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Two long-period X-ray pulsars detected in the SMC field around XTE J0055–727*

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Abstract. An XMM-Newton target of opportunity observation of the field around the transient 18.37 s pulsar XTE J0055–727 in the Small Magellanic Cloud (SMC) revealed two bright, long-period X-ray pulsars in the EPIC data. A new pulsar, XMMU J005517.9–723853, with a pulse period of 701.7 ± 0.8 s was discovered and 500.0 ± 0.2 s pulsations were detected from XMMU J005455.4–724512 (=CXOU J005455.6–724510), confirming the period found in Chandra data. We derive X-ray positions of RA = $00^h54^m55\overset{s}{.}88$, Dec = $-72°45'10\overset{''}{.}5$ and RA = $00^h55^m18\overset{s}{.}44$, Dec = $-72°38'51\overset{''}{.}8$ (J2000.0) with an uncertainty of $0\overset{''}{.}2$ utilizing optical identification with OGLE stars. For both objects, the optical brightness and colours and the X-ray spectra are consistent with Be/X-ray binary systems in the SMC.

Key words. galaxies: individual: Small Magellanic Cloud – stars: neutron – X-rays: binaries – X-rays: galaxies

1. Introduction

The Small Magellanic Cloud harbours a large number of high mass X-ray binary (HMXB) systems, more than are known in the Large Magellanic Cloud and the Milky Way (see compilations by Haberl & Sasaki 2000; Yokogawa et al. 2003) despite the much smaller mass of the SMC. The catalogue of Haberl & Pietsch (2004) comprises 65 HMXBs and candidates in the SMC with at least 37 showing X-ray pulsations which indicate the spin period of the neutron star in orbit around a high mass early type star. The number of X-ray pulsars in the SMC has meanwhile further grown by five: for three of the known candidate HMXBs pulsations of 202 s, 500 s and 138 s were detected, an X-ray source known from ROSAT was discovered as 34.1 s pulsar and 18.37 s pulsations were found in RXTE observations of the SMC. In addition accurate Chandra positions enabled the location of two RXTE-discovered pulsars with 82.4 s and 7.78 s period, the latter identified with SMC X-3 (see Corbet et al. 2004, and references therein).

The non-imaging instruments on RXTE allowed the 18.37 s transient pulsar XTE J0055–727 to be located to an accuracy of only $0.1° \times 0.06°$. Hence, we proposed an XMM-Newton target of opportunity observation which was performed on December 18, 2003. We could not detect 18.37 s pulsations from any of the weaker sources seen in the EPIC images due to insufficient counting statistics and were therefore not able to identify the target. However, the two brightest X-ray sources were found to exhibit pulsations with longer periods (Haberl et al. 2004). XMMU J005517.9–723853 (hereafter J0055–7238) is a new pulsar and XMMU J005455.4–724512 (hereafter J0054–7245) is identified with CXOU J005455.6–724510 by position and X-ray period of ~500 s. Here we present the results of a temporal and spectral analysis of the X-ray data of these two SMC pulsars and propose optical counterparts with properties as expected for Be/X-ray binary systems.

2. XMM-Newton observation and analysis

The XMM-Newton observation of the field around the transient pulsar XTE J0055–727 in the SMC was performed on December 18, 2003 between 14:32 UT and 19:48 UT. The EPIC-pn instrument (Strüder et al. 2001) was operated in large window imaging mode for a net exposure of 16.1 ks, while EPIC-MOS1 and MOS2 (Turner et al. 2001) were operated in full frame imaging mode for 14.4 ks and 18.5 ks, respectively. For optical light blocking the medium filter was used in all cameras. The data were processed using the XMM-Newton analysis package SAS version 5.4.1 to produce the photon event files and binned data products such as images, spectra and light curves. Events for spectral and temporal analysis of the two pulsars were extracted from circular regions (radius 30″) around the source positions and from nearby source-free regions for background spectra.

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2.1. X-ray pulsations

We performed a timing analysis of the EPIC data of the two bright sources visible in the images following the approach of Zavlin et al. (2000, and references therein). First, we searched for pulsations in the broad band (0.3−5.0 keV) EPIC-pn data using the Rayleigh Z_1^2 technique in the range 0.001–4 Hz. Strong peaks in the probability density function were found with Z_1^2 of 108.9 and 126.5, which correspond to a period detection confidence of $1.0{-}1.5 \times 10^{-19}$ and $1.0{-}2.3 \times 10^{-23}$ for J0054–7245 and J0055–7238, respectively (neglecting that the period of J0054–7245 was already known). Then, periods and 1σ errors were determined using the Odds-ratio method based on the Bayesian formalism to 701.7 ± 0.8 s (J0055–7238) and 500.0 ± 0.2 s (J0054–7245). EPIC-pn light curves in different energy bands (0.3−2.0 keV, 2.0−5.0 keV and the total 0.3−5.0 keV) were folded with the pulse period and are shown in Fig. 1. The broad band pulse profile is highly structured for both objects with some indication for hardness ratio changes during individual dips/peaks. Although over the whole pulse period the hardness ratio is formally consistent with a constant value, at certain phases the hardness ratio changes over 3−4 phase bins accumulating 3−4σ deviations from the average (J0054–7245: phase 0.4; J0055–7238: phases 0.6 and 0.85).

2.2. X-ray spectra

Pulse phase averaged EPIC-pn and -MOS spectra were extracted using single+double pixel events (pattern 0−4) and pattern 0−12, respectively and binned to obtain at least 100 counts per bin. The three spectra for each pulsar were fit simultaneously (using XSPEC v11.3) with the same model only allowing a free normalization factor between the different instruments. Errors were determined for 90% confidence levels. A simple power-law (PL) model including photo-electric absorption by matter with solar abundance did not reproduce the data well (reduced $\chi^2 > 1.58$, see Table 1). Then other models which were used in the past to fit X-ray spectra of HMXBs were applied: adding a soft component like black-body (BB) or thermal plasma (MEKAL) emission or a power-law with exponential high-energy cutoff (PL*EXP). For both objects the fits with the latter three models are acceptable but do not allow us to formally differentiate between them. In Table 1 the characteristic parameters are listed (photon index γ, temperature kT, high energy cutoff $E_{\rm cut}$ and folding energy $E_{\rm fold}$) together with observed fluxes and intrinsic source luminosities (only for the models with acceptable fit) and reduced χ^2 values per degree of freedom (d.o.f.). The EPIC spectra together with the PL plus MEKAL models (the other acceptable models do not look different) are plotted in Fig. 2.

2.3. Source identifications

X-ray source positions were obtained from a combined analysis of the EPIC images and are given by Haberl et al. (2004). The uncertainties are dominated by the $\sim 3''$ systematic bore-sight error (90% confidence[1]). In the following we derive improved X-ray coordinates by reducing this systematic uncertainty.

In a first step the accurate ($0.6''$) Chandra position of J0054–7245 (=CXOU J005455.6–724510) enables us to optically identify this 500 s pulsar. J0054–7245 was also detected by Chandra when it was found to be pulsating with a period of 503.5 ± 6.7 s (Edge et al. 2004c). This clearly establishes that both sources are identical. The position is also within the error circles of AX J0054.8−7244 (Yokogawa et al. 2003) and of RX J0054.9–7245 which was proposed as HMXB candidate by Haberl & Sasaki (2000) due to the presence of a close emission line object (MA93#809 Meyssonnier & Azzopardi 1993). Using the finding chart provided by these authors allows the identification of MA93#809 with a star covered by the SMC UBVR CCD survey of Massey (2002) and also listed in the OGLE BVI photometry catalogue (Udalski et al. 1998). Optical positions and available magnitudes are summarized in Table 2. The presence of a ∼15 mag star inside the error circle of the Chandra position clearly establishes it as the optical counterpart of the X-ray source (detected by Chandra and XMM).

The 701 s pulsar J0055–7238 is located within the $9''$ error radius of the ROSAT source RX J0055.2–7238 (Haberl et al. 2000). The ROSAT PSPC hardness ratios indicated a hard source but were tainted with large errors. No archival Chandra observation covers the source. After applying the boresight correction found for J0054–7245 above (with a remaining uncertainty of $\sim 0.3''$) to J0055–7238, also for this source a bright optical counterpart is found in the catalogues used above with properties given in Table 2. The fact that in both cases objects with brightness and colours as expected for Be star companions are found in the sub-arcsecond error circles strongly supports their correct identification. In a final step we use both objects to determine the most precise source positions (additional much fainter X-ray sources in the field have larger statistical errors and do not allow further improvement). For both pulsars the originally EPIC derived X-ray position is systematically shifted with respect to the optical position by $+0\overset{s}{.}5$ in RA and $+1\overset{''}{.}4$/$+1\overset{''}{.}7$ in Declination. After correction we derive final X-ray coordinates of RA = $00^{\rm h}54^{\rm m}55\overset{s}{.}88$ and Dec = $-72°45'10\overset{''}{.}5$ (J2000.0) for J0054–7245 and RA = $00^{\rm h}55^{\rm m}18\overset{s}{.}44$ and Dec = $-72°38'51\overset{''}{.}8$ (J2000.0) for J0055–7238. The remaining uncertainty (including $0.13''$ statistical error) is $0.2''$.

The inferred effective temperature and bolometric luminosity of the optical counterparts given by Massey (2002) suggest spectral types of O9 V for both stars. Assuming this spectral type the measured $B-V$ indices imply $E(B-V)$ of 0.28 and 0.48 and $N_{\rm H} = 1.6 \times 10^{21}$ cm^{-2} and 2.8×10^{21} cm^{-2} for J0054–7245 and J0055–7238, respectively.

3. Discussion

The December 2000 XMM-Newton observation of the SMC region around XTE J0055–727 revealed two X-ray

[1] See the statistical analysis of the 1XMM catalogue prepared by the XMM-Newton Survey Science Centre Consortium (`http://xmmssc-www.star.le.ac.uk`).

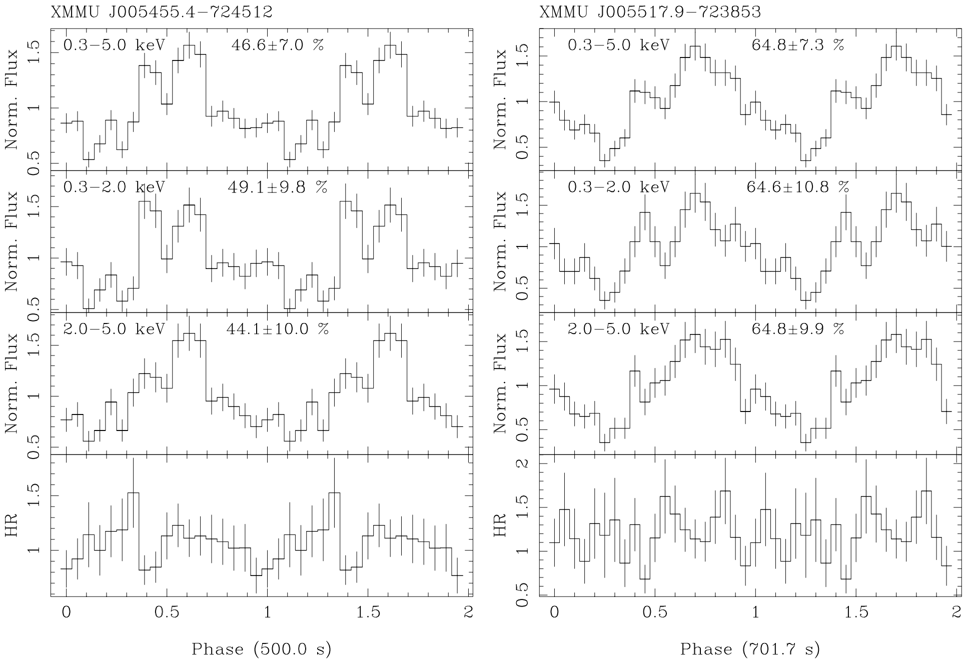

Fig. 1. EPIC-pn light curves folded at the pulse period in broad, hard and soft energy bands together with the hardness ratio, the ratio of the count rates in the hard to the soft band. The pulsed fraction, defined as (mean – minimum)/mean), in each energy band is given in %.

Table 1. Spectral fit results.

Model[1]	N_H [10^{22} cm^{-2}]	γ	kT [keV]	E_{cut} [keV]	E_{fold} [keV]	Flux[2] erg cm^{-2} s^{-1}	$L_x^{(3)}$ erg s^{-1}	$L_x^{i\,(4)}$ erg s^{-1}	χ^2_r/d.o.f.
XMMU J005455.4–724512									
PL	0.15	1.05	–	–	–	–	–	–	2.03/35
PL+BB	$0.83^{+0.15}_{-0.22}$	1.05 ± 0.13	$0.095^{+0.015}_{-0.010}$	–	–	1.45×10^{-12}	6.3×10^{35}	4.9×10^{36}	1.25/33
PL+MEKAL	$0.90^{+0.16}_{-0.26}$	1.02 ± 0.12	$0.18^{+0.06}_{-0.04}$	–	–	1.46×10^{-12}	6.3×10^{35}	5.3×10^{36}	1.30/33
PL*EXP	0.06 ± 0.05	0.40 ± 0.14	–	3.9 ± 0.9	$6.5^{+2.8}_{-1.6}$	1.39×10^{-12}	6.0×10^{35}	6.2×10^{35}	1.18/33
XMMU J005517.9–723853									
PL	0.45	0.96	–	–	–	–	–	–	1.58/19
PL+BB	1.3 ± 0.4	1.31 ± 0.20	0.10 ± 0.02	–	–	9.22×10^{-13}	4.0×10^{35}	6.5×10^{36}	0.81/17
PL+MEKAL	1.7 ± 0.4	1.42 ± 0.19	$0.13^{+0.06}_{-0.03}$	–	–	9.11×10^{-13}	3.9×10^{35}	1.1×10^{38}	0.72/17
PL*EXP	0.19 ± 0.15	$0.26^{+0.4}_{-0.9}$	–	2.6 ± 1.6	$5.2^{+4.4}_{-2.7}$	8.98×10^{-13}	3.9×10^{35}	4.1×10^{35}	0.84/17

[1] For definition of spectral models see text. [2] Observed 0.5−10.0 keV flux. [3] X-ray 0.5−10.0 keV luminosity (including absorption).
[4] Source intrinsic X-ray luminosity in the 0.1−10.0 keV band (corrected for absorption) for a distance of 60 kpc.

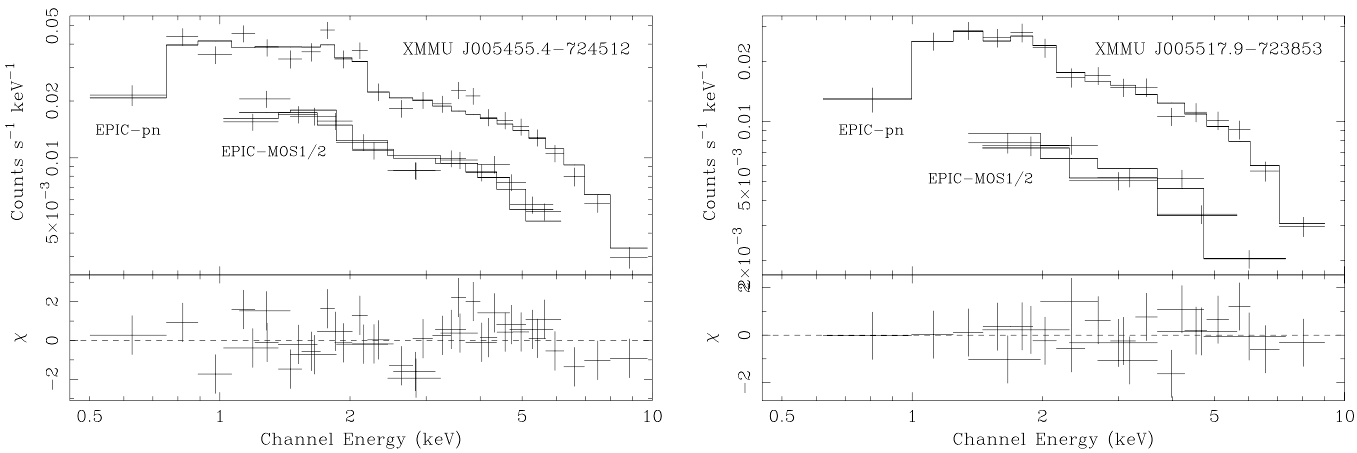

Fig. 2. EPIC spectra of the two pulsars. The histograms show the best-fit model comprising a power-law and a thermal plasma emission component. The total number of counts used in the spectral analysis was 3943 and 2301 for J0054–7245 and J0055–7238, respectively.

Table 2. Optical identifications.

Source	Catalogue	RA and Dec (2000.0)	V mag	$B-V$	$U-B$	$V-R$	$V-I$
XMMU J005455.4–724512	UBVR	$00^h54^m55\overset{s}{.}88$ $-72°45'10\overset{''}{.}5$	14.78	−0.05	−0.90	−0.86	–
	OGLE	$00^h54^m55\overset{s}{.}87$ $-72°45'10\overset{''}{.}7$	14.99	−0.02	–	–	0.20
XMMU J005517.9–723853	UBVR	$00^h55^m18\overset{s}{.}47$ $-72°38'51\overset{''}{.}6$	15.87	−0.15	−0.83	−0.94	–
	OGLE	$00^h55^m18\overset{s}{.}43$ $-72°38'51\overset{''}{.}8$	16.01	−0.08	–	–	0.30

pulsars with long pulse periods. The 500 s pulsar J0054–7245 was the brighter of the two and was detected by Chandra on July 4, 2002, with pulsations reported by Edge et al. (2004c). It was detected during three ROSAT observations in May 1993, April 1994 and April/May 1997. Using the parameters derived from the EPIC spectra and the ROSAT PSPC and HRI spectral response to estimate expected ROSAT count rates, shows that this pulsar exhibits variations in flux by about a factor of 3 with intensities lowest in May 1993 and highest in December 2000. During several other ROSAT observations the source was not detected. However, the detection threshold did not reach the low flux level at which the source was detected in 1993 (large off-axis angles, short exposures) and no additional information about variability can be inferred. The source is probably also identical to the ASCA source AX J0054.8–7244 (Yokogawa et al. 2003) which was detected in Nov. 1998 at a flux level of 4.9×10^{-13} erg cm^{-2} s^{-1}, similar to the low intensity state in May 1993. J0055–7238 is a newly discovered X-ray pulsar in the SMC with a period of 701 s. While it was the fainter of the two pulsars during the XMM-observation, it was the slightly brighter (~20%) one during the 1993 PSPC observation, the only time when it was detected by ROSAT. Assuming the EPIC spectral parameters shows that it was brighter by 40% during December 2000 compared to May 1993. Eight non-detections by ROSAT and also by ASCA suggest that J0055–7238 is overall fainter than J0054–7245, falling below the detection thresholds of the ROSAT and ASCA observations (which were, however, close or even above the detection flux) most of the time. Both pulsars seem to belong to the class of Be/X-ray binaries with long pulse period and moderate intensity variations.

Spectral analysis of both pulsars shows that a power-law with photo-electric absorption does not reproduce the EPIC spectra properly. Including soft emission components or an exponential cut-off yields acceptable fits, but the statistical quality does not allow us to decide between these models. The major difference between the cut-off model and the two component models is the resulting absorption column density, which is consistent with the Galactic foreground value of 6×10^{20} cm^{-2} for the cut-off model. However, the reddening inferred from the suggested optical counterparts is incompatible with such low absorption and favours the soft component models. On the other hand the absorption is very high for the thermal plasma model which leads to an implausibly high intrinsic source luminosity in particular for J0055–7238. A large fraction of the column density may be local to the source and the different emission components might suffer different amounts of absorption. This could indicate that the spectrum at lower X-ray energies is more complex as it is seen from other HMXBs in the Magellanic Clouds. E.g. the pulse phase averaged spectrum of EXO 053109-6609.2 (Haberl et al. 2003) shows power-law components attenuated by different column densities. A similar behaviour of the two pulsars presented here is expected if the absorption changes with pulse phase as it is indicated by the pulse profiles.

With the new discovery of the 701 s pulsar J0055–7238 the number of pulsars in the SMC has grown to 45 (Corbet et al. 2004) and future X-ray observations of the SMC promise to find more.

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