8 kpc). Our obtained quiescent temperatures and fluxes are similar to that found for SAX J1750.8−2900 by Lowell et al. (2012) using *XMM–Newton* data. We have also tried to fit the flare spectrum with both the BBODYRAD and the NSATMOS model, but the spectrum could not be adequately fitted with those models (with reduced χ^2 ranging from 1.8 to 2.3). This clearly demonstrates that the flare spectrum cannot be described by a single thermal component and therefore it is quite different from the quiescent spectrum. We note that multiple component models, e.g. a power-law component plus a thermal component, could fit the data adequately but no meaningful constraints on the thermal component could be obtained due to the low statistical quality of our data.

3 DISCUSSION

The neutron-star X-ray transient SAX J1750.8−2900 was monitored in quiescence using *Swift*/XRT. During one of those observations, we detected a faint flare which lasted <16 d (as determined using triggered follow-up observations with *Swift*/XRT) and had an estimated 0.5–10 keV peak luminosity of $\sim(3\text{–}4) \times 10^{34}$ erg s^{-1}, which is a factor of ∼3–4 times higher than the quiescent level observed with the XRT. Our observed quiescent luminosity is consistent with that measured previously by Lowell et al. (2012) using *XMM–Newton*.

Similar flares reaching a factor ∼10 above the quiescent level have been seen in a few transient neutron-star LMXBs. Regular monitoring observations of the Galactic Centre with *Swift*/XRT (Degenaar & Wijnands 2009, 2010) caught an accretion flare from KS 1741−293 that reached a 2–10 keV peak luminosity of $\sim 3 \times 10^{34}$ erg s^{-1} and lasted <4 d (Degenaar & Wijnands 2013). That same monitoring programme also detected a short flare from GRS J1741−2853, which reached up to $\sim 9 \times 10^{34}$ erg s^{-1} (2–10 keV) and had a duration of approximately one week (Degenaar & Wijnands 2009). In both sources, the short-lived flare was followed by a brighter and longer (i.e. normal) outburst within a few weeks (both sources are very regularly active).

[2] For the NSATMOS model fits, the source distance was fixed at 6.8 kpc and the neutron-star mass and radius at 1.4 $M_\odot$ and 10 km, respectively. We also fixed the fraction of the neutron star that is emitting to 1 (the whole surface is emitting). For the blackbody fit, the normalization (which equals the radius in km squared divided by the distance in units of 10 kpc squared) is poorly constrained (19^{+4777}_{-19}).

Table 2. Spectral fit results.

Parameter	χ^2_ν (dof)	Photon index	Temperature[a] (keV)	$F^b_{\rm abs}$ (10^{-13} erg s^{-1})	$F^b_{\rm unabs}$ (10^{-13} erg s^{-1})	$L^c_{\rm X}$ (10^{34} erg s^{-1})
			$N_{\rm H} = 4 \times 10^{22}$ cm^{-2}			
Flare	1.3 (8)	2.4 ± 1.3		12 ± 5	46 ± 16	2.5 ± 0.8
Quiescence						
– Blackbody	0.5 (2)		0.3 ± 0.2	0.6 ± 0.2	12 ± 5	0.6 ± 2.8
			$N_{\rm H} = 6 \times 10^{22}$ cm^{-2}			
Flare	1.5 (8)	2.8 ± 1.6		11 ± 5	78 ± 15	4.2 ± 0.8
Quiescence						
– NSATMOS	1.0 (3)		0.15 ± 0.02	0.6 ± 0.2	16 ± 7	0.9 ± 0.3

[a]For the NSATMOS model, we assumed a neutron-star mass of 1.4 M$_\odot$, a radius of 10 km and a distance of 6.8 kpc.
[b]The fluxes are for the energy range 0.5–10 keV. The errors on the fluxes are determined using the method outlined in Wijnands et al. (2004).
[c]The luminosities are calculated from the unabsorbed 0.5–10 keV flux by assuming a distance of 6.8 kpc.

For SAX J1750.8−2900, we did not observe a new outburst shortly after the flare, although faint outbursts (with peak luminosities below 10^{36} erg s^{-1}) are easily missed. Another source, XTE J1701−462, displayed several weak flares (with a peak luminosity of $\sim 10^{34-35}$ erg s^{-1}; 2–10 keV), with the first one occurring within one year after the end of its most recent outburst, but others occurred several years (>3 years) later (Fridriksson et al. 2010, 2011).

3.1 Accretion flares

A natural explanation for these faint flares appears to be low-level accretion activity during quiescence, although such events are not easy to understand within the disc instability model that provides the frame work to describe the observed outburst–quiescent cycles of transient neutron-star LMXBs (e.g. Lasota 2001). The processes at work at the very low accretion luminosities we observed during the flare of SAX J1750.8−2900 and those we observe in the other sources are not well understood. When fitting the flare spectrum of SAX J1750.8−2900 with an absorbed power-law model, the obtained photon index is rather high (although with large error bars), which is similar to what has been seen for other neutron-star X-ray binaries at such luminosities (e.g. in't Zand, Cornelisse & Méndez 2005; in't Zand et al. 2009; Armas Padilla et al. 2011, 2013b; Degenaar, Wijnands & Miller 2013). This relatively soft spectrum is consistent with the accretion models which assume that at those luminosities the flow can be described as a radiation-inefficient accretion flow or as an advection-dominated accretion flow (see e.g. the discussions in Tomsick, Kalemci & Kaaret 2004; Armas Padilla et al. 2011).

However, when high-quality data are obtained at those luminosities, the situation becomes more complex: a prominent thermal component can clearly be detected (Armas Padilla et al. 2013b; Degenaar et al. 2013), most probably due to thermal emission from the neutron-star surface. This thermal emission is likely caused by low-level accretion on to the surface. When including this soft component in the spectral models, the power-law component becomes significantly harder (with a photon index of ∼1.5) than when only a single power-law component is fitted to the data. This might indicate that at different luminosities, the power-law component is caused by different physical processes (see also the discussion in Armas Padilla et al. 2013b). Sadly, the quality of our flare spectrum does not allow us to determine what exactly causes the relative softness of the flare spectrum of SAX J1750.8−2900. Clearly, to make progress in understanding the accretion processes at very low accretion rates, high-quality data (i.e. obtained with *XMM–Newton*) need to be acquired to study the different spectral components in more detail. However, the short duration of the flare (<16 d, similar to the flare durations seen in other sources) indicates that such accretion flow can come and go on relatively short time-scales and this needs to be incorporated in the models.

3.2 Origin of the quiescent emission

The fact that we see a flare from SAX J1750.8−2900 that is likely related to a short and weak accretion event raises the question whether low-level accretion is also relevant for the out-of-flare quiescent emission. If a residual accretion flow would reach the neutron-star surface, it would very likely generate a thermal spectrum that is indistinguishable from that of a cooling neutron star (e.g. Zampieri et al. 1995, i.e. given the low statistics of quiescent data from neutron-star X-ray transients). Lowell et al. (2012) discuss the quiescent properties of the source, as observed with *XMM–Newton*. They used the cooling curves presented by Yakovlev & Pethick (2004) to compare the observed quiescent luminosity with that expected from a cooling neutron star and reach the (correct) conclusion that the source is too bright (thus too hot) and it cannot be explained using those cooling curves. This could suggest that low-level accretion on to the neutron star is indeed important in quiescence. The accretion luminosity would then mask the cooling emission and the neutron star would be significantly colder than inferred and would be consistent with the cooling models. However, significant uncertainties exist in the theoretical cooling curves, and when using slightly different assumptions, cooling curves can be constructed that allow such a hot neutron star: for example, using the mass accretion rate and the observed quiescent luminosity for the source as given in Lowell et al. (2012), it can be seen that the source falls right on top of the bremsstrahlung cooling curve presented in fig. 1 of Wijnands et al. (2013). Therefore, it is feasible that the source indeed harbours a hot neutron star. It would then be one of the few whose core cools very slowly due to the absence of strong neutrino emission processes.

In addition, several extra arguments can be given that we do observe the cooling emission from SAX J1750.8−2900 instead of radiation due to residual accretion. Lowell et al. (2012) do not observe a power-law component in the quiescent spectrum obtained with *XMM–Newton* (consistent with the *Swift* results, although our constraints are not very strong). Although it is not fully clear whether at low accretion rates indeed a power-law component should be present (possibly only a thermal component will be seen if the accretion rate is low enough and the matter falls on to the neutron-star surface; Zampieri et al. 1995), during the flare the spectrum was totally dominated by a power law despite that the luminosity was only a factor of 3–4 higher than the quiescent level. One might therefore expect that at only a slightly lower accretion rate, also a power-law component might be present. Furthermore, our inferred quiescent luminosity is consistent with that reported by Lowell et al. (2012), which was measured ∼2 years previously (in addition, a faint outburst occurred between our observations and theirs). This strongly indicates that at this luminosity level, the source is not highly variable, as one would expect if accretion would play a significant role.

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