Subarcsecond radio observations of the dwarf starburst galaxy NGC 3077

Daniel Rosa-González

1INAOE, Luis Enrique Erro 1, Tonantzintla, Puebla 72840, Mexico
2Astrophysics Group, Blackett Laboratory, Prince Consort Road, London SW7 2AZ

Accepted 2005 September 27. Received 2005 September 12; in original form 2005 July 4

ABSTRACT

We present the first subarcsecond radio observations of the nearby dwarf starburst galaxy NGC 3077 obtained with the MERLIN interferometer. We have detected two resolved sources which are coincident with the positions of two discrete X-ray sources detected by Chandra. One of the radio sources is associated with a supernova remnant (SNR) and the observed radio flux is consistent with having a non-thermal origin. The age of the SNRs of about 760 yr is between the average age of the SNRs detected in M82 and those detected in the Milky Way and the Large Magellanic Cloud. We use this detection to calculate a star formation rate (SFR) of 0.28 M⊙ yr⁻¹, which is similar to the SFR calculated by using far-infrared and millimetre observations but larger than the SFR given by optical recombination lines corrected for extinction. The other compact radio source detected by MERLIN, which is coincident with the position of an X-ray binary, has the properties of an HII region with a flux density of about 747 μJy, which corresponds to an ionizing flux of 6.8 × 10⁵⁰ s⁻¹. A young massive stellar cluster with a mass of ~2 × 10⁵ M⊙ detected by the Hubble Space Telescope could be responsible for the production of the ionizing flux.

Key words: galaxies: dwarf – galaxies: individual: NGC 3077 – galaxies: starburst – radio continuum: galaxies.

1 INTRODUCTION

The study of small starburst galaxies such as NGC 3077 has been favoured recently mainly because of the implications that these objects have in the standard model of galaxy evolution (e.g. Baugh, Cole & Frenk 1996). In the hierarchical scenario, smaller systems form first and then become the building blocks of the massive galaxies that are observed in the local Universe. These systems, which are the most numerous type of galaxy, could be responsible for an important fraction of the reionization of the Universe. Moreover, due to the low gravitational potential of those galaxies the interstellar medium might be allowed to escape from the host, more easily contributing to the enrichment of the intergalactic medium at early epochs. However, the expelling of newly processed matter depends not only on the mass of the host and the power of the burst but also on the distribution of the interstellar medium and the presence of a dark matter halo surrounding the host galaxy (e.g. Silich & Tenorio-Tagle 2001).

Nearby compact starburst galaxies are excellent laboratories in which to study the starburst phenomenon. In fact, compact starburst galaxies have been used to test the validity of different star-forming tracers (e.g. Rosa-González, Terlevich & Terlevich 2002), to study the interaction of the burst with the interstellar medium (e.g. Martin 1998; Silich et al. 2002), and to study the enrichment of the intergalactic medium due to the break out of superbubbles (e.g. Kunth et al. 2002).

It is only in the nearby Universe that the physical processes related to the current starburst event can be studied in great detail. The presence of a recent starburst event – triggered by the interaction of NGC 3077 with M81 and M82 – has been confirmed by several independent tracers. The International Ultraviolet Explorer (IUE) ultraviolet (UV) spectra revealed the presence of massive stars no older than 7 × 10⁷ yr (Benacchio & Galletta 1981). The peak of the Pa nebula – a tracer of young star formation regions – (Böker et al. 1999; Meier, Turner & Beck 2001; see Fig. 1) is located between two CO complexes detected by the Owens Valley Radio Observatory (Walter et al. 2002). Walter et al. conducted a comprehensive multi-wavelength study of NGC 3077, relating the atomic and molecular gas with the observed H I regions. By combining CO and emission-line observations, they concluded that the star formation efficiency – defined as the ratio between the Hα luminosity and the total amount of molecular gas – in NGC 3077 is higher than the corresponding value in M82. They conclude that the recent star formation activity in NGC 3077 and M82 is probably due to their interaction with M81.

The extinction-corrected Hα flux indicates a star formation rate (SFR) of about 0.05 M⊙ yr⁻¹, concentrated in a region of about 150 pc in diameter (Walter et al. 2002). This value is lower than the SFR given by extinction-free tracers of the SFR such as the millimetre continuum or the far-infrared (FIR). In fact, the SFR given by observations at 2.6 mm by Meier et al. (2001) gives a SFR
of 0.3 in agreement with FIR measurements from Thronson, Wilton & Kir (1991).

Maps of radio emission can reveal SNRs and H\pi regions as well as other tracers of the star-forming activity within a galaxy, such as recombination emission lines and FIR radiation. They are closely related to the evolution of massive stars also, and therefore to the recent star-forming history of the galaxy (e.g. Muxlow et al. 1994). In this paper we present for the first time radio maps of NGC 3077 with subarcsec angular resolution.

For consistency with previous publications of radio observations we assume a distance to NGC 3077 of 3.2 Mpc throughout the paper (e.g. Tammann & Sandage 1968).

2 OBSERVATIONS

NGC 3077 was observed in 2004 May using the MERLIN interferometer, including the Lovell telescope at Jodrell Bank. NGC 3077 and the phase reference source I0954+658 were observed during a total time of about 21.5 h. The flux density scale was calibrated assuming 7.086 Jy for 3C 286. The observations were made using the wide field mode and an observing frequency of 4.994 GHz in each hand of circular polarization using a bandwidth of 13.5 MHz. Visibilities corrupted by instrumental phase errors, telescope errors or external interference were flagged and discarded by using the local software provided by Jodrell Bank Observatory. The unabsorbed field of view of 30 arcsec in radius allows us to cover the main active star-forming region revealed by emission-line images (see Fig. 1). The data were naturally weighted using a cell size of 0.015 arcsec. The images were deconvolved using the CLEAN algorithm described by Hogbom (1974). The rms noise over source-free areas of the image was ~60 \mu Jy beam\(^{-1}\). The final MERLIN spatial resolution after restoring the image with a circular Gaussian beam was 0.14 arcsec. At the assumed distance of NGC 3077, this angular size corresponds roughly to 2 pc.

3 DISCRETE X-RAY SOURCES AND THEIR RADIO COUNTERPARTS

At X-ray wavelengths, a star formation event is characterized by the presence of diffuse emission associated with hot gas (e.g. ROSAT observations of NGC 3077 by Bi & Arp 1994) but also by the presence of compact objects associated with SNRs and high-mass X-ray binaries (e.g. Fabbiano 1989). Recent Chandra observations of NGC 3077 (Ott, Martin & Walter 2003) revealed the presence of hot gas within expanding H\alpha bubbles. Ott et al. found that the rate at which the hot gas is deposited into the halo is a few times the SFR measured by Walter et al. (2002). Ott et al. (2003) found six discrete X-ray sources close to the centre of the galaxy, but also associated with bright H\pi regions (see Fig. 1). The details of these are given in Table 1.

The X-ray spectrum of S1, S5 and S6 was found to peak in the range ~0.8–1.2 keV. The X-ray spectral properties suggest that S1, S5 and S6 are SNRs. The X-ray spectra of these sources was best fitted with a Raymond–Smith collisional plasma (Ott et al. 1995) and Very Large Array (VLA) observations with a resolution of 54 arcsec (Condon 1987). Recent VLA observations of NGC 3077 at 1.4 GHz have reported an unresolved source located in the same position (Walter et al. 2002).

In Fig. 2 we present the resultant MERLIN radio map which shows strong emission coincident, within the Chandra positional errors, with the position of the S1 X-ray source.

The semicircular morphology of the source showing the presence of bright knots is similar to SNRs observed in other galaxies, e.g. 43.18+58.3 in M82 (Muxlow et al. 1994) or SN1986D in NGC 891 (Pérez-Torres, Alberdi & Marcaide 2004). The SNR has a noticeable asymmetry that could be due to interaction with the surrounding media. In fact, a giant molecular cloud (GMC) with a mass of \(\sim 10^4\) M\(_\odot\) has been detected in CO (Meier et al. 2001). This GMC has a projected size of 79 × 62 parsec\(^2\) (5.3 × 4.1 arcsec\(^2\)) and the centroid of the emission is localized just 1.1 arcsec from the SNR in the north-east direction.\(^1\) The interaction of the remnant with this GMC could be the cause of the asymmetry detected in the radio map.

Due to the non-thermal nature of the SNR emission, radio sources with temperatures higher than 10\(^5\) K can be unambiguously identified as SNRs (e.g. McDonald et al. 2002). For this radio source, we measure a peak flux of 595 ± 60 \mu Jy beam\(^{-1}\), which corresponds to a brightness temperature of 1.24 ± 0.125 × 10\(^8\) K for the given MERLIN spatial resolution at 5 GHz. The angular size of the source – measured on the map using the 3\(\times\) rms contour – is roughly 0.5 arcsec, which corresponds to a physical size of about 8 pc at the assumed distance of NGC 3077. If the SNR has expanded with a constant velocity of 5000 km s\(^{-1}\) (e.g. Raymond 1984) we deduce that the progenitor star exploded about 760 yr ago. This age is longer than the average age of the SNRs detected in M82 (~200 yr) and shorter than the average ages of 2000 and 3000 yr of the SNRs detected in the Milky Way and in the Large Magellanic Cloud (LMC), respectively (Muxlow et al. 1994).

The assumption of constant expansion velocity is quite naive, and the size of the observed SNR depends, among others, on the density of the interstellar medium, initial kinetic energy or the size of the

\(^1\) The position of the GMC is 10^4:\hspace{1mm}03^m:18.85, +68^\circ:43^\prime:57^\prime\prime.
The lifetime of massive star progenitors of the SNRs observed in NGC 3077 is much shorter than the Hubble time; therefore, the results with those from observations of M82 (Muxlow et al. 1994). We can reach values of 5000 km s\(^{-1}\) for the expansion velocity in order to compare our\(\nu\)SN)o f1.3\(\nu\)SN with the calculated supernova rate we obtain a SFR for NGC 3077 of 0.28 M\(_{\odot}\) yr\(^{-1}\). The estimated SFR is in reality an upper limit because the presented observations are sensitive to older SNRs, which we did not detect. Assuming that the flux of a SNR decay with a rate of \(\sim 1\) per cent yr\(^{-1}\) (e.g. Kronberg & Sramek 1992; Muxlow et al. 1994), the 3\(\sigma\) detection limit of 180 \(\mu\)Jy beam\(^{-1}\) allows us to detect older SNRs with ages of 880 yr, implying a lower supernova rate of 1.14 \(\times 10^{-3}\) yr\(^{-1}\). This fact produces a change in the calculated SFR of about 14 per cent.

The flux density of the SNR was calculated by using the AIPS task IMSTAT, which adds the observed fluxes within the area defined by the SNR at three times the noise level. We obtain a flux of 2100 \pm 175 \(\mu\)Jy. For this SNR, the relation between the size and the flux density is consistent with the relation found by Muxlow et al. (1994) for a sample of SNRs detected in M82 and the LMC. This relation, where the flux density is inversely proportional to the diameter, is not consistent with simple adiabatic losses in a synchrotron-emitting source, and an extra source of relativistic particles must come from another reservoir of energy in the form of thermal or kinetic energy present in the remnant (Miley 1980).

The ratio between radio and X-ray fluxes \(R_{r-x}\) = \(5 \times 10^{0}\) \(F_{5\text{GHz}}/F_{x}\) is highly variable and depends on the nature of the object, the surrounding media prior to the supernova explosion and the time at which the SNR is observed. Table 2 shows the values of \(R_{r-x}\) for a small sample of SNRs which include the brightest SNRs in our galaxy, Cassiopeia A and Crab Nebula. For the galactic SNRs, the radio data, which include morphological type, flux and spectral index, were obtained from the Green catalogue (Green 2004). This catalogue is based on observations at 1 GHz. We used the given spectral index to estimate the flux at 5 GHz in order to compare with our observations. For the case of SN1988Z we used the data compiled by Aretxaga et al. (1999) and for the case of NGC 7793-S26, the data from Pannuti et al. (2002). The X-ray data are from the compilation by Seward et al. (2005) except S1 and S3 from Ott et al. (2003), SN1006AD from Dyer et al. (2001), SN1988Z from Aretxaga et al. (1999) and NGC 7793-S26 from Pannuti et al. (2002). The value of \(R_{r-x}\) goes from 0.02 \(\times 10^{-4}\) for the case of SN1986AD to 0.2722 for Vela. The value of \(R_{r-x}\) for S1 is within the observed range.

The other candidates to SNRs – S5 and S6 – were not detected by the present observations. The X-ray fluxes of S5 and S6 are 50 and six times, respectively, lower than the X-ray flux of S1 (see Table 1).

Table 1. Discrete X-ray sources detected in NGC 3077. Sources marked with an asterisk have been detected at 5 GHz by the present observations. The proposed type is based only in the X-ray observations. X-ray unabsorbed fluxes and luminosities (columns 6 and 7) are based on the best-fitting spectra for each individual source (see text for details).

<table>
<thead>
<tr>
<th>Source</th>
<th>RA (J2000)</th>
<th>Dec. (J2000)</th>
<th>X-ray photons (counts)</th>
<th>Proposed type</th>
<th>Flux ((\times 10^{-15}) erg cm(^{-2}) s(^{-1}))</th>
<th>Luminosity ((\times 10^{32}) erg s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1*</td>
<td>10 03 18.8</td>
<td>+68 43 56.4</td>
<td>133{\pm}12</td>
<td>SNR</td>
<td>96.58</td>
<td>14.98</td>
</tr>
<tr>
<td>S2</td>
<td>10 03 19.1</td>
<td>+68 44 01.4</td>
<td>114{\pm}11</td>
<td>Accreting</td>
<td>71.56</td>
<td>11.10</td>
</tr>
<tr>
<td>S3*</td>
<td>10 03 19.1</td>
<td>+68 44 02.3</td>
<td>119{\pm}11</td>
<td>Accreting</td>
<td>65.14</td>
<td>10.10</td>
</tr>
<tr>
<td>S4</td>
<td>10 03 17.8</td>
<td>+68 44 16.0</td>
<td>37{\pm}7</td>
<td>Supersoft source</td>
<td>5.92</td>
<td>0.92</td>
</tr>
<tr>
<td>S5</td>
<td>10 03 17.9</td>
<td>+68 43 57.3</td>
<td>17{\pm}4</td>
<td>SNR</td>
<td>2.06</td>
<td>0.32</td>
</tr>
<tr>
<td>S6</td>
<td>10 03 18.3</td>
<td>+68 44 03.8</td>
<td>17{\pm}4</td>
<td>SNR</td>
<td>17.09</td>
<td>2.65</td>
</tr>
</tbody>
</table>

Equation (1) was calculated by using a Scalo initial mass function (IMF), with a lower mass limit of 5 M\(_{\odot}\) and an upper limit of 100 M\(_{\odot}\) (Condon 1992). In any galaxy, most of the stellar mass is located in low-mass stars; therefore, to calculate the total SFR, including the mass contained in stars with masses lower than 5 M\(_{\odot}\), we need to multiply the factor 24.4 in equation (1) by 9. Combining equation (1) with the calculated supernova rate we obtain a SFR for NGC 3077 of 1.3 \(\times 10^{-3}\) M\(_{\odot}\) yr\(^{-1}\). The other candidates to SNRs – S5 and S6 – were not detected by the present observations. The X-ray fluxes of S5 and S6 are 50 and six times, respectively, lower than the X-ray flux of S1 (see Table 1).
Table 2. Observed properties of a small sample of SNRs. Column 2 shows the type of galactic SNR based on radio observations. Types S and F correspond to shell or filled-centre structure, respectively, and type C if the SNR shows a composite morphology. Column 3 is the radio spectral index. Radio and X-ray fluxes are given in columns 4 and 5. The last column shows the ratio between radio and X-ray fluxes as defined in the text.

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Spectral index</th>
<th>Flux at 5 GHz (mJy)</th>
<th>X-ray flux ($\times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$)</th>
<th>$R_{r-x}$ ($\times 10^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>–</td>
<td>–</td>
<td>2.10</td>
<td>9.66 $\times 10^{3}$</td>
<td>10.87</td>
</tr>
<tr>
<td>Cassiopeia A</td>
<td>S</td>
<td>0.77</td>
<td>7.88 $\times 10^{5}$</td>
<td>2.06 $\times 10^{1}$</td>
<td>19.12</td>
</tr>
<tr>
<td>Tycho</td>
<td>S</td>
<td>0.61</td>
<td>2.10 $\times 10^{4}$</td>
<td>1.99 $\times 10^{0}$</td>
<td>5.27</td>
</tr>
<tr>
<td>Kepler</td>
<td>S</td>
<td>0.64</td>
<td>6.78 $\times 10^{3}$</td>
<td>6.85 $\times 10^{0}$</td>
<td>4.95</td>
</tr>
<tr>
<td>W49B</td>
<td>S</td>
<td>0.48</td>
<td>1.76 $\times 10^{4}$</td>
<td>9.00 $\times 10^{0}$</td>
<td>0.98</td>
</tr>
<tr>
<td>RCW103</td>
<td>S</td>
<td>0.50</td>
<td>1.25 $\times 10^{6}$</td>
<td>1.70 $\times 10^{0}$</td>
<td>0.37</td>
</tr>
<tr>
<td>SN1006-AD</td>
<td>S</td>
<td>0.60</td>
<td>7.23</td>
<td>2.00 $\times 10^{0}$</td>
<td>0.02</td>
</tr>
<tr>
<td>SN1181</td>
<td>F</td>
<td>0.10</td>
<td>2.81 $\times 10^{4}$</td>
<td>2.70 $\times 10^{0}$</td>
<td>520</td>
</tr>
<tr>
<td>Crab</td>
<td>F</td>
<td>0.30</td>
<td>6.42 $\times 10^{5}$</td>
<td>2.88 $\times 10^{1}$</td>
<td>11.14</td>
</tr>
<tr>
<td>Vela</td>
<td>C</td>
<td>0.60</td>
<td>6.66 $\times 10^{5}$</td>
<td>8.87 $\times 10^{1}$</td>
<td>3755</td>
</tr>
<tr>
<td>G292.0+1.8</td>
<td>C</td>
<td>0.40</td>
<td>7.88 $\times 10^{3}$</td>
<td>2.09 $\times 10^{0}$</td>
<td>1.89</td>
</tr>
<tr>
<td>SN1988Z</td>
<td>–</td>
<td>–</td>
<td>5.30 $\times 10^{1}$</td>
<td>4.00 $\times 10^{1}$</td>
<td>6.62</td>
</tr>
<tr>
<td>NGC 7793-S26</td>
<td>–</td>
<td>0.60</td>
<td>1.24</td>
<td>3.90 $\times 10^{1}$</td>
<td>15.90</td>
</tr>
</tbody>
</table>

Notice that these observations did not rule out the possibility that the observed radio source is an old SNR, and further observations at longer wavelength with similar angular resolution and sensitivity are necessary. S3 has $R_{r-x} = 5.73 \times 10^{-4}$, which is within the range of values observed in SNRs. However, the observed ratio $R_{r-x}$ in well-studied SNRs (Table 2) covers at least five orders of magnitudes, and therefore the $R_{r-x}$ value cannot be used to discriminate between SNRs and other types of objects.

Due to the calculated brightness temperature and the X-ray spectrum of S3, the probability that the observed radio emission is coming from an H II region is the most plausible. S3 is probably embedded by the H II nebula but the X-ray flux from the binary and the radio flux have no common origin.

The free–free emission associated with an H II region can be translated to the number of ionizing photons, $N_{UV}$ by (Condon 1992)

$$N_{UV} \geq 6.3 \times \left( \frac{T_e}{10^4 \text{ K}} \right)^{-0.45} \left( \frac{\nu}{10^{12} \text{ GHz}} \right)^{0.1} \left( \frac{L_T}{10^{30} \text{ W Hz}^{-1}} \right).$$

The flux density estimated for the H II region associated with S3 was $747 \pm 127 \mu$Jy. If we assume that the observed flux has a thermal origin, we can estimate the thermal luminosity, $L_T$. We calculated that the number of UV photons coming from the observed region is $6.77 \pm 1.15 \times 10^{50} \text{ s}^{-1}$. Taking into account that O stars produce between $2 \times 10^{30}$ and $1 \times 10^{30} \text{ s}^{-1}$ UV photons (e.g. Mas-Hesse & Kunth 1991), we conclude that only a few massive stars are responsible for the ionization of the observed nebula. A bright stellar cluster (named cluster 1 by Harris et al. 2004) was detected by the Hubble Space Telescope at just 0.3 arcsec from the detected H II region. This cluster with a mass between $59 \times 10^3$ and $219 \times 10^3 \text{ M}_\odot$ and an estimated age of 8 Myr could be the source of ionization of the observed H II nebula. We used the sn99 synthesis model (Leitherer et al. 1999) to estimate the evolution of the ionizing photons for the case of a Salpeter IMF and masses varying between 0.1 and 100 $\text{M}_\odot$. Fig. 4 shows the results of the sn99 code for a young cluster with masses within the ranges of masses of cluster 1. Using the calculated number of ionizing photons from equation (2) we estimate that the H II region has an age between 3.3 and 5.3 Myr, which is just two times lower than the age obtained by Harris and...
collaborators based on optical observations. Notice that the stellar cluster associated with the H II region is the most massive young cluster observed in NGC 3077 and deeper observations are necessary to obtain radio images of the H II regions associated with the other 55 clusters detected in NGC 3077 by the Hubble Space Telescope.

One of the most interesting discrete X-ray source in NGC 3077 is S4. This source exhibited no emission above ~0.8 keV, and was classified as a so-called ‘supersoft source’. The X-ray luminosity of this source is one order of magnitude lower than the luminosities of the sources S1 and S3. This source was fitted by Ott et al. (2003) by using a blackbody law. Roughly half of the supersoft sources with optical counterparts have yet to be identified with a known type of object (e.g. Di Stefano & Kong 2003). Unfortunately, we did not detect any radio counterpart associated with this source.

4 SUMMARY

The radio observations presented in this paper found two of the six discrete sources detected in X-ray by the Chandra observatory. These observations resolved for the first time the SNR detected in radio several decades ago. The compact radio source with a diameter of about 0.5 arcsec coincides with a Chandra point source, which also shows characteristics typical of a SNR. The SFR of NGC 3077 based on the size of the detected SNR of 0.28 M⊙ yr⁻¹ is equal to values derived by continuum millimetre observations and the SFR given by the FIR, both extinction-free tracers of the current SFR. The size of the SNR is about two times larger than the size of the largest SNR detected in M82, indicating that the star-forming region coincides with the X-ray source S3, an X-ray binary system. We estimate a flux density of 747 µJy for this source. Assuming that all this energy has a thermal origin, we estimate that only a few massive stars are necessary to ionize the observed nebula. A massive and young stellar cluster observed by the Hubble Space Telescope coincides with the position of both the S3 X-ray source and the H II region.

ACKNOWLEDGMENTS

MERLIN is a national facility operated by the University of Manchester at Jodrell Bank Observatory on behalf of the UK Particle Physics and Astronomy Research Council (PPARC). I gratefully acknowledge the advice and technical support given by Peter Thomasson, Anita Richards and other members of the Jodrell Bank Observatory. I also thank Elena Terlevich, Gilermo Tenorio-Tagle, Roberto Terlevich, Divakara Mayya, Paul O’Neill and Antonio García Barreto for useful discussions. An extensive report from an anonymous referee greatly improved the final version of the paper.

REFERENCES

Raymond J. C., 1984, ARA&A, 22, 75

This paper has been typeset from a TeX/LaTeX file prepared by the author.