VLBI observations of supernova remnants in Messier 82

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ABSTRACT
We have used the European VLBI Network (EVN) at 18 cm to study five of the more compact radio sources in the starburst galaxy M82. The angular resolution of the observations is 15 mas, corresponding to 0.2 pc at the distance of M82. The observations reveal shells ranging in diameter from 40 to 90 mas (0.6 to 1.4 pc), although the strongest source 41:95:1575 is only marginally resolved by these measurements (~20 x 10 mas²).

We have found clear evidence for expansion in one of the shell sources 43:31:1592 by re-analysing, in wide-field mode, EVN data taken in 1986. Between 1986 and 1997 this source has increased its diameter by 13:6±2 mas, corresponding to an average expansion velocity of 9850±1500 km s⁻¹. If we assume that the remnant is in free expansion, this is consistent with a supernova event in the early 1960s. Hence this remnant is almost certainly younger than the strongest, most compact source 41:95:1575 which was known to be present in the 1960s. 41:95:1575 shows no clear evidence for expansion (<4000 km s⁻¹), consistent with a greater age; this is further evidence of its anomalous status. Comparison of the EVN images with earlier MERLIN data is also consistent with expansion in at least two more of the sources. We discuss the flux density variability of the compact sources in M82 and conclude that, with the exception of 41:95:1575 and two transient sources, there is little evidence for significant changes in flux density of most of the remnants since the early 1980s.

Key words: supernova remnants – galaxies: individual: M82 – galaxies: ISM – galaxies: starburst – radio continuum: galaxies – radio continuum: ISM.

1 INTRODUCTION

Strong, extended 60-μm emission from the central regions of late-type galaxies is usually assumed to indicate a high star formation rate which cannot be sustained for the lifetime of the galaxy (e.g. Rieke et al. 1980). In view of its inferred relatively short lifetime, this phenomenon is usually known as a starburst.

In the radio the starburst emits non-thermal emission extended over several kiloparsecs (Condon 1992) which is ascribed to synchrotron emission from relativistic electrons generated by supernovae. The discovery of compact, non-thermal radio sources in a number of starbursts (Unger et al. 1984; Kronberg, Bierman & Schwab 1985; Antonucci & Ulvestad 1988) was consistent with this model, with most of the compact sources being either radio supernovae or supernova remnants (SNRs).

The best-studied example of a starburst is the central kiloparsec of the nearby irregular galaxy M82. Over 50 compact radio sources are associated with the central starburst, and MERLIN observations (Muxlow et al. 1994) showed the sources to have sizes ranging from 0.3 to 4 pc with many having shell or partial shell structures. These structures and sizes, along with the non-thermal spectral index and lack of rapid variability, confirmed the identity of many of the sources as SNRs. These SNRs in M82 and other starbursts are proving an increasingly valuable tool in understanding the physics of the star formation process. Assuming that these SNRs are produced by young massive stars, with ages of the order of 10⁶ yr, the SNRs trace the recent star formation history of the galaxy. Furthermore, if the supernova rate can be established, then this gives a direct measure of the formation rate of massive stars, which can be used, assuming an initial mass function, to estimate the total star formation rate.

An additional incentive for studies of SNRs in starbursts is that, unlike studies in our own Galaxy, the sample of SNRs in a starburst is well-defined and largely free from selection effects.
All the SNRs are essentially at the same distance from the observer and can be observed with the same sensitivity and angular (and linear) resolution. Hence nearby starbursts can be considered as laboratories in which to investigate, both statistically and individually, the properties of a well-defined sample of SNRs.

In the case of M82, a number of the stronger sources were not adequately resolved by MERLIN and hence there is a need for higher angular resolution observations which can only be obtained via very long baseline interferometry (VLBI). Furthermore, at the angular resolution of VLBI, it is possible to measure the bulk expansion velocity of the SNR shells on a time-scale of a few years. A number of VLBI studies have been undertaken of M82, most of which have concentrated on the most luminous source 41.95 + 575 (e.g. Wilkinson & deBruyn 1990), and although Bartel et al. (1987) showed that some of the remnants were extended on VLBI scales, only 41.95 + 575 was imaged.

In this paper we report on two European VLBI Network (EVN) observations, separated by approximately a decade, which image the radio emission from a number of the more luminous, compact SNRs in the central kiloparsec of M82. We shall assume the distance of M82 to be 3.2 Mpc (Burbidge, Burbidge & Rubin 1964) throughout the analysis, which corresponds to a linear scale of 15 pc per arcsecond.

2 THE OBSERVATIONS AND IMAGE PROCESSING

2.1 1997 observations

Observations of M82 and a nearby phase calibrator, 0955+697, were conducted at 1652 MHz on 1997 June 2–3 using eight telescopes of the EVN. The telescopes received left-hand circular polarization (LCP). The network was composed of the Effelsberg 100-m, Lovell 76-m, Medicina 32-m, Noto 32-m, Onsala 25-m, Westerbork 25-m, Cambridge 32-m and Torun 32-m antennas. The observations were made with the Mark III recording system (mode B) with a total bandwidth of 28 MHz, and were conducted in phase-reference mode with a cycle of 10 min on the target (M82) and 3 min on the phase calibrator.

The data were correlated at the Max-Planck-Institut für Radioastronomie, Bonn, using the MkIIIa processor. The correlator used a pre-averaging time of 4 s and a frequency resolution of 0.5 MHz. The M82 data were processed at one correlator position, namely the position of the brightest SNR, 41.95 + 575. All subsequent data processing was performed with the National Radio Astronomy Observatory (NRAO) aips package. The visibility amplitudes were calibrated using the system temperature and gain information provided for each antenna. We estimate that the absolute calibration is uncertain by up to 10 per cent. The residual delays, fringe rates and antenna gains were determined from 0955 + 697 and then interpolated and applied to M82.

The collection of radio SNRs in M82 spans almost 1 arcmin across the sky (Fig. 1). Hence, in order to avoid the effects of bandwidth and time smearing, the data were kept in the form of 56 independent (but contiguous) 0.5-MHz channels and were not averaged in time. The calibrated M82 data were then simply transformed and CLEANed using the aips program imagr in multi-field mode using a cellsize of 5 mas. The fields were centred around the known MERLIN positions of the SNRs. Further improvements to the phase calibration were made using standard self-calibration techniques. The maps were restored with a FWHM 15 mas circular beam, and the rms noise off-source was 70 µJy beam−1. The flux densities and sizes of the detected sources are summarized in Table 1. Unfortunately, the increase in resolution, from 50 mas with MERLIN at 6 cm to 15 mas with the EVN, results in an order-of-magnitude decrease in surface brightness sensitivity. This is offset, to some extent, by taking...
advantage of the non-thermal spectra of the sources and observing at L band. Although this is the waveband at which the EVN is the most sensitive, only five of the ∼50 sources were reliably detected. Uniformly weighted maps of these five sources are shown in Fig. 2.

The positions of the sources have been measured relative to the phase reference source 0955 + 697, which we assumed to be at a J2000 position of 09h59m10s0. The 21 cm observations were made by Very Large Array (VLA) 6-cm observations of this source with respect to the International Earth Rotation Service (IERS) calibrator 0954 + 658. Using this position we derive the J2000 position of 41.95 + 575 of 09h59m10s639, +69°32′17″.724. This was derived by Very Large Array (VLA) 6-cm observations of this source at around 1986 December 11 in a wide-field mode.

2.2 1986 observations

These observations were made at 21 cm on 1986 December 11 in a project in which S. W. Unger was principal investigator. Unlike the 1997 observations, only four telescopes were used: Lovell 76-m, Effelsberg 100-m, Westerbork 25-m and the 32-m dish at Medicina. The observations lasted 12 h with frequent observations made of the calibrator source 0235 + 164 for the purposes of delay tracking and bandpass calibration; a total of 16 13-min scans were obtained on M82. The data were taken using the MKIII recording system (Mode A) with a total bandwidth of 56 MHz in LCP from 1376 to 1430 MHz. Correlation was carried out at the MKIII correlator in Bonn, with an effective channel width of 1 MHz and an averaging time of 2 s.

The post-processing used the 15OCT97 version of the AIPS package. Unfortunately two of the 12 nine-track tapes were unreadable after 10 years of storage, but this had only a minor effect on the quality of the final image. Calibration was applied using a priori telescope gain curves and system temperature measurements taken during the observations.

The data on 0235 + 164 were used in an initial fringe-fit to set the delays and to determine a complex bandpass correction for each antenna. These were then applied to M82, and a final fringe-fit performed using M82 itself which was well detected on all baselines. Self-calibration and imaging were then performed in a wide-field mode.

Unfortunately, not all observing logs could be found, so the flux calibration was based on the total flux density of 41.95 + 575 which was adjusted to be consistent with the value of 160 ± 15 mJy interpolated from MERLIN and other VLB1 measurements for this epoch (Trotman 1996) at 21 cm. The 14 ± 4 mJy measured flux density of one of the sources, 43.31 + 592, is slightly lower than the 19.5 ± 1 mJy MERLIN measurement reported by Unger et al. (1984), which may be due to missing extended emission in the VLB1 images.

The smaller number of telescopes, together with uncertainties in the calibration, resulted in noise in the 1986 images being typically 120 μJy beam⁻¹. Because of this lower sensitivity, only two sources (41.95 + 575 and 43.31 + 592) of the five sources seen in the 1997 data were reliably detected, although marginal detections were obtained on 44.01 + 596 and 45.17 + 612, together with a consistent upper limit on 43.18 + 583. To facilitate comparisons with the 1995 data, the images were restored with a 15-mas beam. The two detected sources are shown in Fig. 3, and their measured parameters are given in Table 1.

As there was no phase reference used in the observations, no absolute positions can be obtained from these 1986 data. However, if it is assumed that the peak brightness of 41.95 + 575 has remained fixed in position, this can be used to register the 1997 and 1986 images of 43.31 + 592 (see Section 3.2.3).

3 DISCUSSION

3.1 Structures

As can be seen in Figs 2 and 3, the only source that is not well-resolved is 41.95 + 575 (Kronberg & Wilkinson 1975). However, even this source is extended in PA ≈ 53° and at least two components are present in this PA in both the 1997 and 1986 data. Gaussian fitting to these images gives a separation of ∼20 mas (see below) which agrees with higher resolution observations (Bartel et al. 1987; Wilkinson & de Bruyn 1990; Trotman 1996). These authors have suggested the source to have a shell-like structure extending ∼20 by 10 mas, consistent with a very compact (∼0.2 pc) SNR.

Of the other four sources, three (43.31 + 592, 44.01 + 596 and 43.18 + 583) show definite shell structures consistent with SNRs, although Wills et al. (1999) have noted similarities between 44.01 + 596 and Sgr A and argue that it could contain an active galactic nucleus. The remaining source, 45.17 + 612, shows a complex structure, although the eastern part may show part of a shell and hence the source could be two overlapping remnants.

The sizes of the shells are in reasonable agreement with the sizes deduced from the MERLIN 5-GHz data. In the case of 43.31 + 592, however, the shell size was clearly overestimated from the MERLIN data as a result of assuming that an extended component to the east was part of the shell. The sizes are...
consistent with the flux density versus diameter plot based on the
MERLIN 5-GHz data (Muxlow et al. 1994).

All the sources detected by the EVN are clearly compact, having linear sizes of $\approx 1$ pc. Despite their compact size, all the
remnants show some deviation from circular symmetry, which
suggests that they are already interacting with density gradients
and/or clouds in the interstellar medium. Even in the case of
43.31 + 592, which appears the most circularly symmetric, there
is a gap on the eastern side of the shell which is adjacent to weaker
emission which extends further from the centre than the typical
shell radius. In the case of 43.18 + 583 there appear to be large
deviations from axisymmetry as it appears to have an elliptical
structure. Finally, if 41.95 + 575 is indeed an SNR then it is
surprisingly distorted ($20 \times 10$ mas$^2$) and clearly cannot be in free,
and hence symmetrical, expansion despite its compact size and
high inferred pressure.

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3.2 Expansion velocities

3.2.1 Background

Although the supernova rate can be inferred from the SNR luminosities (e.g. van Buren & Greenhouse 1994), a less model-dependent measurement can be obtained by combining the SNR luminosities and diameters (Muxlow et al. 1994). This latter method does, however, require an estimate of the average expansion velocities of the remnants, which Muxlow et al. (1994) have tentatively measured to be \(-5000\,\text{km\,s}^{-1}\). Furthermore, carefully matched VLBI observations between 1987 and 1990 have shown that the expansion velocities of SNRs in M82 were as low as those in the 1986 measurement, which could be interpreted as an expansion rate of \(\sim2500\,\text{km\,s}^{-1}\) (Trotman 1996). If, indeed, all the expansion velocities of SNRs in M82 were as low as this, then estimates of the supernova rate would also be underestimates, and hence it is important to establish whether the low expansion velocity of 41.95 + 575 is typical or anomalous.

3.2.2 Measurements on 41.95 + 575

In Figs 2 and 3 it can be seen that 41.95 + 575 is elongated along PA \(\sim53^\circ\) at both epochs. Our resolution is insufficient to discern the possible shell structure seen in higher resolution observations. A single 2D Gaussian fit to the data gives the half-power sizes shown in Table 1. The 1997 size appears to be significantly larger than the 1986 measurement, which could be interpreted as an expansion over the 10.5 yr of \(3\,\text{mas}\) along each of the major and minor axes, respectively. This results in expansion velocity estimates of between 3000 and 4000 km s\(^{-1}\).

However, the situation is clearly more complex, as higher resolution measurements (e.g. Wilkinson & deBruyn 1990; Trotman 1996) have shown that there are at least two bright regions present. These are visible in our data, particularly on cross-cuts made along the major axis; 1D Gaussian fitting gives separations along this PA of approximately 20 mas for both the 1986 and 1997 data, and is consistent with the higher resolution data in ruling out large (\(>5000\,\text{km\,s}^{-1}\)) expansion velocities. It is interesting to note that, whereas the peak flux density of the northeastern component has decreased by a factor of \(\sim4\) over the 10.5 yr, the south-western component remained approximately constant at \(\sim13\,\text{mJy}\).

It appears that the intrinsic expansion velocity of 41.95 + 575 is indeed low; this could be a consequence of the ejection of a very massive shell from a supermassive (\(>50\,\text{M}_\odot\)) star. However, as we will discuss in Section 3.4, an alternative explanation for the low expansion rate could be that 41.95 + 575 is an SNR immersed in a very dense, high-pressure, molecular cloud. This confinement may also produce the high intrinsic radio luminosity seen in this source.

3.2.3 The expansion of 43.31 + 592

This source shows the best-defined shell and, because of its relatively high brightness, was well-detected in both the 1986 and 1997 data. There are three main components present in the shell at both epochs. It is clear from Fig. 4 that the source has expanded significantly in the 10.5 yr between these observations.

The image of 43.31 + 592 at epoch 1986.9 has been registered relative to the peak of 41.95 + 575. Hence, if we assume that, between 1986 and 1997, 41.95 + 575 has insignificant proper motion and that structural changes have not significantly moved the position of the peak, we can accurately register the images of 43.31 + 592 at both epochs. In Fig. 4 we show the two images of 43.31 + 592 registered by this method. The maxima of the three components seen in the 1986 shell are marked by crosses, and their positions compared with corresponding maxima in the 1997 image in Table 2. It can be seen that in all three cases the maxima
of the components have shifted outwards which is consistent with expansion of between 5 and 8 mas (Table 2).

The shell diameters were measured using several methods, including Gaussian fits to a series of cross-cuts through the centre, averaging radially using the AIPS task IRING and fitting circles to the shell maxima. Using these methods the 1997 and 1986 data give average diameters of $42.1 \pm 1.5$ and $28.5 \pm 1$ mas respectively. Hence the shell diameter of $43.31 + 592$ has increased by $13.6 \pm 2$ mas between 1986 December and 1997 June, corresponding to a bulk expansion velocity, relative to the shell centre, of $9850 \pm 1500$ km s$^{-1}$ assuming a distance of 3.2 Mpc. Hence if the remnant were in free expansion then it would have been 25 yr old in 1986, suggesting an origin in a supernova event in the early 1960s. If the shell is decelerating, it could, of course, be even younger, although it appears to have been present in the 1972 observations of Kronberg & Wilkinson (1975), which sets a lower limit to its age.

Note that in the 1997 image there are small deviations from circular symmetry in the north-eastern quadrant, which is consistent with a slightly larger shell radius. This larger radius is at a point where the shell brightness is at a minimum, and may represent plasma escaping with a higher than average expansion velocity, possibly into a region of lower ambient density. This would, of course, suggest that the main shell is already decelerating and hence approaching the end of the free expansion phase.

3.2.4 Possible expansion in other sources

In addition to $43.31 + 592$, both $44.01 + 596$ and $43.18 + 583$ show good evidence for shell-like structure in the 1997 data (Fig. 2). $45.17 + 612$ has a more complex structure, but even this shows evidence for a partial shell in the eastern segment. Unfortunately, these sources were only marginally detected in our 1986 EVN data, which do not give reliable first-epoch measurements of shell diameters. However, some shell sizes can be obtained from epoch 1992.6 MERLIN 5-GHz images of these sources (Muxlow et al. 1994), observed with a 35-mas beam, which can be used to investigate their expansion.

The MERLIN 5-GHz image of $43.18 + 583$ shows a well-defined, almost circular, shell with a diameter of $\sim$75 mas. The 1997.5 EVN 18-cm image of this source (Fig. 2) has poor signal-to-noise ratio with much of the shell only defined by the lowest ($0.1$ mJy beam$^{-1}$) contour. Although the three strongest components are consistent with a shell diameter of $90 \pm 10$ mas, the weaker emission appears to form elongated structure $75 \times 110$ mas$^2$ in extent. Hence there is marginal evidence that the shell could have expanded by $\sim5-10$ mas, possibly non-symmetrically. However, better quality VLBI images are required for a definitive result.

The EVN image of $44.01 + 596$ shows a definite shell-like structure, with the brightest part of the shell to the south-east. The northern and western parts of the shell are not as well-defined, and shell diameters ranging between 50 and 65 mas can be fitted to the

![Figure 4. Contour maps of the 1986.9 and 1997.5 EVN images of 43.31 + 592.](https://academic.oup.com/mnras/article-abstract/307/4/761/1066685)

### Table 2. Expanding knots in 43.31 + 592.

<table>
<thead>
<tr>
<th>Component</th>
<th>1986.9 position J2000</th>
<th>1997.5 position J2000</th>
<th>shift mas</th>
<th>Expansion velocity km s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SE knot</td>
<td>$09^h55^m52^s028.72$ +69°40′45″4075</td>
<td>$09^h55^m52^s029.36$ +69°40′45″4031</td>
<td>5.4</td>
<td>7800</td>
</tr>
<tr>
<td>SW knot</td>
<td>$09^h55^m52^s024.47$ +69°40′45″4129</td>
<td>$09^h55^m52^s023.45$ +69°40′45″4145</td>
<td>5.6</td>
<td>8100</td>
</tr>
<tr>
<td>N knot</td>
<td>$09^h55^m52^s025.55$ +69°40′45″4308</td>
<td>$09^h55^m52^s024.36$ +69°40′45″4359</td>
<td>8.0</td>
<td>11 600</td>
</tr>
</tbody>
</table>

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data. Unfortunately, the MERLIN 5-GHz measurements do not resolve this shell, and Gaussian fits are required to establish a size of 45 × 50 mas². If the 1997 18-cm EVN image is convolved with the same 35-mas beam as the 1992 MERLIN observations, there is a definite extension to the north, and a Gaussian fit to the data gives a FWHM size of 48 × 61 ± 3 mas which suggests an expansion of a few mas. However, such Gaussian fits do not give good measures of shell diameters, and it is essential that the shells be well resolved before definitive measurements can be made of expansion velocities.

The 18-cm EVN image shows the eastern part of 45.17 + 612 to have a possible partial shell structure with a radius of ~40 mas. When convolved to 35-mas resolution the structure looks similar to the 5-GHz MERLIN image, although the extension to the north-west is only present on the 18-cm data. No accurate estimates of shell radii can be made in this source, although future measurements using registered images could be used to measure the velocities of individual components (as we have done for 43.31 + 592).

### 3.3 Flux density variations of the compact sources

There is no doubt that the flux density of the most luminous source, 41.95 + 595, is decreasing rapidly at ~8.5 per cent per year (e.g. Trotman 1996). The initial variability studies of the other sources indicated that their flux densities were also decreasing at 5 to 10 per cent per year (Kronberg & Sramek 1985). However, later studies (e.g. Kronberg & Sramek 1992), using longer time periods, showed that much of the earlier variability has been overestimated. However, in view of the young age deduced for 43.31 + 592 from the expansion measurements (Section 3.2.3), some variability in this source might be expected. Hence we will review, in some detail, the published flux density measurements and evidence for variability for this particular source.

The early work by Kronberg & Sramek (1985) suggested that the 5-GHz flux density of 43.31 + 592 had decreased by 12.5 per cent over a 2.7-yr period, implying a half-life of ~14 yr; however, subsequently the 5-GHz flux density of this source has shown only a marginal change from 10.9 ± 0.3 mJy in 1981.1 (Kronberg & Sramek 1985) to 10.3 ± 0.2 mJy in 1995.6 (Wills et al. 1997). Hence there is little evidence that its 5-GHz flux density has varied significantly over 15 yr, in agreement with the results presented by Kronberg & Sramek (1992). Similarly, at 3.6 cm 43.31 + 592 shows little evidence for a flux density decrease over more than two decades. In 1972 the source was tentatively detected with a flux density of ~11 mJy (Kronberg & Wilkinson 1975). Subsequent more accurate measurements gave flux densities of 7.16 ± 0.09 mJy in 1990 (Huang et al. 1994) and 7.95 ± 0.1 mJy in 1994 (Allen & Kronberg 1998). Finally, at L band the 18-cm flux was 19.5 ± 1 mJy in 1982 (Unger et al. 1984) and 22 ± 2 mJy in 1995 [we have extrapolated the 21-cm Wills, Pedlar & Muxlow (1998) measurements using the spectral index from Allen & Kronberg (1998)].

Hence there is no evidence that the flux density of 43.31 + 592 has varied at any frequency by more than a fraction of a per cent per annum over at least a decade. The lack of variability is more consistent with an SNR rather than a radio supernova. This interpretation is consistent with its linear size of ~1 pc which is larger than any normal circumstellar medium. Hence, apart from its relatively young age, there seems no observational reason to consider 43.31 + 592 to be other than an SNR.

This behaviour seems typical of many of the compact sources in M82, as the L-band flux densities of many of the sources appear to have remained approximately constant over more than a decade. For example, we can compare the 18-cm flux densities of the eight strongest sources measured by Unger et al. (1984) in 1982 with the 1994 21-cm measurements of Wills et al. (1998), we find that only 41.95 + 575 has shown a significant decrease with time, and that the flux densities of the others have either remained constant within the measurement errors or in some cases possibly increased.

#### 3.3.1 Evidence for transient sources

Most of the sources in M82 do not show rapid variability, but there are at least two cases in which a rapid change in flux density has been observed, typical of a radio supernova. These are 41.5 + 597, the 6-cm flux density of which decreased from 7.1 mJy in 1981 February to less than 1.5 mJy in 1982 April (Kronberg & Sramek 1985), and 40.59 + 558, which was detected in 1992 (Muxlow et al. 1994) with a 6-cm flux density of ~1 mJy and yet was not detected in the earlier work by Kronberg et al. (1985) or by 1995 MERLIN or VLA observations. We cannot, of course, rule out phenomena other than radio supernovae for these transient sources, and more frequent multi-frequency monitoring at high angular resolution is required to establish their properties with more precision.

### 3.4 Properties of the supernova remnants in M82

The distinction that is usually drawn between radio supernovae and radio SNRs is that the former are caused by an interaction of the supernova shock wave with the circumstellar medium, whereas the latter occur when the shock wave interacts with the interstellar medium (e.g. Weiler & Sramek 1988). Hence, ideally, a typical radio supernova will show a rise and decay of flux density on a time-scale of a few years as the shock wave passes through the circumstellar medium, and will have a size measured in astronomical units rather than parsecs (e.g. Chevalier 1992). This type of behaviour has been observed in a number of extragalactic radio supernovae (e.g. see Hyman et al. 1995). On the other hand, the radio emission from SNRs may not rise to a maximum until a significant fraction of the interstellar medium has been swept up, possibly several hundred years after the initial supernova explosion (e.g. Gull 1973).

This somewhat simplistic distinction between radio supernovae and radio SNRs is becoming less clear, and several extragalactic radio supernovae have been found to have flux density decay times measured in decades rather than years (e.g. Weiler & Sramek 1988). Furthermore, the recovery of radio emission associated with supernova events in the 1950s and 1960s has led Hyman et al. (1995) to suggest that the supernova shock could interact with the circumstellar medium for several decades. Terlevich et al. (1992) have investigated the properties of supernovae that interact with a dense circumstellar medium, and conclude that they may miss the adiabatic Sedov phase altogether.

It is important to note that currently there is little observational information about the radio properties of supernova events with ages between a few decades (e.g. SN 1979c, etc.) and several hundred years (e.g. Cas A). However, in the M82 starburst there is good evidence that many of the compact radio components are SNRs in this missing age range (Muxlow et al. 1994), and our
expansion velocity measurements confirm that at least one of the more compact M82 remnants has an age measured in decades. Although it is one of the more compact objects, 43.31 + 592 is similar in size, flux density, spectral index and structure to many of the other sources in M82. There is no evidence of a sudden change in any of the observed parameters (e.g. radio luminosity, linear size, variability and spectra) of these sources which might be expected to indicate the transition from radio supernovae to SNRs. Hence we conclude that in the case of M82 most of the compact sources are SNRs with ages ranging from decades to several hundred years.

It is clear that in M82 we are dealing with supernova events taking place in an environment different from both our own Galaxy and the interstellar media of many of the external galaxies in which radio supernovae have been observed. Hence it is important to note that conclusions we draw about SNRs in M82 may not apply to normal galaxies. The starburst region contains large numbers of high-density molecular clouds (e.g. Güsten et al. 1993). We can use simple arguments to estimate the ambient densities around the SNR. If we consider the case of 41.95 + 575, then the low expansion velocity and asymmetric structure (see Section 3.2.2) imply that the remnant is no longer in its free expansion stage. Hence, if we assume that the mass ejected (e.g. 5 M_☉ as a conservative estimate) by the supernova is approximately equal to the mass of interstellar medium swept up by the 41.95 + 575 shell, then this is consistent with an ambient density of >10^4 atom cm⁻³.

As we have argued in Section 3.2.3, 43.31 + 592 may also no longer be in free expansion, and we can argue that the rest of the shell is already being slowed down by higher density gas. Hence, equating the swept-up volume with an ejected mass of ~5 M_☉, we infer a density of ~1000 atom cm⁻³.

It is interesting to note that these inferred densities are consistent with the two phases of warm, dense compact clouds (60 K, 10^4 cm⁻³) and the extended cool, lower density ‘inter-cloud’ component (20 K, 10^3 cm⁻³) obtained for molecular gas in M82 by Güsten et al. (1993). Hence we may tentatively conclude that the majority of the SNRs are interacting with the intercloud molecular gas, whereas 41.95 + 575 is still contained within a dense molecular cloud.

4 CONCLUSIONS

These observations have established the structures of five of the most compact radio sources associated with the starburst in M82. Four of the sources show shell-type structures which, when combined with their lack of strong radio variability, non-thermal radio spectrum and small linear size, strongly supports their identification as young SNRs.

A comparison of the structure of 43.31 + 592 in 1997 with earlier Epoch EVN measurements taken in 1986 shows that the remnant is expanding at ~10^4 km s⁻¹. However, the most luminous remnant, 41.95 + 575, has a much lower expansion velocity (<4000 km s⁻¹), and we speculate that it either originates from a very massive star, or is contained in a high-density medium.

Global VLBI observations which took place in 1998 November will provide higher resolution observations of these sources at a later epoch. In addition, MERLIN 5-GHz matched observations between 1990 and 1998 can be used to constrain the expansion velocities of the larger remnants. Monitoring the evolution of these shells in M82 over the next few decades will provide a unique opportunity to observe the interaction of young SNRs with the interstellar medium in a starburst region.

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