High angular resolution studies of starburst galaxies

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This review discusses the importance of high angular resolution radio studies of starburst galaxies, and emphasises the value of VLBI measurements in this area. Current methods of estimating the starformation rate in starburst galaxies are discussed, and compared with a method in which observations of supernova remnants in starburst galaxies are used to independently estimate supernova rates. Starformation rates can then be estimated via the initial mass function. The nearby starburst in Messier 82 is used as case study and the prospects for studies of more distant objects discussed.

1. Starformation rates in starburst galaxies

When the rate of starformation is so high that it cannot be maintained in equilibrium over the lifetime of a galaxy the phenomenon is known as a 'starburst'. There is strong evidence that the starformation rate increases with redshift (eg Cram 1998), implying that starbursts were common in the early universe, most likely associated with galaxy formation. However starburst galaxies are still relatively common in the nearby universe although the majority appear now to be associated with interacting systems or mergers.

The most widely used diagnostic of a starburst is the far infra-red luminosity (eg Reike et al 1980). This is believed to be due to emission from dust grains which have been heated by photons from young stars created in the starburst. If it is assumed that most of the energy in photons emitted by young stars eventually results in heating the dust - which re-radiates it as black-body thermal continuum in photons, then starformation rate (SFR) for stars more massive than $5M_\odot$ can be estimated (eg Cram et al 1998) from the far-infrared luminosity ($L_{60\mu}$) as

$$SFR(M \geq 5M_\odot) = \frac{L_{60\mu}}{5.1 \times 10^{23}}\ M_\odot yr^{-1}$$

The starformation rate can also, in principle, be measured by observations of the properties of the UV photons from O and B stars although this method is severely compromised in many starbursts because of the extinction intrinsic to the starburst. An indirect measure of the UV photons can be made by determining the parameters of the HII regions ionised by them. This can be carried out via optical (eg Hα) emission lines (eg Kennicutt 1983) although quantitative measurements of individual starbursts are again compromised by dust extinction.

Thermal free-free emission at cm wavelengths offers an alternative method of deriving the HII region parameters unaffected by dust extinction. Hence if the thermal free-free luminosity L_T of a starburst is known, then the flux of Lyman continuum (N_{UV}, in photons sec^{-1}) can be estimated from (eg Condon 1992)

$$N_{UV} \geq 6.3 \times 10^{52} {T_e}^{-0.45} \nu^{0.1} L_T$$

where T_e is the electron temperature in units of 10^4K, ν is the observing frequency in GHz and L_T is the thermal free-free luminosity in units of 10^{20} Watt Hz^{-1}. N_{UV} can then be converted into a starformation rate via the relation

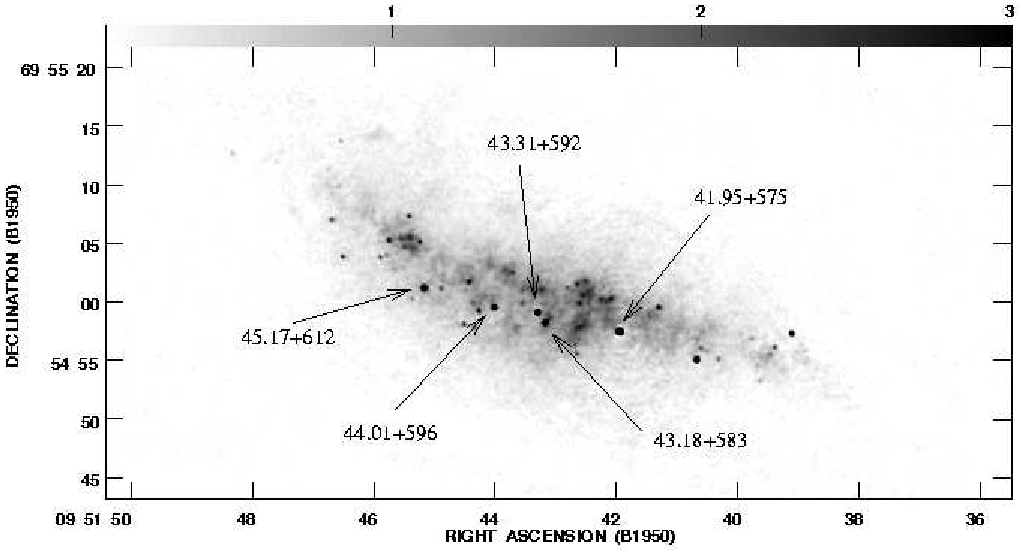

FIGURE 1. The 20cm VLA+MERLIN radio image showing the compact radio sources in M82. The sources which have been studied with VLBI are labelled

$$SFR(M \geq 5M_{\odot}) = \frac{N_{UV}}{3.5 \times 10^{53}} \; M_{\odot}yr^{-1}$$

The main difficulty with this method is the problem of separating the thermal free-free emission from the non-thermal synchrotron emission which will dominate the radio luminosity particularly at the longer wavelengths.

The non-thermal radio continuum can also be used to infer the starformation rate in galaxies. This is mainly on the basis of the surprisingly good correlation between the far-infrared and radio luminosity (eg Helou et al 1985). As the most likely source of relativistic electrons responsible for the non-thermal emission is supernova explosions, it is generally assumed that the non-thermal radio luminosity is determined by the supernova rate in a galaxy and hence the starformation rate. Thus if a Miller-Scalo initial mass function (IMF) is assumed then a supernova rate of ν_{sn} per year will imply a starformation rate of

$$SFR(M \geq 5M_{\odot}) = 25\nu_{sn} \; \mathrm{M_{\odot}yr^{-1}}$$

Hence this accounts for the tight correlation between the far infrared & radio continuum luminosity as both measurements are linked via a common starformation rate (eg Cram et al 1998). Note that, as pointed out by Condon (1992), the starformation rate inferred from supernova rates and UV photon fluxes are sensitive to the IMF in different ways. Hence, in principle, accurate measurements of starformation rate using these methods could be used to, at least, constrain the IMF in starburst galaxies.

2. Supernova remnants in starburst galaxies

In the early 1980s MERLIN (Unger et al 1984) and the VLA (Kronberg et al 1985) discovered $\sim$ 50 compact sources in the nearby starburst Messier 82 (see Figure 1). Subsequently most of these sources proved to be supernova remnants (Muxlow et al 1994) on account of their steep spectrum, parsec-scale sizes and high brightness temperatures. The benefits of studying supernova remnants in starburst galaxies can roughly divided into two areas.

Firstly, those areas in which the supernova remnants give information on the starburst. As well as determining the global supernova, and hence starformation, rate, the distribution of the SNR, unaffected by extinction, shows the structure of the starburst approximately 10^7 years ago. This can be compared with the HII region distribution which traces the current starburst. In addition, via absorption studies, the continuum emission from the remnants can be used as a high angular resolution probe of the ionised (Wills et al 1997), atomic hydrogen (Wills et al 1998, 2000) and molecular gas (eg OH, H_2CO etc) associated with the starburst.

Secondly, the study of these compact sources in starburst galaxies provides unique information on the properties and evolution of supernova remnants. Unlike galactic samples of supernova remnants which have large distance uncertainties and have usually been observed with a variety of linear resolutions and sensitivities, the sample of remnants in a given starburst are essentially at the same distance and have been observed with identical angular/linear resolution and sensitivity (For example as the starburst in M82 has a size of <1kpc, then assuming a distance of 3200 kpc, the differences in relative distance for the sample of remnants is less than 0.03%!). Furthermore, many of the supernova remnants in starbursts cover a unique age range. The youngest supernova remnant in our galaxy appears to be Cass A with an age $\geq$ 300 years. VLBI studies of extragalactic radio supernovae from different galaxies have given considerable information on the early evolution of supernova remnants. However because such observations have only been feasible with VLBI since the late 1970s, little is known currently about the behaviour of such objects with ages greater than 20 years. As we shall discuss below, it seems likely that the remnants in M82 have ages ranging from 30 to $\sim$1000 years and hence observations of remnants in starbursts enables their properties to be parameterised over this age range.

As well as M82, populations of compact sources have been studied in a number of other starburst galaxies including NGC253 (Antonucci & Ulvestad 1988), NGC4736 (Duric & Dittmar 1988), NGC3448 (Noreau & Kronberg 1987), NGC2146 (Tarchi et al 2000) and NGC4038/9 (Neff & Ulvestad 2000). However, as yet, most of these other starburst galaxies have not been observed with sufficiently high linear resolution to measure the sizes of supernova remnants, and often there is some contamination by HII regions which have to be eliminated either by measuring their spectrum and/or brightness temperature.

3. M82 - a case study

Although comprehensive studies of supernova remnants have been carried out in nearby galaxies such as the Large Magellanic Cloud (Mills et al 1984), M31 (Braun 1990) and M33 (Duric et al 1993), these have relatively low starformation rates, and hence contain few young, compact, bright remnants. The nearest starburst galaxies are NGC253 and M82 of which the latter is by far the best studied. At present M82 is the only starburst in which both the sizes and luminosities of a large number of remnants have been measured (Muxlow et al 1994). In addition, an extensive flux monitoring campaign has been carried

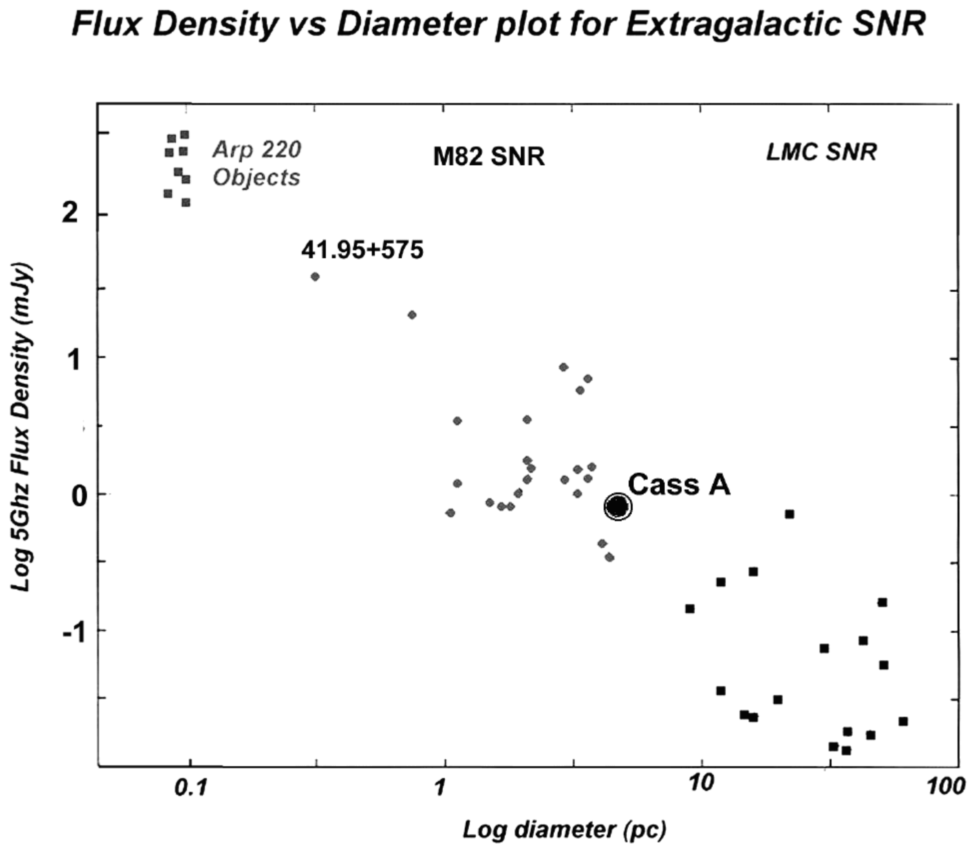

FIGURE 2. A plot of size vs 5GHz flux density for the compact sources seen in M82 compared with Cass A (from Muxlow et al 1994). The flux densities for supernova remnants in the Large Magellanic Cloud (Mills et al 1984) scaled to be at the distance of M82 are shown, together with the approximate parameters of the Arp220 estimated from Smith et al 1998.

out by Kronberg et al (2000) to investigate their radio variability. In Figure 2 we show a plot of the flux density vs size of the remnants in M82 compared with samples in the LMC and Arp220 (both scaled to 3.2Mpc). From this plot it can be seen that most of the M82 remnants are more luminous and more compact than Cass A. One question which needed to be addressed is whether the size of the remnants is a function of age, or whether the sizes are determined by the ambient density.

One method of distinguishing between these possibilities is to measure directly the expansion velocities of the remnants. To this end EVN measurements were carried out at two epochs and an expansion velocity of one of the brighter remnants measured to be $\sim$ 10000 km s^{-1} (Pedlar et al 1999). If the remnant is in free expansion this implies an age of $\sim$ 35 years, or shorter if significant deceleration has occurred. Recent Global VLBI measurements (McDonald et al 2000) of these remnants (Figure 3a) have angular resolutions of a few milliarcseconds corresponding to $\sim$ 0.06pc and hence the direct measurement of deceleration should be possible in a few years. Given that 43.31+592 must have originated before it appeared on the early images in 1972 (Kronberg & Wilkinson 1975) it is already possible to rule out Sedov expansion suggesting that at least this remnant is still expanding close to free expansion. It therefore appears that the size of at

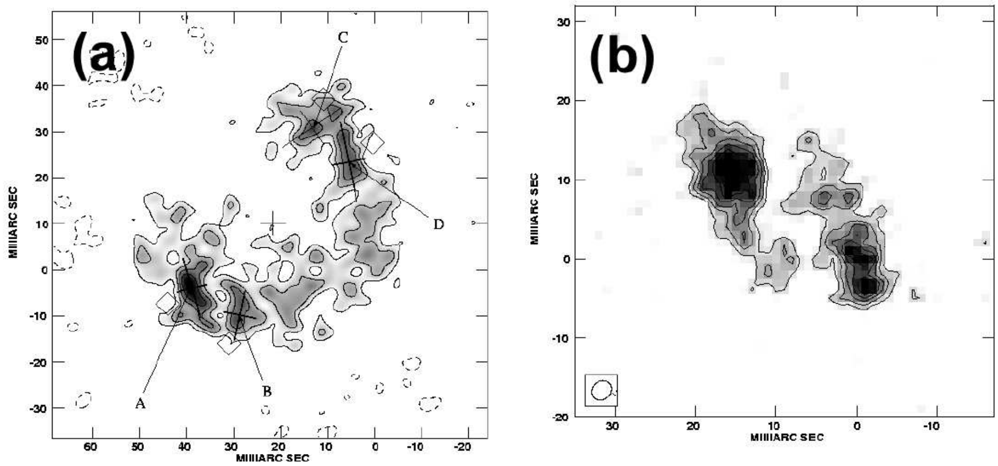

FIGURE 3. **(a)** A 20cm Global VLBI image of the remnant 43.31+592 in M82 with an angular resolution of 4mas(= 0.06pc). The positions of the 4 most prominent knots are marked with crosses, and the open diamonds indicate the position of the knots in 10 years after 1998.9 (assuming the remnant continues to expand at 10000 km s^{-1}) **(b)** 20cm global VLBI image of 41.95+575 - the most luminous compact source in M82. The angular resolution is 2.7×2.3 mas. (from McDonald et al 2000)

least some of the remnants give an estimate of their age, and hence assuming a common expansion velocity of 10000 km s^{-1}, or simply assuming that all the remnants more compact than Cass A are less than 330 years old, gives a supernova rate of ~ 0.07 yr^{-1}. This can be used to calculate a starformation rate ($\geq 5M_{\odot}$) of $\sim 1.8M_{\odot}$ yr^{-1}. This is consistent with the ($\geq 5M_{\odot}$) starformation rates derived from the FIR emission , non-thermal radio continuum and the thermal continuum all of which give values close to $2M_{\odot}$ yr^{-1}. The supernova remnant technique will improve as the properties of the remnants are better understood. In addition, for regions with high starformation rates, it should be possible to measure the supernova rate directly by radio monitoring on timescales of a few years. Somewhat dissapointingly, although M82 has now been monitored for almost two decades (Kronberg et al 2000), no new supernova has been detected. However as the expected rate, on average, is only one every $\sim$ 14 years, this is not unlikely.

4. Compact ultra-luminous objects

The most luminous compact source in M82 (41.9+575) appears to be anomalous when compared to the other sources. Not only is it more than an order of magnitude more luminous than typical remnants in M82, but its luminosity has been decreasing rapidly (8.5% per annum) since its discovery in the mid 1960s. Furthermore recent global VLBI measurements (Figure 3b) show an elongated structure which could be consistent with collimated ejection rather than a shell. Unlike the shell supernova discussed above the object is not expanding at $\sim$ 10000 km s^{-1} and limits of $<$ 2500 km $s^{-}1$ have been determined. One explanation for this object is that it is a supernova remnant confined by a high density medium, although other possibilities require investigation.

Note that the current radio luminosity and size of 41.9+575 appear to be intermediate between the typical remnants in M82, and the compact objects recently discovered in Arp220 (Smith et al 1998) and Mkn273 (Carilli & Taylor 2000). Note that in the

1960s 41.95+575 was of comparable luminosity to the Arp220/Mkn273 objects. Thus it is possible that the compact objects seen in Arp220 and Mkn273 may be similar to 41.9+575.

5. Prospects

As young supernova remnants have sizes of the order of a few parsec, in principle milliarcsecond VLBI studies have the angular resolution to investigate remnants in starbursts up to a distance of $\sim$ 100Mpc. Unfortunately the brightness temperature sentsitivity of current instruments limit VLBI studies of normal remnants to a few nearby objects. Even in M82 only $\sim$10% of the remnants can be studied. If these studies are to extend to more distant objects, an increase in sensitivity of 1 to 2 orders of magnitude is necessary. This will be provided partly by increasing the observing bandwidth of instruments such as MERLIN and the EVN, although in the longer term a large increase in the collecting area for VLBI, using technology anticipated for SKA, will also be required.

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