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VLBI Imaging of Young Radio Supernovae

A. Alberdi[1], and M.A. Pérez-Torres[1]

Instituto de Astrofísica de Andalucía (IAA, CSIC), P.O. Box 3004, E-18080 Granada, Spain
e-mail: antxon@iaa.es,torres@iaa.es

Abstract. In this contribution, we present an overview of several young radio supernovae studied with the VLBI technique. Imaging radio supernovae has permitted, among other things, to characterize the structure of the emitting region, and to estimate the deceleration of supernovae expansion and to probe the circumstellar interaction, thus yielding relevant information on the ejecta and circumstellar density profiles. We review results on high resolution observations of the nearby radio supernovae: SN 1979C, SN 1986J, SN 1993J and SN 2001gd. Finally, we review recent results on the detection of radio supernovae in starburst galaxies, the so-called "Supernova Factories".

Key words. Radio Supernovae; Starburst Galaxies

1. Introduction

Radio emission has been detected from a very small percentage of supernovae. From those, only the radio supernovae that are young, very bright and nearby can be studied with the high resolution provided by the Very Long Baseline Interferometry (VLBI) technique.

The radio emission from supernovae is usually explained within the standard interaction model (SIM), initially proposed by Chevalier (1982). In this model, a self-similarly expanding shell-like structure, from which the observed synchrotron radio emission from relativistic electrons (N(E)=N_o $E^{-\gamma}$) arises, is formed as a result of a strong interaction between the high velocity expanding supernova ejecta (density profile, $\rho_{ej} \propto r^{-n}$) and the ionized circumstellar medium (CSM; density profile, $\rho_{csm} \propto r^{-s}$). It can be shown that the expansion of the shell radius decelerates with time ($R \propto t^m$; m=(n-3)/(n-s)). For n>5, self-similar solutions are possible: the radii of forward shock, reverse shock, and contact discontinuity are related, and all evolve in time with the same power law. In the SIM, it is assumed that both magnetic energy density and relativistic energy density evolve with time as the post-shock thermal energy density. The relevant sources of absorption are free-free absorption by thermal electrons in the CSM, coexisting both uniform and clumpy absorbers (Weiler et al. 2002), and synchrotron self-absorption (Fransson & Björnsson 1998; Pérez-Torres et al. 2001).

With VLBI observations, imaging of the structure of the radio supernova as it expands is possible. With a detailed analysis of the images, it is possible to determine the deceleration of the supernova expansion, to estimate the ejecta and CSM density profiles, to image the distortions of the shock front and potentially detect the formation of Rayleigh-Taylor instabilities.

Send offprint requests to: A. Alberdi

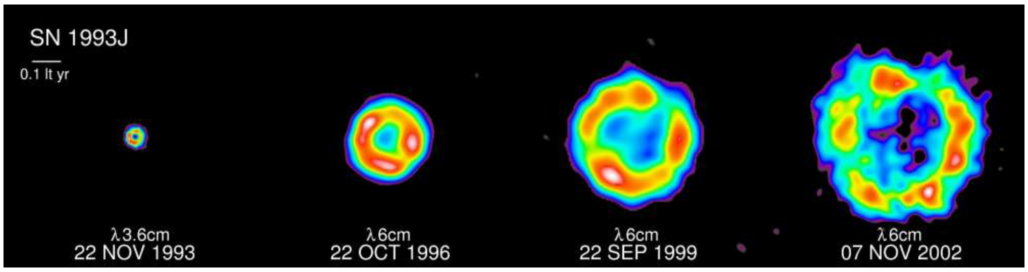

Fig. 1. Sequence of images of SN 1993J from VLBI observations obtained 239, 1304, 2369 and 3511 days after explosion.

2. Radio Supernovae

2.1. SN 1993J in M81

SN 1993J is the radio supernova whose evolution has been monitored in greatest detail. It exploded on March 28th, 1993 and its radio emission was discovered a few days later. Its brightness and proximity has permitted unprecedented VLBI studies since the date of explosion. Marcaide et al. (1995a) showed that SN 1993J had, at an age of 239 days, a shell-like radio structure, the youngest ever discovered in a supernova. As seen in Fig. 1, the radio shell was almost circularly symmetric, suggesting for the supernova explosion and the expanding radio shell a nearly spherical symmetry. Marcaide et al. (1995b) presented the first movie of the angular expansion of a radio supernova. The movie included observations from day 182 to day 541. SN 1993J has already been imaged, and its angular expansion monitored, for more than ten years. Along these years, the supernova has expanded rather isotropically (as seen in a 2D sky projection) showing a circular shell-like structure, with deviations from circularity of the outer radius smaller than 3%. However, the brightness distribution around the source center has been systematically changing both in time and azimuth. We show in Fig. 1 four images of SN 1993J obtained on 22 November 1993 (age 239 days), 22 October 1996 (age 1304 days), 22 September 1999 (age 2369 days) and 7 November 2002 (age 3511 days).

Alberdi & Marcaide (2004) (and references therein) have modelled the supernova expansion through day 3511 allowing for a change of deceleration rate in the expansion of SN1993J (implying two deceleration parameters). The best fit is obtained with the following parameters: $m_1 = 0.93{\pm}0.06, m_2 = 0.82{\pm}0.01$, and $t_{\rm br} = 383 \pm 121$ days (see Fig. 2). This fit has a reduced χ^2_ν=2.18. Analyzing the same data set with only one deceleration parameter we obtain $m = 0.83 \pm 0.01$, with a reduced χ^2_ν=2.76. This change in the angular growth rate of SN 1993J could be due to i) a change in the density profile of the CSM caused by a changing mass loss rate of the progenitor and/or ii) a change in the density profile of the supernova ejecta. Since there is increasing evidence that synchrotron self-absorption (SSA) is also relevant for SN 1993J (Pérez-Torres et al. 2001; Mioduszewski et al. 2001; Fransson & Björnsson 1998) and that the light curves can be explained by a standard $s = 2$ density profile for the presupernova wind (Fransson & Björnsson 1998), the expansion deceleration could be associated with n (ejecta density profile) changing from 14.9 to 7.6, which is in agreement with expections for a red supergiant progenitor for SN 1993J. The supernova emission is becoming progressively more dominated by swept-up material, with the evolution of the supernova governed by the interaction of the high energy particles in the shell with the surrounding medium. Assuming s=2 and typical values for the mass-loss rate and wind velocity ($\dot{M} = 5 \times 10^{-5} M_{\odot}$/yr, v_w= 10 km/s), the swept-up mass after 3157 days, $\sim 0.4\ M_{\odot}$, is comparable to the low-mass envelope, thus favoring a binary scenario for the explosion.

A fit to the radio spectra of SN 1993J from ~70 up to 2820 days shows a clear, albeit slow,

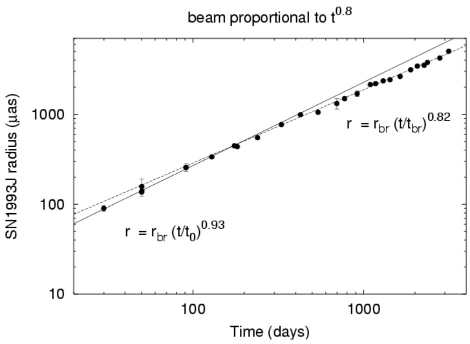

Fig. 2. Weighted least squares fit to the outer shell radius of SN1993J as a function of time since explosion, allowing for a change in its deceleration rate. The VLBI data up to $t \leq t_{\rm br}$=383 days (where the solid and dashed lines in the figure cross each other) can be well fitted by a power-law with index m_1=0.93±0.06 (solid line), while for $t \geq t_{\rm br}$ the best fit is given by a power-law of index m_2=0.82±0.01 (dashed line). Note that the scale is logarithmic.

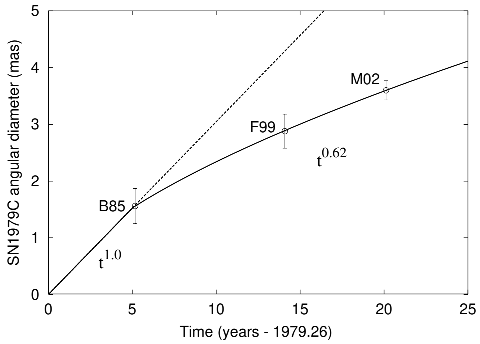

Fig. 3. Angular diameter of SN 1979C, in milliarcseconds, against time since explosion. The solid line indicates a possible expansion, which goes undecelerated (m = 1) for the first five years, and strongly decelerated (m = 0.62) from then on.

evolution with α changing from $\simeq -1$ to $\simeq -0.67$ (Pérez-Torres et al. 2002a). Fransson & Björnsson (1998) have determined a magnetic field of B$\sim 64\,(R_s/10^{15}cm)^{-1}$ G, which argues strongly for a turbulent amplification behind the shock.

2.2. SN 1979C in M100

SN1979C was discovered in the galaxy M100 on 4 April 1979. VLBI observations of SN 1979C taken about 5 yr after its explosion did not resolve the radio structure of the supernova. The observations were consistent with an undecelerated expansion of the supernova (m = 1) for the first five years. We observed SN 1979C on June 1999 using VLBI at 18 cm and estimated an angular size of 1.80 mas for the outer shell supernova radius. Combining our VLBI observations ($t \sim 20$ yr) with those by others, we could estimate both the deceleration parameter, m, and the epoch at which the deceleration most likely started. We estimate that the supernova shock was initially in free expansion (m = 1.0) for the first 6 ± 2 yr and then experienced a very strong deceleration, characterized by a value of the deceleration parameter of m = 0.62 (see Fig. 3; Marcaide et al. 2002). These results are consistent with a constant stellar wind velocity and a constant mass-loss rate as deduced from X-ray observations (Immler et al. 2005).

Such strong deceleration implies that the mass of the CSM swept up by the shock front, $M_{\rm swept}$, must be comparable to or larger than the mass of ejected hydrogen-rich envelope, $M_{\rm env}$. Assuming a standard s=2 CSM density profile, we estimate $M_{\rm swept} \sim 1.6\,M_\odot$. Momentum conservation arguments then suggest that $M_{\rm env} \sim 0.9\,M_\odot$. Therefore, if SN 1979C originated in a binary star system, the low value of $M_{\rm env}$ suggests that the companion of the progenitor star stripped off most of the (initial) hydrogen-rich envelope mass of the progenitor, prior to the explosion. If we assume equipartition between fields and particles for SN 1979C and consider the observed level of radio emission, the minimum magnetic field should be in the range of 10–80 mG, which suggests turbulent amplification as the most promising amplification mechanism.

2.3. SN 1986J in NGC 891

SN 1986J exploded in the galaxy NGC891. We used archival 6 cm VLBI observations of SN 1986J taken on February 1999. The supernova showed itself as a highly distorted shell of

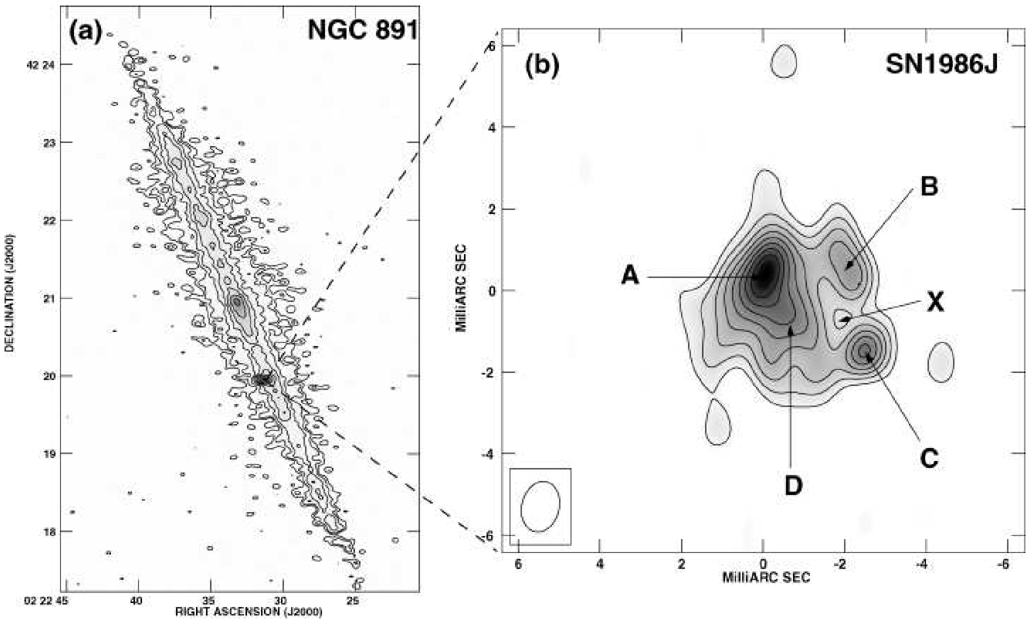

Fig. 4. VLA image (left) of the galaxy NGC 891 and its supernova SN 1986J, at the same frequency (5 GHz) and epoch of the global VLBI observations (right).

radio emission, indicative of a strong deformation of the shock front (see Fig. 4). The brightness distribution was anisotropic, and clearly indicated an ongoing asymmetric expansion. We determined an angular size of ~4.7 mas (~ 0.22 pc). We estimated a value of $m \approx 0.90$, indicative of just a mild deceleration in the expansion of SN 1986J (Pérez-Torres et al. 2002b).

We found $M_{\rm swept} \sim 2.2 M_\odot$. Considering the mild deceleration suffered by SN 1986J and momentum conservation laws, $M_{\rm env} \sim 12 M_\odot$. This value suggests that the supernova progenitor likely kept intact most of its hydrogen-rich envelope by the time of explosion, and favors a single star scenario for SN 1986J. As in the case of SN 1979C, magnetic field turbulent amplification is likely acting in SN 1986J, if equipartition between particles and fields exists (the magnetic field should lie in the range (13 – 90) mG).

Recently, a bright, compact radio component has been discovered near the center of the expanding shell of SN 1986J. This component has an inverted radio spectrum, different from that of the shell (Bietenholz et al. 2004). This new component could be the link between a young supernova and a black hole or neutron star.

2.4. SN 2001gd in NGC 5033

The Type IIb supernova SN 2001gd in NGC 5033 (see Fig. 5) was discovered by on 24 November 2001 by Nakano et al. (2001); however, its explosion date is uncertain. Matheson et al. (2001) pointed out that an optical spectrum obtained on 2001 December 4 was almost identical to that of SN 1993J obtained on day 93 after explosion, suggesting that SN 2001gd would also be a strong radio emitter. In fact, Stockdale et al. (2002) detected SN 2001gd on 2002 February 8 at centimetre wavelengths with the Very Large Array (VLA).

We performed 8.4-GHz VLBI observations of SN 2001gd in NGC 5033 on 2002 June 26 and 2003 April 8 (see Fig. 6). The radio structure is not resolved for any of the two epochs. We estimated angular diameter sizes for the supernova by model fitting (Pérez-Torres et al.

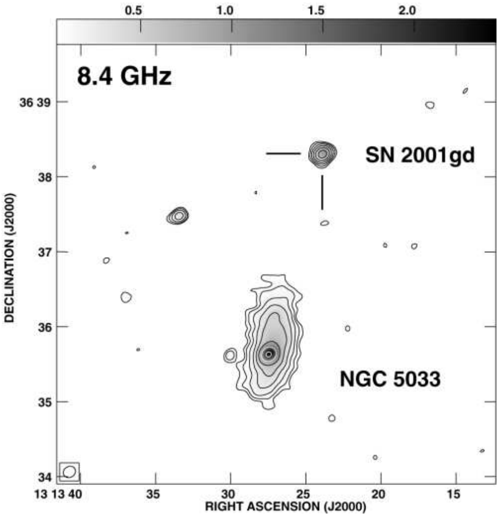

Fig. 5. Hybrid image of the galaxy NGC 5033 and its supernova SN 2001gd made at 8.4 GHz with the VLA, from observations on 2003 April 8.

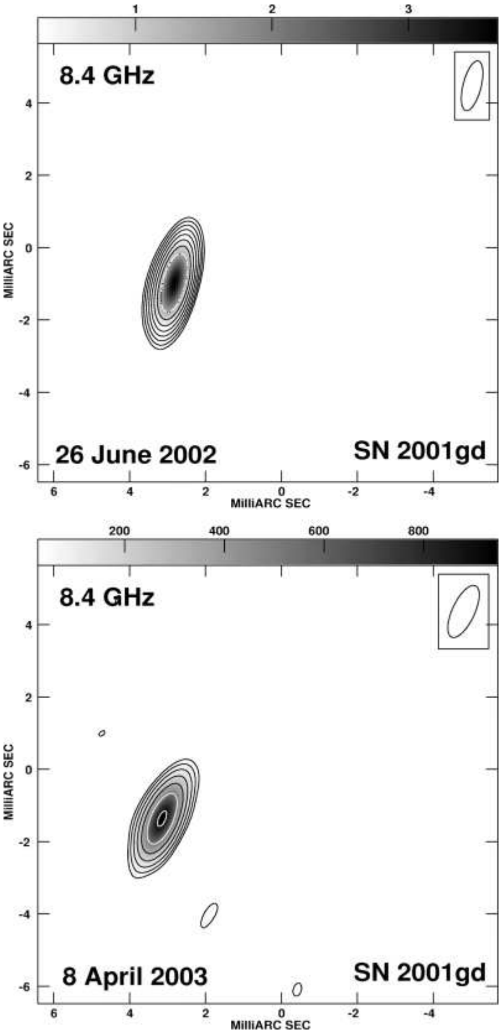

Fig. 6. 8.4 GHz VLBI images of SN 2001gd

2005). Our data nominally suggest a relatively strong deceleration for the expansion of SN 2001gd, but the possibility of a free supernova expansion cannot be excluded. From our VLBI observations on 2003 April 8, and assuming equipartition between fields and particles, we inferred an average magnetic field of $B_{min} \approx$ 50-350 mG, which suggest that turbulent amplification is acting..

Pérez-Torres et al. (2005) have also presented multiwavelength Very Large Array (VLA) measurements of SN 2001gd made at the second VLBI epoch at frequencies of 1.4, 4.9, 8.4, 15.0, 22.5 and 43.3 GHz. The VLA data are well fitted by an optically thin, synchrotron spectrum (α = -1.0±0.1), partially absorbed by thermal plasma. The best fit to the VLA radio spectrum can also be used to infer the most likely ranges for the electron temperature in the wind (T_e=2-20 $\times 10^4$K) and the mass-loss rate, ($\dot{M} = (2-12) \times 10^{-5} M_\odot \cdot yr^{-1}$).

SN 2001gd was detected on 2002 December 18 by XMM-Newton. The supernova X-ray spectrum is consistent with optically thin emission from a soft component (associated with emission from the reverse shock) at a temperature of around 1 keV. The X-ray spectrum is consistent with expectations from X-ray emission from Type II supernovae, and suggests the interaction of a relatively shallow supernova ejecta density profile (n$\sim$10), with a standard circumstellar wind density profile (s=2.0), characterized by a presupernova mass-loss rate of $\dot{M} = 2.5 \times 10^{-5} M_\odot \cdot yr^{-1}$ for SN 2001gd.

2.5. Other Radio Supernovae

Other radio supernovae have also been studied with VLBI:

SN 1987A: Radio emission from SN1987A in the Large Magellanic Cloud was detected immediately after outburst. The rapid flux density evolution and the low radio luminosity were consistent with interaction of the shock wave with a fast low-density wind from the blue supergiant progenitor Sk−69°202. VLBI observations indicated a fast (> 19000 km s^{-1}) shock front (Jauncey et al. 1988). SN1987A re-emerged as a radio source in 1990.5 (Staveley-Smith et al. 2004). Radio monitoring observations from day 1000 indicate an approximate linear increase to date. Intrinsically, SN1987A is still 8000 times fainter than SN1993J at maximum. High resolution images taken with ATCA show a ring-like structure, which has been modelled as a thin spherical shell and a number of hotspots (Manchester et al. 2002). The remnant continues to expand at a rate of 3500 ± 100 km s^{-1}. The spectrum of SN1987A is non-thermal with an index $\alpha \approx -0.8$, and currently increasing at a rate of $\dot{\alpha} = 0.02$ yr^{-1}.

M82: M82 is a well known nearby (distance of 3.2Mpc) starburst galaxy. The central 1 kpc region contains at least 30 compact supernova remnants (SNR) with ages of less than around 1000 years which have been imaged at high angular resolution by MERLIN and VLBI. The size of the remnants range from 0.3 pc to 5 pc. The relatively compact remnants in M82 are found to be expanding over a wide range of velocities unrelated to their size. Pedlar et al. (2004) tentatively conclude that the lower expansion velocities (∼ 2000 km/s) are found for those remnants in dense clouds, while the higher expansion velocities (∼ 10000 km/s) are found for those remnants in front of dense HI/CO/OH clouds.

3. Supernova Factories

The discovery of ultraluminous and highly luminous infrared galaxies has stimulated the scientific discussion about the relative contribution of an active galactic nucleus or a compact luminous starburst to the total galaxy luminosity. Arp 220 is the prototype ultraluminous infrared galaxy with a luminosity of log $L_{FIR} = 12.11 L_{\odot}$. Smith et al. (1998) showed, using VLBI observations, that on linear scales from 1 to 30 pc the compact radio emission consists of a dozen unresolved sources, with flux densities between from 0.2 to 1.2 mJy, which were interpreted as luminous SN 1986J-like radio supernovae. This interpretation supported a simple starburst model for the Arp 220 infrared luminosity that has a supernova rate of 1.75-3.5 yr^{-1}.

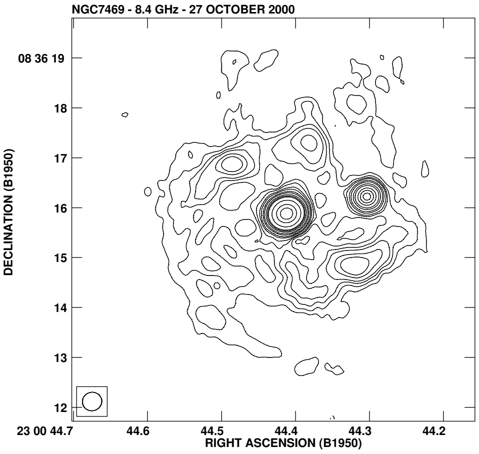

Fig. 7. 8.4 GHz VLA A-configuration image of NGC 7469 from observations on 27 october 2000. SN 2000ft is located in the circumnuclear starburst, at a distance of 600 pc of the nucleus.

NGC 7469 is a well known barred spiral galaxy located at a distance of 70 Mpc, containing a luminous Seyfert 1 nucleus surrounded by a dusty starburst of about 1 kpc in size (Wilson et al. 1991). NGC 7469 is also a very luminous infrared galaxy with Lir(8-1000μm) = 5 x $10^{11} L_{\odot}$ were 2/3 of the luminosity is emitted by the starburst (Genzel et al. 1995). Moreover, there is evidence for a $10^7 M_{\odot}$ central black hole coming from reverberation mapping.

Colina et al. (2001) initiated a high sensitivity VLA A-configuration X-band monitoring program of NGC 7469 in order to detect radio supernovae. In fact, on 2000 October 27 a strong compact radio source was detected in the circumnuclear starburst of NGC 7469i (see

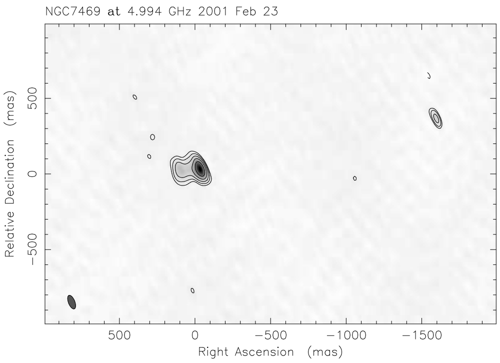

Fig. 8. 5 GHz MERLIN image of NGC 7469 from observations on 23 February 2001. NGC 7469 nucleus shows a core-jet structure. The circumnuclear starburst is resolved.

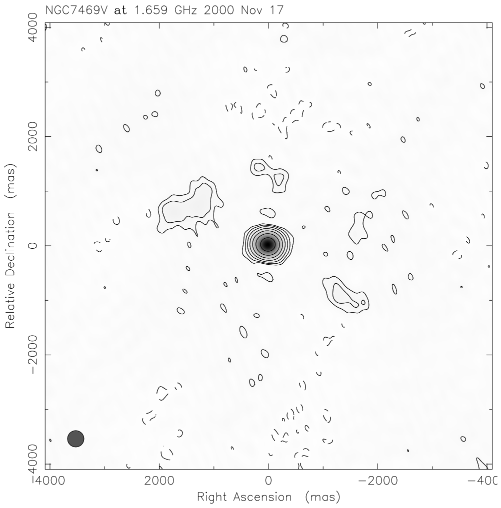

Fig. 9. 1.6 GHz MERLIN image of NGC 7469 from observations on 17 November 2000. SN 2000ft is not detected.

Fig. 7). The variation in flux for the first six months after detection confirmed the source as a radio supernova (Colina et al. 2002). It was named SN 2000ft and it is the first radio supernova ever detected in the circumnuclear ring of a Seyfert 1, luminous infrared galaxy and at a distance of a mere 600 pc from the galaxy nucleus. At a distance of 70 Mpc, SN 2000ft is one of the most luminous and distant radio supernovae ever detected.

After the discovery, a multifrequency radio continuum monitoring program of NGC 7469/SN 2000ft was initiated. All 8.4 GHz VLA maps show a similar structure to that shown in Fig. 7: a bright unresolved core, an extended region of emission showing a two-arm spiral-like morphology, and the radio supernova. All 5 GHz MERLIN maps (see Fig. 8) show also a similar structure consisting of a core-jet structure galaxy nucleus and the radio supernova SN 2000ft. The extended, diffuse emission coming from the circumnuclear starburst is completely resolved. The 1.6 GHz MERLIN maps (see Fig. 9) show the source to consist of the galaxy nucleus, which is basically unresolved, and the extended structure. SN 2000ft is not (or marginally) detected three years after its discovery in the radio.

We have monitored the flux density evolution of SN 2000ft for three years after its discovery and have fitted the light curves in terms of the "mini-shell" model of Chevalier (1982). We conclude (Alberdi et al. 2005) that i) the radio evolution of SN 2000ft shows the typical characteristics of a luminous type II supernovae. SN 2000ft shows a 8.4 GHz peak luminosity of 9.4×10^{20} W Hz^{-1}, a spectral index of α=0.9±0.1, and a power-law flux density time decay of β=-1.81; ii) the non-detection of SN 2000ft at 18cm continuum 1.5 years after detection is explained considering the existence of a foreground free-free absorption; iii) the evolution of SN 2000ft is governed by the interaction between the supernova ejecta and the circumstellar medium. The galactic interstellar medium is not influencing the supernova evolution yet, despite SN 2000ft having exploded in a very dense, dusty, magnetized and radiation dominated environment compared to the local interstellar medium of spirals.

Recently, young radio supernovae have been found in other luminous infrared galaxies. Gallimore & Beswick (2004) have presented multi-epoch and multi-frequency VLBA images of NGC 6240. Its far infrared luminosity, $L_{IR} \sim 6 \times 10^{11}\ L_{\odot}$, is similar to the NGC 7469 luminosity. The inner structure consists of two Seyfert-like low-luminosity Active Galactic Nuclei, probably associated with two nuclei in an early phase of a merger process, and a third source whose properties suggest its interpretation as a luminous radio supernova. Neff et al. (2004) have imaged the nearby galaxy merger Arp 299 with the VLA and the VLBA. Its infrared luminosity, $L_{IR} \sim 3 \times 10^{11}$ $L_{\odot}$, is typical of the luminous infrared category, within a factor of two of the NGC 7469 luminosity. Its arcsecond scale consists of bright radio sources, probably complexes of supernova remnants, within diffuse emission. Five compact radio sources have been found within one of these complexes, most of which have flat or inverted radio spectra, a property that is typical of young type II supernovae near their peaks. We should note that the peak luminosity and CSM opacity of the brightest radio supernovae in the ultraluminous infrared galaxy Arp 220, of the radio supernova in the luminous infrared galaxy NGC 6240, and of the young radio supernovae in Arp 299, are comparable to the values of SN 2000ft and typical of type II radio supernovae. Moreover, the inferred supernova rates for the nuclear regions of NGC 6240 and Arp 299, in the range 0.5-1 SN/yr, are in agreement to the value found for NGC 7469.

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