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Doubling the number of Be/X-ray binaries in the SMC*

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Abstract. A correlation of X-ray source and H_α emission-line object catalogues in the Small Magellanic Cloud (SMC) shows that more than two thirds of the optically identified Be stars in Be/X-ray binaries are found as emission-line objects in the catalogues. On the basis of this result we propose up to 25 X-ray sources mainly from recent ROSAT catalogues as new Be/X-ray binaries and give their likely optical counterparts. Also for the five yet unidentified X-ray pulsars in the SMC we propose emission-line stars as counterparts. This more than doubles the number of known high mass X-ray binary systems in this nearby galaxy. The spatial distribution of the new candidates is similar to that of the already identified Be/X-ray binaries with a strong concentration along the SMC main body and some systems in the eastern wing. The new candidates contribute mainly to the low-luminosity end of the X-ray luminosity distribution of Be/X-ray binaries. A comparison with the luminosity distribution in the Milky Way reveals no significant differences at the high-luminosity end and the large number of low-luminosity systems in the SMC suggests that many such systems may still be undetected in the Galaxy. The overall ratio of known Be to OB supergiant X-ray binaries in the SMC is an order of magnitude larger than in the Galaxy, however, might show spatial variations. While in the eastern wing the ratio is comparable to that in the Galaxy no supergiant X-ray binary is currently known in the main body of the SMC. Possible explanations include a different star formation history over the last ~ 15 My.

Key words: galaxies: Magellanic Clouds – galaxies: stellar content – stars: variables: general – X-rays: stars

1. Introduction

In high mass X-ray binaries (HMXBs) a neutron star or black hole orbits a massive early-type star and accretes matter either via Roche-lobe overflow or from the stellar wind which powers the X-ray emission (for recent reviews see Nagase 1989; White et al. 1995; Bildsten et al. 1997). One divides the class of HMXBs according to the stellar type of the mass donor star into supergiant X-ray binaries with luminosity class I-II OB star and Be/X-ray binaries with luminosity class III-IV Be star companions. Be/X-ray binaries form the larger sub-group of HMXBs. Balmer emission lines in the optical spectrum and a characteristic infrared excess are attributed to the presence of circum-stellar material, probably forming a disk in the equatorial plane of the Be star. Be/X-ray binaries often show transient behaviour with two types of outbursts. X-ray outbursts repeating with the orbital period are most likely associated with the passage of the neutron star through the circum-stellar disk in an eccentric orbit while giant outbursts, often lasting longer than a binary period, probably arise from an expansion of the disk.

Currently about 100 HMXBs and candidates are known. Nearly one third were found in the Magellanic Clouds (MCs) from which the majority is located in the Small Magellanic Cloud (SMC, Coe 1999). Most of the Be/X-ray binaries in the SMC were discovered in recent years by X-ray missions like ASCA, BeppoSAX, ROSAT and RXTE (Nagase 1999). From 20 optically identified HMXBs in the SMC only one is securely associated with a supergiant system (the X-ray pulsar SMC X–1) and from 11 of the 19 Be/X-ray binaries X-ray pulsations were detected. Five additional X-ray pulsars are yet to be identified, but are most likely also Be systems. The location of such a large number of HMXBs at a similar distance makes the SMC ideally suited for statistical and in particular spatial distribution studies of the population of HMXBs in a galaxy as a whole.

Recent surveys to look for H_α emission-line objects in the SMC were performed by Meyssonier & Azzopardi (1993, hereafter MA93) and Murphy & Bessell (1999, MB99). The survey of MA93 mainly covers the main body and eastern wing of the SMC and their catalogue lists 1898 emission-line stars. The catalogue of MB99 covers nearly all the area where ROSAT PSPC observations of the SMC are available (except the southern half of the most south-east observation) but is less sensitive (372 objects, partially in common with MA93). A main goal of MA93 and MB99 was to identify planetary nebulae in the SMC, however, the catalogues also contain Be stars. MA93 state that all three at the time of publication known B[e] supergiants which were covered by the survey were detected. Very few Be/X-ray binaries were known in the SMC until 1993 and it was not noticed that the Be stars proposed as optical counterparts for SMC X-3, 2E 0050.1–7247 and 2E 0051.1–7304 were listed in

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* Figs. 3–6 are only available electronically with the On-Line publication at http://link.springer.de/link/service/00230/

MA93 as emission-line stars (LIN 198, AzV 111 and AzV 138, respectively). A correlation of the larger sample of Be/X-ray binaries known today in the SMC shows that most of them are found in the catalogues of MA93 and MB99. In this paper we use the identification of X-ray sources with emission-line stars to propose new very likely candidates for Be/X-ray binaries in the SMC (Sect. 2). X-ray source catalogues of the SMC which we used for our correlations with the emission-line star catalogues were published by Wang & Wu (1992) based on Einstein IPC observations (Seward & Mitchel 1981, Inoue et al. 1983, Bruhweiler et al. 1987) and by Haberl et al. (2000, HFPK00) produced from ROSAT PSPC data. We also used a preliminary version of the ROSAT HRI catalogue of Sasaki et al. (2000b).

2. X-ray sources and H_α emission-line stars

A cross-correlation of the 517 PSPC X-ray sources in the SMC region (HFPK00) with the catalogue of H_α emission-line stars published by MA93 (1898 entries) yielded 46 possible optical counterparts (distance $< \sqrt{r_{90}^2 + 10^2}$ to account for systematic uncertainties in X-ray and optical positions, where r_{90} denotes the 90% statistical uncertainty of the X-ray position in arc seconds). An additional object correlating with a PSPC source was found within the catalogue of candidate emission-line objects of MB99. From this sample of 47 objects one coincides with a known supernova remnant, three with supersoft sources and ten with optically identified Be stars proposed as optical counterparts for the X-ray sources. Extending the search by using additional SMC X-ray sources such as from the ROSAT HRI catalogue of Sasaki et al. (2000b), the Einstein IPC catalogue of Wang & Wu (1992) and X-ray pulsars discovered by instruments on ASCA, BeppoSAX and RXTE yields another three emission-line stars identified with known Be stars. Our correlation results are summarized in Table 1 which is sorted in right ascension.

Columns 2-4 of Table 1 give the source numbers in the X-ray catalogues for ROSAT PSPC (HFPK00), ROSAT HRI (Sasaki et al. 2000b) and Einstein IPC (Wang & Wu 1992). For sources detected by ROSAT coordinates with statistical 90% error (from HFPK00 when detected by the PSPC or from Sasaki et al. 2000b when detected by HRI only) are given in columns 5-7. For the group of IPC sources which were not detected by ROSAT, the IPC coordinates and a 40″ error as published in WW92 is given. The three digits in column 8 denote the number of PSPC detections in the energy bands 0.1 - 0.4 keV, 0.5 - 0.9 keV and 0.9 - 2.0 keV. With a few exceptions most of the sources were detected mainly in the higher energy bands which indicates a hard X-ray spectrum. HFPK00 used count ratios in the different energy bands, the hardness ratios, for a spectral classification of the PSPC sources. However, very hard sources without detection in the lower energy bands were not classified in HFPK00 because of large errors on the hardness ratios. Column 9 lists the maximum observed X-ray luminosity for Be/X-ray binaries and candidates derived in this work. The values are selected from literature or computed from ROSAT count rates using the conversion factor $1.67{\cdot}10^{37}$ erg s^{-1}/cts s^{-1} (see Kahabka & Pietsch 1996, hereafter KP96), typical for X-ray binaries with hard spectrum at the distance of the SMC. HRI count rates were converted to PSPC rates using a multiplication factor of 3.0 (Sasaki et al. 2000a). Luminosities derived from count rates are indicated with colon. For all given X-ray luminosities we assume a distance of 65 kpc to the SMC.

Column 10 of Table 1 lists the entry number of the nearest object in MA93 (MB99 in one case) and column 11 the MA93 classification type (2 = SNR; 5 = planetary nebula, PN; 9 = late type star). The distance between X-ray and optical position as listed in MA93 (MB99) is listed in column 12. B, V and R magnitudes found in the literature for identified sources are given in columns 13-15. When available B and R obtained from the USNO A2.0 catalogue are listed for the remaining sources. In the last column identifications are given together with references and new proposals are marked with '?' behind the source type.

From the total of 18 high mass X-ray binaries in the SMC with known Be star as proposed counterpart 13 are found in the emission-line catalogues of MA93 and MB99. For completeness the remaining five Be/X-ray binaries are also listed in Table 1.

The identification of most known Be/X-ray binaries with stars in the emission-line catalogues of MA93 and MB99 suggests that un-identified X-ray sources with emission-line star counterparts are most likely also Be/X-ray binary systems. Other objects like SSSs and SNRs can be recognized by their very soft X-ray spectrum (in contrast to the Be/X-ray binaries with hard spectrum) or by their X-ray source extent, respectively. In the following section we summarize the 18 X-ray sources optically identified as Be/X-ray binary. We then propose emission-line stars as likely Be counterparts for the five un-identified pulsars and in addition for 25 hard X-ray sources.

2.1. Supersoft sources

Three supersoft sources detected by ROSAT were identified with emission-line objects in the catalogue of MA93. Two of them are associated with planetary nebulae (PN) while the remaining one is identified with a symbiotic star in the SMC. More detailed information on the individual sources and finding charts with X-ray error circles can be found in Sect. 6.1.

2.2. Optically identified Be/X-ray binaries

For 19 X-ray sources in the SMC nearby Be stars were optically identified and proposed as counterparts, suggesting a Be/X-ray binary nature. Eighteen were covered by ROSAT observations and information on the individual sources is summarized in Sect. 6 where also finding charts are found. The HEAO source 1H 0103–762 was not observed with ROSAT (see KP96 and references therein). Also we do not include the HMXB candidates RX J0106.2–7205 (Hughes & Smith 1994) and EXO 0114.6–7361 in our summary. For RX J0106.2–7205 no optical spectrum from the suggested counterpart is published yet, which would confirm its proposed Be star nature. For EXO 0114.6–7361 Wang & Wu (1992) propose the B0 Ia star AzV 488 as

Table 1. X-ray sources correlating with emission-line objects in the catalogues of MA93, MB99 or identified Be-stars

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	No RP	No RH	No EI	RA (J2000.0)	Dec	r_{90} [″]	det	L_x erg s^{-1}	No MA	T	dist [″]	B	V	R	Remarks
1	567	–	–	00 32 56.1	-73 48 19	12.9	012	$1.3\cdot10^{37}$	–	–	–	–	–	–	Be/X RXJ0032.9-7348, 2 Be stars (KP96, SCB99)
2	404	–	–	00 41 16.4	-73 06 41	35.6	100	–	22	5	31.5	18.4:	–	17.0:	[fg Star] GSC 9141.4223?
3	436	–	–	00 45 37.9	-73 13 54	29.4	001	$1.2\cdot10^{35}$:	114	–	23.4	18.3:	–	16.9:	Be/X?
4	413	–	16	00 47 12.2	-73 08 26	6.8	012	–	165	2	4.5	–	–	–	SNR 0045-73.4 (RLG94) 13cm
5	295	–	19	00 47 18.4	-72 39 42	49.8	001	–	168	9	21.1	–	–	–	AGN? Radio SMC B0045-7255 (FHW98) 13cm
6	434	–	18	00 47 23.4	-73 12 23	4.0	012	$2.4\cdot10^{35}$:	172	–	1.6	–	–	–	Be/X? [hard]
7	512	23	–	00 48 23.1	-73 31 43	24.1	620	–	218	9	15.1	–	–	–	SSS RXJ0048.4-7332, symbiotic star M0 (KP96, M92)
8	392	–	–	00 48 33.7	-73 02 24	7.6	011	$1.2\cdot10^{35}$:	238	–	6.5	14.6:	–	16.9:	Be/X?
9	351	–	–	00 49 02.5	-72 50 52	13.7	002	$6.1\cdot10^{36}$	–	–	–	17.01	16.92	–	Be/X AXJ0049-729, 74.67 s pulsar (YK98a, KP98, SCB99, CO00)
10	427	–	–	00 49 29.6	-73 10 56	5.5	002	$4.1\cdot10^{35}$	300	–	2.6	18.1:	–	15.6:	Be/X? AXJ0049-732, 9.132 s pulsar (IYK98, FPH00b)
11	511	[4]28	–	00 49 30.7	-73 31 09	1.8	011	$1.2\cdot10^{35}$:	302	–	22.2	–	–	–	Be/X?
12	468	–	–	00 49 43.8	-73 23 02	14.9	001	$2.7\cdot10^{34}$:	315	–	14.7	17.7:	–	15.4:	Be/X?
13	444	34	–	00 50 44.3	-73 15 58	4.9	023	$1.8\cdot10^{36}$	387	–	6.9	15.41	15.44	–	Be/X AXJ0051-733, 323.2 s pulsar (CSM97, YK98b, SC98, CO00)
14	514	–	–	00 50 46.8	-73 32 47	33.7	010	$2.4\cdot10^{34}$:	393	–	9.2	–	–	–	Be/X?
15	421	36	–	00 50 56.5	-73 10 09	4.5	013	$1.1\cdot10^{35}$:	414	–	3.5	–	–	–	Be/X?
16	–	37	–	00 50 56.9	-72 13 31	1.4	–	$2.9\cdot10^{37}$	413	–	2.7	15.8:	–	16.4:	Be/X AXJ0051-722 91.12 s pulsar (CML98b, L98, SCB99)
17	349	–	–	00 51 19.5	-72 50 43	15.6	001	$3.6\cdot10^{34}$:	447	–	14.6	–	–	–	Be/X?
18	99	–	–	00 51 51.4	-71 59 50	47.7	001	–	502	9	22.3	14.6:	–	13.3:	AC?
19	424	41	25	00 51 51.5	-73 10 31	2.2	055	$4.7\cdot10^{35}$:	504	–	4.2	13.1:	14.4	14.4:	Be/X RXJ0051.9-7311 (CSM97, SCC99)
20	[3]265	–	27	00 51 53.1	-72 31 50	2.0	112	$1.4\cdot10^{36}$	506	–	1.3	13.12	13.4	–	Be/X RXJ0051.8-7231, 8.9 s pulsar (ISA97, SCB99)
21	–	–	26	00 51 54.2	-72 55 36	40.0	–	$6.0\cdot10^{34}$	521	–	28.6	–	–	–	Be/X?
22	–	43	–	00 52 05.4	-72 25 55	15.8	–	$5.6\cdot10^{37}$	531	–	7.1	15.0	–	15.4:	Be/X SMC X-3
23	453	44	29	00 52 13.9	-73 19 13	1.9	011	$1.3\cdot10^{37}$	552	–	5.1	–	14.62	14.54	Be/X RXJ0052.1-7319, 15.3 s pulsar (LPM99, ISC99)
24	–	–	31	00 52 52.7	-72 48 22	40.0	–	$1.6\cdot10^{35}$	618	–	7.8	14.28	14.28	15.6:	Be/X 2E0051.1-7304, AzV138 (GH85)
25	94	[4]46	32	00 52 54.7	-71 58 08	2.0	004	$2.0\cdot10^{37}$	623	–	13.2	15.39	15.46	14.7:	Be/X RXJ0052.9-7158 (CSM97,SCC99) =? XTEJ0054-720 169.3 s pulsar
26	246	[4]48	–	00 53 24.1	-72 27 14	2.1	001	$6.4\cdot10^{34}$:	667	–	31.0	17.0:	–	15.8:	Be/X?
27	242	–	34	00 53 53.3	-72 27 01	25.7	012	$7.4\cdot10^{36}$	717	–	22.7	–	–	–	Be/X? XTEJ0053-724, 46.63 s pulsar (CML98b)
28	547	–	–	00 54 30.8	-73 40 55	10.5	011	$8.4\cdot10^{37}$	–	–	–	15.7	16.0	–	Be/X SMCX-2 (KP96)
29	248	–	–	00 54 33.1	-72 28 08	45.7	001	$1.5\cdot10^{36}$:	772	–	26.6	–	–	–	Be/X? [hard]
30	324	57	–	00 54 55.3	-72 45 06	5.6	012	$3.0\cdot10^{35}$:	809	–	4.7	16.8:	–	14.8:	Be/X?
31	241	58	35	00 54 55.4	-72 26 46	3.5	023	$3.0\cdot10^{37}$	810	–	3.1	15.24	15.28	–	Be/X XTEJ0055-724, 59.07 s pulsar (ML98, SCI98, SCB99, CO00)

[1] B denotes 11 detections
[2] Entry in catalogue of MB99
[3] Parameters from observation 600453 when source was bright
[4] HRI position and error
[5] ASCA position and error

Table 1. (continued)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	No RP	No RH	No EI	RA (J2000.0)	Dec	r_{90} [″]	det	L_x erg s^{-1}	No MA	T	dist [″]	B	V	R	Remarks
32	–	–	38	00 56 03.3	-72 21 32	40.0	–	$4.0\cdot10^{34}$	904	–	29.6	15.7:	–	14.3:	Be/X?
33	270	–	–	00 57 15.4	-72 33 38	25.9	000	–	993	–	27.1	17.2:	–	16.7:	?
34	117?	71?	40	00 57 32.4	-72 13 17	40.0	–	–	1021	–	23.6	15.4:	–	13.7:	?
35	114	73	41	00 57 48.4	-72 02 42	7.9	001	$1.6\cdot10^{36}$	1036	–	9.5	16.8:	–	17.7:	Be/X? AXJ0058-720, 280.4 s pulsar (YK98b)
36	136	74	–	00 57 50.1	-72 07 56	5.1	012	$4.3\cdot10^{35}$:	1038	–	1.3	16.7:	–	15.8:	Be/X? [hard]
37	87	–	–	00 57 59.5	-71 56 37	19.2	001	$5.7\cdot10^{34}$:	1044	–	21.1	17.1:	–	15.5:	Be/X?
38	–	76	–	00 58 12.9	-72 30 45	3.1	–	$2.1\cdot10^{35}$:	–	–	–	16.7:	14.9	15.5:	Be/X RXJ0058.2-7231 (SCC99)
39	47	79	43	00 58 37.2	-71 35 50	1.3	[1]B30	–	1083	5	1.8	16.8:	–	15.3:	SSS 1E0056.8-7154, PN LIN333 (KP96)
40	53	–	–	00 59 11.3	-71 38 45	2.8	111	$5.0\cdot10^{37}$	[2]179	–	10.1	14.21	14.08	14.03	Be/X RXJ0059.2-7138, 2.763 s soft pulsar (H94, SC96)
41	51	–	–	00 59 41.7	-71 38 15	14.5	300	–	1159	5	5.7	16.8:	–	16.5:	SSS? RXJ0059.6-7138, PN LIN357 (KPFH99)
42	132	93	–	01 01 01.1	-72 06 57	2.8	011	$1.3\cdot10^{36}$	1240	–	8.5	–	–	–	Be/X RXJ0101.0-7206 (KP96, SCB99)
43	159	[4]95	–	01 01 20.5	-72 11 18	1.6	013	$6.6\cdot10^{35}$:	1257	–	4.7	–	–	–	Be/X? [nonstar]
44	121	96	46	01 01 37.0	-72 04 19	7.2	[1]06B	$3.8\cdot10^{35}$:	1277	–	5.5	17.7:	–	16.4:	Be/X?
45	220	97	–	01 01 51.0	-72 23 26	8.1	025	$2.2\cdot10^{35}$:	1288	–	9.8	14.7:	–	14.3:	Be/X?
46	92	–	–	01 02 51.3	-71 57 43	18.2	000	–	1338	–	14.1	15.1:	–	13.6:	?
47	–	–	49	01 03 06.9	-72 32 59	40.0	–	–	1357	5	4.8	–	–	–	?
48	77	–	–	01 03 07.1	-71 51 47	11.8	001	–	1365	–	14.6	18.8:	–	17.8:	?
49	143	101	50	01 03 14.0	-72 09 16	3.4	067	$1.5\cdot10^{36}$	1367	–	1.1	14.73	14.80	14.74	Be/X SAXJ0103.2-7209, 345.2 s pulsar (ISC98, HS94, CO00)
50	106	105	–	01 03 37.0	-72 01 39	5.0	013	$3.0\cdot10^{35}$:	1393	–	7.2	–	–	–	Be/X?
51	317	–	–	01 04 07.4	-72 43 59	17.7	002	$3.8\cdot10^{34}$:	1440	–	9.0	14.1:	–	14.4:	Be/X? or AGN? 13cm
52	–	108	–	01 04 35.6	-72 21 43	2.3	–	$4.8\cdot10^{34}$:	1470	–	4.0	14.8:	–	15.1:	Be/X?
53	163	110	–	01 05 08.9	-72 11 44	6.6	012	$1.5\cdot10^{35}$	1517	–	7.7	–	–	–	Be/X? AXJ0105-722, 3.343 s pulsar (YK98c, FHP00a)
54	737	–	–	01 05 42.3	-72 26 15	15.7	001	$1.8\cdot10^{34}$:	1544	–	12.8	14.2:	–	14.0:	Be/X?
55	120	–	–	01 05 54.8	-72 03 54	5.5	011	$6.5\cdot10^{34}$:	1557	–	3.7	–	–	–	Be/X?
56	279	–	56	01 07 10.9	-72 35 36	11.1	001	$2.3\cdot10^{34}$:	1619	–	10.1	16.6:	–	15.4:	Be/X?
57	253	–	–	01 09 01.2	-72 29 07	17.6	012	–	1682	5	12.3	–	–	–	? [hard]
58	[5]446	–	–	01 11 14.5	-73 16 50	30.0	–	$2.0\cdot10^{38}$	–	–	–	15.24	15.32	15.37	Be/X XTEJ0111.2-7317, 31.03 s pulsar (CLC98a, WF98, ISC99, CHR99)
59	506	–	–	01 17 41.4	-73 30 49	0.6	122	$1.2\cdot10^{38}$	1845	–	4.3	14.1:	14.2	14.7:	Be/X RXJ0117.6-7330, 22.07 s pulsar (MFH99, CRW97)
60	501	–	–	01 19 37.6	-73 30 06	12.9	001	$1.5\cdot10^{34}$:	1867	–	8.3	15.1:	–	15.8:	Be/X?

References:
(CHR99) Coe et al. 1999, (CLC98a) Chakrabarty et al. 1998a, (CML98b) Corbet et al. 1998b, (CO00) Coe & Orosz 2000, (CRW97) Clark et al. 1997, (CSM97) Cowley et al. 1997, (FHW98) Filipović et al. 1998, (FHP00a) Filipović et al. 2000a, (FPH00b) Filipović et al. 2000b, (GH85) Garmany & Humphreys 1985, (H94) Hughes 1994, (HS94) Hughes & Smith 1994, (ISA97) Israel et al. 1997, (ISC98) Israel et al. 1998, (ISC99) Israel et al. 1999, (IYK98) Imanishi et al. 1998, (KP96) Kahabka & Pietsch 1996, (KP98) Kahabka & Pietsch 1998, (KPFH99) Kahabka et al. 1999, (L98) Lochner 1998, (LPM99) Lamb et al. 1999, (M92) Morgan 1992, (MFH99) Macomb et al. 1999, (ML98) Marshall & Lochner 1998, (RLG94) Rosado et al. 1994, (SC96) Southwell & Charles 1996, (SC98) Schmidtke & Cowley 1998, (SCB99) Stevens et al. 1999, (SCC99) Schmidtke et al. 1999, (SCI98) Santangelo et al. 1998, (WF98) Wilson & Finger 1998, (YK98a) Yogogawa & Koyama 1998a, (YK98b) Yogogawa & Koyama 1998b, (YK98c) Yogogawa & Koyama 1998c

counterpart, however, AzV 477, also a B0 Ia star is even closer to the X-ray position. Both candidates suggest a supergiant type of HMXB. It is remarkable, that together with the only other known supergiant HMXB SMC X–1, EXO 0114.6–7361 is located in the eastern wing of the SMC.

Fourteen of the identified Be/X-ray binaries were detected by the ROSAT PSPC and their X-ray properties can be found in HPFK99. AX J0051–722, SMC X–3 and RX J0058.2–7231 were detected by the ROSAT HRI and are listed in the catalogue of HRI sources in the SMC (Sasaki et al. 2000b). Only 2E 0051.1–7304 was not detected by ROSAT. Thirteen of the proposed Be star counterparts are listed in the catalogues of MA93 and MB99 and only for five X-ray sources the Be counterparts have no entry in MA93 and MB99 (AX J0049–729, SMC X–2, RX J0032.9–7348, RX J0058.2–7231 and XTE J0111.2-7317). RX J0032.9–7348 was not covered by the MA93 survey.

2.3. Optically unidentified X-ray pulsars

Five X-ray pulsars in the SMC were reported for which no optical identifications are published up to day. Four of them were detected by ROSAT PSPC and/or HRI, yielding more accurate positions (HFPK00, Sasaki et al. 2000b) and for the fifth case, XTE J0054–720, several ROSAT sources are found within the large RXTE error circle. In or very close to the ROSAT error circles emission-line objects from MA93 are found and we propose these as optical counterparts. Literature, finding charts and other information on the X-ray binary pulsars is presented in Sect. 6.

Most of the Be stars proposed as optical counterparts for X-ray sources in the SMC, as summarized in the previous section, are found as emission-line objects in the catalogue of MA93. This strongly supports that the unknown emission-line objects within the error circles of the unidentified pulsars are also Be star counterparts of the X-ray pulsars forming Be/X-ray binaries.

2.4. New Be/X-ray binary candidates

From the correlation of X-ray source and emission-line object catalogues 34 hard X-ray sources were found with an H_α emission-line object as possible optical counterpart in the X-ray error circle (see Table 1). The 34 X-ray sources were investigated in detail to obtain more information which can help to identify the nature of the object. Finding charts and notes to the individual sources are compiled in Sect. 6.

Many sources were observed more than once by ROSAT and we looked for long-term time variability. In the case of the PSPC we used the 0.9 – 2.0 keV band because of higher sensitivity for hard sources like Be/X-ray binaries. To combine detections from the different instruments we convert HRI to PSPC count rates by multiplying with 3.0 and IPC to PSPC count rates by multiplying with 1.1 (appropriate for a 5 keV Bremsstrahlung spectrum with $4.3 \cdot 10^{21}$ cm^{-2} absorption column density). Given the uncertainties in the count rate conversions, variability is only treated as significant above a factor of 3. None of the sources was observed with sufficient counting statistics in order to perform a detailed temporal analysis on shorter time scales (within an observation) and to detect X-ray pulsations.

We discuss all un-identified X-ray sources with emission-line object in or close to the error circle in the following and indicate very promising candidates for Be/X-ray binaries with "Be/X?" in the remark column of Table 1.

2.5. Chance coincidences

To estimate the number of false identifications of X-ray sources with emission-line objects in MA93 we shifted the X-ray positions of the sources in an arbitrary direction and cross-correlated again with the MA93 catalogue. To get statistically more reliable results this was repeated with different distances between 1 – 10 arc minutes. For this purpose we used the PSPC catalogue which is most complete. After application of our selection criteria for accepting Be/X-ray binary candidates (likelihood of existence for the X-ray source > 13, no other identification, distance $< \sqrt{r_{90}^2 + 10^2}$) we find on average about seven expected chance coincidences between PSPC sources and emission-line objects in MA93. We emphasize that these are mainly caused by the PSPC sources with the largest position uncertainties. The PSPC sources in Table 1 with the largest errors on the X-ray position and therefore most likely chance coincidences are 99, 248, 295 and 404. Indeed three of them were rejected as Be/X-ray binary candidates due to the presence of other likely counterparts. Similarly PSPC sources 77 and 253 were disregarded. Other X-ray sources with large position errors in Table 1 are the IPC sources which were not securely detected with ROSAT. Also here two were not regarded as Be/X-ray binary candidates. For the 25 new Be/X-ray binary candidates we therefore estimate that about two to three may be misidentifications, most likely among those with position error $r_{90} > 15''$.

3. ASCA binary pulsar candidates

The 1st ASCA Catalogue of X-ray sources in the SMC was compiled by Yokogawa (1999). The sources were classified according to their hardness ratios and Be/X-ray binaries were detected as sources with hard X-ray spectrum in the ASCA energy band. From this classification Yokogawa (1999) proposed eight new Be/X-ray binary candidates (binary pulsar candidates, BPc). We correlated our list of Be/X-ray binary candidates with the ASCA catalogue and find for five of the eight BPc a likely counterpart within $2'$ (the maximum ASCA position uncertainty). In addition one out of the nine (probably because of its low flux) unclassified ASCA sources also correlates with a PSPC Be/X-ray binary candidate. In Table 2 the Be/X-ray binary candidates with likely ASCA counterpart are summarized. The first three columns show ASCA source number, classification and observed X-ray luminosity (0.7 – 10 keV, but corrected for the distance of 65 kpc used throughout this paper) from Yokogawa (1999). The next two columns contain PSPC source number and distance between ASCA and PSPC position and the last two

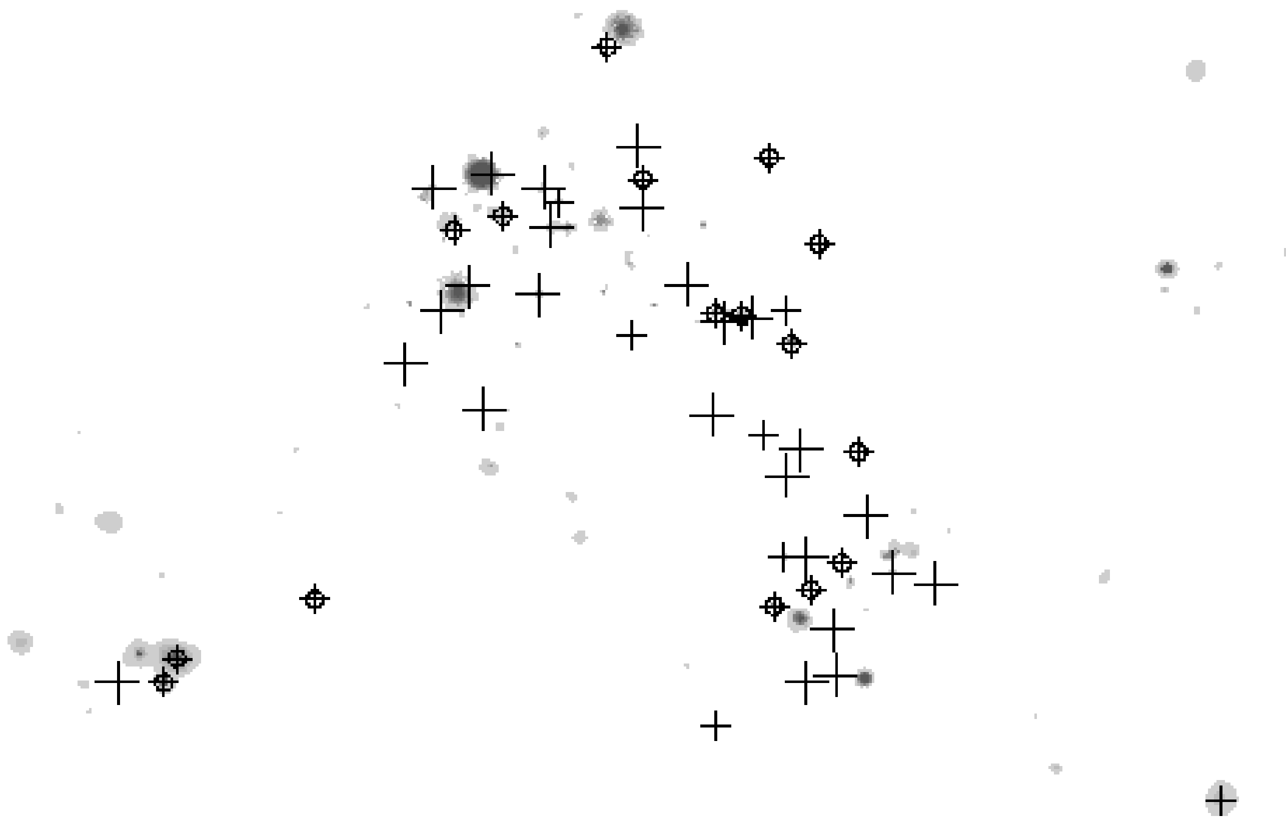

Fig. 1. Distribution of HMXBs in the SMC. X-ray pulsars are marked with circle. The 25 new candidates from this work are indicated by the larger crosses

columns give the same for HRI sources. The X-ray luminosities observed by ASCA are generally a factor of 1.2 – 2.4 higher than the ROSAT values (Table 1) which may only partly be explained by X-ray variability. Finding a systematically higher luminosity with ASCA is probably caused by the different sensitive energy bands and/or different intrinsic source spectrum. In particular the PSPC count rate to luminosity conversion is very sensitive to the assumed absorption. In the case of ASCA sources 36 (PSPC 279) and 7 (PSPC 468) the ASCA/ROSAT luminosity ratio is much higher than average (4.2 and 17, respectively), indicating strong flux variability.

Table 2. Be/X-ray binaries with likely ASCA counterparts

ASCA			PSPC		HRI	
No	Class	L_x [erg s^{-1}]	No	d [″]	No	d [″]
2	BPc	$3.5{\cdot}10^{35}$	434	30.1	–	–
6	BPc	$2.9{\cdot}10^{35}$	511	39.8	28	27.8
7	BPc	$4.6{\cdot}10^{35}$	468	52.1	–	–
27	BPc	$8.6{\cdot}10^{35}$	159	15.6	95	19.0
28	BPc	$2.6{\cdot}10^{35}$	220	11.3	97	20.1
36	UN	$9.6{\cdot}10^{34}$	279	56.5	–	–

4. Optical identifications

An optical identification campaign of a selected sample of hard ROSAT PSPC sources from the catalogue of HFPK00 was started independently to the present work (Keller et al. in preparation). From three of the X-ray sources presented here, spectra were taken which in all cases revealed a Be star nature of the proposed counterpart from the MA93 catalogue. This confirms RX J0057.8–7207 (PSPC 136, Sect. 6.4.8) as Be/X-ray binary and also the proposed counterpart for the pulsar AX J0105–722 (PSPC 163, Sect. 6.3.2, see also Filipović et al. 2000a) as Be star. RX J0051.9–7311 (PSPC 424, Sect. 6.2.8) was independently identified by Schmidtke et al. (1999). These results can be taken as further evidence that the emission-line objects we propose for counterparts of X-ray sources are indeed Be stars.

5. The Be/X-ray binary population of the SMC

The spatial distribution of the SMC HMXBs including the new candidates from this work is shown in Fig. 1. Nearly all new candidates are located along the main body of the SMC where most of the optically identified Be/X-ray binaries are concentrated. Only one new candidate is found in the eastern wing near the supergiant HMXB SMC X–1, where already two other Be/X-ray pulsars are known. The distribution is not biased due to incomplete coverage, neither in the optical nor in X-rays and makes the strong concentration of Be/X-ray binaries in certain areas of the SMC more pronounced.

The X-ray luminosity distribution of Be/X-ray binaries and candidates in the SMC is compared to that of systems in the Galaxy in Fig. 2. To do this we intensively searched the literature on galactic Be/X-ray binary systems. We derived 31 galactic sources with $L_x^{max} > 10^{33}$ erg s^{-1} which are summarized in Table 3 (which should be mostly complete). The luminosity estimates of galactic systems are often hampered by uncertain distances and different energy bands of the observing instrument. This may cause luminosity uncertainties by a factor of $\sim$10 in some cases but should not change the overall distribution drastically.

The new candidates in the SMC mainly raise the number of Be/X-ray binaries with luminosities $\log(L_x^{max}) < 35.5$ (21 out of 24 are new candidates). This can easily be explained by the high sensitivity of the ROSAT instruments which allowed to detect Be/X-ray binaries in their low-state while most of the higher luminosity Be/X-ray binaries were discovered during outburst. X-ray luminosities derived from detectors sensitive at higher energies (typically 0.5 – 10 keV) might be up to a factor $\sim$2 higher than those derived from ROSAT count rates (see Sect. 3) which would shift the low-luminosity end in Fig. 2 by 0.3 dex to the right. However, such a shift would not change the overall distribution significantly. Recently, in the Galaxy several likely low-luminosity Be/X-ray binaries were discovered by BeppoSAX and ASCA (1SAX J1324.4-6200, Angelini et al. 1998; AX J1820.5-1434, Kinugasa et al. 1998; AX J1749.2-2725, Torii et al. 1998; 1SAX J1452.8-5949, Oosterbroek et al. 1999; AX J1700062-4157, Torii et al. 1999). ROSAT also contributed new low-luminosity systems (RX J0440.9+4431, RX J0812.4-3114, RX J1037.5-5647, RX J0146.9+6121, Motch et al. 1997). However, the high absorption in the galactic plane makes the detection of low-luminosity X-ray sources in the ROSAT X-ray band and their optical identification difficult. This might explain the smaller number of low-luminosity Be/X-ray binaries discovered so far in the Galaxy compared to the SMC and might suggest that the luminosity distribution of Be/X-ray binaries is very similar in the SMC and our Galaxy. In this case many more such systems are expected to be found in our Galaxy which would significantly contribute to the hard X-ray galactic ridge emission (Warwick et al. 1985).

Various authors have suggested the existence of a population of low-luminosity systems which are usually persistent X-ray sources showing moderate outbursts and long pulse periods (e.g. Kinugasa et al. 1998; Mereghetti et al. 2000), somewhat different to the high-luminosity systems with strong outbursts and shorter pulse periods. The SMC results suggest that the low-luminosity sources even dominate the Be/X-ray binaries in number. From the fact that about one third of the already identified Be/X-ray binaries is not listed in current emission-line catalogues even more such systems are expected to be found in the ROSAT X-ray source catalogues of the SMC. On the other hand some of them will be observed with higher maximum luminosity in future outbursts, but if they indeed form a class of low-luminosity Be/X-ray binaries like X Per, the outbursts are expected to be small changing the luminosity distribution immaterial.

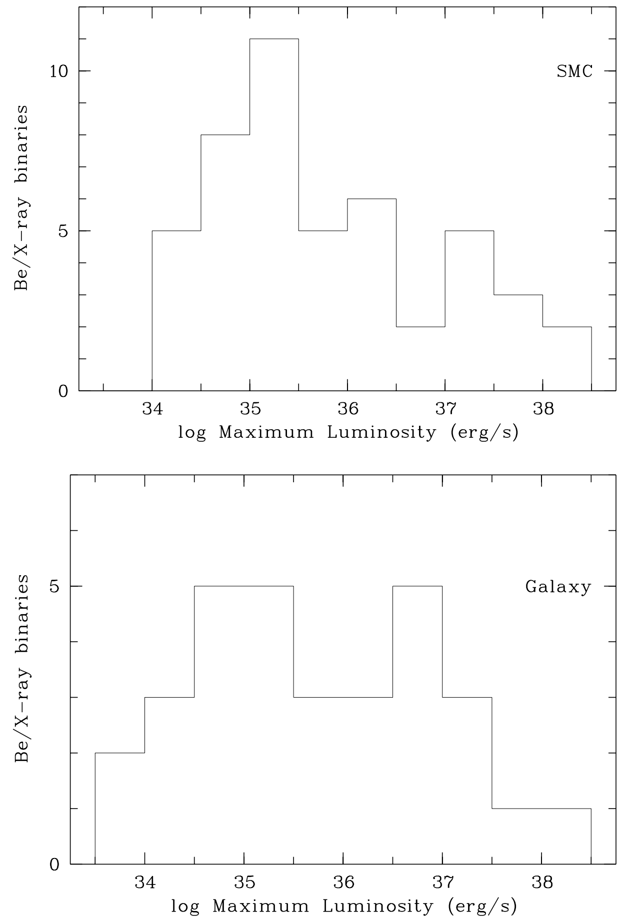

Fig. 2. Distribution of observed maximum X-ray luminosity of Be/X-ray binaries in the SMC and the Galaxy. Including the candidates from this work, which form a population of low-luminosity systems, 47 Be/X-ray binaries are found in the SMC

There is a large difference in the number of OB supergiant HMXBs between the Galaxy and the SMC. In the SMC at most two such systems are identified (SMC X-1 and maybe EXO 0114.6–7361) resulting in an overall ratio of Be to supergiant X-ray binaries of more than 20. In the Galaxy this proportion is more of order 2 (12 supergiant systems in the Galaxy are listed in the reviews of White et al. 1995 and Bildsten et al. 1997). It is remarkable that the SMC supergiant HMXBs are all located in the eastern wing giving rise to a local Be/supergiant HMXB ratio similar to that in the Galaxy. In contrast no supergiant HMXB is known in the SMC main body making the difference more extreme. One possible explanation is a different star formation history. Be/X-ray binaries evolve from binary star systems with typical total mass of $\sim$20 $M_\odot$ within about 15 My (van den Heuvel 1983) while the more massive supergiant HMXBs are formed on shorter time scales. The latter therefore would trace more recent epochs of star formation than the Be/X-ray binaries. The comparatively large number of Be/X-ray binaries in the SMC in this view suggests a burst of star forma-

Table 3. Be/X-ray binaries and likely candidates located in the Galaxy

Name	Pulse period [s]	d [kpc]	L_x^{max} [erg s^{-1}]	Reference for L_x^{max}
4U0115+63	3.6	4	$3.0{\cdot}10^{37}$	Tamura et al. (1992)
V0332+53	4.4	3	$3.2{\cdot}10^{37}$	Takeshima et al. (1994)
2S1553-542	9.3	10	$7.0{\cdot}10^{36}$	Apparao (1994)
GS0834-430	12.3	5	$1.1{\cdot}10^{37}$	Wilson et al. (1997)
XTEJ1946+274	15.8	5	$5.4{\cdot}10^{36}$	Campana et al. (1999)
2S1417-624	17.6	10	$8.0{\cdot}10^{36}$	Apparao (1994)
RXJ0812.4-3114	31.9	9	$1.1{\cdot}10^{36}$	Reig & Roche (1999a)
EXO2030+375	41.8	5	$1.0{\cdot}10^{38}$	Parmar et al. (1989)
GS2138+56	66.3	3.8	$9.1{\cdot}10^{35}$	Schulz et al. (1995)
GROJ1008-57	93.5	2	$2.9{\cdot}10^{35}$	Macomb et al. (1994)
GS1843-02	94.8	10	$6.0{\cdot}10^{36}$	Finger et al. (1999)
4U0728-25	103	6	$2.8{\cdot}10^{35}$	Corbet & Peele (1997)
A0535+26	105	2.4	$2.0{\cdot}10^{37}$	Apparao (1994)
AXJ1820.5-1434	152	4.7	$9.0{\cdot}10^{34}$	Kinugasa et al. (1998)
1SAXJ1324.4-6200	171	10	$9.8{\cdot}10^{34}$	Angelini et al. (1998)
GROJ2058+42	198	7	$2.0{\cdot}10^{36}$	Wilson et al. (1998)
RXJ0440.9+4431	203	3.2	$3.0{\cdot}10^{34}$	Reig & Roche (1999b)
AXJ1749.2-2725	220	8.5	$2.6{\cdot}10^{35}$	Torii et al. (1998)
GX304-1	272	2.4	$1.0{\cdot}10^{36}$	Apparao (1994)
4U1145-619	292	0.5	$7.4{\cdot}10^{34}$	Apparao (1994)
4U2206+54	392	2.5	$2.5{\cdot}10^{35}$	Saraswat & Apparao (1992)
A1118-616	405	5	$5.0{\cdot}10^{36}$	Apparao (1994)
1SAXJ1452.8-5949	437	9	$8.7{\cdot}10^{33}$	Oosterbroek et al. (1999)
AXJ1700062-4157	715	10	$7.2{\cdot}10^{34}$	Torii et al. (1999)
X Persei	836	0.83	$1.9{\cdot}10^{35}$	Haberl (1994)
RXJ1037.5-5647	860	5.0	$4.5{\cdot}10^{35}$	Reig & Roche (1999b)
RXJ0146.9+6121	1412	2.5	$3.5{\cdot}10^{35}$	Haberl et al. (1998)
A0114+65		2.6	$1.7{\cdot}10^{34}$	Motch et al. (1997)
Gamma Cas		0.188	$3.9{\cdot}10^{34}$	Apparao (1994)
1E0236.6+6100		3.1	$2.0{\cdot}10^{34}$	Motch et al. (1997)
1H0521+373			$4.0{\cdot}10^{33}$	Apparao (1994)

tion about 15 My ago while relatively few massive early-type stars were born during the last few million years.

It is remarkable that the Large Magellanic Cloud (LMC) may also have experienced a burst of star formation about 16 My ago as was derived from optical photometric surveys by Harris et al. (1999). LMC and SMC resemble in the relative composition of their X-ray binary populations, both rich in HMXBs but very few old low-mass X-ray binaries (Cowley et al. 1999), suggesting a common star formation history triggered by tidal interaction during close encounters of LMC, SMC and Milky Way. However, according to present day modeling the last encounter occurred ∼0.2 Gy ago (Gardiner & Noguchi 1996), too early for the formation of the Be/X-ray binaries we see today in X-rays. Therefore, the event which caused the origin of the frequent SMC (and LMC?) Be/X-ray binaries remains still unclear. Also the different numbers of HMXBs detected in LMC and SMC relative to their total mass need to be explained.

6. Notes to individual sources

In the following notes X-ray source numbers refer to the catalogues of Wang & Wu (1992) for Einstein IPC, of HFPK00 for ROSAT PSPC and of Sasaki et al. (2000b) for ROSAT HRI. Finding charts with X-ray error circles are shown in Figs. 3, 4, 5, and 6, for SSSs, already identified Be/X-ray binaries, unidentified X-ray pulsars and new Be/X-ray binary candidates, respectively. The order within each group of sources follows Table 1 and for faster access to the table entry the running number is given together with source name.

6.1. Supersoft sources

7) RX J0048.4–7332: The SSS RX J0048.4–7332 was discovered by Kahabka et al. (1994) and identified as the symbiotic M0 star SMC 3 by Morgan (1992). This star is listed in MA93 as object 218 and classified as late type star, consistent with the spectral type determined by Morgan (1992). The accurate HRI position (source 23) confirms the identification of the PSPC source (512).

39) 1E 0056.8–7154: This SSS was discovered in Einstein data (Inoue et al. 1983) and was detected with ROSAT PSPC (source 47) and HRI (79). It coincides in position with the SMC planetary nebula N67 (Aller et al. 1987) which is listed as object 1083 in MA93.

41) RX J0059.6–7138: This very soft source was discovered by HFPK00 (PSPC 51) and proposed as new SSS due to its positional coincidence with the planetary nebula LIN 357 (1159 in MA93) in the SMC.

6.2. Optically identified Be/X-ray binaries

1) RX J0032.9–7348: Stevens et al. (1999) identified two Be stars within the PSPC error circle of RX J0032.9–7348, discovered by KP96 as variable source with hard X-ray spectrum. The a factor of $\sim$5 smaller error radius obtained from a different PSPC observation by HFPK00 (source 567), however, still contains both Be stars which are very close to each other (Fig. 4). The two stars were not covered by the survey of MA93.

9) AX J0049–729: Yokogawa & Koyama (1998a) reported X-ray pulsations in ASCA data of this source. Kahabka & Pietsch (1998) suggested the highly variable source RX J0049.1–7250 (KP96) as counterpart. Stevens et al. (1999) identified two Be stars, one only $3''$ from the X-ray position and one just outside the error circle given by KP96. The revised position of PSPC source 351 in HFPK00 makes the more distant Be star further unlikely as counterpart (see Fig. 4). None of the two Be stars turns up in the list of emission-line objects of MA93 with the nearest entry (279) $58''$ away.

13) AX J0051–733: Yokogawa & Koyama (1998b) discovered X-ray pulsations from this source in ASCA data. The X-ray source was detected in Einstein IPC, ROSAT PSPC and HRI archival data and the 18 year history shows flux variations by at least a factor of 10 (Imanishi et al. 1999). Cowley et al. identified already 1997 a Be star as optical counterpart of the ROSAT HRI source RX J0050.8–7316 (HRI 34) which is located within the ASCA error circle. Cook (1998) reported a 0.708 d period from this star using data from the MACHO collaboration. The source was also detected by the PSPC (source 444) and coincides with object 387 in MA93.

16) AX J0051–722: Corbet et al. (1998b) reported 91 s X-ray pulsations from ASCA observations of this pulsar which was originally confused with the nearby 46 s pulsar XTE J0053-724 in XTE data. AX J0051–722 was not detected by the PSPC. An HRI detection reduced the position uncertainty and Stevens et al. (1999) identified a Be star as likely optical counterpart. The X-ray source is found as source 37 in the HRI catalogue and the star is identical to the only emission-line object from MA93 (413) in the ASCA error circle.

19) RX J0051.9–7311: This X-ray source was detected by Cowley et al. (1997) during ROSAT HRI observations of Einstein IPC source 25 and identified with a Be star by Schmidtke et al. (1999). It is identical to PSPC source 424 and HRI 41. The Be star is found as object 504 in MA93.

20) RX J0051.8–7231: This source was reported as strongly X-ray variable by KP96 and is associated with the X-ray pulsar 2E 0050.1–7247 (Israel et al. 1997). Observed X-ray luminosities range between $5\cdot10^{34}$ erg s^{-1} and $1.4\cdot10^{36}$ erg s^{-1} (Israel et al. 1997). The star AzV 111 (object 511 in MA93) was proposed as counterpart for 2E 0050.1–7247 while Israel et al. (1997) identified another H_α active star within their error circle of RX J0051.8–7231 which is larger than that of KP96. Also the position error given for the corresponding PSPC source 265 by HFPK00 is large. The detection of the source in the PSPC observation 600453p (used by KP96) where the source was bright was rejected by the semi-automatic analysis of HFKP99 because the detection was close to the support structure of the detector entrance window. A careful analysis (and using the latest processed data of 600453p) of the photons of the source in the detector frame shows, however, that it moved nearly parallel to the window support structure and that it was not affected by it. In Table 1 therefore the parameters derived from this PSPC observation are given. They confirm the results of KP96 with small error circle (see Fig. 4). Both AzV 111 and star 1 of Israel et al. (1997) are outside this error circle which, however, contains a Be star identified by Stevens et al. (1999). This star is found as object 506 in MA93 and is the most probable counterpart of RX J0051.8–7231.

22) SMC X–3: This long-known X-ray source was not detected by the ROSAT PSPC but is included in the HRI catalogue as source 43. The Be star counterpart (e.g. Crampton et al. 1978) corresponds to object 531 in MA93.

23) RX J0052.1–7319: Lamb et al. (1999) reported X-ray pulsations from the variable source RX J0052.1–7319 (KP96) found in ROSAT HRI and CGRO BATSE data. Israel et al. (1999) identified a Be star as likely optical counterpart. It is found in MA93 as object 552 and was detected as X-ray source by IPC (29), PSPC (453) and HRI (44). The strong X-ray variability by a factor of $\sim$200 between different HRI observations (Kahabka 2000) strongly supports the identification as Be/X-ray binary.

24) 2E 0051.1–7304: For this source, listed as entry 31 in the Einstein IPC source catalogue of Wang & Wu (1992), the Be star AzV 138 (Garmany & Humphreys 1985) was proposed as optical counterpart. AzV 138 corresponds to object 618 in MA93. 2E 0051.1–7304 was not detected in ROSAT observations.

25) RX J0052.9–7158: This source was detected as X-ray transient by Cowley et al. (1997) during ROSAT HRI observations of Einstein IPC source 32 (the largest circle in the finding chart of Fig. 4. Upper limits derived from PSPC observations imply flux variations by at least a factor of $\sim$350 (Cowley et al. 1997). The strong variability and the hard X-ray spectrum imply a Be/X-ray transient consistent with the suggested Be star counterpart (Schmidtke et al. 1999). The Be star is identical to object 623 in MA93. The X-ray source was detected by ROSAT (PSPC 94 and HRI 46, the HRI position is most accurate as indicated by the smallest error circle in the finding chart of Fig. 4) and is located near the edge of the error circle of XTE J0054-720. Due to the large position uncertainty of XTE J0054-720 it is, however, not clear if they are identical.

28) SMC X–2: The long known Be/X-ray binary SMC X–2 was caught in outburst with 0.4 cts s^{-1} by the ROSAT PSPC (source 547, see KP96 and references therein). Another PSPC observation yielded an upper limit indicating X-ray variability of more than a factor of 670. Optical spectra of the Be counterpart were taken by e.g. Crampton et al. (1978). The Be star is

located on the rim of the PSPC error circle (Fig. 4) and is not contained in the MA93 catalogue.

31) XTE J0055–724: X-ray pulsations from this source were discovered by RXTE (Marshall & Lochner 1998) and confirmed in a SAX observation (Santangelo et al. 1998). Santangelo et al. (1998) also report pulsations from archival ROSAT data reducing the positional uncertainty. Stevens et al. (1999) identified a Be star as optical counterpart which corresponds to object 810 in MA93 and which is inside the error circle of PSPC source 241 and HRI source 58.

38) RX J0058.2–7231: RX J0058.2–7231 was detected as weak HRI source by Schmitdke et al. (1999) and identified with a Be star. It is contained in the HRI catalogue (source 76) but not found in the PSPC catalogue of HFPK00. The Be star is not detected in the emission-line star surveys of MA93 and MB99.

40) RX J0059.2–7138: This transient X-ray pulsar with peculiar soft component in the X-ray spectrum was discovered by Hughes (1994) during an outburst with a 0.2 – 2.0 keV luminosity of $3.5 \cdot 10^{37}$ erg s^{-1}. The X-ray source was identified with a Be star by Southwell & Charles (1996) as star 1 in their finding chart which is identical to the emission-line object 179 in MB99.

42) RX J0101.0–7206: This source was suggested as X-ray transient by KP96 with a flux variability of at least a factor of 30. Stevens et al. (1999) identified a Be star as optical counterpart. Object 1 in their Fig. 1f corresponds to entry 1240 in MA93.

49) SAX J0103.2–7209: Israel et al. (1998) reported X-ray pulsations from this source consistent in position with the Einstein source 1E 0101.5–7225. They confirm the Be star suggested as counterpart for the Einstein source by Hughes & Smith (1994) as the only object in the SAX error circle showing strong H_α activity. OGLE observations presented by Coe & Orosz (2000) confirm this. The Be star corresponds to object 1367 in MA93 and was also detected by PSPC (source 143) and HRI (101).

58) XTE J0111.2–7317: Chakrabarty et al. (1998a) reported X-ray pulsations found in RXTE data from this source located about 30′ from SMC X–1. Wilson & Finger (1998) confirmed the pulsations from CGRO BATSE data and Chakrabarty et al. (1998b) derived an improved position from ASCA data. Two Be stars were identified by Israel et al. (1999) within or near the ASCA error circle of 30″. The closer of the two was concluded as most likely counterpart of XTE J0111.2–7317 by Coe et al. (1999). This Be star has no counterpart in MA93. A week source with existence likelihood of 14.5 is found in the PSPC catalogue (446). The large error circle of 61″ overlaps with the ASCA one and includes the position of the Be star. There is an additional MA93 object (1731) within the RXTE error circle and the second Be star found by Israel et al. (1999) is identical to object 1747 in MA93 but both are outside the ASCA and PSPC confidence regions (see Fig. 4).

59) RX J0117.6–7330: Similar to the previous source X-ray pulsations were discovered from the X-ray transient RX J0117.6–7330 (Clark et al. 1997) in ROSAT PSPC and CGRO BATSE data (Macomb et al. 1999). Between two PSPC observations, about 8 months apart, the count rate diminished by a factor of 270. Clark et al. (1997) identified a Be star counterpart which is identical to object 1845 in MA93 and also within the error circle of X-ray source 506 in the SMC PSPC catalogue.

6.3. Optically unidentified X-ray pulsars

10) AX J0049–732: AX J0049–732 was discovered as X-ray pulsar by Imanishi et al. (1998). Filipović et al. (2000b) reported two hard X-ray point sources from the catalogue of HFPK00 as possible counterparts to the ASCA pulsar. They suggest one of them (PSPC source 427) as the more likely counterpart due to its identification with an emission-line object in MA93 (number 300).

25) XTE J0054–720: The position of this X-ray pulsar could only be determined to an accuracy of 10′ radius (Lochner et al. 1998). There are at least five X-ray sources detected by the HRI within that circle (labeled 1 through 5 in Fig. 5 which correspond to the catalogue sources 55, 50, 62, 59 and 46, respectively). Object 2, 4 and 5 were also detected by the PSPC (104, 157 and 94). The southern of the three (also detected by IPC, 36) is proposed as active galactic nucleus (AGN) by HFPK00 and the northern (PSPC 94, HRI 46, IPC 32?) was identified as Be/X-ray transient RX J0052.9-7158 (see Sect. 6.2.2). The Be star counterpart of RX J0052.9-7158 coincides with object 623 in MA93. It is not clear if this Be/X-ray binary is identical to the RXTE pulsar. A final identification requires the detection of pulsations from RX J0052.9-7158.

27) XTE J0053–724: Corbet et al. (1998a) discovered this pulsar and report a ROSAT source within the error box. The pulse period, originally confused with AX J0051–722, was clarified by Corbet et al. (1998b). HFPK00 give source 242 as likely counterpart of XTE J0053–724. A single emission-line object from MA93 (717) is found inside the intersecting error circles of IPC source 34 and the PSPC source.

35) AX J0058–720: X-ray pulsations from this source were discovered by Yokogawa & Koyama (1998b) in ASCA observations. The source was detected in archival Einstein IPC, ROSAT PSPC and HRI data which span 18 years and showed flux variations by more than a factor of 100 (Tsujimoto et al. 1999). This high variability already strongly suggests a Be/X-ray binary. A single emission-line object from MA93 (1036) is found within the PSPC error circle (source 114) which is also consistent with the HRI position (73). It is not clear whether IPC source 41 originates from the same X-ray source. It may also be associated with another emission-line object (1039 of MA93) closer to the IPC position or completely unrelated.

53) AX J0105–722: Yokogawa & Koyama (1998c) reported AX J0105–722 as X-ray pulsar. From several nearby objects in MA93 number 1517 is closest to the X-ray position of PSPC source 163. This PSPC source was identified as likely counterpart of the ASCA pulsar in an area of complex X-ray emission by Filipović et al. (2000a) combining the ROSAT X-ray and radio data. The star 1517 in MA93 is the northern and bluer component of a pair of stars close to the error circles of PSPC and HRI detection (110). The nearby IPC source 53, 77″ to

the north-east is most likely associated to the SNR DEM S128 (Filipović et al. 2000a).

6.4. New Be/X-ray binary candidates

2) RX J0041.2–7306: HFPK00 classified PSPC source 404 as foreground star based on the hardness ratios. An emission-line object in the error circle is classified as planetary nebula by MA93 indicating a chance positional coincidence. This makes the identification with the bright star just outside the error circle most likely.

3) RX J0045.6–7313: This source (PSPC 436) was detected once in the 0.9 – 2.0 keV band of the PSPC. An emission-line object in the error circle suggests an Be/X-ray binary.

5) RX J0047.3–7239: The PSPC error circle of RX J0047.3–7239 (source 295) overlaps with that of IPC source 19. An emission-line object (168 in MA93 and classified as late type star) and two radio sources from the catalogue of Filipović et al. (1998) are located in the X-ray confidence region. A point-like radio source as counterpart would favour an AGN identification leaving the nature of RX J0047.3–7239 ambiguous.

6) RX J0047.3–7312: RX J0047.3–7312 (PSPC 434) is most likely identified with the emission-line star 172 in MA93. The fluxes derived from PSPC detections show a factor of nine variations, supporting that the X-ray source is a Be/X-ray binary. RX J0047.3–7312 is probably identical to IPC source 18, which showed an intensity within the range observed by the PSPC. It is also the likely counterpart of ASCA source 2 in Yokogawa (1999; see Sect. 3), an X-ray binary candidate detected with similar intensity.

8) RX J0048.5–7302: The emission-line object 238 in MA93 is the brightest optical object in the error circle of RX J0048.5–7302 (PSPC 392). A Be/X-ray binary is suggested.

11) RX J0049.5–7331: An HRI detection (source 28) with much improved X-ray position compared to the PSPC (source 511) confirms the identification with the emission-line object 302 in MA93. RX J0049.5–7331 is the probable counterpart of ASCA source 6 in Yokogawa (1999; see Sect. 3) further supporting the likely Be/X-ray binary nature.

12) RX J0049.7–7323: This source (PSPC 468) was detected once in the 0.9 – 2.0 keV band of the PSPC. An emission-line object in the error circle suggests an Be/X-ray binary. RX J0049.7–7323 is also the likely counterpart of ASCA source 7 in Yokogawa (1999), classified as X-ray binary candidate (see Sect. 3).

14) RX J0050.7–7332: RX J0050.7–7332 was only once detected by the PSPC (514) and the emission-line object in the error circle suggests a Be/X-ray binary identification.

15) RX J0050.9–7310: HRI (source 36) and PSPC (source 421) detections are consistent with the identification of RX J0050.9–7310 with the emission-line object 414 in MA93, suggesting a Be/X-ray binary.

17) RX J0051.3–7250: Two close emission-line objects suggest RX J0051.3–7250 (PSPC 349) as Be/X-ray binary, but make the identification ambiguous.

18) RX J0051.8–7159: The emission-line object 502 (MA93) found in the error circle of RX J0051.8–7159 (PSPC 99) is classified as late type star in MA93. An active corona of this star may be producing the X-ray emission. The large error circle contains, however, another bright object which could also be responsible for the X-rays. The nature of RX J0051.8–7159 remains therefore unclear.

21) WW 26: Two emission-line objects from MA93 are found near IPC source 26 (hardness ratio 0.51, WW92). Object 521 is located inside the error circle while 487 can not be completely ruled out as counterpart. No ROSAT detection could improve on the position. A Be/X-ray binary nature is suggested.

26) RX J0053.4–7227: A precise HRI position (source 48 at the rim of the error circle of PSPC 246) with the emission-line star 667 (MA93) as brightest object in the error circle makes RX J0053.4–7227 a likely Be/X-ray binary.

29) RX J0054.5–7228: The uncertainty in the position of RX J0054.5–7228 (PSPC 248) is relatively large and six emission-line objects from MA93 are found as possible counterparts to the X-ray source. It is therefore a likely Be/X-ray binary but the optical counterpart remains ambiguous.

30) RX J0054.9–7245: Precise ROSAT X-ray positions (PSPC 324 = HRI 57) include an emission-line star (809 in MA93) with typical Be star magnitudes as brightest object in the error circles. A factor of five X-ray flux variability (the source was bright during a HRI observation) strengthens the identification as Be/X-ray binary.

32) WW 38 = 2E 0054.4–7237: An emission-line object (904 in MA93) is found inside the error circle of IPC source 38 suggesting a Be/X-ray binary. The source was not detected by ROSAT.

33) RX J0057.2–7233: This weak PSPC source (270) was marginally detected once in the hard 0.5 – 2.0 keV band with a likelihood of 10.4. Unlike all other hard sources in Table 1 it was not detected in the 0.9 – 2.0 keV band and therefore is unlikely a Be/X-ray binary.

34) WW 40 = 2E 0055.8–7229: The error circle of IPC source 40 contains two emission-line objects from MA93. Object number 1021 is identified as Be star AzV 111 while 1016, located further north, is of unknown type. ROSAT detected an X-ray source inside the IPC error circle (HRI 71 and PSPC 117 with consistent positions) which, however, is located between the two emission-line objects. The relation between the ROSAT and the Einstein source and the emission-line objects is unclear. IPC, HRI and PSPC count rates are consistent within a factor of two, which may indicate that they come from the same X-ray source. However, the accurate ROSAT positions make an association with one of the nearby objects from MA93 unlikely.

36) RX J0057.8–7207: Again small error circles from ROSAT HRI (source 74) and PSPC (source 136) observations make the identification of RX J0057.8–7207 with an emission-line star (1038 in MA93) very likely. PSPC detections with factor of eight different intensities and an HRI detection during an X-ray bright state which increases the variability to a factor of about 37, make a Be/X-ray binary nature highly probable.

37) RX J0057.9–7156: Be/X-ray binary candidate from positional coincidence of PSPC source 87 with emission-line object 1044 in MA93 which shows typical optical brightness.

43) RX J0101.3–7211: PSPC detections of this source (PSPC 159 = HRI 95) indicate flux variations by at least a factor of 15 and the source was not detected in other observations (upper limit a factor of 100 below the maximum count rate). This high variability and the presence of an emission-line star (1257 in MA93) in the small X-ray error circles likely exclude any other explanation than a Be/X-ray binary. It also is the likely counterpart of ASCA source 27 in Yokogawa (1999; see Sect. 3), an X-ray binary candidate.

44) RX J0101.6–7204: Two accurate positions from HRI (source 96) and PSPC (source 121) observations suggest the identification of RX J0101.6–7204 with object 1277 in MA93. The factor of three variability supports a Be/X-ray binary nature of RX J0101.6–7204 which is probably identical to the IPC source 46 in WW92.

45) RX J0101.8–7223: RX J0101.8–7223 (PSPC 220 = HRI 97) shows X-ray flux variations of a factor of three. The emission-line star 1288 (MA93) exhibits magnitudes typical for a Be star in the SMC and is located near the overlapping area of HRI and PSPC error circles. We suggest RX J0101.8–7223 as Be/X-ray binary as it is also the probable counterpart of ASCA source 28 in Yokogawa (1999; see Sect. 3), an X-ray binary candidate.

46) RX J0102.8–7157: This weak PSPC source (92) was only once marginally detected in the broad 0.1 – 2.4 keV band. The low detection likelihood of 10.5 and the non-detection in the hard bands indicates that it may not be real, or is at least not a hard source. A Be/X-ray binary nature is therefore unlikely.

47) WW 49: The IPC source 49 (WW92 give a hardness ratio of 0.21) contains a faint emission-line object (1357 in MA93) classified as planetary nebula. The spectral hardness of the IPC source is inconsistent with an SSS interpretation. The positional coincidence is likely by chance.

48) RX J0103.1–7151: This source was detected only once by the PSPC (source 77) and the lowest upper limit indicates variability by at least a factor of five, suggesting the detection of a single outburst. The emission-line object near the rim of the PSPC error circle is, however, the optically weakest (see Table 1), unusual in comparison with identified Be/X-ray binaries and candidates derived from this work. We therefore do not regard RX J0103.1–7151 as prime candidate for a Be/X-ray binary.

50) RX J0103.6–7201: Small error circles from HRI (source 105) and PSPC (source 106) observations make the identification with object 1393 in MA93 very likely. RX J0103.6–7201 shows variability by a factor of three between the ROSAT observations, consistent with a Be/X-ray binary.

51) RX J0104.1–7243: Two emission-line objects and a radio source from the catalogue of Filipović et al. (1998) close to RX J0104.1–7243 (PSPC 317) make the identification somewhat ambiguous. The most likely identification with emission-line star 1440 in MA93 suggests RX J0104.1–7243 as Be/X-ray binary.

52) RX J0104.5–7121: This source was not detected by the PSPC but the accurate HRI position (source 108) includes only the emission-line object 1470 from MA93 as bright object in the error circle. RX J0104.5–7121 is therefore very likely a Be/X-ray binary.

54) RX J0105.7–7226: An emission-line star (1544 in MA93) in the PSPC error circle (737) suggests RX J0105.7–7226 as Be/X-ray binary.

55) RX J0105.9–7203: A single bright object (the emission-line star 1557 in MA93) is found in the small PSPC error circle (source 120), which makes the identification of RX J0105.9–7203 as Be/X-ray very likely.

56) RX J0107.1–7235: The probable PSPC detection (279) of IPC source 56 improves the X-ray position and allows to identify it with the emission-line star 1619 in MA93. The source was a factor of 10 brighter during the Einstein observation and is also the likely counterpart of ASCA source 36 in Yokogawa (1999; see Sect. 3) detected with a factor $\sim$4 higher intensity. A Be/X-ray binary nature is likely.

57) RX J0109.0–7229: The emission-line object 1682 in MA93 is classified as planetary nebula. X-ray sources associated with planetary nebulae appear as SSSs which is not compatible with the hard spectrum of RX J0109.0–7229 (PSPC 253). The positional coincidence of RX J0109.0–7229 is therefore by chance and the nature of the X-ray source is unclear.

60) RX J0119.6–7330: This source (PSPC 501) was detected once in the 0.9 – 2.0 keV band of the PSPC. An emission-line object in the error circle suggests a Be/X-ray binary.

7. Summary

We reviewed the identification of eighteen known Be/X-ray binaries in the SMC and found that thirteen of them are listed in emission-line object catalogues of Meyssonier & Azzopardi (1993) and Murphy & Bessell (1999). From a general correlation of SMC X-ray source and H_α emission-line object catalogues we propose optical counterparts for the five optically unidentified X-ray pulsars and present 25 new Be/X-ray binary candidates together with their likely optical counterparts. This more then doubles the number of know high mass X-ray binary systems in the SMC.

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