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A multi-frequency study of the SMC region around AX J0105-722

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Abstract. We present a high-resolution multi-frequency study of the Small Magellanic Cloud (SMC) region around the X-ray pulsar AX J0105-722. From ROSAT PSPC images we resolve this source into several X-ray sources. We combine X-ray, radio-continuum and optical data to identify the sources: for RX J0105.1-7211 we propose an emission line star from the catalogue of Meyssonier & Azzopardi (1993) in the X-ray error circle as the likely optical counterpart. This catalogue contains several known Be/X-ray binaries strongly suggesting RX J0105.1-7211 as new Be/X-ray binary in the SMC. RX J0105.1-7211 is most probably also the counterpart of the ASCA X-ray pulsar AX J0105-722. RX J0105.4-7209 confirms DEM S128 as supernova remnant (SNR) and RX J0105.5-7213 is very likely a background AGN.

Key words: galaxies: Magellanic Clouds – ISM: individual objects: AX J0105-722 – ISM: individual objects: DEM S128 – ISM: supernova remnants – stars: binaries: general – X-rays: galaxies

1. Introduction

Recently, Yokogawa & Koyama (1998) reported a new ASCA X-ray pulsar in the SMC named as AX J0105-722 with a pulse period of 3.34300$\pm$0.00003 s (observations made on 21-23 May 1996) from a source at RA(J2000)=$1^h05^m06^s$ and Dec(J2000)= $-72^\circ11'08''$. The positional error from their observations is estimated to be $\sim$1$'$ (at 90% confidence) and a power-law X-ray spectrum with photon index 2.2$\pm$0.3 was derived.

This SMC region has been surveyed at Hα wavelengths by Davies et al. (1976) which named this region as DEM S128 and classified it as a faint and diffuse H II region with diameter of $1.'5 \times 1.'2$. Bica & Schmitt (1995) also classified DEM S128 using the ESO/SERC R and J Sky Survey as a H II region with embedded association and diameter of $1.'6 \times 1.'3$ (position angle = 40°).

The first X-ray sources in this region were reported from the Einstein satellite observations. Inoue et al. (1983) detected the X-ray source (IKT 24) and due to positional coincidence (within the X-ray positional error) with DEM S128 they classified this source as a supernova remnant (SNR). The source is also included (without classification) in the Einstein SMC catalogues of Bruhweiler et al. (1987) and Wang & Wu (1992) as BKGS 14 and WW 53, respectively.

The only nearby X-ray source from the ROSAT PSPC catalogue of Kahabka et al. (1999), RX J0105.3-7210 (source 191) shows X-ray extent suggesting an SNR identification with DEM S128. Filipović et al. (1998a) found that the Parkes radio source SMC B0104-7226 coincides with the X-ray source and because of Hα emission this source was classified as SNR. However, in the ROSAT observations analyzed by Kahabka et al. (1999), RX J0105.3-7210 was detected at an off-axis angle of 23$'$ where the ROSAT resolution is already degraded and several sources may contribute to its emission.

Schwering & Israel (1989) detected the IRAS source LI SMC 170 which was identified as the counterpart to the radio source SMC B0104-7226 (Filipović et al. 1997, 1998b). However, no other SNR criteria were applied to confirm the nature of this object. Also, this region was surveyed with the MOST radio telescope at 843 MHz (Turtle et al. 1998; Amy & Ball 1993). For more details of all these earlier observations see Table 1.

Recently, Haberl et al. (1999) produced an improved catalogue based on the complete set of ROSAT PSPC pointed data of the SMC. It includes in particular an observation centered only 5$'$ from AX J0105-722 which was not analyzed by Kahabka et al. (1999) and allowed a survey of the area with good resolution. The catalogue contains six sources in the vicinity of the ASCA source indicating the complexity of X-ray emission in that area. Here, we present new results from ROSAT PSPC X-ray, Australia Telescope Compact Array (ATCA) radio-continuum and CTIO optical studies of the region around AX J0105-722 in order to identify its counterpart and confirm the SNR nature of DEM S128.

2. Observations and data analysis

2.1. X-ray data

The ROSAT archive contains several pointed PSPC and HRI observations centered close to the field of AX J0105-722. More

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Table 1. Details of previous observations of the region near AX J0105-722.

Source Name	Frequency	Instrument	RA (J2000) h m s	Dec (J2000) ° ′ ″	Reference
DEM S128	Hα	UK Schmidt 1.2m	01 05 21.4	–72 08 44	Davies et al. (1976)
DEM S128	R and J Band	ESO/UK Schmidts	01 05 21.6	–72 08 44	Bica & Schmitt (1995)
IKT 24	X-ray	Einstein IPC	01 05 20.4	–72 12 27	Inoue et al. (1983)
BKGS 14	X-ray	Einstein IPC	01 05 30.4	–72 10 28	Bruhweiler et al. (1987)
WW 53	X-ray	Einstein IPC	01 05 24.5	–72 11 16	Wang & Wu (1992)
RX J0105.3-7210	X-ray	ROSAT PSPC	01 05 20.4	–72 10 21	Kahabka et al. (1999)
LI SMC 170	IR	IRAS	01 05 19.6	–72 08 57	Schwering & Israel (1989)
SMC B0104-7226	Radio	Parkes	01 05 37.6	–72 10 02	Filipović et al. (1997)
AX J0105-722	X-ray	ASCA	01 05 06.0	–72 11 08	Yokogawa & Koyama (1998)

Table 2. Summary of new X-ray and radio-continuum observations of the region of AX J0105-722.

X-ray Obs. Date	Seq. Number	RA (J2000) h m s	Dec (J2000) ° ′ ″	Exp (sec)
12 May 1993	500142p	01 04 02	–72 01 48	4909
29 October 1993	500250p	01 04 38	–72 05 23	20860

Radio Telescope	Freq. (GHz)	Beam Size	rms Noise (mJy/b.a.)	Reference
ATCA	1.42	90″	0.4	FS98
ATCA	2.37	45″	0.5	FS98
MOST	0.843	45″	0.5	Amy & Ball (1993)

details on the ROSAT mission can be found in Trümper (1982). The two nearest ROSAT PSPC (energy range 0.1 – 2.4 keV) observations which have best angular resolution were used in this study. For more details of the PSPC observations see Table 2. In Fig. 1 we show the ROSAT PSPC image (“hard” energy range 0.5 – 2.4 keV) of the AX J0105-722 region. It was obtained from combining the two PSPC observations, binned to 5″ pixels and smoothed for better representation. Several ROSAT HRI observations were performed within the field of AX J0105-722 but larger offsets from the source and lower exposure times did not allow deeper quantitative study than was obtained from the PSPC observations.

The ROSAT PSPC catalogue of the SMC of Haberl et al. (1999) contains six sources in the AX J0105-722 region which are marked in Fig. 1 and listed in Table 3 with properties taken from the catalogue. Source positions, RA and Dec, are given in J2000 coordinates in Column 2 and Column 3, respectively. The statistical (90%) positional error is given in Column 4 (a systematic error of 7″ should be added). Count rate (0.1 – 2.4 keV, Column 5), source extent (Column 8), hardness ratios (HR1) and (HR2) (Columns 6 and 7, respectively) are extracted from Haberl et al. (1999). HR1 is defined as HR1=(hard-soft)/(hard+soft) and HR2 is defined as HR2=(hard2-hard1)/(hard2+hard1) where soft, hard, hard1 and hard2 denote the PSPC count rates in the energy bands 0.1 – 0.4 keV, 0.5 – 2.0 keV, 0.5 – 0.9 keV and 0.9 – 2.0 keV.

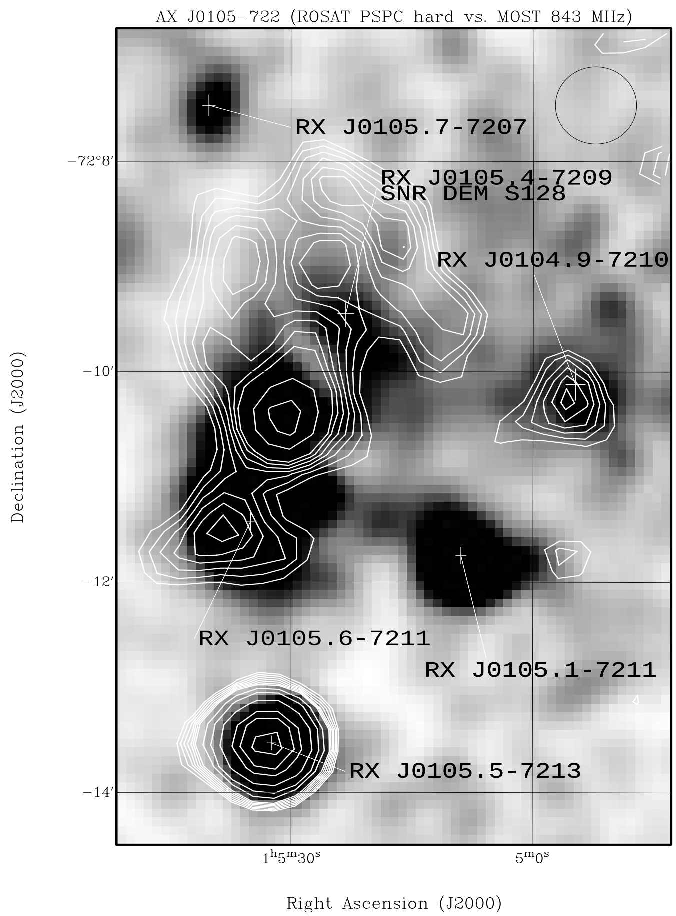

Fig. 1. ROSAT PSPC (energy range 0.5 – 2.4 keV) image (gray-scale) of AX J0105-722. Contours represent the radio continuum image at 843 MHz. The synthesized beam of the MOST observations is 45″ × 45″ (upper right corner) with r.m.s. noise (1σ) of 0.4 mJy. Contours are 1.5, 1.75, 2, 2.25, 2.5, 2.75, 3, 4, 5, 7, 10, 12 and 15 mJy

2.2. Radio-continuum data

The region around AX J0105-722 was observed as part of the ATCA mosaic observations of the SMC with a baseline of 375 m at frequencies of 1.42 and 2.37 GHz with corresponding angular resolution of $\sim 90''$ and 45″ (Table 2). More information about these observations can be found in Staveley-Smith et al. (1997)

Table 3. Measured ROSAT PSPC properties of objects near AX J0105-722. Suggested source types are discussed in the text (Sect. 3); BG correspond to background object, Be/X to Be/X-ray binary and SNR to supernova remnant.

Source X-ray Name	RA (J2000) h m s	Dec (J2000) ° ′ ″	P_e (″)	Count Rate cts sec^{-1}	HR1	HR2	EXT (″)	Type
RX J0104.9-7210	01 04 54.7	–72 10 07.1	17	0.0101±0.0010	1.00±0.11	1.00±1.40	35	?
RX J0105.1-7211	01 05 08.9	–72 11 44.9	7	0.0069±0.0007	1.00±0.20	0.40±0.09	—	Be/X
RX J0105.4-7209	01 05 23.2	–72 09 26.9	13	0.0122±0.0011	1.00±0.09	–0.05±0.08	28	SNR
RX J0105.5-7213	01 05 32.4	–72 13 31.7	4	0.0073±0.0007	1.00±0.37	0.46±0.09	—	BG
RX J0105.6-7211	01 05 35.0	–72 11 25.3	8	0.0163±0.0010	1.00±0.09	0.09±0.06	17	?
RX J0105.7-7207	01 05 40.2	–72 07 28.1	10	0.0017±0.0004	1.00±0.87	1.00±2.29	—	?

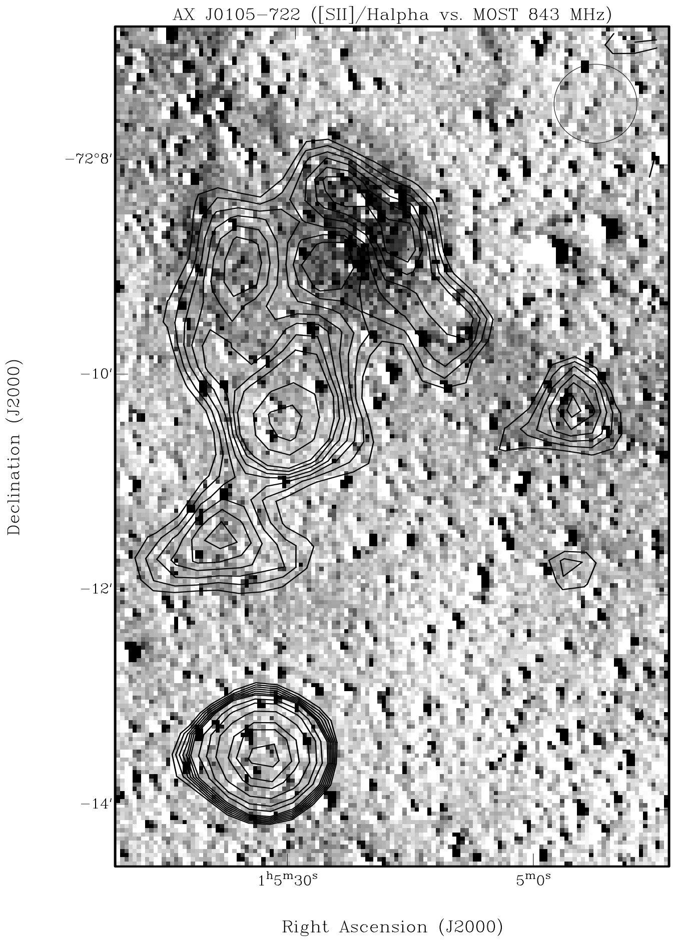

Fig. 2. Map of the [S II]/Hα ratios overlaid with contours of the MOST 843 MHz image of AX J0105-722 as in Fig. 1. The darker areas indicate [S II]/Hα >0.5 (shocked gas), while the lighter areas indicate ratios <0.5 (photo-ionized gas)

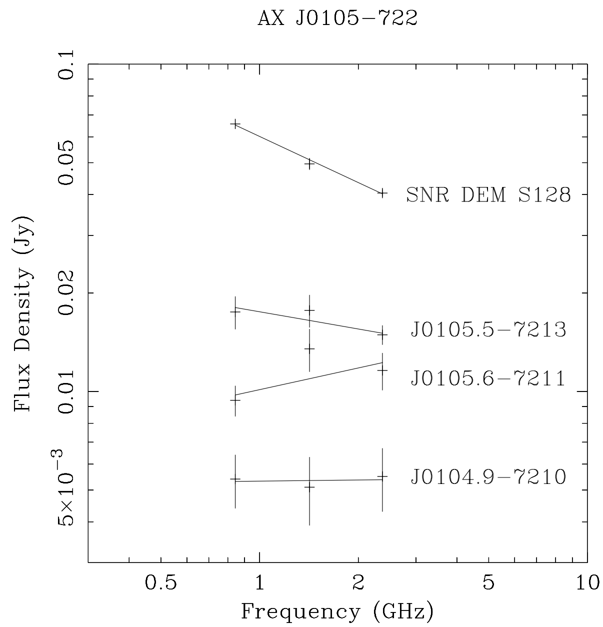

Fig. 3. Radio spectral index plots of the radio-continuum sources found within the area of AX 0105-722. The steep spectrum of SNR DEM S128 (α=–0.48±0.06) is distinctively different from those of the other three radio-continuum objects which are likely background objects (AGNs, quasars or radio-galaxies)

and Filipović & Staveley-Smith (1998; hereafter FS98). The MOST data used in this study were part of the SMC survey at 843 MHz (Turtle et al. 1998). Amy & Ball (1993) studied the SMC SNR 1E 0102.2-7219 which is $\sim$10′ north-west from the region AX J0105-722. We used a subset of their observations and more details about the observing procedure can be found in their paper. Radio contours of these observations are shown in Figs. 1 and 2.

We list in Table 4, for each detected radio object, positions (RA and Dec) with positional errors (P_e), integrated flux densities at the given frequency, the spectral index and suggested source type. The position and flux density for each source at a given radio frequency were determined using the two-dimensional elliptical Gaussian-fitting algorithms in the MIRIAD software package (Sault & Killeen 1999). The radio emission from DEM S128 is extended (Fig. 1) and we fitted one source in that area (J0105.4-7209) with a radius of 90″. That includes the bright knot at RA(J2000)=01^{h}05^{m}30^s and Dec(J2000)= –72°10′27″ which could be a contaminating background object. Estimates of the spectral index (α) of each radio feature/source are based on flux densities obtained from corresponding radio-frequencies. The spectral index α is defined by the relation $S_\nu \sim \nu^\alpha$, where S_ν is the integrated flux density and ν is frequency. The errors in spectral index ($\Delta\alpha$) have been deduced given the scatter in flux density. In Fig. 3, we plot the spectral indices of the radio sources listed in Table 4.

Table 4. Measured radio-continuum properties of objects within AX J0105-722. Listed positions (RA and Dec) and positional error $\mathrm{P_e}$ are from 843 MHz observations. Source types are discussed in the text (Sect. 3); BG correspond to background object and SNR to supernova remnant.

Source Radio Name	RA (J2000) h m s	Dec (J2000) ° ′ ″	$\mathrm{P_e}$ (″)	$\mathrm{S_{843\,MHz}}$ (Jy)	$\mathrm{S_{1.42\,GHz}}$ (Jy)	$\mathrm{S_{2.37\,GHz}}$ (Jy)	$\alpha \pm \Delta\alpha$	Ratio [S II]/Hα	Type
J0104.9-7210	01 04 55.9	-72 10 18.2	5	0.0054	0.0051	0.0055	–0.01±0.11	—	?
J0105.4-7209	01 05 24.2	-72 09 23.4	20	0.0657	0.0496	0.0404	–0.48±0.06	0.6	SNR
J0105.5-7213	01 05 33.1	-72 13 31.6	1	0.0175	0.0177	0.0149	–0.17±0.09	—	BG
J0105.6-7211	01 05 38.2	-72 11 34.6	3	0.0094	0.0135	0.0116	+0.22±0.11	—	?

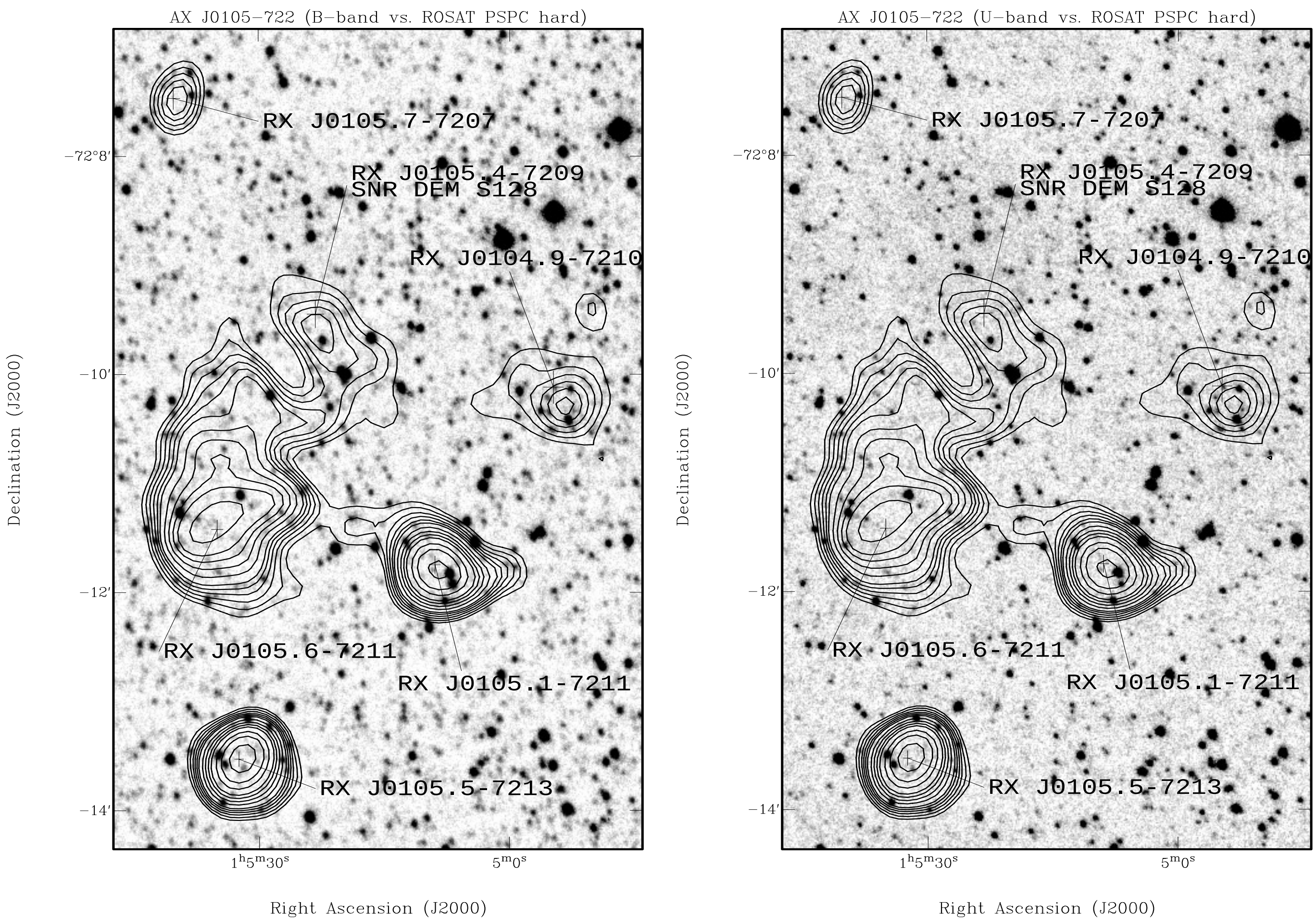

Fig. 4. Optical images (gray-scale) of the SMC region AX J0105-722 in the B-band (left) and U-band (right) obtained from ESO Schmidt plates. Contours represent the ROSAT PSPC image of Fig. 1. Contours are: 0.35, 0.4, 0.45, 0.5, 0.55, 0.6, 0.7, 0.8, 0.9, 1, 1.2, 1.4 and 1.7 cts ksec^{-1}

2.3. Optical data

Optical images of this part of the SMC (field centre RA(J2000)=00^{h}43^{m}30^s and Dec(J2000)= –72°45′) were obtained on 26 July 1998 using the STIS CCD camera (2048 × 2048 pixels; FOV 1.3°) on the 0.6/0.9 m Curtis Schmidt Telescope at CTIO. The two filters used were Hα ($\lambda = 656.7$ nm $\Delta\lambda$=6.8 nm) and [S II] (λ=674.4 nm $\Delta\lambda$=5.0 nm) and the exposure times were 600 sec. Also, a red continuum filter ($\lambda = 685.2$ nm $\Delta\lambda$=9.5 nm) was used to obtain images of the continuum background (mostly stars). The 2.3″ pixels, though large for point sources, are much smaller than the structures we are studying here.

Optical U and B band images of the investigated area were obtained from ESO Schmidt plates digitized at the Centre de Donnees astronomiques de Strasbourg (CDS) using the Aladin service which provides data produced by the CAI-MAMA facility. In Fig. 4 the images are overlaid with X-ray contours. The brightest objects in the X-ray error circle of RX J0105.1-7211 are a pair of stars ∼10″ away from the X-ray position.

3. Discussion

In the following we compare radio-continuum, ROSAT PSPC and optical CTIO (Hα and [S II]) images (Figs. 1 and 2). We discuss several features/sources that coincide, among which the most prominent are DEM S128, RX J0105.1-7211 and RX J0105.5-7213. We note that the X-ray sources RX J0105.1-7211 and RX J0105.7-7207 are seen only in X-ray but not at radio wavelengths.

3.1. DEM S128 (RX J0105.4-7209)

The emission nebula DEM S128 (RX J0105.4-7209) shows a prominent steep radio-continuum spectrum of α=–0.48$\pm$0.06 (Fig. 3) which is typical for SNRs (Filipović et al. 1998a). DEM S128 coincides with the extended X-ray source RX J0105.4-7209 which exhibits HR1 and HR2 typical for SNRs (Haberl & Pietsch 1999). No significant X-ray flux variations were found between the two ROSAT PSPC observations, also consistent with an SNR nature. Possibly the most sensitive diagnostic for identifying SNRs is narrow-band optical CCD imaging in the light of Hα and [S II] (Rosado et al. 1994). The ratio of the [S II] to Hα emission in nebulae provides an ideal discriminator between H II regions, which typically show [S II]/Hα of $\sim$0.1, and SNRs, which usually have ratios $>$0.5. In the case of DEM S128 we measure [S II]/Hα ratios of 0.6 to 0.65 (averaged over areas of $\sim$30 arcsec^2). Therefore, indicators from three different wave-bands independently confirm the SNR nature proposed by Inoue et al. (1983). The diameter of the SNR DEM S128, as measured along an east-west line, is about 150$''$ or 45 pc at the distance of the SMC (65 kpc; Feast 1999). From the radio-continuum images the SNR DEM S128 can be classified as a so-called barrel-shaped (bilateral) remnant (Gaensler 1998). We note that the radio-continuum emission from SNR DEM S128 could be contaminated with a point-like background source which is located at the south limb of the SNR. Further high-resolution observations will clarify the morphology of this SNR.

3.2. RX J0105.6-7211

The X-ray and radio source RX J0105.6-7211 is found about 75$''$ south from DEM S128. In both wave-bands this source shows extent and shell-shape typical for SNRs. However, the radio-continuum spectrum is inconclusive and we fail to detect any optical emission. Therefore, the nature of this source at present remains ambiguous.

3.3. RX J0104.9-7210

The source RX J0104.9-7210 is also not classified despite positive detection at all observed frequencies. Contradictory properties of this object emphasize the complexity of the whole AX J0105-722 region.

3.4. RX J0105.5-7213

The bright X-ray and radio source RX J0105.5-7213 shows a flat radio spectrum with α=–0.15$\pm$0.09 (Fig. 3). The X-ray spectrum is hard as indicated by HR2=0.46$\pm$0.09. To investigate long term time variations in the flux of the X-ray sources we compared the two PSPC observations which were performed about six months apart. RX J0105.5-7213, of similar intensity to RX J0105.1-7211 during the October 1993 observation was not detected in May 1993 implying an even higher variability than shown by the latter source (see below). However, no optical counterpart is detected in any of our optical images. Therefore, we classify this source to be an optically faint background AGN. This is important as this AGN could serve (together with other background sources in the field of the SMC) as a potential probe of the extragalactic ISM (Crampton et al. 1997).

3.5. RX J0105.1-7211

No radio-continuum emission is detected for the X-ray source RX J0105.1-7211. Between the two PSPC observations RX J0105.1-7211 increased in count rate from (1.5$\pm$0.6) 10^{-3} cts s^{-1} to (4.1$\pm$0.5) 10^{-3} cts s^{-1}, i.e. by a factor of 1.7 – 5.1 in the 0.5 – 2.0 keV band (note the different energy band to that used in Table 3). From ESO U/B images (Fig. 4) we notice two stars near the position of the X-ray source, with the northern of the two stars showing stronger U-band emission. We identify this northern star with an emission line object in the catalogue of Meyssonier & Azzopardi (1993, MA93). The object number 1517 in MA93 is located only 7$\farcs$7 away from the X-ray position, consistent within the errors. The catalogue of MA93 contains most of the other already identified Be/X-ray binaries in the SMC (Haberl et al., in preparation) and also an MA93 object is proposed as the counterpart of the ASCA pulsar AX J0049-732 (Filipović et al. 1999). This strongly suggests RX J0105.1-7211 as new Be/X-ray binary which also is most likely the counterpart of the ASCA X-ray pulsar AX J0105-722 originally discovered by Yokogawa & Koyama (1998). Unfortunately, the archival ROSAT PSPC/HRI data cannot confirm the pulsations from the X-ray source due to poor statistics. Further high-resolution optical and X-ray observations are necessary to unambiguously identify RX J0105.1-7211 as a Be/X-ray binary and counterpart of AX J0105-722.

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