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Young supernovae in the starburst galaxy M82

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Summary. MERLIN observations at frequencies of 408, 1666 and 4995 MHz reveal 18 compact (< 0.25 arcsec) radio sources within the central few hundred parsecs of M82. M82 is well known as a 'starburst' galaxy, and it is probable that these objects are either radio supernovae or young supernova remnants. The distribution of radio sources appears asymmetric with respect to the centre of the galaxy, and we suggest that this is due to the current region of star formation lying within a molecular ring.

1 Introduction

The irregular galaxy M82 has been intensively studied in all wavebands since the discovery by Lynds & Sandage (1963) of a system of Hα filaments extending along the galactic minor axis out to 3 kpc from the galactic plane. The central few hundred parsecs of M82 appears optically as a complicated maze of star clusters, giant H II regions, and dust lanes (e.g. O'Connell & Mangano 1978) and is also an extended radio (Hargrave 1974; Kronberg & Wilkinson 1975, henceforth KW; Kronberg, Biermann & Schwab 1981, henceforth KBS), infrared (Abolins *et al.* 1979; Rieke *et al.* 1980) and X-ray (Watson, Stanger & Griffiths 1984) source. Although the nature of the filamentary system is still unclear (e.g. Axon & Taylor 1978), it seems likely that the current activity within the central few hundred parsecs of M82 is powered by a massive burst of star formation, probably triggered by an interaction with the nearby companion M81 (Rieke *et al.* 1980). M82 is therefore an example of a 'starburst' galaxy (Weedman *et al.* 1981), and its proximity makes it an ideal prototype for studying this phenomenon in detail; at an assumed distance of 3 Mpc, 1 arcsec corresponds to about 15 pc.

Previous radio observations of M82 have suggested the presence of a number of discrete compact (typically < 2 arcsec) radio sources embedded in the extended radio source (KW). By far the strongest of these is the object 41.9+58, which has a steep spectrum at frequencies above 1 GHz, and whose flux density at these frequencies is known to be decreasing with an *e*-folding time of about 15 yr (Kronberg & Biermann 1983, henceforth

KB). This object is known to possess milliarcsec-scale structure (e.g. Shaffer & Marscher 1979; Jones, Sramek & Terzian 1981). The other compact radio sources are weak compared to the diffuse radio emission and so an attempt to study them requires high-resolution radio observations which resolve out the diffuse radio emission. Recent 5-GHz VLA observations of M82 by KB reveal about 30 compact radio sources, and we have independently observed these sources using MERLIN (Davies, Anderson & Morison 1980) at frequencies of 408 MHz (73 cm), 1666 MHz (18 cm) and 4995 MHz (6 cm), in order to study their radio spectra and spatial distribution.

2 Observations

The dates and frequencies of our MERLIN observations of M82 are given in Table 1. The flux density scales at 408 and 1666 MHz were set using observations of 3C 48 and 3C 286 (Baars *et al.* 1977). We made 4995-MHz observations at 2 epochs and used 3C 84 as a flux density calibrator; the variability of 3C 84 means that the flux density scale at this frequency is uncertain by about 10 per cent. The calibrated data were corrected for atmospheric phase and gain errors using the self-calibration technique described by Cornwell & Wilkinson (1981); this technique is helped by the presence of a strong reference feature within the map, and the compact source 41.9 + 58 is ideal for this purpose. The final corrected data were then Fourier transformed and CLEANed (Högbom 1974). We used restoring beams of 1.0, 0.25 and 0.08 arcsec at 408, 1666 and 4995 MHz respectively. This analysis procedure does not give any absolute positional information, and so in order to compare our maps with other observations we have assumed a position for 41.9 + 58 of RA $09^h\,51^m\,41^s.95$, Dec. $+69^\circ\,54'\,57''.5$ (KW).

At 4995 MHz a long integration time was required in order to detect 41.9 + 58, and this severely restricted the field of view of the final maps. At 408 MHz the visibility amplitudes on the shorter MERLIN spacings were dominated by the diffuse radio emission. As the main purpose of these observations was to look for compact structure embedded in this diffuse emission, we only used the longer spacings at this frequency: this somewhat increased the noise level on the final map.

Most of the discussion in this paper is concerned with the 1666-MHz MERLIN map, on which the thermal noise level is about 1 mJy per beam area. However, this is a large map, with structure close to the noise level, and it is important to understand how self-calibration affects flux density measurements. We have therefore produced some simulated data by computing the visibilities that would be observed if the radio source in M82 consisted of the 18-component model described later. At each data point, baseline-dependent noise having a Gaussian distribution of amplitude and random phase was added in order to simulate the effects of system noise. Then, in order to simulate atmospheric phase errors, we added a telescope-dependent phase error randomly distributed between 0 and 360°, completely corrupting the visibility phase but preserving the closure phase. The important test is

Table 1. Dates and frequencies of MERLIN observations of M82.

Frequency (MHz)	Date of observation	Flux density of 41.9+58 (mJy)
408	1981 Sept 26	210 ± 20
1666	1982 Dec 11	207 ± 10
4995	1982 May 14	95 ± 10
4995	1983 Sept 22	80 ± 10

whether it is then possible to use self-calibration to obtain a map which agrees with the original 18-component model; we find that, by starting with a point-source model and carrying out a few self-calibration iterations, we do obtain agreement to within the thermal noise.

3 Results

The most important result reported in this paper is the detection of a large number of compact radio sources within the central few hundred parsecs of M82. At 1666 and 408 MHz respectively we detect 19 and 5 radio sources at or above the 2σ levels of 2 and 8 mJy. The limited field of view of the 4995-MHz MERLIN observations means that only 41.9 + 58 is detected at this frequency. The 1666-MHz map is shown in Fig. 1, and in Table 2 we list flux densities and positions of the radio sources relative to 41.9 + 58. The sources are identified in order of decreasing 1666-MHz flux density, using the naming convention described by KW. Because of the relatively high noise level on the 408-MHz map, many of the sources detected at 1666 MHz were not detected at 408 MHz, and for these we have quoted upper limits at the 3σ level of 12 mJy.

Conservatively, on the basis of the 1666-MHz observations alone, we would count as definite detections only the eight radio sources which are detected at or above the 4σ level of 4 mJy. In addition, two of the marginal detections at 1666 MHz are confirmed by the 408-MHz observations, yielding a total of 10 sources. The compact radio sources discussed in this paper have been independently discovered by KB using the VLA at 5 GHz with a resolution of 0.4 arcsec. We produced an overlay of the MERLIN map at 1666 MHz in order to compare this with the VLA map at 5 GHz (KB). There is excellent positional agreement between the two sets of observations, confirming all except one of the sources (source no. 19) in Table 2.

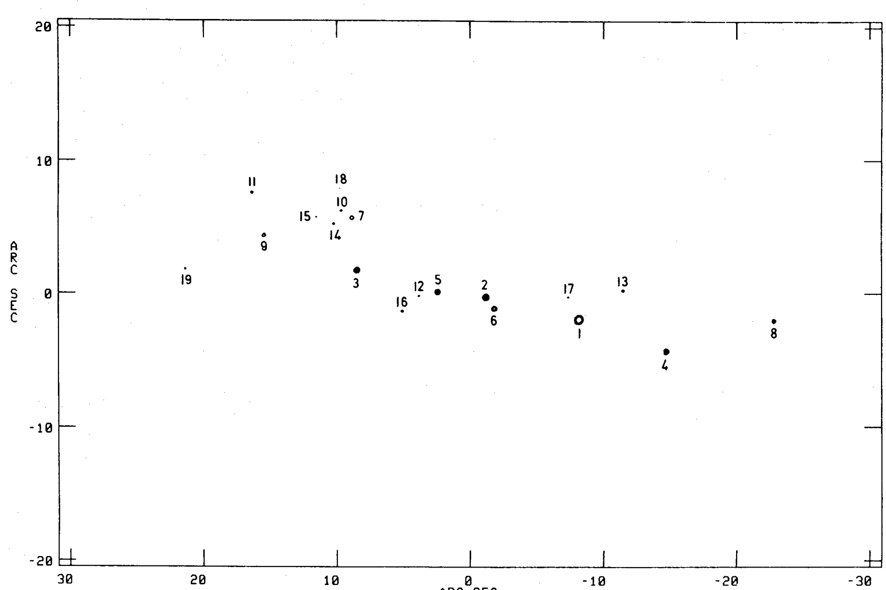

Figure 1. 1666-MHz MERLIN map of M82, with the lowest contour at 1 per cent of the peak brightness of 207 mJy per beam. This figure is only intended to show the quality of the final map, and flux densities and relative positions of the numbered components are listed in Table 2.

Table 2. Positions and flux densities of the sources.

Source number	Source name	Position relative to 41.9+58 (arcsec)		Flux densities (mJy)	
		RA	Dec	408 MHz	1666 MHz
1	41.9+58	0.0	0.0	212±20	207.0±10
2	43.3+59	7.0	1.7	23±4	19.5±1
3	45.2+61	16.6	3.7	16±4	12.5±1
4	40.7+55	-6.6	-2.3	9±4	10.0±1
5	44.0+60	10.6	2.1	<12	9.5±1
6	43.2+58	6.3	0.8	<12	8.5±1
7	45.3+65	17.0	7.8	<12	5.0±1
8	39.1+57	-14.6	-0.1	12±4	4.0±1
9	46.6+64	23.6	6.3	<12	3.5±1
10	45.4+66	17.8	8.2	<12	3.5±1
11	46.7+67	24.6	9.5	<12	3.0±1
12	44.3+59	12.0	1.8	<12	3.0±1
13	41.3+60	-3.4	2.2	<12	3.0±1
14	45.5+65	18.3	7.2	<12	3.0±1
15	45.8+65	19.7	7.7	7±4	2.5±1
16	44.5+58	13.2	0.6	<12	2.5±1
17	42.1+59	0.8	1.7	<12	2.5±1
18	45.4+67	17.9	9.8	7±4	2.0±1
19	47.7+61	29.5	3.8	<12	2.0±1

A comparison with the lower resolution radio observations of KW and KBS is less profitable, as the compact radio sources seen in the MERLIN observations are not differentiated from the more diffuse emission. Indeed, most of the sources listed by KW are not seen in the MERLIN maps. This is presumably either because they are resolved out by the MERLIN observations or because they are variable. If the KW radio sources were shown to be variable, then this would have important implications for their origin (see below), but our attempts to look for variability using the available low-resolution maps (Hargrave 1974; KW; KBS) proved inconclusive because of the differences in resolution and observing frequency.

There is also little detailed correspondence between the compact radio sources and particular objects seen in observations in other wavebands. For example, the compact radio sources are not coincident with the optical/infrared knots of Kronberg, Pritchet & van den Bergh (1972). We illustrate this in Plate 1 which shows the location of the compact radio sources on an optical photograph of M82 taken by Blackman, Axon & Taylor (1979). Similarly, a comparison of our radio observations with the *Einstein* observations shows that, although the diffuse X-ray source is centred on 41.9 + 58, the individual X-ray sources listed by Watson *et al.* (1984) do not correspond in any case with compact radio sources.

None of the compact radio sources appear to be resolved by the 1666-MHz observations and so we can place an upper size limit of 0.15 arcsec (~ 2 pc) for the stronger radio sources [S(1666 MHz) > 10 mJy] and 0.3 arcsec for the weaker ones. 41.9 + 58 is also unresolved by the 4995-MHz observations, implying an upper size limit of 0.08 arcsec. From Table 2 it can be seen that none of the 7 strongest radio sources has a steep radio spectrum between 408 and 1666 MHz.

4 Discussion

4.1 WHAT ARE THE COMPACT RADIO SOURCES?

From source count data at 1400 MHz (Benn *et al.* 1982), we estimate a probability of order 10^{-3} that one of the sources listed in Table 2 is a background object. The compact radio sources are therefore associated with M82, and, as they lie in a region thought to be under-

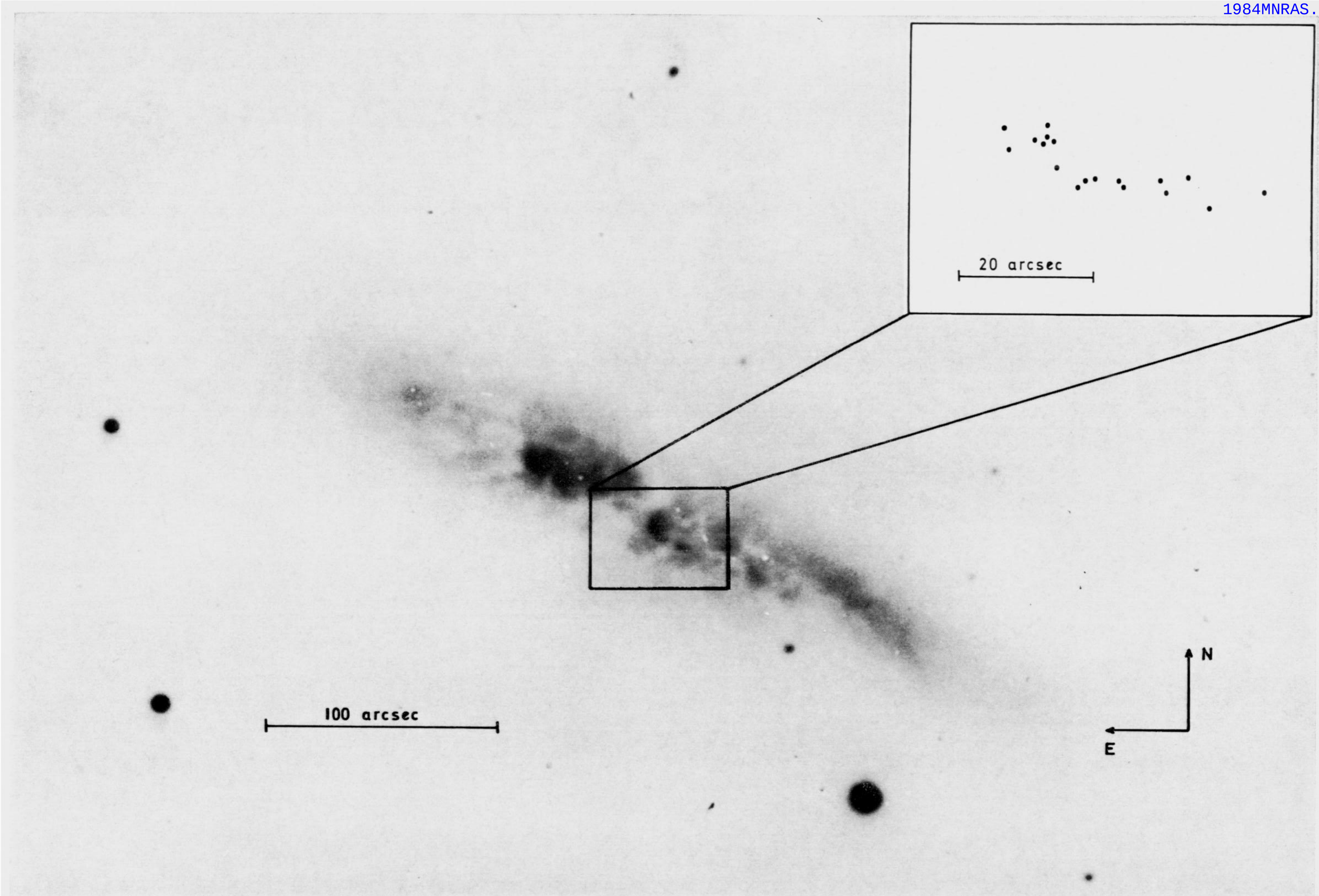

Plate 1. The positions of the 18 compact radio sources discussed in the text compared with an *R*-band optical photograph of M82 produced by Blackman *et al.* (1979).

going a massive burst of star formation (Rieke *et al.* 1980), it seems reasonable to associate them with this starburst. Since the brightness temperatures of the compact radio sources are all greater than about 10^5 K, we can rule out the idea that the compact radio sources are H II regions. The most plausible explanation is therefore that they are either supernova remnants or young radio supernovae located in the disc of M82.

Although a high supernova rate is predicted for M82 by Rieke *et al.* (1980) on the basis of infrared observations, the large optical extinction ($A_V \approx 26$; Rieke *et al.* 1980) to the centre of the galaxy means that these supernovae would not be observed optically. Radio-emitting counterparts to optically observed supernovae have, however, been observed in a few nearby galaxies (Weiler *et al.* 1983) and, for M82, radio observations may provide the only direct means of observing such supernova events (*cf.* NGC 4258; van der Hulst *et al.* 1983). The few existing observations of radio supernovae (Weiler *et al.* 1983; van der Hulst *et al.* 1983) indicate that the radio emission turns on shortly after the optical supernovae, with a luminosity of up to 200 times that currently observed for Cas A. The radio emission appears initially at high frequencies, moving to lower frequencies as the supernova evolves, giving rise in the early stages to a low-frequency turnover at frequencies as high as 5 GHz. Lifetimes vary; the flux density of the radio supernova in NGC 4258 halved in 1 yr (van der Hulst *et al.* 1983), whilst SN 1979c in M100 shows no sign of fading 4 yr after the original event (Weiler *et al.* 1983). Nevertheless, it is apparent that the time spent in the radio supernovae phase is short compared with the age of a classical supernova remnant, and if the compact radio sources are radio supernovae then we might expect them to show variability in both the total flux density and the spectral peak on time-scales of between a few and a few tens of years.

The alternative is that some of the compact radio sources are classical supernova remnants similar to Cas A. At the distance of M82, Cas A would have a flux density at 1666 MHz of 1.6 mJy, just below our detection limit of 2 mJy, and an angular size of 0.1 arcsec. If some of the weaker compact radio sources are classical supernova remnants, then we expect them not to show strong variability and to have steep radio spectra.

The high luminosities of at least the five strongest compact radio sources suggests that they must be radio supernovae, an interpretation supported by VLA observations which

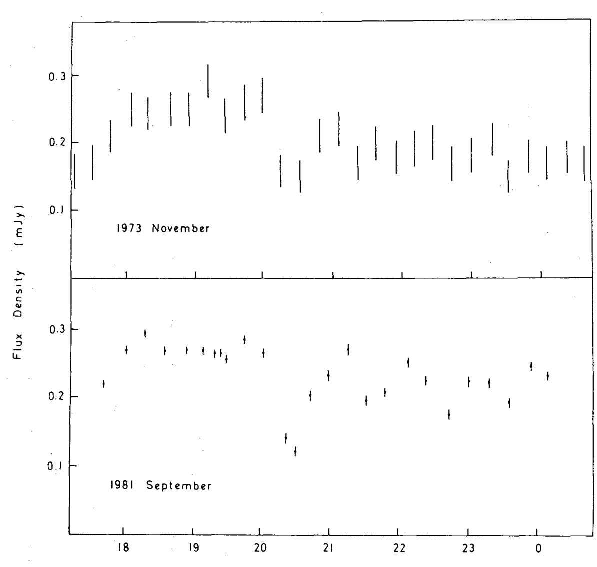

Figure 2. Visibility amplitude on the 127-km MK1A–Defford interferometer baseline plotted as a function of hour angle for the 408-MHz data at the two epochs discussed in the text.

show that a number of them are variable (Kronberg & Biermann 1984). As described above, we might also expect these radio sources to show low-frequency turnovers at frequencies as high as 5 GHz. Although they do indeed appear to have fairly flat or inverted spectra between 408 and 1666 MHz, the turnovers are not necessarily intrinsic to the radio sources, as ionized gas in the disc of M82 with an emission measure of $10^5 - 10^6$ pc cm^{-6} would be sufficient to produce low-frequency turnovers at 408 MHz. This emission measure is rather high, but is attainable if it arises in an H II region near to a source. Flux density measurements at higher frequencies are required to distinguish between the two explanations.

If we take the typical lifetime for a radio supernova to be about 10 yr (as compared to a typical age for a young supernova remnant such as Cas A of a few hundred years), and assume for the moment that at least the five most luminous compact radio sources are radio supernovae, then this leads to a supernova rate of greater than 0.5 yr^{-1}. This is in surprisingly good agreement with the value of 0.3 yr^{-1} derived by Rieke *et al.* (1980), considering the crude nature of both estimates, showing that the interpretation of the compact radio sources as radio supernovae is at least consistent with the other available observations.

4.2 THE NATURE OF 41.9 + 58

41.9 + 58 is an order of magnitude brighter than any of the other compact radio sources. It is therefore the only one which can be easily distinguished from the surrounding diffuse radio emission and hence has already been studied in some detail. We must, however, be cautious about drawing too many parallels with the other compact radio sources. 41.9 + 58 has dominated the radio structure of M82 for at least 15 yr, as compared to a supernova rate inferred from infrared observations of about one every 3 yr (Rieke *et al.* 1980), and so it may be atypical. *VLBI* observations (Geldzahler *et al.* 1977; Shaffer & Marscher 1979; Jones *et al.* 1981; Wilkinson & de Bruyn 1984) show 41.9 + 58 to possess milliarcsec-scale structure, and it is tempting to identify 41.9 + 58 as an 'active galactic nucleus', but its position about 10 arcsec (150 pc) from the kinematic centre of M82 (O'Connell & Mangano 1978; Beck *et al.* 1978; Weliachew, Fomalont & Greisen 1984) makes this seem unlikely.

Our flux density measurements for 41.9 + 58 at frequencies above 1 GHz (Table 1) are consistent with earlier observations, which show this object to have a steep spectrum, and a flux density decreasing with an *e*-folding time of about 15 yr (e.g. KB). The radio spectrum turns over at about 1 GHz, and the evidence for variability below this frequency is much less convincing. KB claim that the flux density at 408 MHz has increased between 1973 and 1979. This claim is based upon two single-baseline measurements using the same 127-km baseline (Jodrell Bank Mk1A – Defford). Since these were taken at different hr angles, the apparent increase could be due to structure. As this baseline is now part of the MERLIN interferometer network, we have extensive data at all hr angles, and in Fig. 2 we plot visibility amplitude against hr angle for the 1973 data of KW together with our 1981 data. Any flux density increase is less than the variability in fringe amplitude due to structure, and we therefore conclude that, at 408 MHz, 41.9 + 58 has not varied by more than 10 per cent over these 8 yr. A better limit than this will only be obtained using maps made at a number of epochs. The lack of variability at 408 MHz suggests that either the opacity at this frequency is changing, or that the emission at 408 MHz arises in an optically-thick shell surrounding the variable source seen at higher frequencies. For further discussion we refer to Wilkinson & de Bruyn (1984).

4.3 DISTRIBUTION OF THE COMPACT RADIO SOURCES

The low-resolution VLA observations of KBS show the diffuse radio source to have a central plateau, away from which the radio emissivity falls steeply. In Fig. 3, we plot the positions of the compact radio sources detected by MERLIN on the low-resolution VLA map, and it can be seen that the distribution is asymmetric, with many of the compact radio sources and all of the strongest ones) lying close to the steep gradient in radio emissivity to the south of the central plateau, whilst there are none to the north of the plateau.

A possible reason why the radio sources appear to lie south of the nucleus of M82 is that this side is nearer to us, and that radio emission from sources to the north is absorbed by ionized gas in the centre of the galaxy. The asymmetry seen in the MERLIN 1666-MHz observations is also seen in the VLA 5-GHz observations, however, and an emission measure of nearly 10^8 pc cm^{-6} would be required to provide significant free–free absorption at such a high frequency. This is physically implausible as the optically-thick thermal emission from the required gas would give rise to a flux density at 5 GHz an order of magnitude greater than that observed by KBS.

The observed asymmetry must therefore reflect the true distribution of compact radio sources rather than being due to obscuration effects, and in this context it is interesting to note that both the Hα and X-ray emission associated with the filamentary system of M82 are asymmetric in the same sense, being much stronger (by a factor of about 10) to the south of the galaxy than to the north (Watson *et al.* 1984; Axon & Taylor 1978). The asymmetry in the distribution of the radio sources could be due either to them lying below, or to them being distributed inhomogeneously within, the tilted galactic disc. A number of observations suggest a model in which the compact radio sources lie within that part of a nearly edge-on ring which is tilted to the south.

Rieke *et al.* (1980) noted that the infrared source in the nucleus of M82 is substantially more centrally condensed at 2 μm than at 10 μm. The emission at 2 μm is probably from a cluster of old red giant stars situated close to the dynamical centre of M82, whilst the emission at 10 μm is likely to arise in hot dust associated with a more recent region of star formation, prompting Rieke *et al.* to suggest that the region of star formation is moving

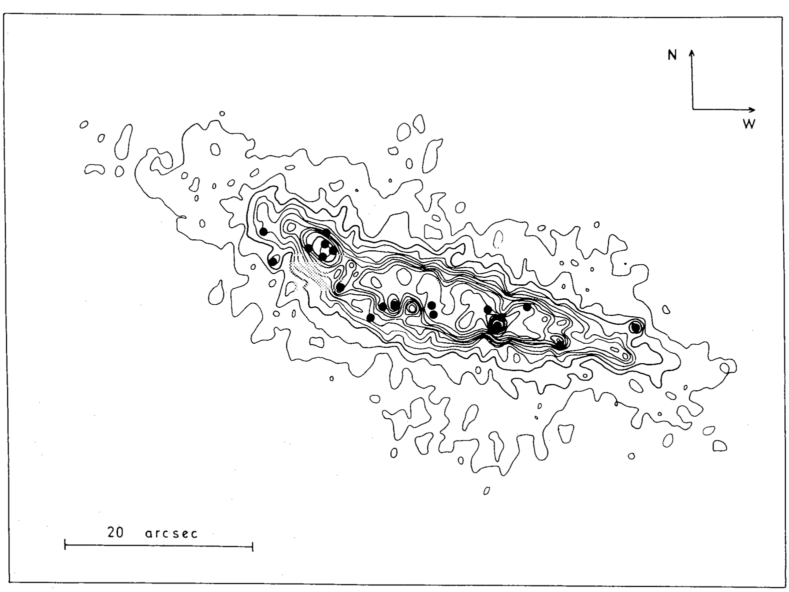

Figure 3. The positions of the 18 compact radio sources discussed in the text plotted on a low-resolution VLA map of the diffuse radio source (Kronberg *et al.* 1981).

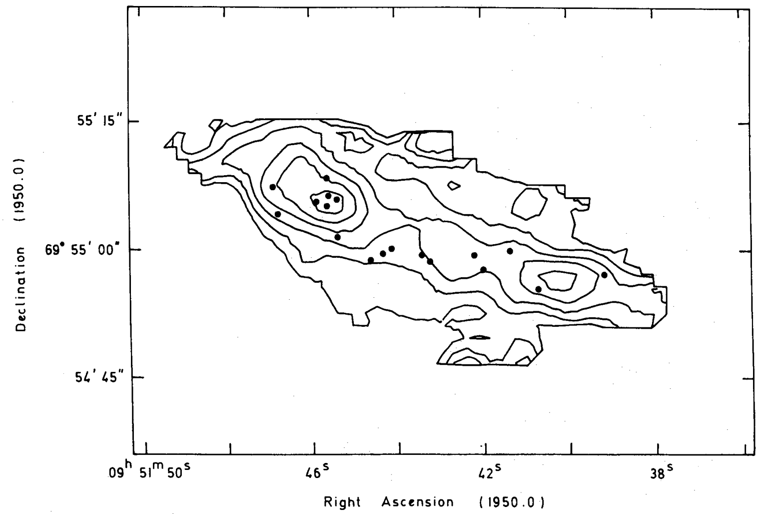

Figure 4. The positions of the 18 compact radio sources discussed in the text plotted on a map of H I optical depth (Wellachew *et al.* 1984).

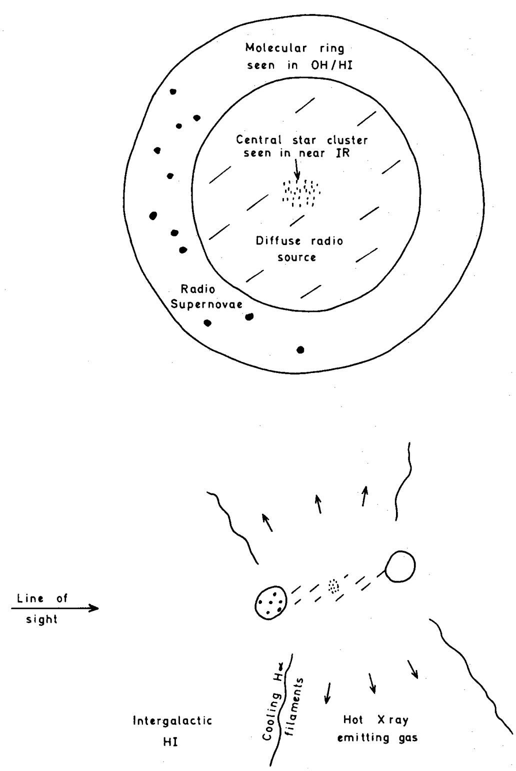

Figure 5. A schematic diagram of the central few hundred parsecs of M82 according to our model, showing both a plane view and a cut.

outwards from the centre of M82. Further evidence in favour of this view has been provided by high-resolution VLA observations of H I and OH absorption against the nuclear continuum radio source, which show the presence of a toroidal ring of cold gas in regular rotation, centred on the dynamical centre of M82 and extending from an inner radius of 170 pc to an outer radius of 340 pc (Weliachew *et al.* 1984). This ring has strong parallels with the molecular ring in our own galaxy (Scoville 1972), and is likely to represent the region of current star formation in M82.

In Fig. 4 we show the positions of the compact radio sources in relation to the H I ring. The radio source distribution is suggestive of an arc of a circle, and it is possible to estimate an inclination of between 75° and 82°, which compares reasonably well with values of between 71° and 82° for the disc of M82 (Blackman *et al.* 1979). Fig. 4 strongly suggests that the compact radio sources are associated with the H I ring, supporting the idea that this is the region where star formation is occurring. In general the compact radio sources lie towards the south of the H I distribution, and the ring model therefore requires that star formation is not occurring uniformly throughout the ring. Evidence for patchy star formation in rings of neutral material in other galaxies has been provided by the structure of the 'hotspot' galaxies (Sersic & Pastoriza 1967) and in particular by recent infrared and radio observations of the face-on galaxy NGC 1097 (Telesco & Gatley 1981; Wolstencroft, Tully & Perley 1984).

In Fig. 5, we give a schematic view of the nuclear regions of M82 according to our proposed model. Within the errors, the near-infrared star cluster of Rieke *et al.* (1980) is coincident with the kinematic centre of M82. Although the total extent of the far-infrared source appears similar to that of the H I ring, the twin peaks of the far-infrared map by Rieke *et al.* (1980) lie inside the peaks in the H I distribution. The bulk of the diffuse radio source lies inside the inner edge of the H I ring, whilst a comparison with X-ray observations (Watson *et al.* 1984) suggests that the ring also laterally confines the X-ray emitting gas. Note that this model is only a first attempt at relating the observed compact radio sources to the other symptoms of nuclear activity in M82, and higher-resolution infrared and X-ray observations are required in order to test it.

An attractive feature of the model is that the filamentary system and supernovae may be related, in that the hot gas responsible for the X-ray emission originates in supernova explosions. As this gas is laterally confined by the H I ring, it will be forced to expand along the minor axis of M82. Rapid cooling of the gas as it expands into the cool neutral hydrogen surrounding M82 will give rise to the observed Hα filaments. The most straightforward explanation for the asymmetry of the filamentary structure is then that the external pressure due to the surrounding H I is larger to the north of the galaxy than to the south.

5 Conclusions

Our observations of M82 detect 18 compact radio sources within the central few hundred parsecs of this 'starburst' galaxy. These objects are probably either radio supernovae or supernova remnants. The MERLIN and VLA results for M82 provide the most direct evidence available that star formation on a massive scale is occurring in the nuclear regions of a galaxy, and strongly support the starburst model for this galaxy. The radio sources are distributed asymmetrically with respect to the centre of M82, and we have suggested that they are associated with a molecular ring similar to that seen in our own galaxy.

The proximity of M82 makes it an excellent laboratory, not only for studying a starburst galactic nucleus, but also for studying the early stages of evolution of supernovae; only four radio supernovae are known other than those in M82. The radio spectra and spectral evolution derived from MERLIN and VLA observations, together with angular size measurements derived from *VLBI* observations, should in the future greatly increase our understanding of these phenomena.

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