THE RADIO PROPERTIES OF SNRs IN THE MAGELLANIC CLOUDS

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An understanding of the radio properties and evolution of Galactic supernova remnants has always been hampered by the difficulty of measuring distances. A conventional wisdom has developed around a set of 'good' calibrators but most workers involved have drawn attention to the uncertainties and the possibility of selection effects distorting results. This major difficulty is completely overcome by studying SNRs in the Magellanic Clouds. Although there is uncertainty in the absolute distance scale, relative distances can be determined to better than 10% and differences of this magnitude are not significant when intercomparing SNRs. There is, however, another set of problems associated with sensitivity and resolution. The Clouds are an order of magnitude more distant than the average distance of Galactic SNRs, thus many of the SNRs are close to or below the sensitivity limits of most of the southern radiotelescopes and, until recently, the resolution available has often been inadequate to separate non-thermal sources from thermal HII regions, so that both flux densities and spectra have been subject to error. Also there are $\sim$ 1000 extragalactic background sources which can mimic the flux density and spectra of SNRs in the Clouds, particularly when close to or behind HII regions; as a result numerous incorrect or doubtful SNR identifications have been suggested.

The first identifications of SNRs in the Clouds were made using the Parkes reflector at a frequency of 1410 MHz and a beamwidth of about 14 arcmin (Mathewson & Healey, 1964 ; Westerlund & Mathewson, 1966); the three strongest radio SNRs were identified with optical nebulosities. Subsequently there have been many radio surveys of the Clouds and specific searches for SNRs. The principal sources of data are listed in Table 1.

Following the initial discoveries of 1964, two major advances can be recognised. In 1972-1973, Mathewson & Clarke carried out the radio-optical searches listed in Table 1 and identified a further ten SNRs in the LMC and two in the SMC, bringing the total to 13 and 2 respectively. In 1981, the first major program of the newly commissioned Molonglo Observatory Synthesis Telescope (e.g. Mills, 1981) was to survey all previously suggested SNR candidates. Preliminary results from this survey,

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Table 1: Principal sources of radio data for Magellanic Cloud SNRs

Frequency GHz	Beam size	Reference	Notes
0.408	2!8 x 3!5	Mathewson & Clarke (1972) Mathewson & Clarke (1973a) Mathewson & Clarke (1973b) Mathewson & Clarke (1973c)	Radio-optical SNR searches in both Magellanic Clouds
		Clarke et al. (1976)	A definitive catalogue of 408 MHz radio sources in both Clouds
0.843	43" x 46"	Mills et al. (1982) Mills et al. (in preparation)	Investigations of SNR candidates in both Clouds using the MOST
1.41	14'	Mathewson & Healey (1964) Westerlund & Mathewson (1966)	First identifications of SNRs in the LMC
1.415	50"	Turtle & Mills (1979)	Size data for bright SNRs in the LMC
5.0	4!1	McGee et al. (1972)	A continuum survey of the LMC
5.0 8.4	4!1 2!6	McGee et al. (1974)	A continuum survey of the SMC
8.4	2!6	McGee et al. (1978)	Measurements on selected sources in the LMC
5.0 14.7	4!1 2!2	Milne et al. (1980)	A search for SNRs in the LMC based on radio spectra

which permits clear separation of the SNRs from contaminating sources and has a high signal-to-noise ratio for the SNRs, are described in this paper.

Candidates were chosen primarily from the Einstein Observatory X-ray catalogues of Seward & Mitchell (1981) for the SMC and Long, Helford and Grebalsky (1981) for the LMC. These X-ray candidates were supplemented by other candidate SNRs previously suggested on the basis of radio and/or optical observations. Altogether 18 candidates were observed in the SMC and 67 in the LMC. Six positive identifications were made in the SMC (Mills et al., 1982). The LMC data are more extensive and complex and some further radio and optical observations will probably be needed

Table 2: Radio SNRs in the Magellanic Clouds

	SMC	
0045-734 (N19)	0049-736 (IE00494-7339)	0102-723 (IE0102.2-7219)
0046-735	0101-724 (IE0101.5-7226)	0103-726 (IE0103.3-7240)
	LMC	
0453-685 (X1)	0519-690 (X26)	0534-699 (X53)
0454-665 (N11L)	0520-694 (X27)	0534-705 (X54,DEM238)
0456-687 (X2, N86)	0525-660 (X34, N49B)	0535-660 (X59,N63A)
0500-702 (X7, N186D)	0525-696 (X35, N132D)	0536-706 (X61,DEM249)
0506-680 (X11, N23)	0525-661 (X36, N49)	0538-691 (X67,N157B)
0509-687 (X13, N103B)	0527-658 (X39, DEM204)	0540-693 (X79,N158A)
0509-675 (X14)	0528-692 (X40)	0547-697 (X88,N135)
0519-697 (X23, N120)	0532-710 (X47, N206)	
	LMC (possible SNRs)	
0505-679 (X10, DEM71)	0538-694	0543-679 (N70)
0536-692 (30DorC)	0543-689 (X82)	0548-704 (X89)

(Mills et al., in preparation); here I will report only on preliminary results which, however, are adequate for several valid and important statistical conclusions.

Positive identifications have been made with 23 SNRs and a further 6 are regarded as possible identifications, subject to some further investigation. At a lower level of probability several others remain to be investigated. With the exception of two SNRs in the SMC, the positive identifications could only be made with X-ray sources which also have associated visible remnants (Mathewson et al., in press). The 'possible' identifications include radio sources in which one or both of these features may be missing. Radio sources identified with SNRs are listed in Table 2; X-ray or common names are in parenthesis.

The basic results for both Clouds are presented in Figure 1 where the absolute radio luminosites of the 29 'confirmed' and the 6 'possible' SNRs are plotted against their diameters. A distance of 55 kpc has been adopted for the LMC and 63 kpc for the SMC. As the small diameter SNRs are not completely resolved by the radiotelescope, a standard procedure has been adopted to deconvolve the response. Two models comprising a thin circular ring and a uniform circular disk have been fitted to the half-power responses along the major and minor axes. The diameter quoted is based on the mean of these four results and is expected to give a good approximation to the actual size for SNRs of typical morphology. The resolution limit is estimated as about 7 pc and three of the SNRs could not be definitely resolved; 0509-687, 0509-675 and 0535-660. Their diameters have been taken from the optical values given by Mathewson et

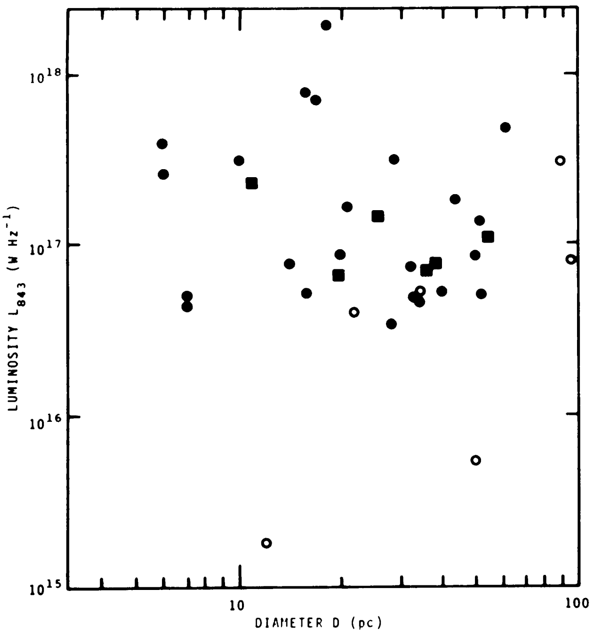

Figure 1. The distribution of radio luminosity for SNRs in both Clouds as a function of the radio diameter. Filled circles and filled squares represent positively identified SNRs in the LMC and SMC respectively. Open circles are the 'possible' SNRs in the LMC.

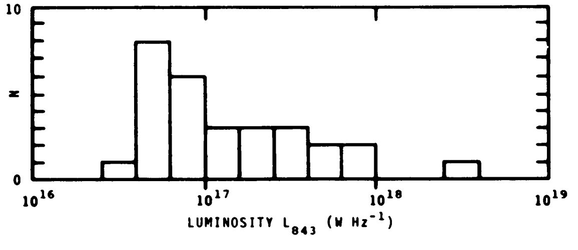

Figure 2. The histogram of radio luminosity for the positively identified SNRs in both Clouds.

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al. (in preparation), 6 pc, 7 pc and 6 pc respectively. The SNR 0540-693 which has an optical diameter quoted as 2 pc is well resolved with a radio diameter of 10 pc.

Figure 1 is best described as a scatter diagram; there is no clear evidence for a common evolutionary track. This is not to say that the radio emission of SNRs does not evolve, but such evolution must be less than the intrinsic scatter in luminosities over the range of diameters 6 - 60 pc. Over most of this range it is believed that the sample is nearly complete; the cut-off at large diameters is almost certainly caused by a cut-off in the X-ray candidates which, when plotted as in Figure 2, show a steep fall-off in X-ray luminosity with increasing diameter. The lower bound on the radio luminosity of confirmed SNRs can hardly be instrumental as it occurs far above the radio detection limit as shown by the detection of much weaker 'possible' SNRs.

Earlier workers found a correlation between luminosity and diameter of the form $L \propto D^{-1}$ (corresponding to the more usual presentation $\Sigma \propto D^{-3}$). It is now evident that such an apparent correlation arose partly from measurement errors due to resolution effects and partly because the low luminosity small diameter SNRs had not been detected. As there is no valid L - D relation, luminosities at all diameters may be combined to give the distribution for 'confirmed' SNRs shown in Figure 3. The distribution is asymmetrical with a logarithmic mean of $\langle L_{843} \rangle = 1.1 \times 10^{17}$ W Hz^{-1}. More than 90% of luminosities lie within a factor of 4 of the mean luminosity.

Another basic statistic is the N-D relation which describes the expansion law of the SNRs. In Figure 3, this relation is plotted for all the 'confirmed' SNRs and those 'possible' SNRs with luminosities between the limits found above. There are 33 such remnants and for diameters below 40 pc the relation may be described by the power law

$$N(<D) = 0.26 D^{1.21 \pm 0.25},$$

where the exponent and its standard error have been obtained by a maximum

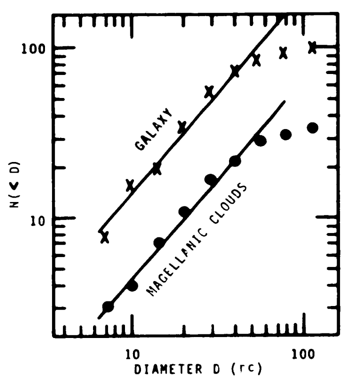

Figure 3. The N-D relation for all SNRs in both Clouds and for Galactic SNRs using the Cloud distance calibration.

likelihood fit. This generally confirms the result obtained by Clarke (1976) on a smaller sample of SNRs in the LMC and shows that the SNRs observed are not undergoing adiabatic expansion in a uniform medium, for which the corresponding relation is $N \propto D^{2.5}$. As suggested with some reluctance by Clarke, interaction with the interstellar medium must be small, but this is no longer to be seriously questioned in view of the increasing acceptance of inhomogeneous models of the medium. It appears that the great majority of detected SNRs in the Clouds have expanded in the hot tenuous phase where they reach large diameters before accreting sufficient material to slow their expansion significantly.

A further significant result from Figure 3 is the flattening of the N-D slope for diameters greater than about 40 pc. One might well ask: what happens to the large diameter SNRs which are deficient by an order of magnitude at diameters around 100 pc? There is no observational evidence for a decrease in radio luminosity below the observed cut-off. Although we would expect their X-ray emission to have fallen below detectable levels, they should still be detected as radio sources and a brightening of the optical emission might be expected. There are, in fact, many large diameter filamentary shells with strong Hα emission visible in the Clouds (e.g. Meaburn, 1980), but these appear to have flat radio spectra. A possible scenario involves a decay of the early synchrotron emission combined with a buildup of free-free emission from the developing ionized shell; some of the old SNRs may thus be masquerading as shell-type HII regions. Two such apparently thermal sources were included in our maps of the LMC and these are both designated as possible SNRs; they are 0543-679 (N70) and 0536-692 (30DorC), with diameters between 90 and 100 pc.

COMPARISON WITH GALACTIC SNRs

In discussing the low slope he found for the N-D relation in the LMC, Clarke (1976) was concerned over the very different form of the corresponding Galactic relation, which was consistent with adiabatic expansion of the remnants. However the Galactic N-D relation was then based on a distance scale derived from a set of calibrators of uncertain distances. Subsequently, the Galactic result was apparently confirmed by Clark & Caswell (1976) using a distance scale based primarily on the Σ-D relation then current for the LMC (i.e. $\Sigma \propto D^{-3}$), together with another set of uncertain Galactic calibrators. We have now seen that the old Σ-D relation in the Clouds is not supported by present results.

In Figure 3, the N-D relation for the Galactic SNRs is obtained from the catalogue of Clark & Caswell (1976) on the assumption that the Galactic and Cloud SNRs are physically identical, i.e. the same assumption as made by Clark & Caswell. However, a distance scale defined by the mean luminosity of the Cloud SNRs is used. At 408 MHz this scale becomes $d_{kpc} = (1280/S_{Jy})^{\frac{1}{2}}$. The N-D relation below 40 pc diameter is then given by

$$N(<D) = 1.05D^{1.15\pm0.14},$$

with essentially the same slope as the Cloud SNRs. The derived expansion laws for the SNRs in the Clouds and the Galaxy are therefore consistent and it appears that they develop in similar environments. The number of SNRs with diameters less than 40 pc found in the Galaxy is three times the corresponding number in the Clouds.

Clark & Caswell list a number of Galactic SNRs with measured distances which they used as calibrators; it is instructive to compare these with distances derived from the equation above. If we define a ratio R between the Cloud-calibrated distance and the measured distance, we find two results. For the optically derived distances, R = 1.5±05.; for the kinematically derived distances, R = 0.80±0.06, with the possibility that R is smaller because many of the kinematic distances are lower limits. There is no significant mean difference for the optically derived distances, although the scatter is large. In deriving the kinematic distances, 10 kpc was assumed as the distance to the Galactic centre. The adopted Cloud distances are therefore consistent with a distance to the Galactic centre of $\lesssim$ 8 kpc, which appears satisfactory in the light of current estimates.

Another result is a new determination of the rate of occurrence of SNRs in the Galaxy, which is a direct function of the expansion law. Clark & Stephenson (1977) identify eight historical supernovae of known age. Six of these are accepted as calibrators; SNR 1054 is rejected as atypical and AD 360 is rejected because the derived occurrence rate is very anomalous and the identification is queried by Clark & Stephenson. Applying the method of Clark & Caswell to the new N-D relation, it is found that the mean time between outbursts is 40±10 yr. If an allowance of $\sim$ 30% is made for incompleteness, the corresponding time is $\sim$ 30 yr. Thus the occurrence rate seems compatible with rates derived from supernovae observed in external galaxies and with estimated birthrates of pulsars. The corresponding mean times between outbursts derived from SNRs detected in the LMC and SMC are $\sim$ 150 yr and $\sim$ 600 yr respectively.

The mean properties of SNRs may be derived from the N-D relation and the occurrence rate. Thus, taking for the Clouds, $N(<D) = 0.26D^{1.2}$ and a mean time between outbursts of 120 yr, we find for the 'average' SNR with diameters between 6 and 40 pc in both Clouds and Galaxy:

$$D_{pc} = 0.057\ t_{yr}^{0.83}$$

$$V_{km\ s^{-1}} = 3.0 \times 10^4\ t_{yr}^{-0.17} = 1.7 \times 10^4\ D_{pc}^{-0.2}$$

where V is the mean expansion velocity of the radio emitting shell.

These relations do not describe the evolution of some 'typical' SNR but represent ensemble averages consistent with the present data. At the time of observation, interaction with the interstellar medium is proceeding and the actual expansion velocity of the radio emitting shells will be well below the mean velocity; it might also be expected that the optical filaments, representing either regions of high interaction or excited knots in the interstellar medium, will have even lower velocities. It is clear that the commonly accepted 'prototype', Cas A, is exceptional in many respects.

While it is expected that further work will modify these preliminary statistics, the qualitative conclusions appear to be reasonably well established. The expansion of most recognised SNRs has been more rapid than predicted by the adiabatic law, their ages are less and their birth-rates higher.

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DISCUSSION

MCKEE: Why does the Galactic N-D relation show a fall off at the same diameter as the Cloud relation?

MILLS: The fall off is thought to have quite different causes in Galaxy and Clouds. The similarity is curious and perhaps significant.