An XMM-Newton observation of the neutron star X-ray transient 2S 1803–245 in quiescence

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ABSTRACT
We observed the neutron star X-ray transient 2S 1803–245 in quiescence with the X-ray satellite XMM-Newton, but did not detect it. An analysis of the X-ray bursts observed during the 1998 outburst of 2S 1803–245 gives an upper-limit to the distance of \( \leq 7.3 \) kpc, leading to an upper-limit on the quiescent 0.5-10 keV X-ray luminosity of \( \leq 2.8 \times 10^{32} \) erg s\(^{-1}\) (3\(\sigma\)). Since the expected orbital period of 2S 1803–245 is several hrs, this limit is not much higher than those observed for the quiescent black hole transients with similar orbital periods.

Key words: accretion, accretion disks – stars: neutron – stars:individual: 2S 1803–245 – X-rays:binaries.

1 INTRODUCTION

Low mass X-ray binaries (LMXBs) are compact binaries in which the primary is a compact object (a black hole or neutron star) that accretes matter from a low mass \((\leq 1M_\odot)\) secondary. An important sub-class of the LMXBs are the soft X-ray transients. These systems spend most of their time in a quiescent state in which little (or no) accretion is thought to take place and X-ray luminosities are \(\leq 10^{34} \) erg s\(^{-1}\). Only occasionally do these transients show outbursts that can last for weeks up to months and reaching X-ray luminosities of \(10^{36–38}\) erg s\(^{-1}\).

Over a dozen neutron star transients have been observed when they were in the quiescent state, and in many cases their spectra show a soft thermal component that is dominant below \(\approx 1\) keV. This is thought to be due to the cooling of the neutron star that has been heated during the previous outbursts (e.g. Verbunt et al. 1994; Brown et al. 1998; Campana et al. 1998). Other mechanisms have also been suggested to explain the quiescent emission for neutron stars, such as residual accretion onto the neutron star (e.g. Campana et al. 1998; Campana & Stella et al. 2000).

Apart from a soft component also a hard power-law component that dominates the spectrum above a few keV has been observed in several systems. This component can contribute a significant fraction to the total X-ray flux, and especially in SAX J1808.4–3658 and EXO 1745–248 this power-law component was the main source of the X-ray flux with no significant contribution from the soft thermal component (Campana et al. 2002; Heinke et al. 2007; Wijnands et al. 2005). The origin of this power-law component is still unclear, although at low luminosities \((L_X < 10^{33} \) erg s\(^{-1}\)) there appears to be an anti-correlation between the fractional power-law contribution to the luminosity and the source luminosity (e.g. Jonker et al. 2004).

One of the distinct differences between black hole transients and neutron star transients is the difference in quiescent luminosities, with the black hole transients being systematically fainter (e.g. Narayan et al. 1997; Menou et al. 1999; Garcia et al. 2001; Lasota 2007). This has been interpreted as evidence for the presence of an event horizon in black holes. Since the energy is radiated away very inefficiently for such very low accretion rates, this will not happen before the matter has crossed the event horizon for black holes and can therefore not be observed, while in neutron stars this should be emitted at the moment the matter falls on the surface and can be detected (e.g. Narayan et al. 1997). However, alternative explanations for this difference in luminosity have been suggested, such as a transition to a jet-dominated regime for black hole transients that carries away most of the material that would otherwise be accreted (Fender et al. 2003).
months (see Fig.1) and that also reached a peak intensity of $\approx 1$ Crab (Marshall et al. 1998). At the beginning of the second outburst the BeppoSAX satellite detected thermonuclear X-ray bursts from this source, establishing its neutron star nature (Müller et al. 1998). A radio counterpart was detected (0.8 mJy) that provided an accurate position ($\alpha=18\text{h}06\text{m}50.72\text{s}$ $\delta=-24^\circ35'28.6''$ J2000) and optical follow-up observations showed a weak ($V\approx 22$) counterpart at the position of the radio source (Hjellming et al. 1998; Hynes et al. 1998). During the peak of the outburst 2S 1803–245 showed some spectral and timing properties of the Z-sources (Wijnands & van der Klis 1999), suggesting that it reached accretion rates comparable to the Eddington rate (Hasinger & van der Klis 1989). Other observations during the decay of the outburst showed that 2S 1803–245 had the spectral and timing characteristics of Atoll sources.

In this paper we report on an XMM-Newton observation of 2S 1803–245 in quiescence, made $\approx 7$ years after its last outburst. Thus far, most of the neutron star transients that have been studied in quiescence showed sub-Eddington outbursts, with 2S 1803–245 being one of the few that reached the Eddington limit. This makes it an interesting source to study how its quiescent properties compare to the other systems. However, in Sect. 2.1 we will show that 2S 1803–245 was not detected during our observation. Combined with the analysis of the X-ray bursts that were detected during its outburst (Sect. 2.2) we determine an upper-limit to the distance, and thereby an upper-limit to its luminosity. In Sect. 3 we will discuss the implications of our findings.

2 OBSERVATIONS AND DATA REDUCTION

2.1 Quiescent observations

We made a 24 ks observation on 2S 1803–245 using the X-ray satellite XMM-Newton from April 5 2005 (UT 22:23:52) until April 6 2005 (UT 05:04:07). We analysed the data from the three EPIC cameras (PN, MOS1, MOS2) that were observing in full window mode and with a thin filter. The data were processed using the Standard Analysis Software (SAS) version 7.0.0. In order to identify periods of high particle background we extracted high energy ($\geq 10$ keV) lightcurves for all cameras. We chose to keep all data where the countrate was less than 0.8 counts s$^{-1}$ for the PN and 0.2 counts s$^{-1}$ for the MOS. This left a net observing time of 14.8 ks for the PN and 20.3 ks for the MOS cameras.

We created images for each individual camera for several energy ranges (0.5-10, 0.5-2, 5-10 keV) but there was no detection of 2S 1803–245 at the position of the radio source detected by Hjellming et al. (1998). Although we think it is unlikely, since its radio flux (0.8±0.3 mJy at 4.86 GHz) is similar to that of the bright neutron star X-ray transients Aql X-1 and XTE 1701–462 (both 0.5 mJy at 4.8 GHz; Fender & Kuulkers 2001, Fender et al. 2006), it cannot be completely ruled that the radio source is not related to 2S 1803–245. We therefore checked the region inside the RXTE error-circle, but no source was present. In order to increase sensitivity we also merged all 3 cameras and again created images in different energy ranges. Still no source is present at the position of the radio source, or even inside the RXTE error-circle (see Fig.2). We therefore conclude that we have not detected 2S 1803–245 in quiescence.

In order to determine an upper-limit on the X-ray flux of 2S 1803–245 we extracted a spectrum for all 3 cameras using a circle with a radius of 20 arcsec around the position of the radio source. This lead to spectra with 9 counts for the PN and 4 counts for each MOS detector. For different spectral models, using the absorption column determined in Sect. 2.2 and combining all cameras, we estimated a 3$\sigma$ upper-limit to the 0.5-10 keV unabsorbed X-ray flux in Table I. We have also compared these limits with a source located closest to the radio position (see Fig.2). This source was detected at 3.8$\sigma$ above the background, and using the same spectral models as in Table I gave comparable flux levels as determined for 2S 1803–245. This makes us confident that the upper-limit on 2S 1803–245 is correct. Using the upper-limit to the distance determined from the X-ray bursts we also show the corresponding luminosity in Table I.
Table 1. 3σ upper-limits to the 0.5-10 keV unabsorbed X-ray flux of 2S 1803–245 in quiescence for different spectral models. The temperature (for the black-body model) and photon index, $\gamma$, (for the power-law model) are fixed at the indicated values, while for all models the absorption column is fixed at $1.47 \times 10^{22} \text{ cm}^{-2}$. Furthermore, we have indicated the corresponding luminosity for a distance of 7.3 kpc.

| Spectral Model     | parameter | $F_{0.5-10}$ (erg cm$^{-2}$ s$^{-1}$) | $L_{0.5-10}$ (erg s$^{-1}$) |
|--------------------|-----------|--------------------------------------|-----------------------------|
| black-body         | kT=0.2 keV| $<4.4 \times 10^{-14}$               | $<2.8 \times 10^{32}$       |
| black-body         | kT=0.5 keV| $<1.5 \times 10^{-14}$               | $<0.96 \times 10^{32}$      |
| Powerlaw           | $\gamma=1.5$| $<2.0 \times 10^{-14}$               | $<1.3 \times 10^{32}$       |
| Powerlaw           | $\gamma=2.0$| $<2.1 \times 10^{-14}$               | $<1.3 \times 10^{32}$       |

2.2 Distance estimate

2S 1803–245 was in the field of view of the Wide Field Cameras (WFCs; Jager et al. 1997) onboard the BeppoSAX satellite (Boella et al. 1997) during its campaigns on the Galactic centre region. During the campaign in the first half of 1998 three X-ray bursts were detected from a position coincident with 2S 1803–245. Using the publicly available data from the All Sky Monitor (ASM) onboard the RXTE satellite we created a lightcurve of the outburst of 2S 1803–245. In Fig. 1 we show its outburst, and have also indicated the time that the bursts observed by the WFCs occurred. We note that all bursts occurred during the beginning of the outburst, and assuming that the peak of the outburst was at the Eddington-limit the X-ray luminosity must have been $\gtrsim 10^{37}$ erg s$^{-1}$ (see below). Since X-ray bursts are most commonly observed when a source is at X-ray luminosities between 0.5-2$\times 10^{37}$ erg s$^{-1}$, but tend to be suppressed at higher luminosities (e.g. Cornelisse et al. 2003), we can be confident that they originated from 2S 1803–245.

The X-ray bursts occurred between April 2 and 10 1998, and in Fig. 2 we show their 3 lightcurves in two different energy-bands. The shapes of the bursts can be described by a fast rise and exponential decay (with e-folding times between 10.1 and 13.5 s), as is characteristic of a thermonuclear X-ray burst. Furthermore, we have also calculated the hardness ratio (8-26 keV/2-8 keV) of the bursts to show that spectral softening occurs during the burst. Finally, we created a lightcurve of the outburst of 2S 1803–245. Using the publicly available data from the All Sky Monitor (ASM) onboard the RXTE satellite we created a lightcurve of the outburst of 2S 1803–245. In Fig. 1 we show its outburst, and have also indicated the time that the bursts observed by the WFCs occurred. We note that all bursts occurred during the beginning of the outburst, and assuming that the peak of the outburst was at the Eddington-limit the X-ray luminosity must have been $\gtrsim 10^{37}$ erg s$^{-1}$ (see below). Since X-ray bursts are most commonly observed when a source is at X-ray luminosities between 0.5-2$\times 10^{37}$ erg s$^{-1}$, but tend to be suppressed at higher luminosities (e.g. Cornelisse et al. 2003), we can be confident that they originated from 2S 1803–245.

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3 DISCUSSION

We have observed 2S 1803–245 during its outburst in 1998 with BeppoSAX and again in a $\gtrsim$20 ks observation in order to determine its quiescent properties. We did not detect the source during the XMM-Newton observations, and were only able to determine an upper-limit on its quiescent flux of $<1.4 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ (3σ). However, to compare this with other neutron star transients in quiescence and the different cooling models for neutron stars, we first need to determine the luminosity and time-averaged mass transfer of 2S 1803–245.

In order to determine its luminosity we presented the analysis of the three X-ray bursts that were observed during the outburst of 2S 1803–245. Since their peak flux was comparable to the continuum flux during the peak of the outburst we can assume that they reached the Eddington limit, which allows us to determine an upper-limit on the distance. However, we must make several assumptions on the neutron star properties in order to determine its Eddington limit. Since all X-ray bursts showed an e-folding time of $\gtrsim 10$ s, indicative for the presence of hydrogen during the burst (e.g. Fujimoto et al. 1981; Cornelisse et al. 2003), we assume that 2S 1803–245 has solar metallicity. Note that we can therefore not use the empirical determined value of $3.8 \times 10^{36}$ erg s$^{-1}$ by Kuulkers et al. (2003), since this is only valid for hydrogen-poor material. Instead, we assume the canonical properties for the neutron star parameters (i.e. radius of 10 km, mass of 1.4$M_\odot$), leading to an Eddington limit of $2 \times 10^{38}$ erg s$^{-1}$. This leads to a maximum distance of $7.3 \pm 0.7$ kpc for 2S 1803–245. Although the formal error on the distance is only 10%, due to the uncertainties in the Eddington limit it will be larger. The largest uncertainty, as suggested by the Eddington value determined by Kuulkers et al. (2003), is that the actual Eddington luminosity could be $\pm 2$ times larger than we used, leading to a distance that is at most $\pm 1.5$ times larger than we estimated. The other uncertainty is that the bursts do not show a clear indication of radius-expansion, suggesting that they did not reach the Eddington limit. However, this suggests that the Eddington flux for 2S 1803–245 must be higher, and therefore its distance lower than the upper-limit we determined above. Despite these uncertainties we have used the distance value of 7.3 kpc to determine the upper-limit on the 0.5-10 keV luminosity given in Table 1.

Following Tomsick et al. (2004) we can estimate the time-averaged mass transfer rate for 2S 1803–245, $\dot{M}$, by assuming that $\dot{M}=sL_{\text{peak}}N$. Here $L_{\text{peak}}$ is the peak luminosity, $N$ is the number of outbursts and $s=1.1 \times 10^{-23}$ s$^{-1}$ cm$^{-2}$ symbolising a value to estimate the average accretion
rate over a period of 33 years for a source that has a similar outburst profile and duration as XTE J2123−058 (see Tom-sick et al. 2004 for its outburst lightcurve). Since the out-burst duration and the profile of 2S 1803−245 is very similar to that of XTE J2123−058 we can use this value of s. Given that 2S 1803−245 has at least 2 outburst over the last 33 years, and that it reached the Eddington luminosity, we esti-mate an average mass accretion rate of $\dot{M} = 7 \times 10^{-11} M_\odot$ yr$^{-1}$. Obviously, there are many uncertainties in this value. For example, it assumes that we have observed all outbursts of 2S 1803−245 that occurred in the last 33 years, that all these outbursts were similar, that these 33 years reflects the real time-averaged mass transfer rate. However, since it is comparable to other estimates for the mass transfer rate, such as using the time interval of the ASM lightcurve as done by Heinke et al. (2007), we think this value is currently the best we can derive.

We can compare the quiescent luminosity and average mass transfer rate of 2S 1803−245 with the predictions of the different cooling models. Heinke et al. (2007) did this for most other neutron star transients that have been observed in quiescence (their Fig. 2). As has already been observed for many other systems (for overviews see e.g. Cackett et al. 2006, Heinke et al. 2007), the quiescent luminosity is too low to be explained by standard cooling models for a low-mass neutron star as calculated by Yakovlev & Pethick (2004). This model predicts a luminosity that is at least an order of magnitude higher than the upper-limit determined for 2S 1803−245. Only the models for more massive neutron stars, where the central density is high enough to have more rapid direct Urca or Urca-like processes, are consistent with our observations. However, we must note that increasing the neutron star mass does increase its Eddington-limit and thereby our estimate for the distance and consequently increases both the upper-limit on the quiescent luminosity and average mass transfer rate. Therefore, we cannot rule out any of the other cooling models at the moment.

Although 2S 1803−245 is fainter than expected for standard cooling models, it is still an order of magnitude brighter than the currently faintest neutron star transient 1H 1905+000 (Jonker et al. 2006). At an upper-limit of $1.8 \times 10^{34} \text{ erg s}^{-1}$ the luminosity of 1H 1905+000 is rivalling that of black hole transients in quiescence (Jonker et al. 2006). This system could challenge the idea that black hole systems should have lower luminosities than neutron star systems in quiescence (e.g. Narayan et al. 1997). However, Menou et al. (1999) predicted that this should only be the case for systems with a similar orbital period. Since there is a strong indication that 1H 1905+000 is an ultra-compact binary (Jonker et al. 2006), it should be able to reach luminosities lower than the average black hole system (but not as low as a black hole transient with a similar period). The orbital period of 2S 1803−245 is currently unknown, but Lasota (2007) gives a relation between the maximum outburst luminosity and orbital period for an hydrogen dominated disk (his formula 3). Using the maximum observed X-ray luminosity for 2S 1803−245, we found that this would result in an orbital period of 9 hrs. Although this is only a rough estimate, it strongly indicates that 2S 1803−245 is not an ultra-compact object. Comparing the quiescent luminosity of 2S 1803−245 with neutron star and black hole transients which have orbital periods around 9 hrs (see Garcia et al. 2001), we note that it is located at the bottom of the region where the neutron stars are located. More interestingly, the current upper-limit is not that much higher than the luminosity of the black holes. This makes 2S 1803−245 an excellent candidate for deep observations with the Chandra telescope to determine its quiescent flux, and find out if it reaches X-ray luminosities comparable to the black hole transients.

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