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MERLIN monitoring of recent core-collapse supernovae

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Abstract. The star formation rate (SFR) in starburst galaxies can be measured by many methods, one of which is through the supernova rate. Due to the heavy dust obscuration in these galaxies, searches for new supernovae in the optical or infra-red can easily miss events occurring in the central starburst regions. As part of a long term program to estimate the SFR in a sample of nearby starbursts we are using MERLIN and the VLA to regularly observe the galaxies for new radio supernovae. As part of this project, regular MERLIN observations have been made of two recent optically bright supernovae: 2004dj and 2004et. Both supernovae are of Type II and have been monitored frequently over periods of a few months, resulting in well sampled radio "light" curves for both objects.

Key words. supernovae:individual:2004dj, 2004et – galaxies:ISM – galaxies:starburst

1. The monitoring program

The supernova (SNe) rate is a useful indicator of the star formation rate (SFR) in starburst galaxies. In active star forming regions with large gas reservoirs it is likely that large numbers of massive stars will form. If all stars with a mass greater than 8 $M_{\odot}$ become supernovae via core collapse then, assuming a reasonable initial mass function, the SFR can be calculated as a simple function of the supernova rate. Searches for new SNe are often carried out optically or in the infra-red which, although able to pick out explosions in the outer parts of starburst galaxies, can miss events in the heavily dust obscured central regions.

In order to observe new supernova events in the optically obscured centres of these galaxies, and hence estimate the SFR, we are using a combination of the NRAO's Very Large Array (VLA, Thompson et al. 1980) and the Multi-Element Radio Linked Interferometer Network (MERLIN, Thomasson 1986) to regularly monitor a sample of ten starburst galaxies over five years. Regular observations will allow the detection and follow-up of new radio supernovae (RSN) and supernova remnants (SNR), while the long timescale of the project will allow the flux evolution of existing remnants to be measured. This will allow estimates of the star formation rates to be determined, leading to a comparison with the rates determined through other indicators.

The observing strategy involves observations of the ten galaxies in the sample, all of which are within 15 Mpc, roughly three times a year. The VLA is used when in A or B configuration as reasonable resolution is required

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in order to separate new events from the rest of the galactic emission, and MERLIN is used when the VLA is in the more compact C or D configurations. Observations need not be more frequent than this as radio emission tends to rise later than at optical wavelengths and persists for several months in the case of core collapse supernovae (Type Ib/c and Type II SNe Weiler et al. 2002). Note that Type Ia SNe are not radio bright to the detection limit of the VLA.

The first observation in this program was carried out using the VLA in B configuration in November 2003. Several epochs have now been completed, with both the VLA and MERLIN, and observations of several supernovae have been made.

2. Results

2.1. J103851+532927

The first result from this program was a previously undiscovered RSN situated one arcminute from the centre of the nearby starburst galaxy NGC 3310 (Argo et al. 2004a). This object (known as J103851+532927) is coincident with a group of HII regions and was visible in archive data as far back as 1986 although, in the early 1990s and before, the flux was at least a factor of five lower. The object is also coincident with a weak X-ray source, although no optical counterpart has been discovered despite searches through archival data.

The source had been noted in previous radio maps of the galaxy (e.g. Kregel & Sancisi. 2001), although it was assumed to be a background quasar. The source displays properties which are uncharacteristic of normal quasar behaviour, however. Firstly the source has a steep spectral index ($\alpha \sim -1.6$ where $S \propto \nu^{+\alpha}$) and secondly it displays large flux variability with a sharp rise, followed by a slower decrease. In the mid-1990s the flux at 1.4 GHz increased by at least a factor of five to almost 10 mJy before decreasing at approximately 10 per cent per year.

Since the discovery of this object, several more observations have been performed using MERLIN, and the resulting radio light curve of this object was published in Argo et al. (2004a). The fact that the SNe appears to have occured in the late 1990s so the radio emission has now persisted for over 5000 days implies that this was a Type II SNe. If the source is at the distance of NGC 3310 then the approximate peak 5 GHz luminosity was $\sim 3 \times 10^{19}$ W Hz^{-1} which, although at the low end of the scale, is consistent with luminosities measured for other Type II SNe (see e.g. Weiler et al. 2002).

2.2. 2004dj

At the end of July 2004 a bright supernova was discovered optically in the nearby starburst galaxy NGC 2403 (Nakano et al. 2004). Peaking at a magnitude of 11.2, this was the brightest supernova seen in a decade. MERLIN observations using a subset of the array began in early August 2004 and continued to early October, followed by imaging runs using the full array in November and December 2004. This allowed a detailed 5 GHz light curve to be determined, see Fig. 1 (Beswick et al. 2005).

The MERLIN observations allowed the position of the source to be determined to an accuracy of better than 50 mas (Argo et al. 2004b), coincident with the optical (Nakano et al. 2004) and *Chandra* X-ray (Pooley & Lewin 2004) positions, and the star cluster n2403-2866 (Larsen & Richtler 1999). This illustrates the usefulness of MERLIN for this kind of program as, at the time, the VLA was in the most compact D configuration. Although 2004dj was observed with the VLA (Stockdale et al. 2004), the measured position was affected by extended emission from the galaxy and lies $\sim 1\farcs2$ from other measurements.

Weiler et al. (2002) find a relationship between the peak luminosity of the prompt emission from a Type II supernova at 6 cm, $L_{\rm 6cm\,peak}$, and the delay between explosion and peak luminosity of the form

$$L_{\rm 6cm\,peak} \simeq 5.5^{8.7}_{3.4} \times 10^{16} (t_{\rm 6cm\,peak} - t_o)^{1.4\pm0.2} \,\mathrm{W\,Hz^{-1}} \quad (1)$$

where $t_{\rm 6cm\,peak} - t_{\rm o}$ is the delay measured in days. For 2004dj, assuming a peak flux density of 1.9±0.1 mJy (equivalent to $L_{\rm 6cmpeak} \approx 2.45 \times 10^{18}$ W Hz^{-1} at the distance of NGC 2403,

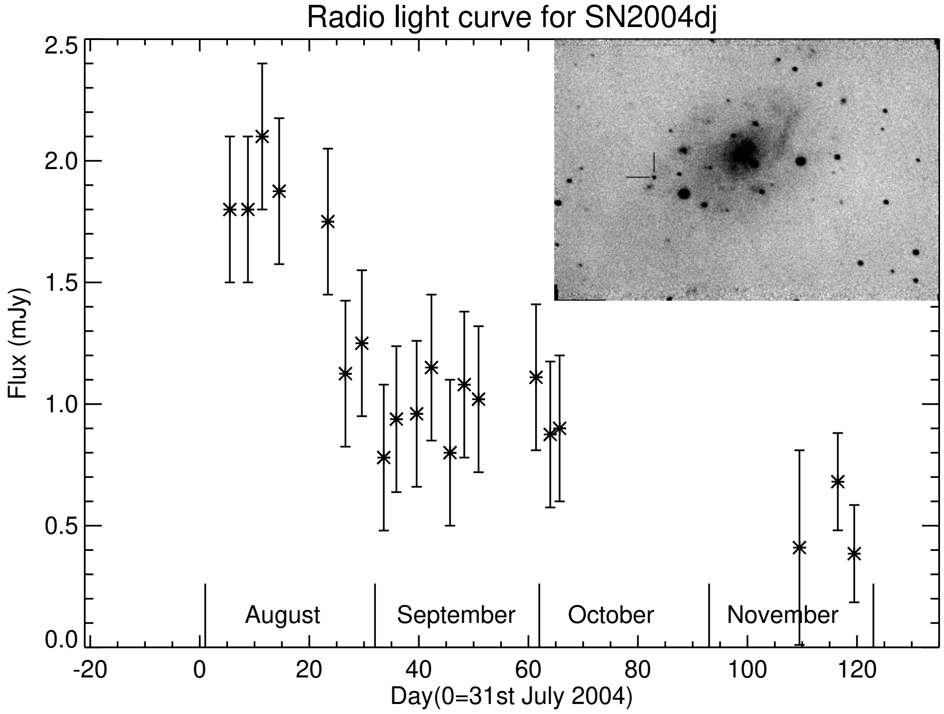

Fig. 1. Radio light curve for SN 2004dj from MERLIN 4994 MHz observations. Observations from day 0 to early October were made with a single 217 km baseline (Cambridge-Defford). Each flux measurement is a 2.5 day vector-averaged point. Subsequent observations were performed using the full MERLIN array. The inset shows an optical image (4×120 s exposures) of the host galaxy NGC 2403 obtained with a 10-inch Schmidt-Cassegrain telescope on April 2nd 2005, SN 2004dj is marked.

making this one of the least luminous radio supernovae ever detected) implies $t_{6\mathrm{cmpeak}} - t_0 = 15^{+42}_{-10}$ days. This places the date of explosion between 11 July and the date of optical detection, 31 July, broadly coincident with spectroscopic observations reported by Patat et al. (2004) which put the age of the supernova at approximately three weeks on August 3rd.

This SNe was optically classified as Type II-P (Patat et al. 2004), a relatively common type of supernova optically, but rarely detected at radio wavelengths. In fact, prior to 2004dj, the only two Type II-P SNe detected by radio telescopes were SN 1999em (Turtle et al. 1987) for which no light curve was established, and the well-observed SN 1987A (Pooley et al. 2002), both of which were also relatively weak radio emitters.

2.3. 2004et

In September 2004 another bright supernova was discovered, SN 2004et (Zwitter et al. 2004). The host galaxy, NGC 6946, is an active starburst in the monitoring sample, and also contains many historical supernovae. As part of the monitoring program there were three recent observations of this galaxy, none of which showed any emission at the position of SN 2004et when re-examined. MERLIN observations began in early October and continued in parallel with observations of 2004dj until December (Beswick et al. 2004b). The resulting radio light curve is shown in Figure 2.

Observations at 5 GHz began while the radio emission was still increasing, with the peak (~2.5 mJy) occuring sometime in early November. Assuming a distance to NGC 6946

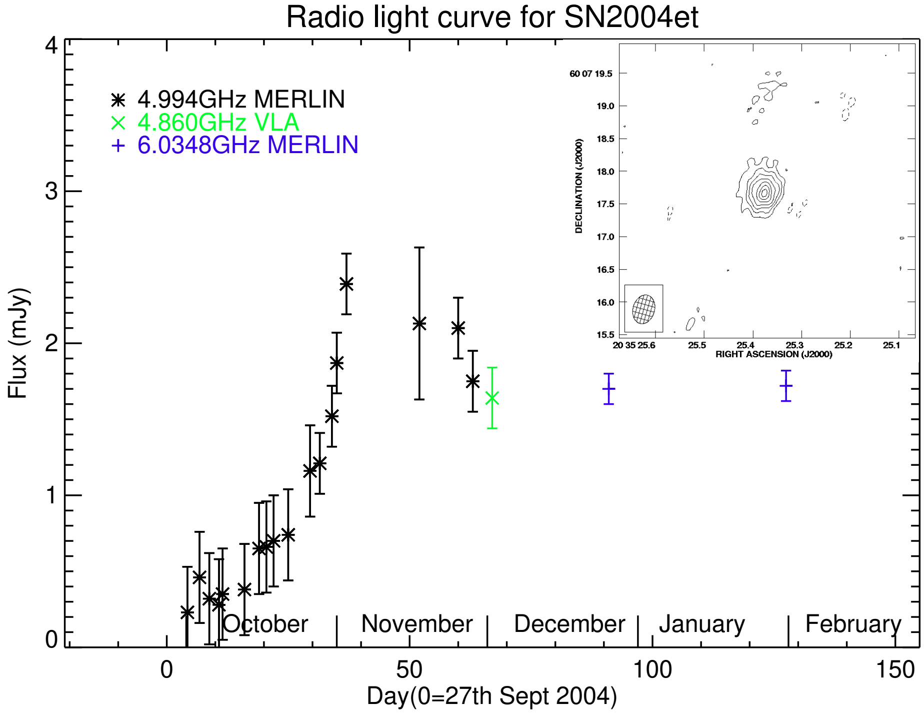

Fig. 2. Radio "light" curve for SN 2004et from MERLIN and VLA observations. These MERLIN observations were also carried out using a subset of the array during October and early November. Points from mid-November onwards are from imaging runs with the full MERLIN array. The mid-November point was affected by bad weather. The final November point is from a scheduled monitoring observation with the VLA. The December and January points were made after the MERLIN frequency change to 6.035 GHz. The contour plot (inset) shows the MERLIN map from an observation on February 9th at 1.6 GHz (see text). Contours are −1, and 1 to 10 × 0.2 mJy/beam.

of 5.5 Mpc (Pierce 1994) gives a peak 5 GHz luminosity of $\sim 8.7 \times 10^{18}$ W Hz^{-1}, 3.5 times more luminous than 2004dj.

For 2004et, equation (1) results in $t_{6\mathrm{cm\,peak}} - t_{\mathrm{o}}$ of 37^{+108}_{-24} days. The peak 6 cm flux was actually measured on day 37 after initial detection, although in this case there is no spectroscopy which gives an estimate of the explosion date. Unfortunately there is a gap in the MERLIN observations of two weeks after the measurement on day 37. The flux could have continued to increase during this period, so there is some additional uncertainty in this figure.

This source was also observed with MERLIN in February 2005 at a frequency of 1.658 GHz and was detected with a flux of 1.5 mJy. VLA monitoring observations in April 2005 detected the source with a flux of 1.5 mJy/beam at 1.425 GHz and (marginally) 0.19 mJy/beam at 4.860 GHz, giving the source a spectral index of $\alpha = -1.9$.

2.4. Other supernovae

2004am: Another event which has been observed with MERLIN as part of this program was the supernova candidate 2004am in M82, reported as an infra-red detection early in 2004 by Mattila et al. (2004a). Observations of M82 have been carried out regularly as part of the monitoring program but, as yet, no radio emission has yet been detected from this object to a

3-σ limit of 0.18 mJy bm^{-1} at 5 GHz (Beswick et al. 2004a).

2004gt: This Type Ib supernova was reported in NGC 4038 in December 2004 (Monard 2004). This galaxy is at too low a declination for reliable observations with MERLIN although, as the system is in the monitoring sample, VLA observations were obtained on November 1st (42 days before the date on which it was discovered optically) and March 17th (95 days after the optical detection). The 5 GHz VLA maps from both epochs show some emission at the position of the source, but nothing above the existing HII region (Neff & Ulvestad 2000). Maps were also obtained at 8.4 and 15 GHz but no emission was detected at the coordinates of 2004gt.

2005V: Reported in January (Mattila et al. 2004b), this event occured in another galaxy in our sample, NGC 2146. MERLIN observations were made in April at 1.6 GHz and in early February at 6 GHz, but no significant emission (3-σ limits: 142 and 207 μJy respectively) has yet been observed.

3. Future

In the near future we intend to continue monitoring of both 2004dj and 2004et. Although the fluxes of both RSN have now decreased significantly, it is important to keep observing both objects in the long term in order to detect the onset of emission from the subsequent remnants. In the longer term, regular observations of the galaxies in the sample will continue, as well as observations of other optically discovered supernovae with MERLIN when practical.

As a by-product of the monitoring program, the large volume of data collected will also allow a thorough investigation of long-term variability of the compact components in each galaxy.

The observations so far show the advantages of using MERLIN compared to the VLA which is in compact configurations for approximately half the year. Programs like this will become much less time consuming when *e*-MERLIN (Garrington et al. 2004) comes on line, as observations which currently take several hours will require much less time due to the dramatic increase (a factor of ~30) in sensitivity.

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