SOFT X-RAY OBSERVATION OF SUPERNOVA REMNANTS IN THE SMALL MAGELLANIC CLOUD

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The Small and Large Magellanic Clouds (SMC and LMC) are the nearest neighbouring galaxies. Their proximity enables us to investigate these galaxies in X-rays in fair detail.

Seward and Mitchell (1981) conducted a complete survey of the SMC from the *Einstein* Observatory, consisting of 40 IPC pointings with an exposure of ∿2000 sec each. 26 sources were detected above a threshold $L_X = 3 \times 10^{35} \mathrm{erg\ s^{-1}}$, if in the SMC. Excluding 5 foreground stars, 10 are distributed in the bar and the spiral arm regions, while the remaining 11 are widely distributed over the ourskirt of the Cloud.

We present the result of the observations of the SMC from the *Einstein* Observatory in which deep exposure of the selected regions of the SMC was performed in order to search for SNR's and SNR-related structures.

1. OBSERVATIONAL RESULTS

Our observation comprises three IPC frames with exposures in excess of 20,000 sec for each, and subsequent three HRI frames with exposures of 13,000 ∿ 18,000 sec. The IPC fields are chosen so as to cover the regions where HI, HII and radio structures are most prominent. Fig.1 shows a mosaic of 7 IPC maps in which 4 maps of Gull and Bruhweiler are included with their kind permission. Presence of X-ray sources besides those reported by Seward and Mitchell are evident.

In our three IPC fields, 25 significant sources are selected in total at a confidence level greater than 3σ. These sources are listed in Table I. Positional coincidence with radio sources and/or HII regions of Davies, Elliot and Meaburn (DEM) (1976) are also indicated. The tabulated X-ray luminosity values are those estimated on the assumption that 1 IPC count $\mathrm{s^{-1}}$ from an SMC source corresponds to $L_X \cong 2 \times 10^{37}$ $\mathrm{erg\ s^{-1}}$ in the energy range 0.15 – 4.0 keV. The interstellar absorption in the SMC tends to give substantial underestimates of the luminosity and overestimates of the hardness ratio. The neutral hydrogen column density in the chosen IPC fields ranges $(2 - 4) \times 10^{21}\ \mathrm{cm^{-2}}$ in the SMC

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Image Centers for Our Fields RA(h,m,s)	Dec(°,',")
00 45 00	-73 30 00
00 54 00	-72 32 00
01 00 00	-72 10 59

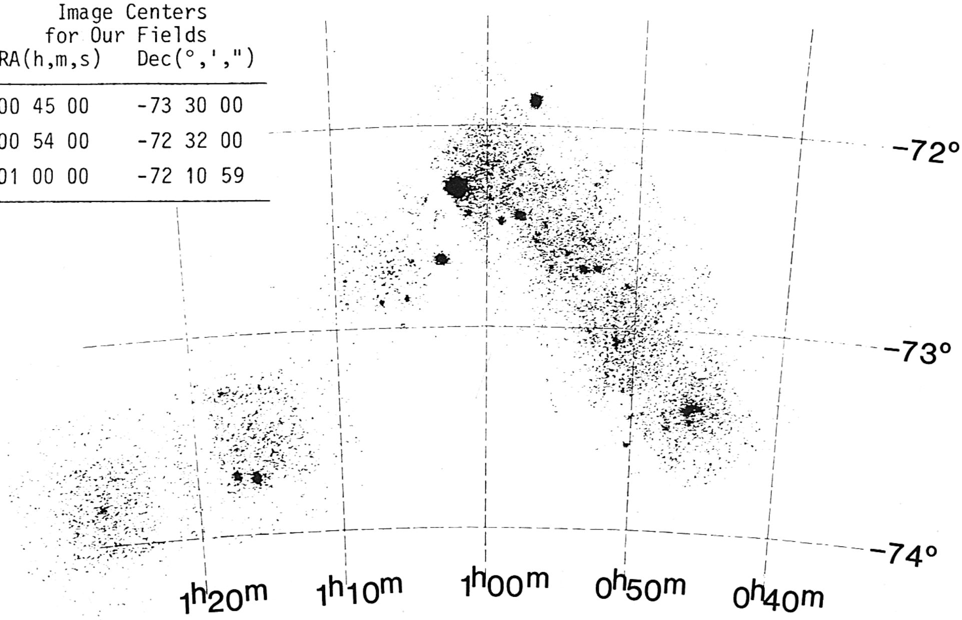

Fig.1 Mosaic of 7 IPC maps. 4 IPC maps by Gull and Bruhweiler are included by their courtesy. (equinox: 1950)

Table I Soft X-Ray Sources Detected

SOURCE NO.	RA (1950) (h,m,s)	Dec(1950) (°,',")	COUNT RATE (s^{-1})	L_X(0.15–4 keV) ($\times 10^{35}$ erg s^{-1})	H(1.5 –4.0keV) / S(0.15 –1.5keV)	H - S / H + S	COMMENTS	ASSOCIATIONS
1	00 45 32	-73 28 51	0.012 ± 0.001	2.4	0.88 ± 0.20	-0.06		
2	00 45 34	-73 25 21	0.029 ± 0.002	5.8	0.31 ± 0.05	-0.56	extended(2.8') or plural	Radio SNR, DEM32
3	00 46 05	-73 21 21	0.003 ± 0.001	0.6				DEM31(N19)
4	00 46 22	-73 35 19	0.003 ± 0.001	0.6				Radio SNR, DEM42(N24)
5	00 47 15	-73 30 15	0.003 ± 0.001	0.6				DEM49?
6*	00 49 33	-73 38 08	(0.015)*	(3.0)*				Radio SNR
7	00 49 54	-73 26 48	0.023 ± 0.001	4.6	0.21 ± 0.07	-0.65		DEM60?
8	00 50 22	-73 35 09	0.015 ± 0.001	3.0	0.63 ± 0.26	-0.23		DEM70
9	00 51 13	-72 14 46	0.003 ± 0.001	0.6				
10	00 52 17	-72 42 46	0.012 ± 0.001	2.4	0.28 ± 0.19	-0.57		
11	00 53 20	-72 42 46	0.006 ± 0.001	1.2	8.0	0.78		
12	00 54 01	-72 44 37	0.003 ± 0.001	0.6				
13	00 54 27	-72 38 07	0.005 ± 0.001	1.0				DEM86
14	00 55 42	-72 42 10	0.008 ± 0.001	1.6	0.81 ± 0.49	-0.10		
15	00 55 55	-72 29 59	0.004 ± 0.001	0.8				
16	00 56 37	-72 33 55	0.005 ± 0.001	1.0				
17*	00 56 54	-71 52 03	0.085 ± 0.003	17.0	0	-1.0	HRI: point-like	Foregr.Star?
18*	00 57 46	-72 26 17	0.029 ± 0.002	5.8	0.43 ± 0.09	-0.40		Radio Em., DEM103(N66)
19	00 59 07	-72 27 46	0.008 ± 0.001	1.6				
20	01 00 05	-72 11 10	0.007 ± 0.002	1.4			extended(∿4') or plural	DEM115(N74),DEM116(N75)
21*	01 01 31	-72 25 52	0.012 ± 0.002	2.4	0.93 ± 0.55	-0.04		Radio SNR
22*	01 02 25	-72 18 00	0.783 ± 0.007	157	0.38 ± 0.01		HRI: extended	Radio SNR, DEM124
23*	01 03 23	-72 39 20	0.084 ± 0.004	16.8	0.15 ± 0.03	-0.74	HRI: extended	Radio SNR, DEM125
24	01 03 45	-72 28 30	0.013 ± 0.002	2.6	0.50 ± 0.14	-0.33	extended(∿3') or plural	DEM128
25	01 04 34	-72 22 10	0.017 ± 0.002	3.4	0.15 ± 0.12	-0.74		DEM131

* Sources previously detected by Seward and Mitchell (1980).

added to that in our galaxy of $(3\text{-}3.5)\times10^{20}cm^{-2}$ (McCammon et al. 1976). Therefore, the X-ray luminosities given in Table I may be regarded as lower limits, apart from a spectrum-dependent uncertainty of the order of a factor of 2. In the present observations, the lowest luminosity of the detected sources, if in the SMC, is $L_X=6\times10^{34}erg\ s^{-1}$ without taking into account the above absorption effect. The detection of sources near this luminosity threshold is not yet complete, however.

2. SOURCE IDENTIFICATION

1) SNR's

Of 25 sources detected, 6 (No's. 2,4,6,21,22 and 23) are identified with the radio SNR's. Mills et al.(1982) identified 6 radio SNR's with the Molonglo Observatory Synthesis Telescope (MOST) from the observations of 18 targets including 16 X-ray sources of Seward and Mitchell (S.M.). Mathewson et al.(1982) subsequently confirmed these 6 sources to be the optical SNR's. All of these 6 radio/optical SNR's are coincident in position with the X-ray sources, 4 of 6 being the S.M. sources. 2 of the 6 SNR's had been previously identified as SNR's by Mathewson and Clarke (1972, 73).

2) Suspected SNR's

Source No.18 is coincident in position with a radio source of Mills et al. (MOST 0057-724). Although evidence for the non-thermal nature of the radio is not firm, we tentatively identify this to be an SNR.

In addition to this, 3 more possible SNR's are selected from the consideration of the hardness ratio. Hardness ratios of the identified SNR's range from 0.15 to 0.9. On the other hand, compact binary X-ray sources with $kT > 3$ keV would give hardness ratios no smaller than 0.7, without taking account of the interstellar absorption in the SMC. 4 sources (No. 7, 10, 17 and 25) satisfy the criterion that the hardness ratio be significantly smaller than 0.7. The source No.17, the second brightest of the present catalog, is however found to be a point source by a subsequent HRI examination. As the source also exhibits an unusually soft spectrum ($kT < 0.1$ keV), we consider it to be a foreground star in our galaxy (no identification yet).

Two more sources, No.20 and 24, are suspected as SNR's. These sources appear extended by approximately 4' and 3', respectively, although a possibility of closely spaced multiple sources could not be totally ruled out. The observed soft X-ray enhancement in such extended regions as large as 80 pc across may be analog of hot bubbles observed in our galaxy. Thus, we have 6 identified plus 6 suspected SNR's in total.

3) Other sources

There remain 12 unidentified sources which are all of low luminosities in the range $L_X \lesssim 10^{35}$ erg s^{-1}. No cataloged galactic or extragalactic objects are coincident in position. The number of interlopers outside the SMC is estimated to be ∿5 for the lowest flux level, based on the detection of ∿0.7 serendipitous sources per square degree above 0.01 IPC counts s^{-1} with an assumed log N – log S slope of -1.5. The locations of these unidentified weak sources, when plotted on the optical image of the SMC, suggest that most of them are within the SMC and distributed along the bar and the arm. We believe that several of these sources with $L_X \lesssim 10^{35}$ erg s^{-1} are, if not all, SNR's in the SMC, since SNR's of this range of L_X are abundant in our galaxy.

3. HRI OBSERVATIONS OF SNR'S

We conducted HRI observations of three brightest sources (No.17, 22 and 23). No.22 and 23 clearly revealed shell-like structures as shown in Fig.2. No.17 was found point-like as mentioned in Section 3. Dopita, Tuohy and Mathewson (1981) reported that the source No.22 was a bright SNR in [OIII] emission with a slightly smaller diameter than that in X-rays. The radio shell of the source No.23 was also well resolved by Mills et al.(1981) and the X-ray and radio shell diameters are in good agreement with each other. The result of the HRI observation is summarized in Table II. If one assumes that these SNR's are in the adiabatic expansion phase, the X-ray luminosity L_X, shell radius r, and temperature kT would yield the initial energy E_0, age t and ambient gas density n_0 by utilizing the conventional shock wave model. n_0 can be estimated from L_X and r with a less model-dependent manner. Assuming a strong shock, $L_X \cong (\pi/3)r^3(4n_0)^2 \Lambda_X(T)$, where $\Lambda_X(T)$ is the X-ray emissivity which is roughly constant and ∿3 x 10^{-23} erg s^{-1}cm^3 for the range kT $\gtrsim$ 0.3 keV. Table II contains so derived n_0 from the HRI result and also for other SNR's for which the shell radius can be estimated on the high-resolution radio maps of Mills et al.. Estimation of E_0 and t are model dependent.

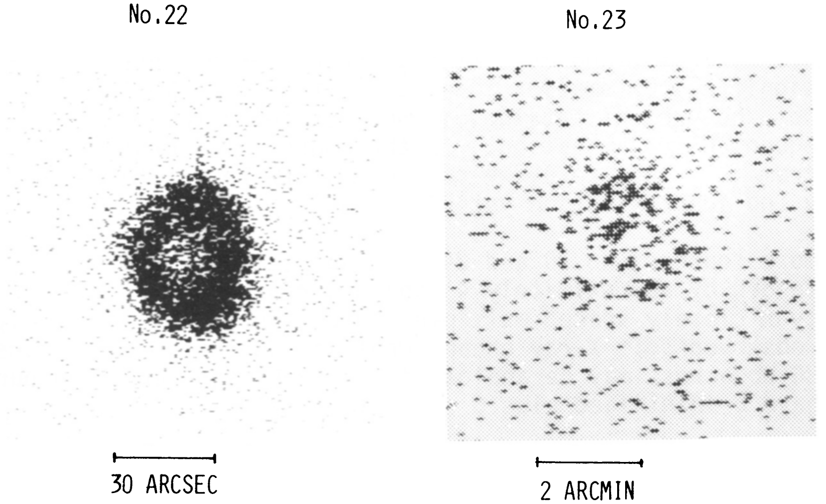

Fig.2 HRI images of No.22 and 23. Both reveal shell-like structures.

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Table II X-Ray and Radio SNR's in the SMC

Source No.	RA(1950) (h,m,s)	Dec(1950) (°,',")	L_X (10^{35} erg s^{-1})	Diameter	(pc)	kT (keV)	n_o (cm^{-3})	E_o (10^{51} erg)	t (10^3y)
2	00 45 34	-73 25 21	5.8	(4')(R) (2.8')(X)	(70) (50)	1.2±0.5	(0.03) (0.05)	(2.6) (1.6)	(16) (11)
4	00 46 22	-73 35 19	0.6	1.1'(R)	19		0.07		
6	00 49 33	-73 38 08	3.0	1.7'(R)	30		0.08		
21	01 01 31	-72 25 52	2.4	<40"(R)	<12		>0.27		
22	01 02 25	-72 18 00	157.	27"(X)	8	1.4±0.5	4.1	0.6	1.7
23	01 03 23	-72 39 20	17.	2.2'(X) 2.2'(R)	38	0.3±0.1	0.13	0.4	18

4. DISCUSSIONS

Long, Helfand and Grabelsky (1981) published their results of the *Einstein* observations of the LMC. In the 75 sources detected in the LMC above a threshold of 10^{35}erg s^{-1}, the identified and suspected SNR's are 25 and 11, respectively. The total number of SNR's in the LMC was estimated to be about 55. These numbers are to be compared with 6 identified and 6 suspected SNR's in 3 IPC fields of the SMC. The luminosity distribution of the identified and suspected SNR's in the SMC is shown in Fig.3 in comparison with that for the LMC (Long et al. 1981). No qualitative difference seems to exist. In the X-ray map of the SMC in Fig.1, there appear several more low-luminosity sources in the fields of Gull and Bruhweiler. While some of them may possibly be SNR's, the number of SNR's in the SMC with a luminosity $L_X \gtrsim 10^{35}$erg s^{-1}may not largely increase. We therefore conclude that the number of SNR's per unit mass is roughly the same in both the Clouds, since the mass ratio of the SMC to the LMC is about 1/5.

X-ray survey of SNR's in our galaxy is by far incomplete. On the other hand, radio searches for the galactic SNR's have been fairly

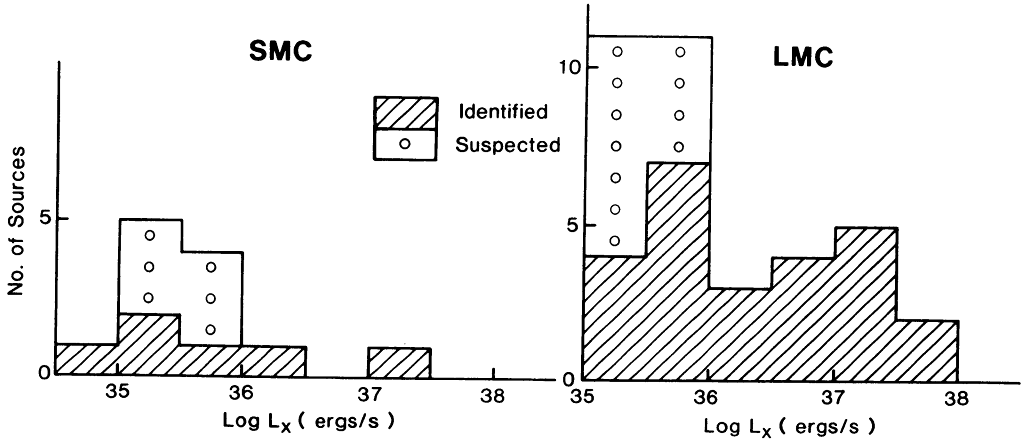

Fig.3 The luminosity distribution of the identified and suspected SNR's in the SMC. Result for the LMC (Long et al. 1981) is also shown for comparison.

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complete. Clark and Caswell (1976) list 120 radio SNR's in our galaxy, in which nearly 30 (and probably more by now) have so far been detected in the X-ray band. Since every X-ray observation of a radio SNR with the *Einstein* sensitivity yielded positive detection and few radio-silent SNR's (except 1E1149.4-6209, Markert et al. 1981) have been found in X-rays, we may safely rely upon the radio result and say that the number of galactic SNR's is not much greater than 120. If the SNR's with luminosities $L_X > 10^{35}$ erg s^{-1} are concerned, even a smaller number will result considering the fact that several of the SNR's so far detected are with luminosities less than 10^{35} erg s^{-1}.

Our galaxy is more massive by a factor of about 20 and 100 than the LMC and the SMC, respectively. If one extrapolates the numbers of SNR's observed in the LMC and the SMC to our galacy in proportion to the system mass, the expected number amounts to about 1000, which is nearly an order of magnitude greater than the probable one. It is an important question whether this discrepancy is due to a smaller occurrence rate of SNR's per unit mass in our galacy than in the Magellanic Clouds or otherwise due to a possibility that many SNR's in our galaxy escaped detection.

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