A&A 434, L9–L12 (2005)
DOI: 10.1051/0004-6361:200500103

Astronomy & Astrophysics

XMM-Newton observations of two transient millisecond X-ray pulsars in quiescence

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Received 28 December 2004 / Accepted 22 March 2005

Abstract. We report on XMM-Newton observations of two X-ray transient millisecond pulsars (XRTMSPs). We detected XTE J0929−314 with an unabsorbed luminosity of $\sim 7\times10^{31}$ erg s^{-1} (0.5−10 keV) at a fiducial distance of 10 kpc. The quiescent spectrum is consistent with a simple power law spectrum. The upper limit on the flux from a cooling neutron star atmosphere is about 20% of the total flux. XTE J1807−294 instead was not detected. We can put an upper limit on the source quiescent 0.5−10 keV unabsorbed luminosity $\lesssim 4\times10^{31}$ erg s^{-1} at 8 kpc. These observations strenghten the idea that XRTMSPs have quiescent luminosities significantly lower than classical neutron star transients.

Key words. accretion, accretion disks – binaries: close – stars: individual: XTE J0929−314, XTE J1807−294 – stars: neutron

1. Introduction

X-ray transient millisecond pulsars (XRTMSPs) provided the (long-sought) direct evidence that the neutron stars in Low Mass X-ray Binaries are spinning fast and possess a sizable magnetosphere. Up to now six sources of this type have been discovered thanks to the Rossi X-ray Timing Explorer (RXTE): SAX J1808−3654 (Wijnands & van der Klis 1998), XTE J1751−305 (Markwardt et al. 2002), XTE J0929−314 (Remillard et al. 2002), XTE J1807−294 (Markwardt et al. 2003a; Campana et al. 2003), XTE J1814−338 (Markwardt et al. 2003b) and, very recently, IGR J00291+5934 (Markwardt et al. 2004).

XRTMSPs belong to the so called neutron star Soft X-ray transient (SXRT) class and form a distinct subgroup. SXRTs show bright outbursts with peak X-ray luminosities in the 10^{36}−10^{38} erg s^{-1} range. SXRTs when in quiescence usually have a luminosity in the 10^{32}−10^{33} erg s^{-1} range (for a review see Campana et al. 1998a). Their quiescent spectra can be described by a soft component (modelled as a neutron star atmosphere spectrum from the entire surface) plus a power law tail which is present in a good number of sources[1] and can account for up to ∼70% of the 0.5−10 keV flux. One exception is represented by the transient EXO 1745−248 in the globular cluster Terzan 5. The quiescent state of this source is bright (a few 10^{33} erg s^{-1}) and its spectrum can be modelled by a power law tail only (Wijnands et al. 2005a). This is just one source in about a dozen of SXRTs.

XRTMSPs display significant differences. Their outbursts are a factor of 10−100 fainter than those of most SXRTs. When in quiescence, XRTMSPs are also fainter. SAX J1808.4−3658 was the first XRTMSP observed in quiescence. XMM-Newton observations allowed us to settle its quiescent spectrum on a firm basis. The spectrum could be modelled with a single power law ($\Gamma = 1.5^{+0.2}_{-0.3}$, 90% confidence level, Campana et al. 2002). For a distance of 2.5 kpc (in't Zand et al. 2001) SAX J1808.4−3658 is underluminous by a factor of two with respect to SXRTs in quiescence ($L \sim 5\times10^{31}$ erg s^{-1}). Recently, Chandra observed two other millisecond X-ray pulsars, XTE J0929−314 and XTE J1751−305 (Wijnands et al. 2005b). XTE J0929−314 was detected with 22 photons only, whereas XTE J1751−305 was not detected (upper limit of 5 photons). A spectral analysis of the XTE J0929−314 data, despite poor statistics, suggested a simple power law spectrum ($\Gamma = 1.8^{+0.6}_{-0.5}$, 90% confidence limit), giving a low 0.5−10 keV luminosity of $7^{+5}_{-2}\times10^{31}\,(d/10\,\mathrm{kpc})^2$ erg s^{-1} (note, however, that the source distance is not yet known). An upper limit of ∼30% on the flux of a soft component could be set. For XTE J1751−305 an upper limit of $(0.2{-}2)\times10^{32}\,(d/8\,\mathrm{kpc})^2$ erg s^{-1} on the 0.5−10 keV luminosity was determined, depending on the assumed spectral parameters (Wijnands et al. 2005b). Taken at face value, these results confirmed that the quiescent counterparts of XRTMSPs are dimmer than those of standard SXRT sources.

[1] This power law tail is not present at all (even with very tight limits) in quiescent Low Mass X-ray Binaries found in increasing numbers in globular clusters (Heincke et al. 2003).

Table 1. XTE J0929−314 spectral fits.

Model	N_H 10^{21} cm^{-2}	Temp./Power law (eV)	Flux$^+$ (10^{-15} cgs)	C-stat.* (chi^2_{red})	Goodness†
NSA	<3.3	$T = 76^{+16}_{-31}$	3.8 (6.1)	6.2 (1.3)	41.6%
Blackbody	<2.1	$T = 267^{+102}_{-125}$	2.9 (3.3)	5.1 (1.0)	25.1%
Power law	<2.6	$\Gamma = 2.0^{+1.9}_{-0.7}$	5.4 (6.3)	1.3 (0.3)	0.5%
Pow+NSA	<2.1	$T = 33^{+30}_{-25}$	6.6 (7.8)	0.8 (0.4)	0.3%
		$\Gamma = 1.6^{+1.7}_{-2.0}$	>95%		

All errors are 90% confidence level, obtained with $\Delta\chi^2 = 2.71$.
Soft component models have a normalization free to vary within the distance range 5−15 kpc.
$^+$ Fluxes are unabsorbed. The first value refers to the 0.5−10 keV energy range, the value in parenthesis to the 0.3−10 keV range. In the last raw the lower limit refers to the contribution of the power law to the total flux.
* C-statistics value for 7 energy bins (in parenthesis is reported the reduced chi^2 for the same fit).
† Percentage of simulated data (Gaussian distribution) which gives a better C-statistics than real data.

Here we report on XMM-Newton observations of XTE J0929−314 (Sect. 2) and XTE J1814−338 (Sect. 3). Our conclusions are described in Sect. 4.

2. XMM-Newton observation of XTE J0929–314

XMM-Newton observed XTE J0929−314 on May 4 2004 for 30 ks. The entire observation was plagued by soft proton flares and no usable data were obtained. A second observation took place on June 12, 2004 for 15.9 ks. The thin filter was used for all three EPIC cameras. We filtered out light background flares for total rates (0.2−15 keV) less than 3.5 [8] c s^{-1} for the MOS [pn] cameras, resulting in 15 [11] ks of good time intervals. The source was barely visible in the pn image. We extracted the pn source spectrum (circular region with $r = 13''$) and the background spectrum (three circular regions around the source on the same CCD with $r = 30''$). For the MOS cameras we did the same with a source extraction region of $r = 13''$ and four background regions of $90''$ around the source. We obtained about 10 (35) counts for MOS (pn) camera in the 0.3−10 keV range, of which about 40% are background events. A search at the known transient position provided a detection with a signal to noise ratio of ∼4.

We then fit together the three spectra. Given the low number of counts, we binned the MOS data to 5 counts per energy channel and the pn data to 8 counts per bin. Given the small number of counts we adopted the Cash statistics (Cash 1979). A soft component model (neutron star atmosphere or black body) did not provide a satisfactory description of the data (see Table 1). We simulated 10 000 spectra (with parameter values drawn from a Gaussian distribution centered on the best fit with sigma from the covariance matrix): about 25−40% of them had a better C-statistics than the actual data. We thus fit the data with a single power law obtaining better results. In this case only ∼1% of the simulated data had a better C-statistics than the real data. The power law photon index was constrained to be $\Gamma = 2.0^{+1.9}_{-0.7}$. A similarly good fit (goodness of ∼1%) could be obtained with the canonical model for neutron star transients in quiescence, i.e. a neutron star atmosphere model plus a power law tail. To derive an upper limit we freeze the best fit power law model and choose the maximal soft component that can be accomodated within the power law fit, degreding the spectral fit to a 10% acceptance with the Cash statistics. The upper limit to the contribution of the soft component in the 0.3−10 keV energy band is ∼20%. The neutron star atmosphere temperature is very soft with $T = 35$−55 eV (depending on the selected normalization) and its bolometric flux amounts to $<2\times10^{-15}$ erg s^{-1} cm^{-2}, corresponding to luminosity $<3\times10^{31}$ erg s^{-1} at 10 kpc.

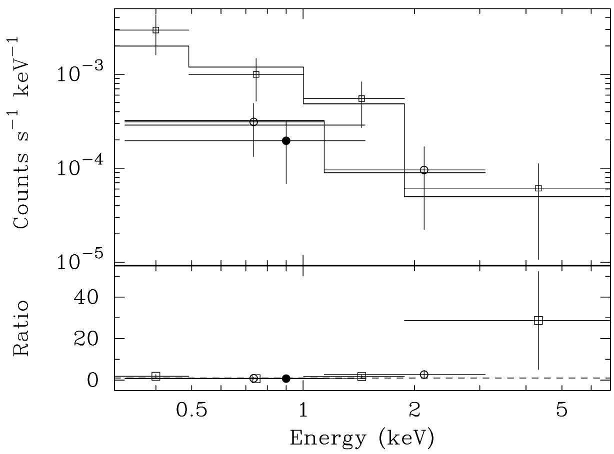

Fig. 1. XMM-Newton spectrum of XTE J0929−314. In the upper panel data along with the best fit power law spectrum are shown: pn data are marked with a open squares, MOS1 data with open circles and MOS2 data with filled circles. In the bottom panel the ratio between the best fit NSA model and the data is plotted. It is apparent that the model is underestimating the data at energies larger than ∼2 keV.

Finally, we searched for flux and spectral variations across the observation as tentatively suggested by Wijnands et al. (2005b) but we did not find any significant variation.

3. XMM-Newton observation of XTE J1807–294

XMM-Newton observed XTE J1807−294 on September 8, 2004 for 39 ks. The thin filter was used for all the three

EPIC cameras. During the observation, several soft proton flares occurred. We filtered MOS [pn] total rate (0.2−15 keV) with at a limiting rate of 5 [10] c s^{-1} for the MOS [pn] cameras, resulting in 32 [5] ks of good time intervals. XTE J1807−294 was not detected in the EPIC images. A 3σ upper limit of 8×10^{-4} c s^{-1} is derived from the 0.5−10 keV pn image. This rate can be translated into a flux assuming a spectral model. We consider the column density observed in outburst $N_{\rm H} = 5 \times 10^{21}$ cm^{-2} (Campana et al. 2003). For a power law with photon index in the 1.5−2 range a limit on the (unabsorbed) flux of $\sim 5 \times 10^{-15}$ erg s^{-1} cm^{-2} can be derived; for a black body model with temperatures in the 0.1−0.3 keV range a limit of $\sim 3 \times 10^{-15}$ erg s^{-1} cm^{-2} can be derived. The distance to XTE J1807−294 is presently unknown. A scale distance of 8 kpc is assumed. At this distance the flux limit implies an upper limit on the 0.5−10 keV luminosity of $\sim 4 \times 10^{31}$ erg s^{-1}.

4. Conclusions

It is becoming apparent that the five XRTMSPs are different from the great majority of SXRTs not only for their outburst properties (periodicities, faint outbursts) but also for their properties in quiescence.

The first object of this class, SAX J1808.4−3658, has been rapidly recognized to have peculiar properties in quiescence, namely the low X-ray luminosity and a simple power law spectrum (Campana et al. 2002). Confirmation that XRTMSP are peculiar came from Chandra observations of XTE J0929−314 and XTE J1751−305 (Wijnands et al. 2005b). XTE J0929−314 was detected at a very low level of $\sim 7 \times 10^{31}$ erg s^{-1} (0.5−10 keV) for a fiducial distance of 10 kpc. The quiescent spectrum is consistent with a simple power law spectrum. The upper limit on the flux from a cooling neutron star atmosphere is about 30% of the total flux. XTE 1751−305 was not detected with an upper limit of $\sim 2 \times 10^{32}$ erg s^{-1} (at 8 kpc, Wijnands et al. 2005b).

We observed XTE J0929−314 with XMM-Newton. Our spectrum is consistent with the Chandra one. Given the better response at high energies we can put a stronger limit of $\lesssim$20% on the presence of a neutron star atmosphere component (consistent with the emission from the entire surface in the 5−15 kpc distance range). The temperature of the putative soft component is extremely soft (∼35−55 eV) so that the bolometric luminosity would be $\sim 3 \times 10^{31}$ erg s^{-1}, at the most. This limit is tighter than the one derived by Wijnands et al. (2005b). Actually, under the hypothesis that deep crustal heating (DCH) is at work (and there are no reasons to beleive it should not), from the observed quiescent luminosity (or the limit on it) one can gain insight on the accretion history of the source (Brown et al. 1998). Wijnands et al. (2005b) estimated a mean accretion powered flux of $F_{\rm acc} = 3.5 \times 10^{-11}$ erg s^{-1} cm^{-2} (for the ∼9 years of RXTE monitoring). Based on DCH theory, the estimate of the mean accretion-powered flux provides a prediction for the quiescent flux $F_{\rm q} = F_{\rm acc}/135 = 2.6 \times 10^{-13}$ erg s^{-1} cm^{-2} (Brown et al. 1998). This is much higher than observed. In order to match our observed upper limit we have to require a much longer quiescent period than the 9 yr of RXTE observations. Using an outburst duration of $t_{\rm o} \sim 73$ d (Galloway et al. 2002) and average flux during outburst $F_{\rm o} \sim 1.6 \times 10^{-9}$ erg s^{-1} cm^{-2}, we can estimate the recurrence time $t_{\rm q}$ from $F{\rm q} \sim \frac{t_{\rm o}}{t_{\rm o}+t_{\rm q}} \times \frac{F_{\rm o}}{135}$. We then derive $t_{\rm q} \sim 780$ yr. This recurrence time is long, even for the most extreme version of disk instability models (Lasota 2001).

Table 2. Quiescent 0.5−10 keV luminosities of neutron star transients.

Name	Distance (kpc)	$\log L$	Ref.
SAX J1808.4–3658	3.15 ± 0.45	31.9	1, 2
XTE J0929–314	10 ± 5	31.8	3, 4
IGR J00291+5934	3 ± 3	31.7	5
XTE J1807–294	8 ± 5	<31.6	4
XTE J1751–305	8 ± 5	<31.5	3
Cen X-4	1.4 ± 0.3	32.7	6, 7
4U 1608–52	3.3 ± 0.5	33.2	8, 2
MXB 1659–29	9.85 ± 1.45	32.5	9, 2
XTE J1709–267	10 ± 2	33.3	10
KS 1731–260	6.2 ± 0.9	32.4	11, 2
SAX J1810.8–2609	5.95 ± 0.85	32.2	12, 2
Aql X-1	5.15 ± 0.75	33.4	13, 2
XTE J2123-058	18.35 ± 2.65	32.7	14, 2
Terzan 5	8.7 ± 3	33.3	15, 2

References – 1: Campana et al. (2002); 2: Jonker & Nelemans (2004); 3: Wijnands et al. (2005b); 4: this work; 5: Jonker et al. (2005); 6: Campana et al. (2004); 7: González Hernandez et al. (2005); 8: Asai et al. (1996); 9: Wijnands et al. (2004); 10: Jonker et al. (2004a); 11: Wijnands et al. (2001); 12: Jonker et al. (2004b); 13: Campana et al. (1998b); 14: Tomsick et al. (2004); 15: Wijnands et al. (2005a).

Following Wijnands et al. (2005b) we can also estimate the expected quiescent luminosity due to DCH based on a mass transfer rate driven by gravitational radiation. We estimated a luminosity of $L_{\rm DCH-GW} \sim 3 \times 10^{32}\, M_{\rm NS}^{2/3}\, M_{\rm c}^2\, Q$ erg s^{-1} (assuming a neutron star and a companion mass $M_{\rm NS} = 1.4\, M_\odot$ and $M_{\rm c} = 0.008\, M_\odot$, respectively, and the amount of heat deposited in the crust per accreted nucleon $Q = 1.45$ MeV). The source distance must be ∼30 kpc to be consistent with this limit.

As already suggested for SAX J1808.4−3658 (Campana et al. 2002) there is an easy explanation for the absence of a soft component in the quiescent spectrum of XTE J0929−314 as well. The theory of deep crustal heating consider only a standard cooling scenario, additional cooling results in lower luminosities. A simple and well-known solution is when the direct Urca process is at work in the neutron star core and neutrino cooling affects the neutron star thermal evolution (Colpi et al. 2001; Yakovlev & Pethick 2004). This can occur only for massive neutron stars with masses higher than ∼1.7−1.8 $M_\odot$. On the other side the power law tail can result either from low level accretion or from the interaction between the relativistic pulsar wind of a turned-on radio pulsar and matter outflowing from the companion (for a detailed discussion see e.g. Campana & Stella 2000).

In the case of XTE J1807−294 our XMM-Newton observation allowed us only to put an upper limit on the source quiescent 0.5−10 keV unabsorbed flux of $\lesssim 5 \times 10^{-15}$ erg s^{-1} cm^{-2} or luminosity $\lesssim 4 \times 10^{31}$ erg s^{-1} at 8 kpc. This limits testifies once more that the quiescent emission of XRTMSP is fainter than classical SXRTs. We can also test the DCH predictions on XTE J1807−294 given its flux history (Markwardt et al. 2003a) in the last few years. Integrating the flux history provided by RXTE pointed data we obtain a 2−10 keV fluence of $\sim 4 \times 10^{-3}$ erg cm^{-2} during the only outburst detected. A bolometric correction factor for the extrapolation of the spectrum to the 0.1−60 keV energy range amounts to ∼2.3, taking the XMM-Newton spectrum in outburst (Campana et al. 2003). If no other outbursts occurred during the RXTE lifetime, we can derive a mean accretion flux of $\lesssim 3 \times 10^{-11}$ erg s^{-1} cm^{-2}. This turns into a predicted quiescent flux of $F_{\rm q} \lesssim 2 \times 10^{-13}$ erg s^{-1} cm^{-2}, much higher than that observed. Taking the upper limit for black body emission derived above, this implies having a recurrence time of $\gtrsim 7$ yr, taking a short outburst duration of ∼40 d (corresponding to the time interval during which we have published data).

The quiescent luminosities of XRTMSPs we obtained confirmed once more that XTE J0929−314 and XTE J1807−294 are fainter than classical SXRTs. We considered the 9 SXRT with known quiescent X-ray luminosities and good distance estimates (Jonker & Nelemans 2005, see Table 2) and compared them with the 5 XRTMSPs (inluding the recently discovered IGR J00291+5934, Jonker et al. 2005). In order to account for the uncertainties in the source distances, we run a MonteCarlo simulation with a random distance within the quoted range in Table 1, and compare the luminosities of the two samples with a Kolmogorov-Smirov test. The (logarithmic) mean chance probability that the two distributions are drawn from the same parent population is ∼1.4%. Clearly this test cannot be regarded as conclusive given, e.g., the presence of upper limits. Despite this, it provides a clear indication of the difference between the two populations at $\sim 2.5\sigma$ confidence level.

The XRTMSP population in quiescence represent a new challenge for the physics of neutron stars. These sources are extremely faint in quiescence, they can be easily detected by Chandra but only poor spectroscopic studies can be carried out by exploiting the XMM-Newton higher throughput, calling for future observations with satellites such as Constellation-X and XEUS.

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