LUMINOUS SUPERNOVA REMNANT CANDIDATES IN M82 AND THE PHYSICAL PROPERTIES OF THE VARIABLE RADIO SOURCE 41.9+58

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ABSTRACT

Large numbers (∿30) of supernova remnant candidates have been revealed in new VLA maps of the inner 600 pc of M82 with subarcsecond resolution. The flux density decrease of the bright source 41.9+58 in the M82 nuclear region is found to be occurring with an approximately constant spectral index of -0.9 at $\nu \gtrsim 3$ GHz, and the low frequency turnover has moved from ∿700 MHz in 1974-1975 to <400 MHz in 1979-81.

A model of 41.9+58 is proposed in which it is, at least initially confined by its own hot ($\sim 10^8$K) pre-SN ejecta, and its relativistic particles are accelerated by a pulsar at its centre.

1. FULL-RESOLUTION VLA MAPS OF THE M82 NUCLEUS

The M82 nucleus has been observed with the full resolution of the VLA (0ʺ.4) at λ6 cm (5 GHz). At this resolution, as Figure 1 shows, a large number of compact ($\lesssim$0ʺ.2) sources are visible from 100 mJy down to 0.5 mJy - the current limit of dynamic range at λ6 cm. Within this flux density range, at least 30 discrete sources can be identified, 16 of which are stronger than 2 mJy. If the majority of these are supernova remnants, they are all more radio luminous than Cassiopeia A which, at the assumed 3.2 Mpc distance of M82, would have a 5 GHz flux density of 0.8 mJy and an angular size of ∿0.2 arc seconds.

A preliminary spectral index comparison between 5 and 15 GHz for the stronger sources in Figure 1 shows that the vast majority have steep spectra, which is consistent with their being powerful supernova remnants. Their luminosities range from 1 → 200 times that of Cas A. In an earlier astrometric comparison between the radio hotspots and optical knots, Kronberg, Pritchet and van den Bergh (1971) and O'Connell and Mangano (1978) determined that there was little, if any, correspondence between radio knots at ∿2" resolution and compact features in the optical and near-infrared. A preliminary comparison at the present, higher radio resolution indicates that this is still the case, which is

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not too surprising in view of the high optical obscuration within most of the inner 600 pc. A more detailed analysis of the new radio maps is in progress, and comparison of the radio features with several optical bands (Kronberg, Biermann and Schwab, 1983) will be published elsewhere.

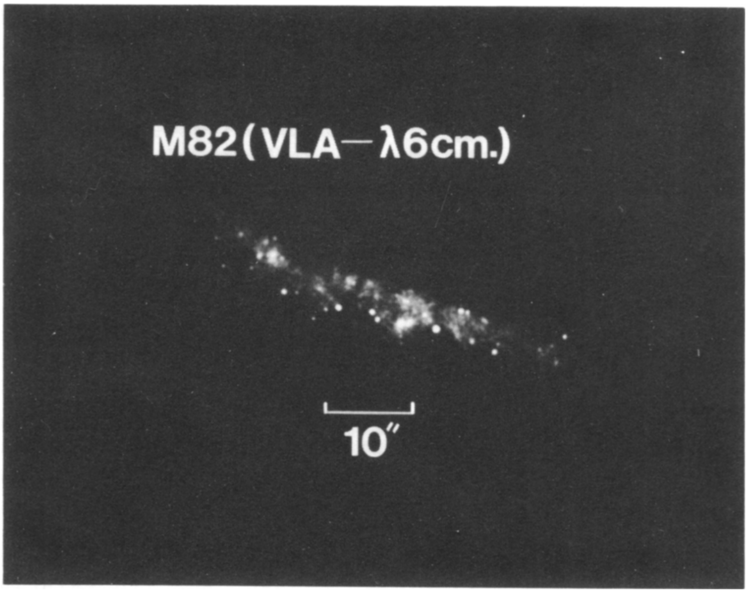


Figure 1. The radio emission from the inner 600 pc of the M82 nucleus, mapped at 0.″4 resolution with the NRAO Very Large Array in 1981. The brightest point source is 41.9+58. The faintest point sources visible in this picture have radio luminosities comparable with that of Cassiopeia A.

O'Connell and Mangano (1978) concluded from the spectral type and colours observed in parts of the M82 disk that a primary encounter with M81 - the likely trigger for M82's current phase of violent activity - occurred somewhat over $\sim 2\times 10^{8}$ years ago. When we compare this "maximum lifetime" of M82's active phase with that of $\lesssim 5\times 10^{7}$ years for the massive stars which are ionizing the central HII regions in M82 (Recillas-Cruz and Peimbert (1970), O'Connell and Mangano (1978)) and also the free-fall time of some of the dense clouds, $\sim 10^{6}$ yrs for $n \sim 1000$ cm^{-3}, it is clear that several generations of massive star formation have occurred recently. This is the likely explanation for the compact radio sources - many are probably supernova - and the ambient synchrotron-emitting cosmic ray gas which is evident in the radio map. The VLA radio observations enable us to deduce a further timescale, namely the time it will take the current cosmic ray clouds to disperse from the central 200 pc of M82. Our VLA maps show that the minimum cosmic ray energy density (assuming equipartition with the magnetic field), ε_{CR}, $\simeq 10^{-9}$ erg cm^{-3}. This gas, being bounded by i/s clouds having $10 \lesssim n \lesssim 2000$ cm^{-3}, will advance with a ram-pressure determined velocity of ~ 100 km/s (we ignore adiabatic losses). We can thus calculate that the present configuration of radio emitting clouds will have dispersed in $\stackrel{<}{\sim}10^6$ years, a time which agrees with the other two independently determined timescales mentioned above (Kronberg, Biermann and Schwab, 1981). Thus the observations support a scenario in which chaotic and expanding cosmic ray clouds envelop and perhaps statically compress dense i/s gas clouds which are induced to collapse into massive stars. The end phases of stellar evolution generate directly, through supernovae, pulsars, etc., and/or indirectly through interstellar turbulence, the next generation of cosmic ray clouds. A self-perpetuating (for a time) scenario of this sort is the most likely explanation of the active condition of the M82 nuclear region. The large implied numbers of massive stars make the M82 nucleus an interesting laboratory for supernovae and their remnants - which we appear to be seeing in large numbers and with very high luminosities, by galactic standards. The next section discusses the properties of the most luminous - presumably stellar - object, namely the variable source labelled 41.9+58 by Kronberg and Wilkinson (1975).

2. THE COMPACT, VARIABLE SOURCE, 41.9+58

This source is by far the most luminous source within the 600 pc long M82 nuclear region. Its spectrum was first defined by Kronberg and Wilkinson (1975) between 408 MHz, where it was optically thick, and 8085 MHz where its spectral slope was found to be steep and close to -0.9 ($S{\sim}\nu^{\alpha}$). Successive NRAO interferometer measurements made between 1971 and 1975 showed further that the 8085 MHz flux was decreasing with time (Kronberg and Clarke 1978), which fact was later confirmed by VLA measurements in 1978 and 1981. VLBI measurements in 1974 by Geldzahler et al. (1977) revealed the remarkable result that, at least at that time, most of 41.9+58's 8 GHz flux came from a region only 1.5 milliarcseconds in diameter ($\sim$1 light month). Figure 2 shows the spectrum of 41.9+58 at 2 epochs; that closest to Geldzahler et al's VLBI measurement, and then in 1981 from simultaneous 20, 6 and 2 cm measurements with the VLA. A repeat by Conway in 1979.1 of Kronberg and Wilkinson's 408 MHz flux measurement indicates that the optically thick flux is increasing, whereas at the higher frequencies it is decreasing with nearly constant slope with an e-folding time of $\sim$15 years. Furthermore, the low frequency turnover ($\tau=1$) frequency, 700 MHz in ca. 1975 has decreased to $\stackrel{<}{\sim}$400 MHz in 1981. The spectral index in 1981 is -0.9, so that the index of the relativistic electron energy spectrum is 2.8. The earliest measurement of 41.9+58's flux in 1966 at 11 cm (Bash, 1968) is consistent with a backwards extrapolation of the spectrum in Fig. 2, and sets a conservative lower limit to the age of 9 years in 1975, and also an upper limit to the average velocity of expansion which is 1270 km/s. Unfortunately no definitive VLBI map has been made since, although a more recent low frequency (18 cm) observations by Jones, Sramek and Terzian (1981) indicate elongated structure up to $\sim$15 mas in p.a. 56° (epoch 1979.4). It is unfortunate that since 1974 no detailed VLBI map has been obtained at $\nu>3$ GHz (where interstellar scattering will not likely obscure the true radio size).

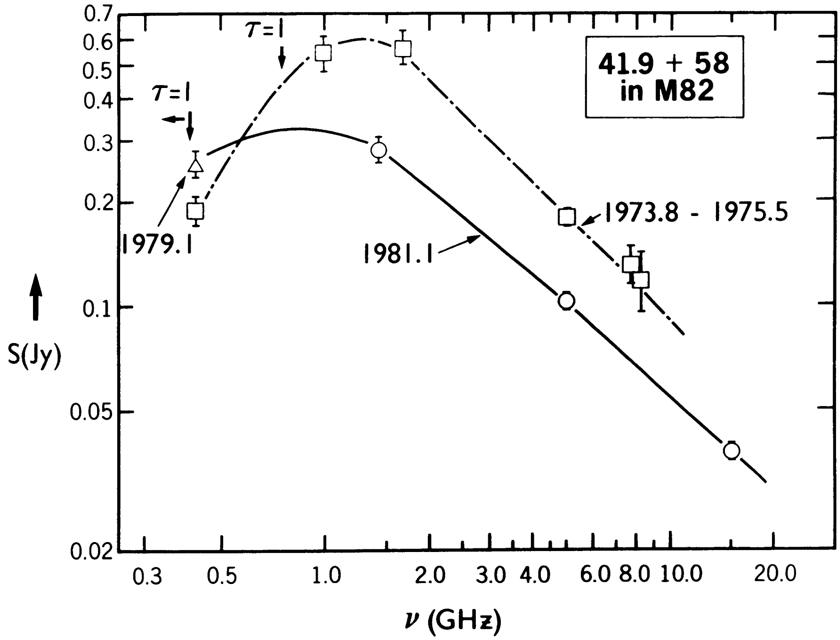


Figure 2. The radio spectrum of 41.9+58 for 2 epochs. The earlier epoch was chosen to include flux density measurements which are relatively close in time to that of the VLBI measurement of the angular size (1974.6) by Geldzahler et al.

If we assume incoherent synchrotron radiation and use the measured ca. 1975 spectrum (Fig. 2) and 7.8 GHz size, some interesting requirements must be imposed on this source's physical parameters (cf. Kronberg and Clarke (1978) and Brown and Neff (1980)): The very well defined low frequency spectral turnover (Fig. 2) establishes a firm upper limit on the synchrotron self absorption (ssa) frequency (ν_{ssa}), as well as the combination of thermal absorption (ν_{th}) both within and in front of the radiating volume. If the value of $\tau=1$ at 700 MHz is due to ssa then the 1.5 mas size and observed luminosity of $6x10^{37}$ erg/s (integrating between 10^7 and 2.10^{10} Hz) require that the magnetic field strength, $B\sin\theta \approx 2x10^{-4}$ gauss. This, being far below the equipartition field (0.13 gauss for equal proton and electron energies (k=1), or 0.4 gauss if k=100), requires a high energy density of relativistic particles, $E_p=3.2x10^{47}$ ergs (k=1), or $1.6x10^{-3}$ ergs cm^{-3}.

The fact that any non-relativistic electrons within the source must also cause $\tau_{th}=1$ at $\nu \lesssim 700$ MHz requires that at most 2.5 $T_8^{3/4} M_\odot$ of non-relativistic gas exists within the source, i.e. $n_{th}<1.16x10^7 \; T_8^{3/4}$ cm^{-3}. This puts an upper limit of $6.3x10^{49}$ erg at $T=10^8$K to its thermal energy content. Comparing n_{th} with the likely density of relativistic electrons, we conclude that the thermal and relativistic particles are present in roughly comparable numbers.

It must be noted here that both the total particle energy and the ratio of n_r/n_{th} are highly sensitive to the dimensions of the radiating volume, and these may have changed significantly from 1975 to 1981. The fact that the frequency at which $\tau=1$ moved significantly downward between 1975 and 1981 (Fig. 2) suggests that the sharp turnover in the 1975 spectrum was indeed due to synchrotron self-absorption, and that 41.9+58 has expanded and decreased in surface brightness. We can then conclude that the $\tau=1$ frequency due to thermal absorption <u>in front of the source</u> (and probably within the source) lies <u>below</u> 400 MHz (the $\tau=1$ frequency in 1981), on the grounds that the optical depth of foreground material is unlikely to change so quickly with time, being less sensitive to the source's radius than the ssa frequency.

Assuming that all the foreground ionized gas exists in a shell of hot thermal gas having thickness ΔR, $\tau_{th}=1$ at $\nu<400$ MHz now requires that the <u>density</u> in the shell has an upper limit given by

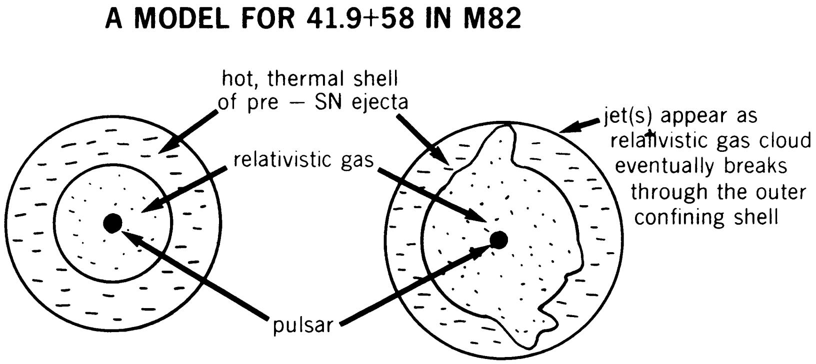
$$n_{shell} \lesssim \frac{6.7\times10^6 T_8^{3/4}}{\Delta R^{1/2}_{(3.10^{16}\mathrm{cm})}} \quad \mathrm{cm}^{-3}$$

The shell must be sufficiently hot, and dense to restrain the expansion of the energetic relativistic electron cloud and at the same time have less than unity optical depth at 400 MHz. We find that, for $T=10^8$K and $n_{shell} \approx 10^7$, these conditions are just satisfied for the epoch 1975 source parameters. This also limits the mass of the shell at $M_{shell} \lesssim 20 T_8^{3/4} M_\odot$. A mass in the range of 1 → 10 $M_\odot$ is probably more realistic, in which case $\Delta R \approx R$ in 1975.

This leads us to propose a model for 41.9+58 in which, in 1975, most of the synchrotron radio emission was within a diameter of $\sim 7\times10^{16}$cm ($\sim$25 light days) and confined by a hot shell of density 10^7 cm^{-3} and temperature $\sim 10^8$K. (Figure 3a). The radio source is expanding slowly (at $v \lesssim 1000$ km/s) and contains a magnetized rotator, probably a pulsar whose rapidly rotating magnetosphere efficiently accelerates the radiating relativistic electrons. The mass of the surrounding thermal shell is too great to be swept up interstellar matter. We postulate that it is the ejecta from the massive star which is undergoing a supernova-like explosion.

The configuration in Fig. 3a is not stable, and the hot, light relativistic gas will expand into instabilities in the surrounding shell as Fig. 3b illustrates schematically. An asymmetrical source and/or jets will develop quickly, and such a phenomenon might explain the asymmetrical source shape observed using 18 cm VLBI by Jones, Sramek and Terzian (1981).

The confining shell would be a source of bremsstrahlung X-rays. We note that the extrapolation of the synchrotron spectrum in Fig. 2 to X-rays would give only 1/20 of the value of $\sim 10^{39}$ erg sec^{-1} reported by Griffiths (1980), and likely associated with 41.9+58. A shell near 2$M_\odot$ having a temperature between 10^7 and 10^8 K in our model would provide



ca. 1975, and earlier
(a)

later
(b)

Figure 3. A suggested physical model for 41.9+58 (left) which is consistent with the physical parameters as measured in ca. 1975. Instabilities will develop quickly in the surrounding hot ejecta which will be "punctured" by the relativistic gas, and an asymmetric growth of overall radio dimensions will develop within a short period of time (right side).

about this much X-ray emission, however it is also possible that inverse compton emission, at least at epoch 1975, also contributed to the X-ray flux. Our calculations serve to show that the X-ray flux from 41.9+58 will be an important guide in a more detailed model than we have described here. A more refined model will require definitive VLBI maps, which are now needed to provide the crucial observational clues to the interesting nature of 41.9+58. A further monitoring of its radio spectrum and X-ray flux is also being undertaken.

It is premature to classify 41.9+58 with other galactic supernovae, since its luminosity exceeds that of Cas A by $\sim$200x. Combined with the large number of luminous (relative to Cas A) objects in Fig. 1 it appears that a much more luminous supernova-like object may commonly exist, at least in regions of very active star formation. It is likewise premature to compare 41.9+58 with the comparably luminous supernova-like radio source recently discovered in M100 (Weiler et al. 1981). Whatever the type of star associated with 41.9+58, it provides us with one of the first opportunities to study the early phase of an explosive stellar event.

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DISCUSSION

DICKEL: These sources are clearly a different class of object than SNR in our galaxy or the other local group galaxies. They are on the average over 100x the brightest one in the Milky Way which says different types of galaxies produce qualitatively different supernovae and remnants. Except for position what is the evidence that 41.9+58 is not just a standard variable quasar?

KRONBERG: Apart from the a priori unlikelihood of finding a background source with S_6>100mJy 3" from the centroid of the M82 radio nucleus, to our knowledge no quasar which varies so quickly with a constant, steep spectrum has been found thus far.

GOSS: (1) What is known about the continuum spectral indices of the SNR candidates in M82? (2) What is the radio structure of the dynamical centre of M82? Is there a nuclear source?

KRONBERG: (1) The majority we have measured thus far, at least among the stronger ones, have steep spectra. Our values are very preliminary but range from $\sim$-0.4 to $\sim$-0.9. (2) The position of the dynamical centre is ill-defined, though approximately at the centre of the radio complex. There is an amorphous complex of radio emission in this area (3"-5" east of 41.9+58) but no obvious radio source at the likely dynamical nucleus.

PACINI: Obviously this source in M82 is probably of the same nature as the other radio supernovae discovered recently. Its long lifetime combined with the known frequency of SN suggests the possibility that similar sources may be detected in a large fraction of galaxies. The signature would be a very compact radio source combined with a transient X-ray source. For the rest, the models for radio supernovae by Chevalier or by Salvati and myself can be tested against the source in M82 and similar systems. Data on combined radio and X-ray evolution are essential in this respect.