A RADIO CONTINUUM SURVEY OF THE MAGELLANIC CLOUDS

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Continuum radio emission from the Large Magellanic Cloud was first detected just 30 years ago (Mills & Little, 1953). Subsequently, surveys of the Clouds were made after each new advance in southern hemisphere instrumentation and the principal surveys are listed and briefly described in Table I. They cover a range of frequencies from 19.7 MHz to 8.4 GHz. The early surveys at low frequencies were chiefly concerned with the overall synchrotron emission from the Clouds but, as resolution improved, emphasis has shifted to the individual sources, both emission nebulae and supernova remnants, which can be recognized as Cloud members. Of recent years the unique position of the Clouds for studying radio sources in external galaxies has been undermined by the development of powerful synthesis telescopes in the northern hemisphere; these have provided equivalent sensitivity and better spatial resolution on M31, and several other northern galaxies can also be studied effectively. However, with the commissioning of the Molonglo Observatory Synthesis Telescope (MOST) in 1981 the Clouds have been restored to their rightful place befitting the closest galaxies.

The MOST is a unique rotational synthesis telescope which, in 12 hours observation, can synthesise a map in real time from a comb of fan beams (Mills 1981). The operating frequency is 843 MHz and the synthesised beam has a half-power width of 43 x 43 cosecδ arcsec. The basic field size defined by the comb of fan beams is 23 x 23 cosecδ arcmin (11 x 11 cosecδ arcmin for early observations). The field may be expanded by a factor of either two or three using a multiplexing system with a corresponding reduction of sensitivity. For the observations described here the rms noise varied between about 0.4 mJy and 0.7 mJy depending on the field size chosen. The sensitivity has now been significantly improved by the installation of low noise FET preamplifiers.

Observations of the Clouds with the MOST began in September 1981 with a study of supernova remnant candidates. These candidates were chosen from the X-ray catalogues of Seward & Mitchell (1981), for the SMC, and Long et al. (1981) for the LMC. Previously suggested SNR identifications from earlier optical and radio observations were also

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Table 1: Principal radio surveys of the Magellanic Clouds

Frequency MHz	Beam Size	Reference	Notes
19.7	85'x104'	Shain (1959)	Contour maps of both Clouds
85.5	48'x 59'	Mills (1959)	Contour maps of both Clouds
408	2!8x3!5	Clarke et al. (1976)	A definitive catalogue of radio sources in both Clouds with maps of individual sources
408 1410	48' 14'	Mathewson & Healey (1964)	Contour maps of both Clouds
2700	8'	Broten (1972)	Contour maps of both Clouds
5000	4!1	McGee et al. (1972)	A catalogue of radio sources in the LMC and maps
5000 8400	4!1 2!6	McGee et al. (1976)	A catalogue of radio sources in the SMC and maps
8400	2!6	McGee et al. (1978)	Measurements on selected sources in the LMC and maps

included. Only a small area of the Clouds was actually mapped in these programs but 6 SNRs were confirmed in the SMC (Mills et al. 1982) and 23 plus 6 possible SNRs found in the LMC (Mills, 1983). There was good reason for believing that many large diameter SNRs were missed by this procedure because the X-ray surveys discriminated against them. Accordingly in the 1982 season the SMC was surveyed with the MOST, essentially completely.

THE SMC SURVEY

Fourteen overlapping fields were mapped, one with a size of 70 x 74 arcmin and the remainder 46 x 48 arcmin, covering about 4 square degrees of the SMC including the 'bar' and the 'wing'. An exceptionally rich area from one of these fields is shown in Figure 1. It is an 'uncleaned' map of the type available immediately after the observation. Three categories of radio source are found.

(i) The most common are background, usually unresolved, sources which are either radio galaxies or quasars. In general their identification is not possible because of the crowded star field. In the rich field of Figure 1, these background sources are outnumbered by the SMC sources.

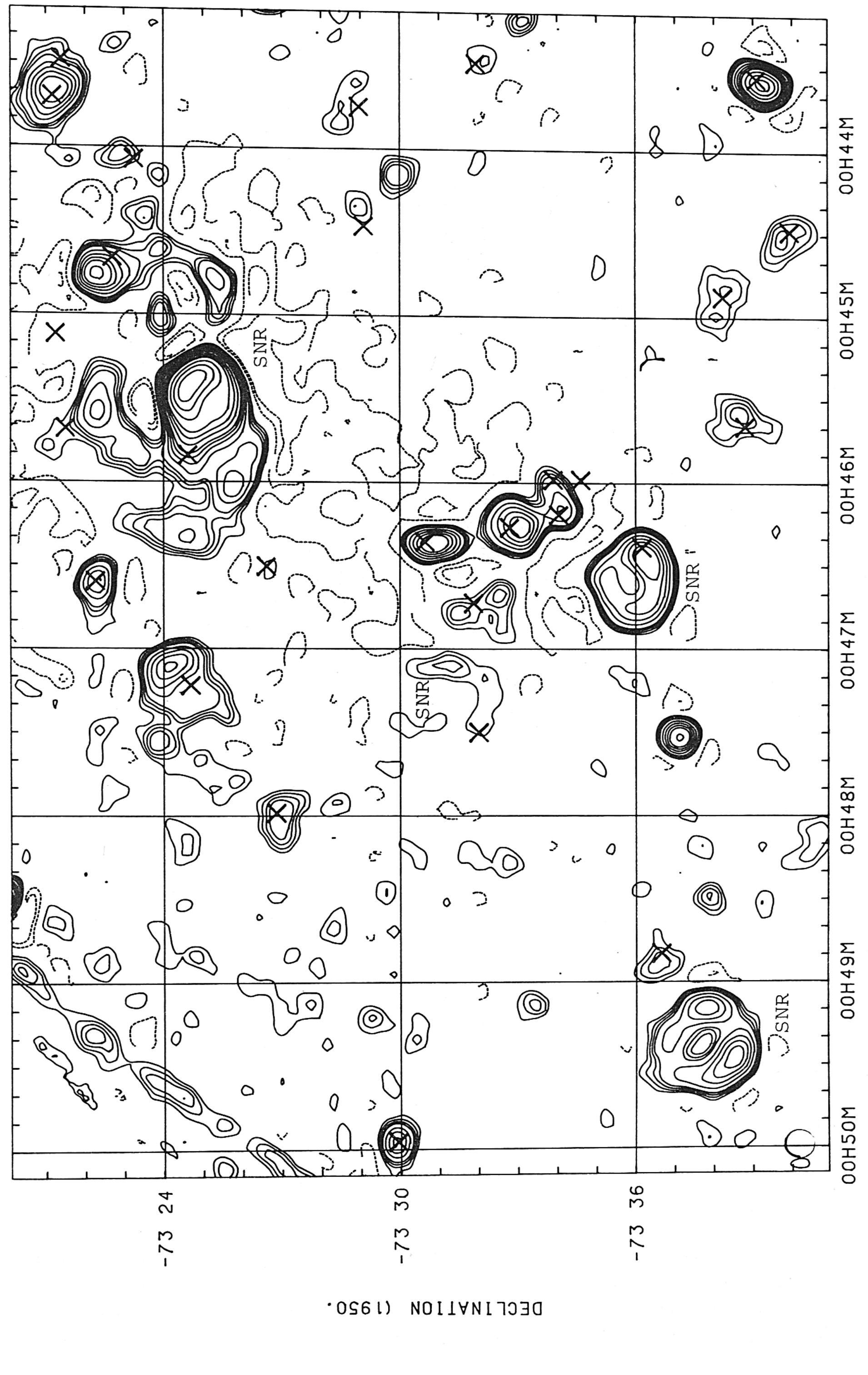

Figure 1. A rich field in the SMC. The catalogued positions of Hα emission regions are shown by crosses. Contour levels (mJy/beam): -4, -2, 2, 3, 4, 5. 7.5, 10, 12.5, 15, 25, 30, 40, 50, 60, 70.

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(ii) Emission nebulae: The detectability of H II regions appears to be better than in the Hα survey by Henize (1956) but generally inferior to the Hα survey of Davies et al. (1976). For a nebula of size between about 30 arcsec and 5 arcmin the minimum emission measure for reliable detection is in the range 300-500. The positions of the nebulosities catalogued by Davies et al. (1976) are indicated by crosses in Figure 1. A comprehensive catalogue of the radio sources is planned in which the integrated flux density and a map of each will be provided. This catalogue will yield information about mass and excitation parameters and, if used in conjunction with Hβ photometry, a direct measure of the interstellar extinction.

(iii) Supernova remnants: These stand out as resolved radio sources, usually with an associated catalogued nebulosity, in which the radio brightness is significantly greater than expected from the Hα brightness classification given by Davies et al. (1976). The larger remnants show a shell or arc-like structure. Confirmation may be obtained by data at other radio frequencies yielding a non-thermal but flattish spectrum, by an apparently associated X-ray source in the catalogues of Seward & Mitchell (1981) or Tanaka (1983) and by optical data. Optical data are often essential to eliminate the possibility of misidentification of a background radio and X-ray galaxy. In collaboration with Mt. Stromlo astronomers, five radio sources from the survey were confirmed as new supernova remnants (Matthewson et al., submitted); three of these are included in the X-ray catalogue of Tanaka (1983). Eleven remnants have now been found in the SMC viz: 0045-739, 0046-735, 0047-735, 0049-736, 0050-728, 0056-725, 0058-718, 0101-724, 0102-722, 0103-726, 0104-723.

THE 30 DORADUS REGION

A systematic survey of the LMC is planned during the next two years using a field size of 70 x 75 arcmin. Apart from the areas mapped around SNR candidates very little data are yet available. It is obvious, however, that the LMC contains much stronger radio sources, both thermal and non-thermal than the SMC. As an example, the region around the 30 Doradus nebula and the interesting emission nebulae to the south are shown in Figure 2; this map has been constructed from the overlap of two 46 arcmin fields and, because of the complexity and brightness of the emission, both fields have been 'cleaned' using a standard algorithm. The 'cleaning' process effectively removes the first negative sidelobe of -8% and has no other significant effects.

The peak Hα and radio brightness are much greater in this region than in the SMC field mapped in Figure 1 and as a result the lowest contour level has been set some five times higher. Also, the catalogue of Davies et al. (1976) is not suitable for very bright complex regions so we have given the Henize (1956) catalogue numbers to the main peaks. However, well away from the 30 Doradus nebula itself, low levels of emission are easily detected and the sensitivity is comparable to that

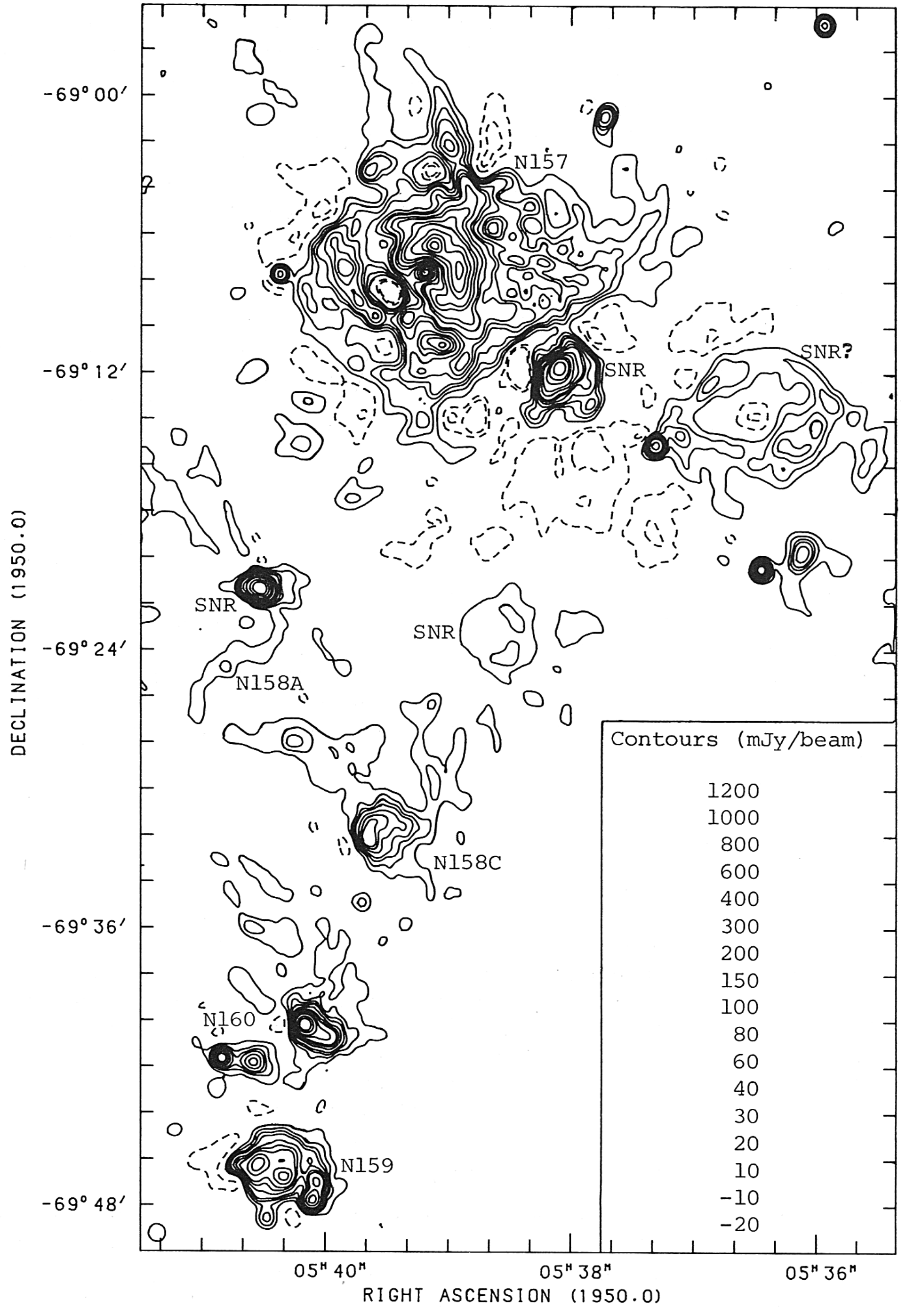

Figure 2. A 'cleaned' map of the 30 Doradus region.

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shown in Figure I. The whole region has been discussed by Mills et al. (1978) and it was shown that the radio emission is predominantly thermal, arising from the numerous H II regions. The present results confirm the main features of the earlier 1415 MHz map obtained with the Fleurs Synthesis Telescope but the greater sensitivity reveals many new correspondences with fainter Hα emission features.

Three SNRs have been identified in the region, 0538-691, 0538-693 and 0540-693. The large 6 arcmin diameter ring source 0536-692 is regarded as a possible old SNR; although its radio spectrum is predominantly thermal there is some evidence for non-thermal emission on the eastern side (Clarke et al. 1976) and a weak X-ray source is also catalogued in the region (Long et al., 1981). Two of the SNRs, 0538-691 and 0540-693, appear to have angular sizes much greater than the optical and X-ray remnant (Mills et al., submitted). However in both cases this could be the result of unassociated background emission and better resolution will be needed to decide.

STATISTICS OF THE SNRs

The SNR candidate survey of the LMC has led to the confirmation of 27 remnants (Mills et al., submitted). Four of the six 'possible' remnants previously listed by Mills (1983) have now been confirmed. It is believed that a reasonably complete sample of SNRs has been obtained with diameters less than about 40 pc but comparisons with the SMC suggest that many large diameter remnants remain to be found when the LMC has been surveyed in its entirety. Mills (1983) described the preliminary statistics based on 29 remnants in both Clouds and showed that the results could not be reconciled with the conventional picture of their properties and evolution. Using the present catalogues containing 38 remnants these preliminary results have been examined more deeply and generally confirmed. There is great diversity in the radio properties and morphologies of the SNRs and no significant correlation between the luminosity and diameter of a remnant is apparent unless selections based on size or luminosity are imposed. No evolutionary track can be recognized. A direct application of the maximum likelihood method to the 24 remnants with diameters between the resolution limit of the radiotelescope, 7 pc, and the maximum diameter for reasonable completeness, 40 pc, yields the number-diameter relation:

$$N(< D) = \frac{1}{3} D^{1.2 \pm 0.35}$$

This result cannot be reconciled with the common assumption that all radio detectable SNRs spend most of their lifetime in the adiabatic or 'Sedov' expansion phase which requires a relation of the form $N \propto D^{2.5}$. The majority of remnants in the Clouds must have expanded to their present sizes with little deceleration of the supernova ejecta. Furthermore there is evidence that the radio remnant does not persist for very long as a recognizable object after significant deceleration has occurred; it appears that the synchrotron-emitting phase of a supernova remnant is

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probably a transient phenomenon lasting perhaps a few thousand years instead of some tens of thousands.

Comparison with the catalogue of Galactic SNRs compiled by Clark & Caswell (1976) produces no convincing evidence that the Galactic SNRs are any different. Because the great majority of Galactic remnants have no independent measure of their distances, a directly observed N-D relation cannot be derived but properties, when they can be compared, are similar. If the simplest assumption is made that the populations are identical and have an N-D relation of slope 1.2, the occurrence rate of SNRs in both Galaxy and Clouds may be estimated using the historical supernovae in the Galaxy as calibrators. The rate is found to be about four per century in the Galaxy and one per century in the two Magellanic Clouds combined. From the distribution of SNR diameters in the Clouds it seems likely that there was a burst of supernova activity in the LMC about four or five hundred years ago; the X-ray and optical data suggests that one remnant may be much younger (0540-693).

SUPERNOVA REMNANTS AS DISTANCE CALIBRATORS

In the course of comparisons between the Galactic and Cloud SNRs, Mills et al. (submitted) derive a distance scale from the Cloud remnants and apply it to the Galactic calibrators. This scale is an improvement on the simple luminosity scale of Mills (1983), used for a similar purpose. It makes use of the regressions of L, the luminosity, and D, the diameter, on Σ, the brightness, of the SNRs. In deriving the scale, distances of 55 kpc and 63 kpc were assumed for the LMC and SMC respectively. The scale is given by

$$d_{kpc} = 46\ S_{843}^{-0.275}\ \theta^{-0.45}$$

where d_{kpc} is the distance to the SNR in kiloparsecs, S is the measured flux density in jansky at 843 MHz and θ is the effective angular diameter in minutes of arc. Application of the scale to the remnants in the Clouds results in a dispersion of about 40 percent for individual SNR distances although the mean distances are, of course, close to those assumed. When applied to the group of Galactic calibrators tabulated by Clark & Caswell (1976) good agreement is found with, however, two minor differences. The calibrators with distances based on optical considerations, on average, have scale distances slightly greater than the optically derived distances. The calibrators using kinematic distances from radio absorption lines are found to have scale distances significantly less, by about 20%. However, these kinematic distances have been based on a distance to the Galactic centre of 10 kpc and this is now believed to be too large.

These comparisons can be used to provide an independent measure of the distances to the Magellanic Clouds as well as the distance to the Galactic centre. Taking the optically derived distances of relatively close SNRs as basic calibrators, distances to the LMC, SMC and Galactic centre are 49 kpc, 60 kpc and 7.2 kpc respectively. The statistical uncertainties are less than 10% but there are further uncertainties in the assumption that the Cloud distance scale may be directly applied to the group of Galactic calibrators and that the optically derived distances have no systematic bias.

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DISCUSSION

Dopita: I worry about the use of SNR radio emission for distance estimation, since VLA work by D'Odorico and his co-workers (including myself) showed that the M31 and M33 relations were different between each other and from that of the LMC. Thus it seems that intrinsic efects (structure of the ISM, IMF, etc.) influence a L-d relationship more than is acceptable for this method to be a useful distance indicator.

Mills: I agree that one must be cautious. There are several reasons for thinking that the Cloud and Galactic SNRs are similar, but this may not be so for other galaxies. In any event, because of selection effects I do not believe that the method could usefully be employed on other galaxies at present.

van den Bergh: How would your interpretation of the V versus D relation be affected if there were a very large range of interstellar magnetic field strengths in the Magellanic Clouds?

Mills: Provided the sensitivity limit of the radio telescopes is well below the SNR emissions, as we seem to have here, I cannot see any significant effect.

Preite-Martinez: I'd like to draw your attention to our work presented at this symposium (Fusco-Femiano and Preite Martinez), in which we show that the N-D relation in the LMC can be explained by a population of SNRs in the adiabatic phase, expanding in a non-homogeneous interstellar medium.

Mills: Our interpretations may not be so very different. I consider that SNRs are only likely to emit at radiofrequencies after significant slowing of the ejecta and that the emission is quenched shortly thereafter. That is, we think it likely that most of the observed SNRs are rather close to the adiabatic phase.

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