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Supernova remnant candidates in the Small Magellanic Cloud

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Summary. Eighteen SNR candidates in the SMC deriving from X-ray, optical and radio observations have been examined at a frequency of 843 MHz. Six SNRs are confirmed, all with flux densities far above the radio detection limit. Other identified radio sources from this sample include a quasar and an emission nebula. Comparison with Galactic SNRs suggest differences in the Σ–D and N–D relations, but the number of SNRs in the present sample is too small for good statistics. The birthrate of SNRs in the SMC is roughly estimated as ~ 1 every 1000 yr.

1 Introduction

The Magellanic Clouds are the only galaxies sufficiently close for a significant study of their supernova remnant populations using current instrumentation. Most attention has been directed towards the LMC but, as the result of an *Einstein Observatory* survey of X-ray sources in the region of the SMC (Seward & Mitchell 1981), many new supernova candidates have been detected there. Previously, two SNR identifications had been proposed by Mathewson & Clarke (1972, 1973), using a combination of optical and radio techniques, but neither of these are included among the X-ray sources.

Here we describe observations of all likely X-ray, optical and radio candidates using the Molonglo Observatory synthesis telescope at a frequency of 843 MHz. This instrument, which has a beamwidth of 43 arcsec and sub-millijansky sensitivity, was first operated in the synthesis mode in 1981 June and is currently undergoing extensive testing and further development. The performance during September–October was adequate to check the radio emission and morphology of these SNR candidates and in most cases to provide definitive answers. The existence of six SNRs has been confirmed.

2 Observations

A brief account of the Molonglo Observatory synthesis telescope (the MOST) has been given by Mills (1982). Details of the design and performance will be presented in subsequent publications. At the time of these observations the telescope was operating in the synthesis mode over a field of about 11 arcmin: day-to-day stability was good but the necessary automatic phase and gain controls had not then been introduced and there were noticeable diurnal variations of beam pointing and system gain. Nevertheless, useful maps were being produced with rms errors in position and flux density of ~ 2 arcsec and ~ 15 per cent respectively. Two observational modes were used.

(i) Full Synthesis. The selected field is tracked for 12 hr and a map generated in real time which is available at the end of the observation. These maps, later precessed to epoch 1950, are shown in the diagrams. The basic synthesized beam has a half-width of 43 arcsec at the pole and first sidelobes of -8 per cent; higher sidelobes are < 1 per cent. For present needs the negative sidelobe causes no problems, so the maps have not been 'cleaned' although an algorithm is available.

(ii) Sampled Field Synthesis. The telescope is directed to a number of fields sequentially with brief observations on each; the process is repeated throughout a 12-hr session, giving a number of observations on each of the selected fields at different position angles. From these observations, 'cleaned' maps may be generated or simply information on position, flux density and morphology obtained by inspection of the 'dirty' maps. Confusion from sources outside the map area is the main limitation of this observing mode.

Full synthesis maps were initially made of the most likely candidates, six of the X-ray sources plus the earlier two radio-optical identifications. A further 10 X-ray sources were observed using sampled field synthesis with seven observations of each field during a 12-hr observing session. Later, three of these fields were mapped using full synthesis. A summary of the observational results is given in Table 1. Upper limits for the peak flux density of undetected sources are about 3 mJy for the full synthesis fields and 20 mJy for the sampled fields.

3 The supernova remnants

Six radio sources have been selected as SNRs. Two have no associated X-ray source but these occur exactly on the boundaries of X-ray fields where the sensitivity is low. Upper limits to their X-ray luminosity have been provided by Seward (private communication). Radio maps of the SNRs are shown in Fig. 1 and their properties are summarized in Table 2. A distance of 59 kpc (McNamara & Feltz 1980) has been assumed in estimating their linear diameters from the angular dimensions. Optical sizes are taken from Mathewson *et al.* (1982). For comparison with data available at the more usual frequency of 1 GHz the radio brightness, Σ, has been calculated by assuming a spectral index of $\alpha = -0.45$.

0045 – 734 (Fig. 1a). This was the first SNR identified in the SMC as the result of a coincidence between a filamentary shell with strong [S II] emission and a Molonglo radio source (Mathewson & Clarke 1972). It is embedded in the emission nebula N19, and the present observations clearly show a bright radio source of the same size as the filamentary structure superimposed on the low-level background of thermal H II emission. Other radio measurements indicate a non-thermal spectrum, but confusion with the H II emission precludes determination of the spectral index.

Table 1. A summary of the observational results.

X-ray source	Radio source	Synthesis Mode	Nature of radio source
1E0007.4-7325	0007-734	Sampled	Unknown
1E0011.7-7458	None	Sampled	
1E0012.7-7308	None	Sampled + Full	
1E0021.3-7241	None	Sampled	
1E0025.7-7555	None	Sampled	
1E0031.7-7042	0031-707	Sampled	Quasar
1E0035.4-7230	None	Full	
	0045-734	Full	SNR
	0046-735	Full	SNR
1E0049.0-7125	None	Sampled	
1E0049.4-7339	0049-736	Full	SNR
1E0056.8-7154	None	Full	
1E0057.6-7228	0057-724	Full	Emission nebula
1E0059.0-7228	None	Sampled	
1E0101.3-7301	0101-730?	Sampled + Full	Unknown
1E0101.5-7226	0101-724	Sampled + Full	SNR
1E0102.2-7219	0102-723	Full	SNR
1E0103.3-7240	0103-726	Full	SNR

0046 – 735 (Fig. 1b). This SNR was also discovered by Mathewson & Clarke (1973) as the result of a coincidence between a radio source and a filamentary shell with strong [S II] emission. The present observations confirm the positional coincidence and show a radio source of typical shell-like structure, and size in close agreement with that of the optical shell. Several catalogued H II regions are nearby and, in particular, N24 is not completely resolved from the SNR. The flux density was obtained by subtracting the estimated flux density of N24 (20 mJy) from the integrated flux density of the complex. Because of the close proximity of this and other H II regions, previous measurements of the flux density were badly confused. No estimate of the radio spectral index has been made but it appears consistent with the mean SNR spectral index of $\alpha = -0.45$.

0049 – 736 (Fig. 1c). The radio source is non-thermal and has typical SNR morphology. The position given in Table 2 is at the centre of the shell and falls just outside the 1 arcmin radius of the X-ray error circle quoted by Seward & Mitchell (1981), but the X-ray position is close to the brightest part of the radio rim. There are no bright H II regions or strong radio sources close to 0049 – 736, so the radio spectral index of $\alpha = -0.4$ quoted by Mathewson *et al.* (1982) should be reliable. Note, however, that this index is based on peak flux densities. In view of the morphology, the coincidence with an extended soft X-ray source, and the non-thermal radio emission, identification with a SNR is secure.

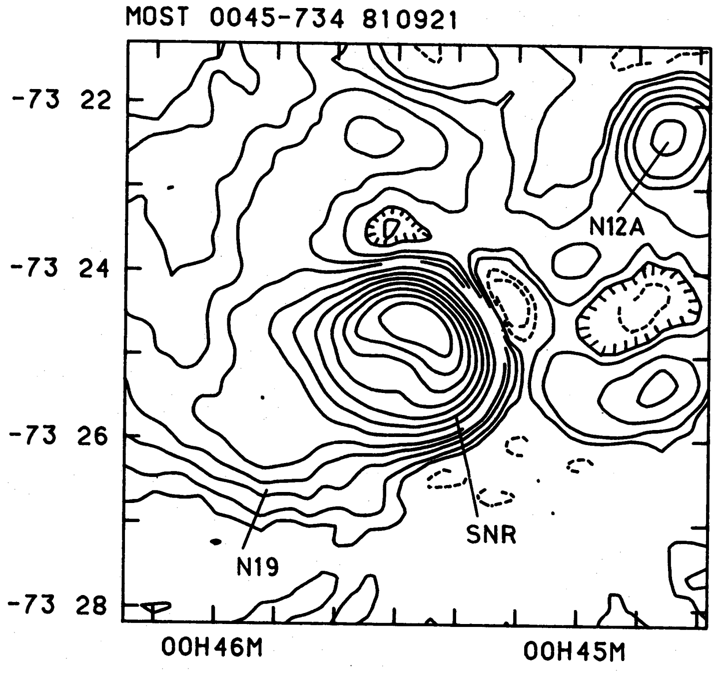
0101 – 724 (Fig. 1d). The centroid of the radio source is well within the 2 arcmin X-ray error circle and Mathewson *et al.* (1982) find typical SNR filamentary structure at its

Table 2. Properties of the supernova remnants.

Radio source	Position (1950)						Flux density	X-ray luminosity	Radio diameter	Optical diameter	Σ
	α			δ							
	h	m	s	°	′	″	mJy	10^{35} erg s^{-1}	pc	pc	10^{21} Wm^{-2} Hz^{-1} sr^{-1}
0045 – 734	00	45	26	–73	24	40	310	<7	26	26	19
0046 – 735	00	46	34	–73	35	50	150	<7	36	31	4.7
0049 – 736	00	49	24	–73	37	40	165	3	39		4.0
0101 – 724	01	01	38.3	–72	26	03	135	5	18		16
0102 – 722	01	02	24.2	–72	17	57	500	200	7.5	7	344
0103 – 726	01	03	34	–72	39	10	220	15	55	60	3.0

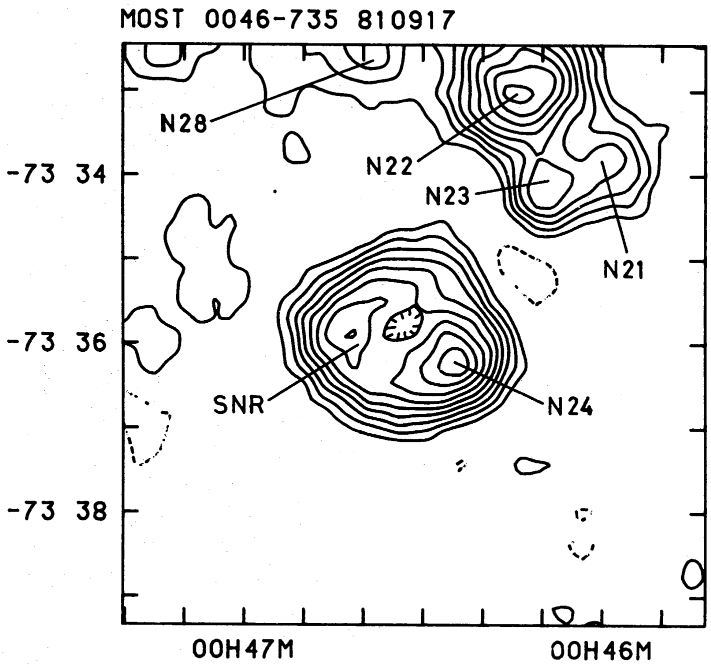
position. Because of the lack of bright Hα emission the source is clearly non-thermal, but no measurements are available of the flux density at other frequencies so the spectral index cannot be derived.

0102 – 722 (Fig. 1e). This SNR has been discussed by Dopita, Tuohy & Mathewson (1981). It is the brightest SNR in the SMC both at X-ray and radio wavelengths and belongs to the class of young oxygen-rich SNRs. It is situated close to the edge of the emission nebula N76 so that, despite its strength, confusion makes it difficult to determine a radio spectral index from observations at higher frequencies. The 408-MHz flux density of 670 mJy (Clarke, Little & Mills 1976) suggests that, after correction for the thermal emission, the spectrum should be rather flat.

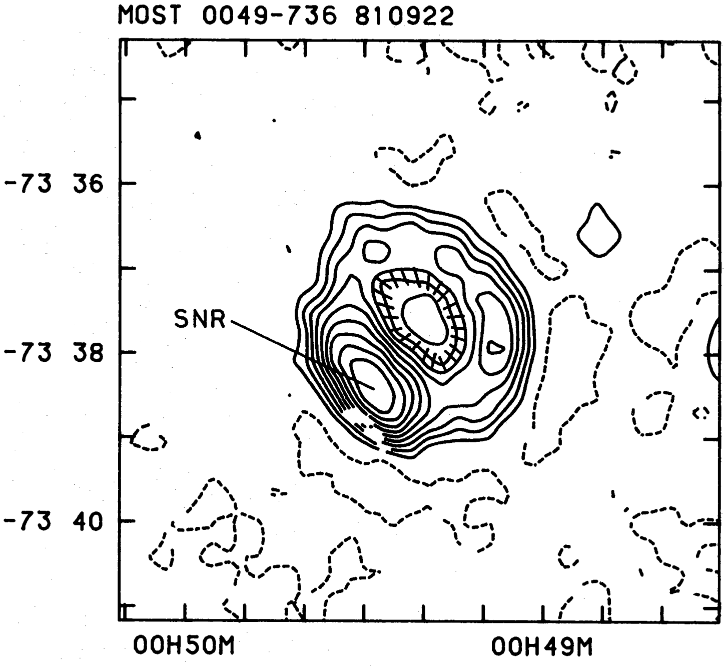


(a)

Figure 1. The confirmed SNRs mapped at 843 MHz with a beamwidth of 43 × 45 arcsec. Emission nebulae catalogued by Henize (1956) are also indicated. Contours are as follows. (a) 0045 – 734: –1, 1, 2, 4, 6, 8, 12, 16, 20, 24, 28, 32, 36, CU; 1 CU = 2.2 mJy/beam. (b) 0046 – 735: –1, 1, 2, 3, 4, 5, 6, 7, 8, 9 CU; 1 CU = 2.4 mJy/beam. (c) 0049 – 736: –1, 1, 2, 3, 4, 5, 6, 7, 8, 9 CU; 1 CU = 2.4 mJy/beam. (d) 0101 – 724: –1, 1, 2, 3, 4, 5, 6, 7, 8, 9 CU; 1 CU = 3.6 mJy/beam. (e) 0102 – 722: –5, –1, 1, 2.5, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90 CU; 1 CU = 3.7 mJy/beam. (f) 0103 – 726: –1, 1, 2, 3, 4, 5, 6, 7, 8, 9 CU; 1 CU = 3.0 mJy/beam.

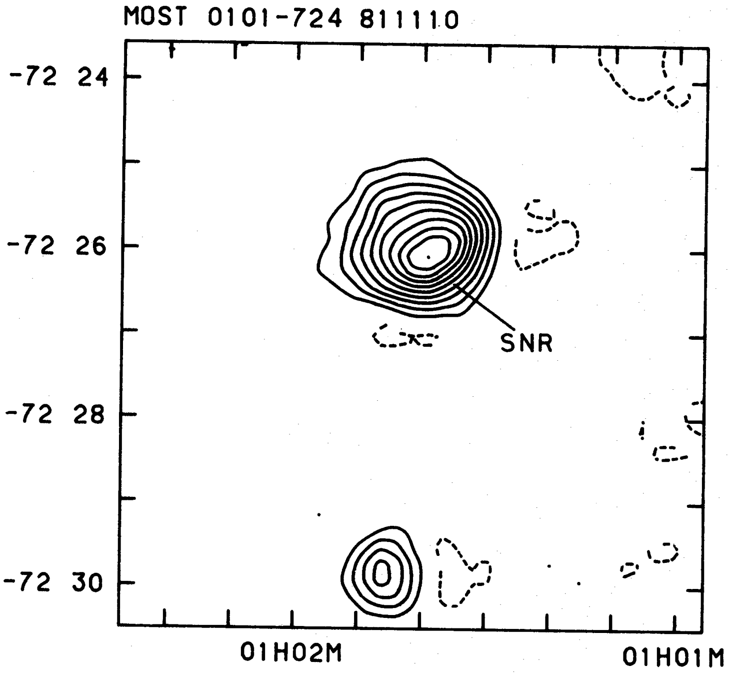


(b)

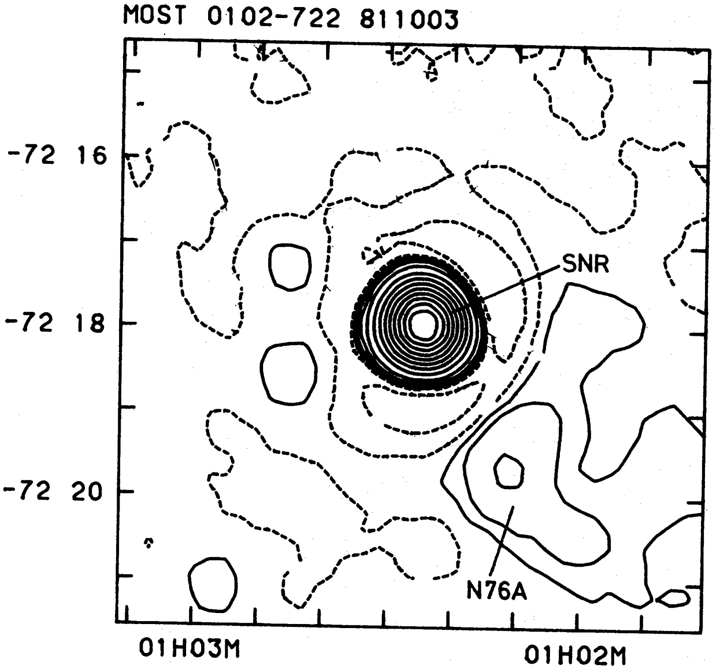


(c)

Figure 1 – *continued*

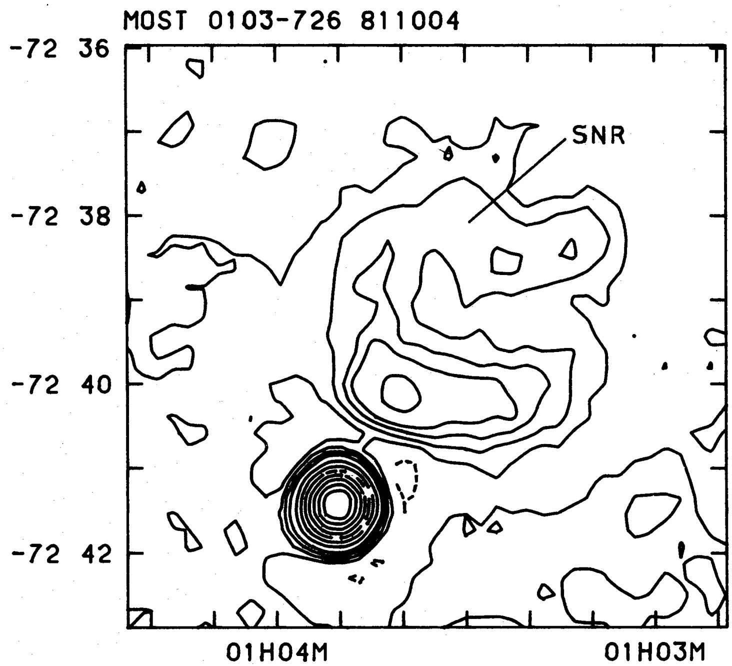


(d)



(e)

Figure 1 – *continued*



(f)

Figure 1 – *continued*

0103 – 726 (Fig. 1f). A large low-brightness SNR superimposed on very weak thermal emission from the nebulosity DEM 15 (Davies, Elliott & Meaburn 1976). The large size and low brightness of the radio source, the background thermal emission and the proximity of a background point source (at $01^h 03^m 49^s.2$, $-72° 41' 21''$) leads to unreliable flux densities at all radio frequencies and no possibility of estimating the spectral index. The flux density given in Table 2 was determined by subtracting an estimated thermal background of 30 mJy. The position given is the centre of the approximately circular source.

4 Other radio sources

0007 – 734. This source is included in the MC4 catalogue (Clarke *et al.* 1976). Sampled synthesis shows that it is a symmetrical double with a component separation of 1.2 arcmin and a centroid position of $00^h 07^m 22^s.8$, $-73° 25' 04''$ (1950). The morphology is typical of a distant radio galaxy or quasar but no obvious identification can be made on the SRC IIIa-J films; the field is crowded and there are several possible stellar or galaxy identifications.

0031 – 707. This source is very similar except that there is a clear identification with a quasar. The source is listed in the MC4 catalogue and sampled synthesis shows that it is also a symmetrical double with component separation of 1.0 arcmin and a centroid position of $00^h 31^m 59^s.4$, $-70° 42' 25''$ (1950).

There is a stellar object of $m_p \simeq 15.5$ mag at a position of $00^h 31^m 58^s.5$, $-70° 42' 26''.4$ (1950). A spectrum taken by M. A. Dopita & I. R. Tuohy (private communication) using the Anglo-Australian telescope shows that the object is a quasar with redshift $z = 0.363$.

0057 – 724 (Fig. 2). This radio source coincides precisely with the giant emission nebula N66, the largest in the SMC. There is no evidence for non-thermal radio emission from the nebula. The integrated flux density is 1.9 Jy at 408 MHz (Clarke *et al.* 1976), 2.2 Jy at

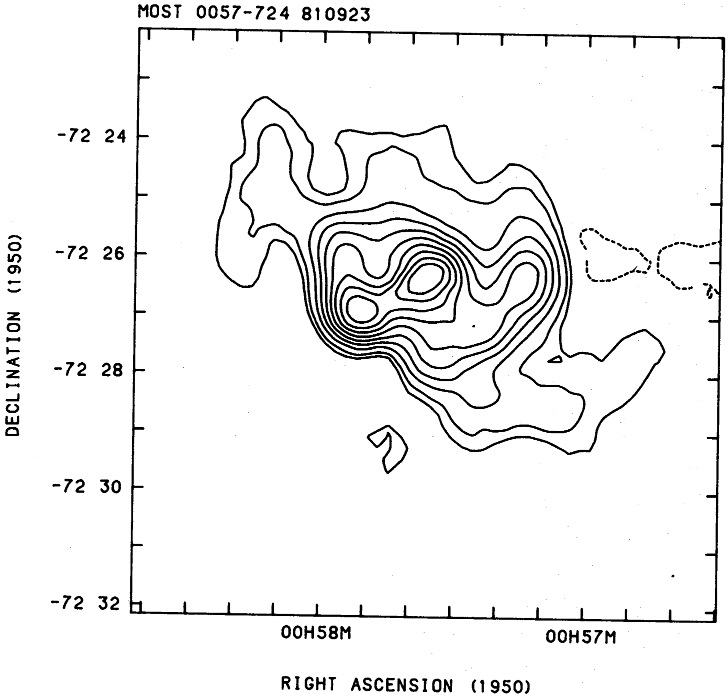


Figure 2. The giant emission nebulae N66 (Henize 1956) mapped at 843 MHz with a beamwidth of 43 × 45 arcsec. Contours are: −1, 1, 2, 4, 8, 12, 16, 20, 24, 28, 32, 36 CU; 1 CU = 2.9 mJy/beam.

843 MHz (present observations) and 2.4 Jy at 5 GHz (McGee, Newton & Butler 1976). Mills & Aller (1971) have compared models of the nebula constructed from 408-MHz and Hβ data and concluded that they are not inconsistent with thermal radio emission. This conclusion is reinforced by the subsequent, more accurate measurement of the flux density at 408 MHz (Clarke *et al.* 1976). It is possible that one or more old SNRs could be associated with N66, but we can find no evidence in support.

0101 – 730. This radio source is about 3 arcmin distant from the X-ray source at a position of $01^{\mathrm{h}}01^{\mathrm{m}}53^{\mathrm{s}}.5$, $-73°03'28''.5$ (1950). The quoted radius of the X-ray error circle is 1.5 arcmin, so that an association of the two sources, while possible, does not seem particularly likely. The source is resolved, roughly circular, with a diameter of 0.7 arcmin, but the flux density is low at 30 mJy. The SRC IIIa-J film is too crowded for an identification. The most likely interpretation is that it is a background radio-galaxy or quasar; if it is a SNR it must belong to the class of faint Type I SNRs identified by Tuohy *et al.* (1982) in the LMC.

5 Discussion

The SNRs have been selected largely on the basis of an X-ray survey which has possibly discriminated against old large-diameter remnants. The wide range of X-ray luminosities also indicates that there may be several below the present detection limit remaining to be discovered. Statistical results must therefore be treated with caution. On the other hand, all the radio measurements are well above the detection limit and it would be interesting to see the results of a systematic radio survey of the whole SMC. This major undertaking may be possible in the 1982 season, when it is expected that the synthesis field of the MOST will have been extended to 1°, together with improved dynamic range and sensitivity.

The most obvious feature of the present distribution of SNRs is their concentration near the two active regions in the SMC which are rich in emission nebulosities and H I. This itself causes some problems of recognition using direct radio–optical comparisons; high-resolution radio observations of good sensitivity at a different frequency are desirable to examine spectral distributions. This may be provided by current modifications to the Fleurs synthesis telescope.

5.1 THE Σ–D RELATION

A fundamental property of a SNR population is the brightness–diameter relation. In Fig. 3 the data from Table 2 are plotted and compared with the relation for galactic SNRs determined by Clark & Caswell (1976). The 408-MHz brightness of Clark & Caswell has been scaled to 1 GHz by assuming a mean spectral index of $\alpha = -0.45$. The resulting brightness is given by $\Sigma = 6.7 \times 10^{-16} D^{-3}$ where D is the diameter measured in parsec.

The plotted points lie to the left of the galactic SNR relation. If this were entirely the result of discrepancies in the relative distance scales, a difference of some 40 per cent would be suggested, an improbably high error. It appears likely that there is a real difference in the physical properties of the detected SNRs in the Galaxy and in the SMC, the latter being systematically fainter in radio emission (by about 1 mag if the distances scales are correct). It does not seem that selection effects could be responsible for this difference, and it will be interesting to compare the results of a similar observational program on the LMC which is currently in progress.

5.2 THE N–D RELATION

The rate of occurrence and evolution of SNRs is determined by the number–diameter relation. This relation is sensitive to sample completeness and, in view of the probable incompleteness of the present sample and the small numbers involved, care must be exercised in the interpretation of our results.

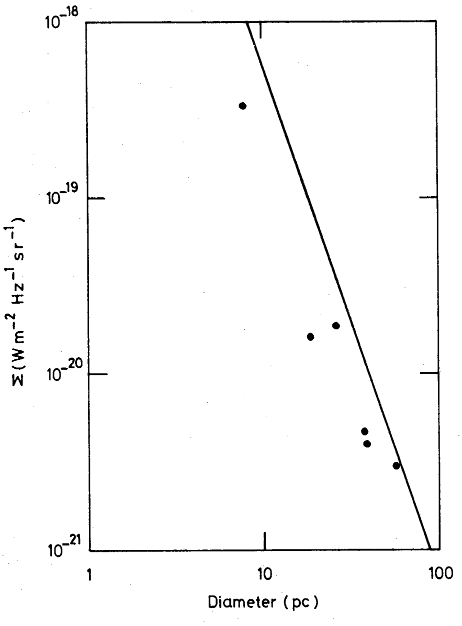


Figure 3. The Σ–D plot at 1 GHz for six SNRs in the SMC compared with the relation for galactic SNRs (solid line).

The *N–D* relation has usually been expressed as integrated counts, that is the total number of SNRs with diameter smaller than a given diameter. This approach does not permit reliable statistics and here we adopt the maximum likelihood method of Crawford, Jauncey & Murdoch (1970) which is based on the differential form of the counts. Restricting attention to the SNRs less than 40 pc diameter, where the Galactic slope is more or less linear (Clark & Caswell 1976), we find

$$N \propto D^{1.6 \pm 0.7}.$$

The Galactic *N–D* relation has been generally regarded as consistent with the Sedov relation for an adiabatic expansion of the remnants, that is $N \propto D^{2.5}$. The present results give a much smaller slope but, in view of the expected incompleteness and the large standard error in the exponent, the difference cannot be regarded as significant.

However, it is well known that a low slope has also been found for the SNRs found in the LMC. Clarke (1976), in a thorough statistical investigation of the data then available, concluded that the slope could not be explained by a combination of statistical fluctuation and incompleteness but suggested that deceleration by interaction with the interstellar medium was smaller than for the galactic SNRs. This was questioned by Milne, Caswell & Haynes (1981) as the result of a new *N–D* relation based on high-frequency observations. Although their slope was smaller than for the galactic relation, the difference was not regarded as significant. It appears that this crucial relation needs further investigation in the LMC before useful comparisons can be made with SMC and galactic results.

The birthrate of SNRs in the SMC may be crudely estimated by comparing the number with diameters less than say 40 pc with the corresponding number found in the Galaxy. The ratio is about 20:1. The mean time between galactic supernova events has been variously estimated as between 10 and 125 yr. If a galactic birthrate of 1 every 50 yr is assumed, the corresponding SMC rate would be ~ 1 every 1000 yr.

The ratio of SNR populations in the Galaxy and the SMC, although large, is some four times less than the ratio of their masses. The relatively greater number of SNRs in the SMC is consistent with a higher proportion of Population I stars in the Cloud.

6 Conclusions

The *Einstein Observatory* survey of the Small Magellanic Cloud by Seward & Mitchell (1981) has proved very successful in finding new supernova remnants, although these do not comprise a large proportion of the X-ray sources detected. We examined 16 likely sources in our program and, of these, only four may positively be identified with SNRs. Another four appear to coincide with radio sources. Two of these radio sources are identified, one with an emission nebula and one with a quasar; the other two are unidentified and presumed to be background objects.

The properties of the four SNRs and two others previously identified in radio–optical studies have been examined and found to differ from galactic SNRs in their *Σ–D* and *N–D* relations. However, uncertainties introduced by the small-number statistics and probable incompleteness of the sample preclude a thorough analysis of the differences. The birthrate of SNRs in the SMC is estimated very roughly as ~ 1 every 1000 yr.

Acknowledgments

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