STRUCTURES AND EXPANSIONS OF SN 1993J AND SN 2004et

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Abstract: Radio emission has been detected from a small subset of supernovae. For those radio supernovae that are strong radio emitters and are not too distant ($\leq$20 Mpc) VLBI observations have been performed and, in some cases, high angular resolution images obtained. Thanks to VLBI observations, source structures and expansion decelerations have been determined. Together with multi-wavelength light curves and optical spectra, these observations have helped characterize the supernova ejecta and the circumstellar medium density profiles. We report on VLBI observations of SN1993J and SN2004et. In the case of supernova SN 1993J, the details of the expansion have been determined with astonishing detail. In the case of supernova SN 2004et, the last radio supernova imaged with VLBI, some considerations about the physical conditions in which this supernova evolves are made.

1 Introduction

Supernovae are dramatic and interesting events. The amounts of energy and the luminosities involved in this kind of explosions are mind boggling. Supernovae are scientifically relevant in many aspects. For example, they are responsible of the presence of heavy elements in the interstellar medium, essential for the existence of life in the Universe, and they play an important role during crucial, poorly understood, early stages of the evolution of the Cosmos, like the *Reionization Era*. Thus, the study of all supernova explosions is important for a good understanding of a wide set of aspects of different topics in modern astronomy: exobiology, cosmology, stellar evolution, etc.

From all supernovae, only a subset of them are detected at radio wavelengths. Radio observations of those supernovae are relevant for understanding aspects related to the evolution of these cosmic explosions, aspects which can be studied only at these wavelengths (i.e. the structure evolution and the expansion deceleration).

Radioemission has been detected only from type II/IIb and Ib/c supernovae, which appear to be the result of the gravitational collapse of massive stars. [1] proposed a model, now called the *Standard Interaction Model (SIM)*, to explain the radioemission from supernovae based on a hydrodynamical model of the expanding ejecta. This model works well to explain the observations, except for some subtle details which are not yet well understood and which suggest some modifications of the basic assumptions. In the next lines, we describe the basic scenario of the SIM-model.

2 The Chevalier Model

The SIM model [1] relates the structure and evolution of the emission from a supernova (in radio, optical, and X-ray bands) with the parameters of a hydrodynamical model which describes the interaction between the supernova ejecta and the circumstellar medium.

The hydrodynamical model used by Chevalier [1] describes the expanding radio supernova (spherical symmetry assumed) as a shell-like structure with a contact discontinuity surface (which physically separates the ejecta from the circumstellar medium) and two shock waves, that propagate in opposite directions with respect to the contact discontinuity. One of these shock waves, the *Forward Shock (FS)*, pushes the circumstellar medium away from the ejecta, accelerating the circumstellar thermal electrons up to relativistic energies. The other shock, known as the *Reverse Shock (RS)*, pushes back the ejecta behind the discontinuity, accounting for the optical and soft X-ray emission.

Assuming a power-law dependence of the ejecta density profile with distance ($\propto r^{-n}$, with $n > 5$) and a power-law dependence of the circumstellar density profile with distance ($\propto r^{-s}$, with $s < 3$), it can be shown that the evolution of this expanding structure is self-similar [1]: the radii of the FS, RS, and contact discontinuity evolve in time with the same power-law. The radius of the shell structure is, then, proportional to t^m, where t is the supernova age and m is the *deceleration parameter*, which is related to the density profiles of the expanding ejecta and the circumstellar medium through $m = (n-3)/(n-s)$. The conditions $n > 5$ and $s < 3$ are well satisfied in supernova explosions. Typical velocities at the beginning of the ejecta expansion can be as large as 20000 km s^{-1}. The deceleration parameters estimated from the studied supernovae are in the range 0.70 - 1.

Since the dense ejecta decelerate as they expand into the rarefied circumstellar medium, Rayleigh-Taylor instabilities originate close to the contact discontinuity and amplify the circumstellar magnetic fields by more than two orders of magnitude, via magneto-hydrodynamic coupling processes. Figure 1 shows a schematic representation of the Chevalier SIM model [1].

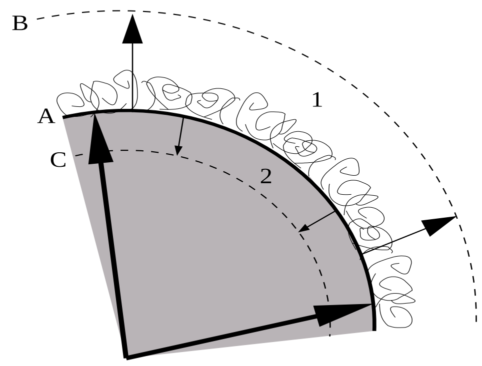

Figure 1: Schematic representation of the Chevalier model [1] (spherically symmetric; not to scale). The shadowed region represents the supernova ejecta. Region 1 corresponds to the shocked circumstellar medium. Line A is the contact discontinuity, near which the Rayleigh-Taylor instabilities form (irregular lines). Line B is the forward shock. Region 2 corresponds to the shocked ejecta. Line C represents the reverse shock. The arrows indicate relative motions. The sizes of the arrows indicate the relative magnitudes of the velocities of each of the components.

The relativistic electrons present in the high energy-density shell spiral along the magnetic field lines, originating radio synchrotron emission which is detected at centimeter wavelengths. In the SIM model, it is also assumed that both the magnetic field energy density and the energy of the relativistic electron population evolve with time as the post-shock thermal energy density [1, 2]. Relevant absorption is produced by thermal electrons in the circumstellar medium (free-free absorption). Taking this absorption into account, together with the time evolution of the magnetic field and the relativistic electron population, it has been possible to model the observed radio light curves of some supernovae (e. g. [3, 4]). Recently, the SIM model has been refined considering alternative power-law profiles ($s \leq 2$) for the circumstellar medium [5, 6] and including synchrotron self-absorption as an additional absorbing mechanism [2, 7]. Other authors [8] have numerically simulated the interaction of the ejecta with the reverse shock using specific explosion models with high density features in the ejecta density structure.

3 VLBI Observations of Radiosupernovae

The first months and years after a supernova explosion conform the most important period for a possible radioemission. Indeed, important information concerning the structure of the ejecta, the pre-supernova stellar wind, and the energies involved in the expansion can only be extracted from observations of the radioemission during the first years after the supernova explosion.

The relatively low absolute luminosities involved and the huge distances for almost all the young supernovae (all the recent cases are extragalactic) make the observation of this kind of sources a hard task, specially using the VLBI technique. Only those radio supernovae that are very bright and nearby ($\leq$20 Mpc) can be studied with VLBI. Until now, the radio supernovae observed with the VLBI technique are SN 1979C [9, 10], SN 1986J [11, 12], SN 1993J [13, 14, 15, 6, 16, 17], the peculiar SN 1987A [18, 19], SN 2001gd [20], SN 2001em [21, 22], some remnants in the galaxy M 82 [23, 24] and SN 2004et [10].

3.1 Supernova SN 1993J

Supernova SN 1993J, in the galaxy M81, located at $\sim$ 3.6 Mpc, is the radio supernova best studied with VLBI. SN 1993J was discovered on 28 March 1993 by Francisco García. Just after explosion, the SN1993J spectrum showed prominent hydrogen lines and was classified as a Type II. Three days after explosion, [26] detected a weak helium emission line, suggesting that this supernova was *evolving* from Type II to Type Ib. It was re-classified as *Type IIb*.

The light curve showed a peculiar behaviour: a brightness peak was found a few days after explosion and, a week later, a second maximum was found. Since then on, the emission has been continuously decreasing. Such light curve was explained with a binary scenario [27, 28, 29], where the companion of a massive, giant, star with an initial main-sequence mass of $\sim$ 15 $M_\odot$ had lost most of its hydrogen envelope to an accreting companion. If the mass of the remaining hydrogen envelope had been only a few tenths of solar masses, then the SN 1993J light curve could be well explained with such model. The first peak would have been produced by the cooling of the shock heated hydrogen in the thin envelope and the second peak would have been produced by the gamma emission from the ^{56}Ni decay.

A multifrequency radio monitoring of SN 1993J has been performed with the VLA and VLBI. [30] discovered the shell-like structure of the radio emission from observations made 8 months after explosion.

Marcaide et al. [15] also made the first *movie* of the expansion of a young supernova based on VLBI observations over the first 2 years since explosion. They found an expanding shell-like structure of almost circular symmetry, suggesting that the shock front is expanding almost isotropically. They also found strong evidence of a self-similar expansion. Later, [6] found a deceleration in the expansion. [16] confirmed and expanded those results.

The VLBI monitoring of SN 1993J has continued over the years by two independent groups. In Figure 2 we show the evolution of the radio structure of SN 1993J over a decade. High resolution images and an animated version of the expansion using all the available data of our group can be downloaded from the web [31].

The high quality data from SN 1993J has permitted us to test several details of the original Chevalier model; some assumptions of the model that had no strong physical justification could be checked and some corrections to the model had to be made in order to explain the radio light curves and the structure evolution.

For instance, from the flux density evolution measured with VLA, there was a clear evidence of synchrotron self-absorption in the shocked circumstellar region [2, 7]. This effect was not considered in the original Chevalier model. The scaling of the magnetic field energy density and the relativistic electron energy density to the thermal energy density of the ejecta was also checked [2]. The relative unimportance of other effects (like inverse Compton scattering or Razin-Tsitovich effect) on the absorption of the radiation and the energy redistribution of the relativistic electrons [2] was also checked.

Bartel et al. [16] and [32, 17], using their own VLBI data, determined the expansion curve over a decade and found different expansion regimes (i. e., changes with time of the deceleration parameter m) during the evolution of the supernova. Surprisingly, they found a “reacceleration” of the supernova at about 5 to 8 years after explosion, with m growing from 0.781 ± 0.009 to 0.860 ± 0.011. They explained this “reacceleration” as produced by components of the ejecta reaching and pushing the outer shocked ejecta (which had previously decelerated due to their interaction with the circumstellar medium), boosting them into a new expansion regime. The authors also relate these changes in the expansion rate with other changes in the flux density and in the spectral index of the radio emission [16], finding observational support for the hydrodynamical simulations of [8], who also claimed a “reacceleration” in their simulated ejecta evolution. It is worth noticing however that this “reacceleration” in the numerical simulations was likely only the result of using a rather particular ejecta profile correspond-

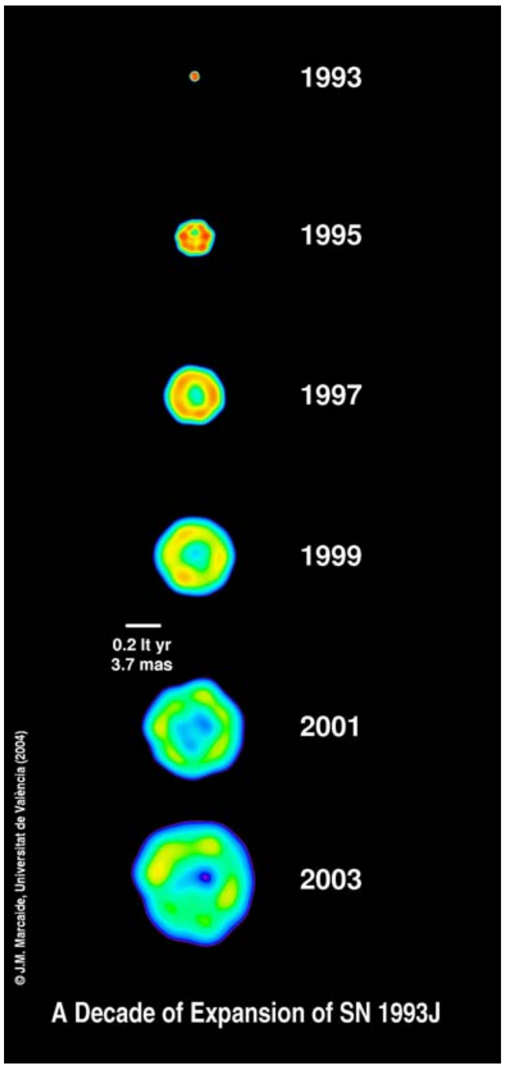

Figure 2: Expansion of SN 1993J over a decade

ing to the 4H47 explosion model from the Nomoto group [33], which had rather unusual high density features.

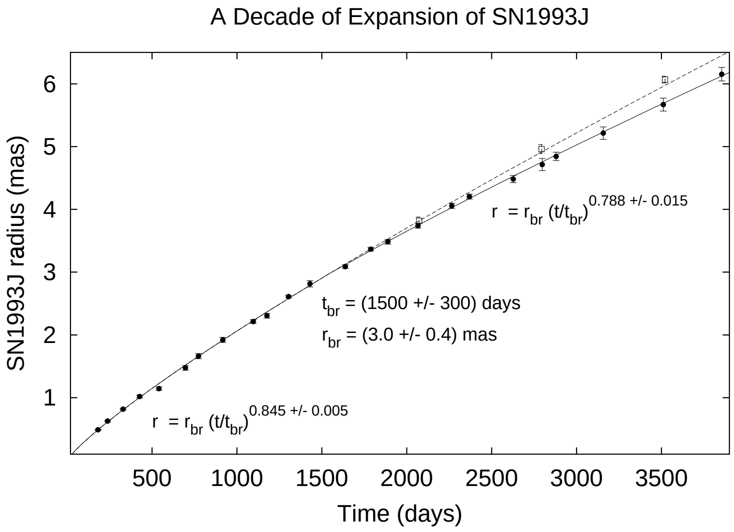

Figure 3: Expansion curve of SN 1993J over a decade. Filled circles correspond to 3.6 and 6 cm data and empty squares correspond to 18cm data. The continuous line corresponds to a model where two deceleration parameters, before and after a break point, are needed to fit the data. The model predictions with the deceleration parameter before the break point have been extended beyond the break (dashed line) to allow a very favorable comparison with the 18 cm data.

Recent analysis of our own data [34], with a similar time coverage to that of Bartel's group, has shown an expansion curve not totally incompatible with that found by [16]. However, we have interpreted our and their results in a completely different way. We do not find any "reacceleration" of the ejecta; we can fit the expansion curve at 6 cm with two regimes; one with $m = 0.845 \pm 0.005$ until day $\sim$1500 after explosion ("break point") and the other with $m = 0.788 \pm 0.015$ for later epochs. We also find a wavelength dependent size of the emitting region that appears after day 1500: the observed supernova radius at 18 cm is larger than the observed radius at 6 cm. The changing deceleration at 6 cm (but not at 18 cm), the wavelength dependent size of the emitting region, the flux density evolution and the time evolution of the spectral index, are all of them interrelated [34]. The expansion curve over a decade found by our group [34] is shown in Figure 3.

3.2 Supernova SN 2004et

Supernova SN 2004et in the galaxy NGC 6946, located at 5.5 Mpc [35], was discovered by [36] on 27 September 2004. [37] constrained the supernova explosion date to 22 September 2004. Spectroscopic observations of [36] and [38] suggest SN 2004et to be a Type II supernova event. [39] have reported the detection of a progenitor candidate for this supernova. The progenitor seems to be a yellow supergiant that may have experienced a red supergiant phase, but could also consist of a binary system of red and blue supergiants. In the latter case, it would be a similar scenario to that of SN 1993J [40].

Argo et al. [41] have monitored the radio flux density of supernova SN 2004et at 5 GHz (also at 6.0 GHz and 1.6 GHz) using the MERLIN and VLA arrays. Monitoring started on October 2004. Unfortunately, the epoch of the 5 GHz luminosity peak could not be well determined due to lack of data during the two weeks around it (such epoch has though been estimated to be 3 November 2004). The peak flux density in this epoch is estimated to be $\sim$2.5 mJy.

We observed supernova SN2004et at 8.4 GHz on 20 February 2005 using a very sensitive VLBI array. The following antennas took part in the observations: the complete VLBA (USA), VLA (USA), GBT (USA), Goldstone (USA), Robledo (Spain), Effelsberg (Germany), and Medicina (Italy).

We scheduled 12-hour long typical phase-reference observations to insure fringe detections. We used the source J2022+614 as phase calibrator (a 3.0 Jy source at an angular distance of 2.2° from the supernova) and observed such calibrator during 25% of the observing time, with duty cycles of $\sim$4 minutes. We used the VLA data to obtain an accurate estimate of the flux density of SN 2004et. We used J2022+614 as the flux calibrator for the VLA data. The flux density of SN 2004et was estimated to be 1.23 ± 0.07 mJy.

Given the very low flux density of SN 2004et, we did not apply any mapping algorithm nor any phase self-calibration to the data. Instead, we fitted several models to the visibilities. We used different models in our fits: a disk (unrealistic, since the circumstellar region is unlikely to be optically thick at this epoch); a uniformly bright sphere; a shell (according to the Chevalier model and previous experience with SN 1993J); two compact emitters that can be interpreted as two hot spots in a shell-like structure, perhaps originated by large inhomogeneities in the circumstellar electron distribution.

As expected, we obtain different size estimates of SN 2004et depending on the models used. We do not know which of these models represents better the true emitting structure of SN 2004et, since the fits are of similar quality. Thus, we can estimate the minimum expansion velocity compatible with our data using the smallest of all our size estimates. This size is 0.5 ± 0.1 mas and corresponds to the model of two compact emitters. The SN 2004et map, shown in Figure 4, was obtained using the model of two compact emitters (the model was first deconvolved from the dirty map using the dirty beam and later the model, convolved with the CLEAN beam, was added to the map; no further CLEANing was applied). The peak flux density of the map is 0.66 mJy beam^{-1} and the rms of the residuals 0.03 mJy beam^{-1}, that is, the peak in our supernova map is ∼22 times over the noise level.

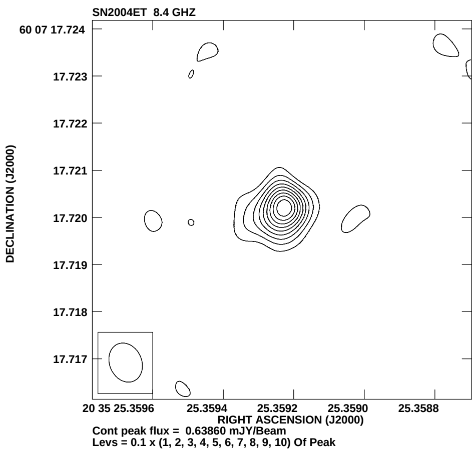

Figure 4: Map of SN 2004et obtained from our VLBI data (see text). The lowest level is at 10% of the peak. The CLEAN beam is shown at the lower left corner.

The radial distance between the point-like sources in the model translates into a mean expansion speed of (20000 ± 2000) km s^{-1}. This velocity is high indeed compared with the theoretical predictions. For supernovae in which synchrotron self-absorption is the dominant absorption mechanism near the peak of emission, and assuming energy equipartition between relativistic particles and magnetic fields, [42] has found a relationship in the supernova light curves between the observing frequency, the size of the emitting region, the peak in the light curve, the supernova age at the peak and the energy distribution of the relativistic electrons. For such a case, one can estimate the expansion velocity of a supernova based on measurements of the peak luminosity at a given frequency, the supernova age at the peak and the synchrotron spectral index.

For the case of SN 2004et, with the 5 GHz flux density peak estimated by [41], using Chevalier's relationship results in an estimated expansion velocity of the radio shell of 9600 ± 700 km s^{-1}. This estimate is more than a factor of 2 below our lowest estimate with VLBI. Thus, some of the assumptions made in [42] may not be correct. Probably, the free-free absorption from the circumstellar medium is, at least, comparable to the synchrotron self-absorption near the peak. If the importance of free-free absorption near the peak for SN2004et is similar to that of other type II-P supernovae, we must expect that the estimates of the expansion velocities in the other cases, when based on the model proposed by [42], will also have important negative biases.

4 Conclusions

Only a small percent of supernovae are detected at radio wavelengths. Only those radio supernovae that emit strongly enough and are not too distant can be observed with VLBI and, consequently, mapped with high angular resolution.

SN 1993J is the best studied radio supernova and constitutes the reference and paradigm of a radio supernova explosion. It exploded in M81, *only* 3.6 Mpc away, and its intrinsic radioemission was so strong that we have been able to map its structure with VLBI at 6 cm for more than a decade. At 18 cm, it will be possible to continue this task for, at least, another decade. The analysis of SN 1993J data allowed for refinements of the Chevalier's Standard Interaction Model and for checking several assumptions of such model that have no strong theoretical justification. There are still some subtle effects in the SN 1993J data that are not well understood.

Each new supernova observed with VLBI represents a new step towards the improvement of the existing models. SN 2004et, the last supernova observed with VLBI, was observed under critical circumstances, with a very low signal level in the fringes. Nevertheless, after a thorough analysis of these data, it could be concluded that synchrotron self-absorption may not be the dominant absorption process near the peak of the radio light curve. This conclusion, if extrapolated to the other type II-P supernovae, can help to improve the determination of the ejecta expansion velocity of future supernova explosions by comparison of radio and optical data.

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