VLA OBSERVATIONS OF SNRs IN M33

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Abstract: The results of a VLA study of the radio continuum properties of supernova remnants in the nearby spiral galaxy M33 are presented. It is shown that a relationship exists between the radio surface brightnesses and the diameters of the 13 detected supernova remnants. The significance of the relation and the constraints it imposes on models of SNR evolution are discussed.

Introduction: The evolution of supernova remnants (SNRs) and their interaction with the interstellar medium is a subject of growing debate, fuelled by both theory and observation. The traditional view holds that SNRs undergo distinct phases of evolution, namely the free expansion, adiabatic and isothermal stages (Woltjer, 1972; Chevalier, 1974; Spitzer, 1978). This view has been supported by radio continuum observations and the establishment of the $\Sigma - D$ relation (Clark and Caswell, 1976; Huang and Thaddeus, 1986) which suggests that the radio emission of an SNR evolves systematically with time. Furthermore, Duric and Seaquist (1986) suggest that, on theoretical grounds, the $\Sigma - D$ relation is a direct consequence of the adiabatic phase of SNR evolution. The opposing viewpoint contends that SNRs undergo free expansion into a rarefied medium, possibly created by the SN precursor wind, and that this phase is terminated by isothermal deceleration caused by the interaction with a dense medium (possibly the material swept up by the wind). In this scenario, the adiabatic phase is not an important factor in the evolution of SNRs (eg Braun, 1985). This view has been supported by observations of SNRs in the LMC (Mathewson et al 1983; Mills et al 1984) in which the cumulative number vs diameter ($N(< D) - D$) relation was found to have the shallow slope characteristic of free expansion.

The difficulty of determining distances to SNRs in our galaxy makes studies of other galaxies, such as the LMC, appealing. However, in order to shed light on SNR evolution in our galaxy, it is important to study galaxies where the SNRs and their environments are more representative of those in our galaxy. Although not a perfect match, M33 is a good candidate because of its proximity and face-on orientation. Optical studies of SNRs in M33, for example, have led to the establishment of $N(< D) - D$ relation that is consistent with free expansion (Blair and Kirshner, 1985). In this paper we wish to describe a radio study of SNRs in M33 with the aim of establishing the presence or absence of a $\Sigma - D$ relation. As noted above, the $\Sigma - D$ relation can be used to test for the adiabatic phase of SNR evolution. Its presence or absence should therefore help shed some light on how SNRs evolve in M33.

Observations: The SNRs in M33 were observed in the process of surveying the 6cm radio continuum emission of this galaxy. The observations were carried

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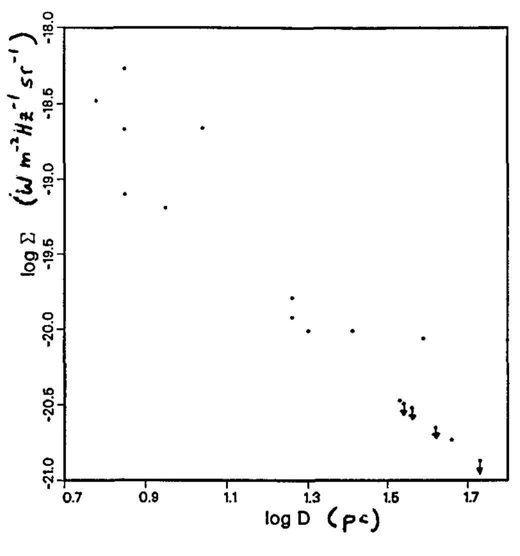
out with the VLA in the C configuration. A total of 19 primary beam fields were needed to map the entire galaxy with integration times ranging from 20 to 90 minutes per field. This allowed us to look for radio emission from all the SNRs referred to in Blair and Kirshner's (1985) paper. The data were 'naturally weighted' in order to maximize the signal to noise ratio and to improve our detection limits. The resulting *rms* noise levels range from 0.03 mJy/beam to 0.1 mJy/beam. Most of the observed SNRs were in fields having a limiting noise level of 0.03 mJy/beam. The resolution ranged from $4.5''$ to $5''$ which at the assumed distance of 650 kpc corresponds to an average linear resolution of ≈ 15 pc.

The radio SNRs were identified by positional coincidence using the optical positions listed by DGD (D'Odorico, Goss and Dopita, 1982). Positional coincidence to 1-$2''$ was achieved for all but the largest remnants. Integrated flux densities and their uncertainties were calculated using areal integration routines in the AIPS (Astronomical Image Processing System, developed by NRAO) package. Of the 20 bona fide SNRs in DGD's list we have detected 13 at the 3σ level or better. Three other SNRs were confused by emission from HII regions and 4 were clearly undetected. The average uncertainty in the integrated flux measurements was ≈ 0.15 mJy.

The $\Sigma - D$ Relation: Using the flux measurements described above and SNR diameters from optical measurements (D'Odorico, Dopita and Benvenuti, 1980; Sabbadin, 1979) we have constructed a plot of $\log \Sigma$ vs $\log D$ to determine if the SNRs in M33 form a $\Sigma - D$ relation. In order to compare with the galactic relation, the 5 GHz fluxes were transformed to 1 GHz by assuming a spectral index of -0.5. The resulting $\log \Sigma - \log D$ plot is shown in the figure below.



A least squares fit to the plotted points results in the following relation:

$$\log \Sigma = -2.5 \log D - 16.5.$$

The uncertainties in the fitted slope and intercept were $\pm$ 0.2 and 0.3 respectively.

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The corresponding relation for the galaxy (Clark and Caswell, 1976) has the form:

$$\log \Sigma = -3.0 \log D - 14.8.$$

The slope of the relation is somewhat flatter than that of the galactic relation. The accuracy of the fit appears to be good enough to suggest that the slope is significantly greater than 2. A slope of 2 corresponds to no systematic evolution of the radio emission. The extent to which selection effects may be producing this result is discussed below. An unusual aspect of the above relation is the low value of the intercept relative to the galactic relation. This suggests that the SNRs in M33 are at least an order of magnitude fainter, at a given D, than those in our galaxy. Possible causes for this difference are discussed below.

Selection Effects: Before a proper interpretation of the above relation can be made it is necessary to consider possible selection effects and observing biases that may affect it. The optically selected sample may be biased against larger remnants because of their lower surface brightnesses and confusion by background objects such as HII regions. This tends to favour the optically brighter remnants. As suggested by Blair and Kirshner (1985) SNRs with $D >\approx 25$ pc are probably undersampled in DGD's list. The detection threshold of the radio observations is such that for resolved remnants, it is independent of their diameters. This favours the radio detection of higher surface brightness remnants for $D >\approx 15$ pc. Very small remnants become inconspicuous as they approach the optical seeing limit and their diameters tend to be overestimated. As a result, the surface brightnesses of these remnants are underestimated. The net result of the selection effects at both very small and very large D is to flatten the $\Sigma - D$ relation. A competing effect occurs when larger remnants are partially resolved so that only portions of their fluxes are detected which results in underestimates of their surface brightnesses. This would tend to significantly steepen the $\Sigma - D$ relation. This problem was avoided in our observations by using integration areas at least as large as the optical areas of the remnants so that any additional uncertainty in the flux densities were incorporated into the error estimates. It is thus unlikely that selection effects are producing the observed steep slope (in fact, they tend to flatten it) and we conclude that the observed $\Sigma - D$ relation signifies a significant departure from the non-evolutionary case ($\Sigma \propto D^{-2}$).

Discussion: The results of the above analysis suggest that a $\Sigma - D$ relation may indeed hold for M33 SNRs. According to Duric and Seaquist (1986) the presence of such a relation is consistent with adiabatic evolution. However, the scatter in the relation is greater than that for the galactic remnants. How can this be reconciled with the fact that M33 SNRs are free of distance uncertainties and that they should therefore form a tighter relation? Furthermore, how can this result be reconciled with Blair and Kirshner's (1985) results that argue against simple adiabatic evolution of SNRs in M33? The answer may lie in Blair and Kirshner's (1985) own discussion of selection effects in their $N(< D) - D$ relation and the possibility that simple adiabatic evolution may be modified by supernova precursor differences and an inhomogeneous interstellar medium. If the interstellar medium of M33 is more clumpy than in our galaxy, varying degrees of SNR interaction with their environment will result for SNRs of the same age and they will achieve different diameters and radio emissivities. Our data support this possibility. The significant difference in the intercepts between the galactic and M33 relations argues for a systematic difference in SNR properties between

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our galaxy and M33. It suggests that the ISM of M33 has a lower average density (and therefore less interaction between remnant and environment) or that supernovae in M33 have systematically lower blast energies. Owing to M33's lower overall mass and possible evolutionary differences, neither scenario can be ruled out. Hughes, Helfand and Kahn (1984) showed that, for the LMC, a flat $N(D) - D$ relation is consistent with adiabatic evolution if there is sufficient scatter in the interstellar gas densities and/or blast energies. Blair and Kirshner (1985) present the same possibility to explain their flat $N(D) - D$ relation for M33. We propose that these same factors may be the cause of the intrinsic scatter in our $\Sigma - D$ relation. If that is the case, adiabatic evolution is consistent with both, our analysis and Blair and Kirshner's optical analysis for M33.

We caution against over-interpretation of our $\Sigma - D$ relation which, after all, is based on only 13 detections. However, the effect of the selection effects described above and the fact that all non-detections are for large remnants ($D > 35$ pc) suggest that the true slope may actually be steeper than measured. As poor as the relation may be in terms of scatter, the data does appear to favour the existence of a $\Sigma - D$ relation.

Conclusions: A VLA, 6 cm study of the radio continuum properties of 13 SNRs in M33 has led to the establishment of a $\Sigma - D$ relation. The relation appears to have a flatter slope than the galactic relation. The much lower intercept of the M33 relation and the large scatter in the data point to significant differences in the blast energies and/or environmental gas densities among the remnants and systematic differences between these factors in M33 and the galaxy. It is proposed that the $\Sigma - D$ relation described here and Blair and Kirshner's (1985) optically derived $N(D) - D$ relation are consistent with adiabatic evolution of SNRs in M33. 20cm VLA observations are planned to measure flux densities for the confused and undetected SNRs thereby increasing the total sample and improving the statistics. More optical searches and identifications of SNRs in M33 would be invaluable in extending the study and verifying the results described above.

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