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5-GHz Global VLBI observations of SN 1986J in NGC891

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Abstract. We have imaged with VLBI the supernova SN1986J in NGC891 at 5 GHz, about 16 yr after its explosion. The image shows a distorted shell of radio emission, indicative of a strong deformation of the shock front. The shell is asymmetric, and we suggest that such asymmetry could be due to the collision of the supernova ejecta with an anisotropic, clumpy (or filamentary) medium. The average speed of the shell has decreased from $\sim$7400 km s^{-1} in 1988.74 down to about 6300 km s^{-1} in 1999.14, pointing to a mild deceleration in the expansion of SN 1986J. Assuming a standard density profile for the progenitor wind, the resulting mass swept-up by the shock front is $\sim$2.2 $M_\odot$. This large swept-up mass, coupled with the mild deceleration suffered by the supernova, suggests that the mass of the hydrogen-rich envelope ejected at explosion was as large as $\sim 12\ M_\odot$. Thus, the supernova progenitor must have kept intact most of its hydrogen-rich envelope by the time of explosion, which favors a single, massive star progenitor scenario.

1. Introduction

SN 1986J in NGC891 is one of the most radio luminous SNe ever discovered. At a distance of $\approx$9.6 Mpc (Tully 1998), it had a peak luminosity at λ6cm about 8 and 13 times greater than SN 1979C and SN 1993J, respectively. The precise date of its explosion is not known, but was estimated on the basis of the available radio and optical data to have exploded around the end of 1982 (Rupen et al. 1987, Chevalier 1987, Weiler, Panagia & Sramek 1990). Based upon its large radio luminosity, Weiler, Panagia, & Sramek (1990) showed that the progenitor star was probably a red giant with a main-sequence mass of $20 - 30\ M_\odot$ that had lost material very rapidly ($\dot{M} \geq 2 \times 10^{-4}\ M_\odot$ yr^{-1}) in a dense stellar wind.

VLBI observations by Bartel et al. (1991) showed that the radio structure of SN1986J had the form of a shell, in agreement with expectations from the standard interaction model (hereafter SIM; Chevalier 1982). The brightness distribution had a minimum of emission located approximately at its center, and the rim of the shell showed several maxima. Those authors showed also the presence of protrusions outside the supernova shell, which was interpreted as evidence of deviation from spherical symmetry. Optical observations have put the SIM scenario for SN 1986J into trouble. Indeed, the low velocities of 500 – 700 km s^{-1} indicated by optical spectra obtained in 1986 (Rupen et al. 1987) and in 1989 (Leibundgut et al. 1991) question the validity of the SIM, since in this model the optical and X-rays arise in the reverse shock, which moves at velocities close to that of the forward shock, i.e., several thousand km s^{-1}. Also, the radio light curves for SN 1986J were not fitted within the SIM for radio supernovae, which led Weiler et al. (1990) to invoke the existence of a mixed thermal absorbing/non-thermal emitting gas, or significant filamentation in the circumstellar matter (CSM). Chugai (1993) has proposed a different model which overcomes the problems of the SIM and seems plausible for SN 1986J. In his model, the supernova envelope is not colliding with a smooth distribution of wind material, but with a clumpy one, and the bulk of the observed X-rays originates in the shocked dense wind clumps. Therefore, the narrow-line ($\sim$500 km s^{-1}) material is not directly related to the shock wave (which moves at much higher velocities), but to the velocity of the shock-excited dense clouds.

Unfortunately, VLBI observations of SN 1986J that might have helped to distinguish between the above competing models have been so scarce since its explosion that only one high-resolution radio image for SN 1986J exists (Bartel et al. 1991). Here, we present the first high-resolution image of SN 1986J at 5 GHz, obtained with a global VLBI array on 21 February 1999, about 16 yr after its explosion.

2. VLBI Observations and Image Processing

We used archival VLBI data for SN 1986J. SN 1986J was observed at a frequency of 5 GHz from 17:00 UT on 21 February 1999 to 04:50 UT on 22 February 1999, using the following VLBI array: The VLBA, phased-VLA, Effelsberg, Medicina, Noto, and Onsala. The telescopes received both left- and right-hand circular polarizations (LCP and RCP) which, after correlation, were combined to obtain the total intensity map presented in this paper. Effelsberg had technical problems (damaged gear) and thus could not take part in the observations. Onsala only recorded in LCP mode, and therefore its data were not used to obtain the total intensity image presented here.

The observations were made with a bandwidth of 64 MHz, and the data were correlated at the VLBA Correlator of the National Radio Astronomy Observatory (NRAO) in Socorro (NM, US). Since SN 1986J was expected to be very faint, at a level of a few mJy, the observations were carried out in phase-reference mode. Our target source, SN 1986J, and the nearby phase-reference source, 3C 66A, were observed alternately during the 12-hr experiment. The observations consisted of $\sim$ 120 s scans on SN1986J and of $\sim$ 70 s scans on 3C 66A, plus a few additional seconds of antenna slew time to make a duty cycle of 190 s. 3C 66A was also used as amplitude calibrator for SN 1986J. The source 3C 84 was observed as a fringe finder. The correlated data were analyzed using the Astronomical Image Processing System (AIPS). The visibility amplitudes were calibrated using the system temperature and gain information provided for each telescope. The instrumental phase and delay offsets among the 8-MHz baseband converters in each antenna were corrected using a phase calibration determined from observations of 3C 84. The data for the calibrator 3C 66A were then fringe-fitted in a standard manner, and exported into DIFMAP for mapping purposes. The final source model obtained for 3C 66A was then included as an input model in a new fringe-fitting search for 3C 66A. In this way, the solutions obtained were structure-free. The phases, delays, and delay-rates determined for 3C 66A were then interpolated and applied to SN 1986J. The SN 1986J data were then transferred into DIFMAP for mapping purposes. Standard self-calibration techniques and purely uniform weighting were used to achieve maximum resolution in the hybrid map shown in Fig. 1.

3. A distorted radio shell in SN1986J

The only other available radio image of SN 1986J is that obtained by Bartel et al. (1991) corresponding to 29 September 1988. Our global VLBI image of 21 February 1999 shows a variety of details (see Fig. 1). The most remarkable thing is that the brightness distribution of SN 1986J still shows the form of a shell, even though more than 10 years have passed since the last observations. However, the shell shows changes in the brightness distribution between the two epochs.

Our image shows that the radio shell morphology of SN 1986J is asymmetric. Several bright spots in Fig. 1 seem to delineate a highly distorted shell –whose minimum of emission is not at its center– and are indicative of a significant deformation of the shock front. The three spots outside the shell structure are at contours of 3 times the off-source root-mean-square (rms) noise. Hence they could be real, and correspond to protrusions likely due to an existing dense, clumpy external medium around SN 1986J (Chugai 1993). However, their peaks range from 0.23 to 0.25 mJy/beam, less than the minimum of emission within the shell. Therefore, they could be as well mere artifacts of the image reconstruction procedure, in which case the protrusions seen by Bartel et al. (1991) must have disappeared between the two VLBI observing epochs (September 1988 and February 1999). If so, this could be interpreted as being due to the shock front having entered a region of the pre-supernova wind with different density properties.

Various models have been proposed to account for the asymmetric morphologies seen in supernovae. Khokhlov et al. (1999) have modeled jet-induced explosions of core collapse supernovae. The end result is a highly aspherical supernova with two high-velocity jets of material moving in polar directions, and slower moving, highly distorted ejecta containing most of the supernova material. Our image does show evidence for bright emission ‘spots’ (the possible ‘jets’) in several directions, not just in two opposite ones. Moreover, all the spots seem well confined within the supernova shell. Therefore, the existence of high-velocity jets in SN 1986J seems unlikely. Blondin, Lundqvist & Chevalier (1996) have suggested that an axisymmetric density distribution in the wind from a supernova progenitor leads to protrusions emerging along the symmetry axis. These authors find that for a power-law supernova density profile, the flow approaches a self-similar state after $\sim$10 yr in which the protrusion length is 2–4 times the radius of the main shell. This does not seem to be the case for SN1986J either, where there is not even an apparent symmetry in the flow. The protrusions outside the shell, on the other hand, could be formed by an asymmetric distribution in the wind similar to that invoked by Blondin et al. (1996), though not restricted to be axisymmetric. We believe that the most likely scenario for the origin of the strongly asymmetric brightness distribution of the radio shell structure is that of a supernova envelope colliding with a clumpy (Chugai 1993, Chugai & Belous 1999), or a filamentary wind (Weiler et al. 1990). Our image gives support to this model and, in addition, shows that the clumpy, or filamentary wind must probably be inhomogeneous to produce a highly distorted shell. (We note that the clumpy/filamentary model does not explain the co-existence of shocked material expanding at an average bulk velocity, that of the shell, and of material expanding at 2–4 times this velocity, necessary to explain the existence of protrusions outside the shell.)

3.1. Deceleration of the expanding shell

At a distance of 9.6 Mpc (Tully 1998), 1 mas corresponds to a linear size of 1.44×10^{17} cm $\approx$ 0.047 pc. Based on 8.4 GHz VLBI observations, Bartel et al. (1991) found a (largest) angular size of $\sim$3.7 mas ($\approx 5.33 \times 10^{17}$ cm $\approx$ 0.17 pc) for the shell of SN 1986J, 5.74 yr after its explosion (assumed it took place on 1983.0). The corresponding mean linear velocity would then be $\sim$14,700 km s^{-1}

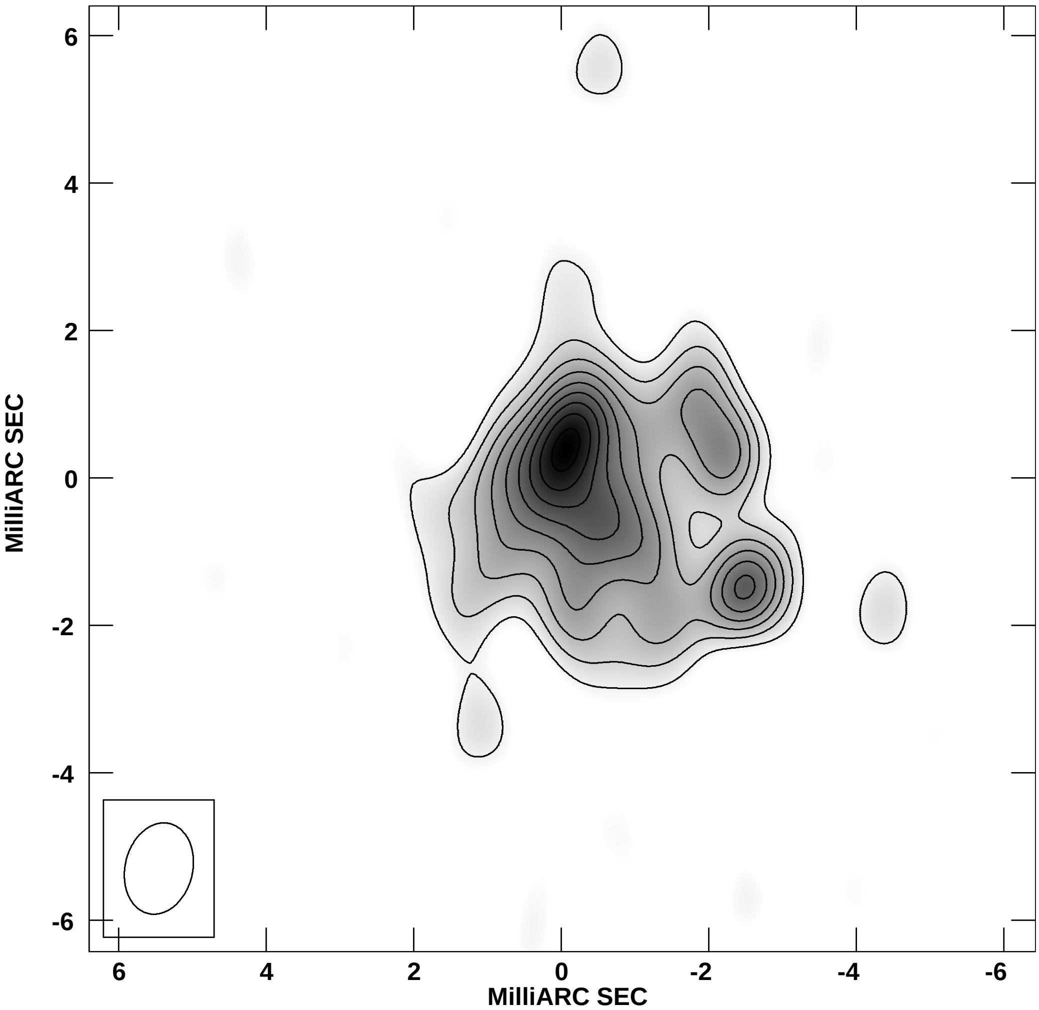

Fig. 1. Global Very-Long-Baseline Interferometry (VLBI) hybrid map at 5-GHz of SN 1986J on February 21, 1999. The contours are (3,5,7,9,11,13,15,17,19) $\times$ 56 μJy beam^{-1}, the off-source root-mean-square (rms) noise. The peak of brightness of the map is 1.13 mJy beam^{-1} and the restoring beam is 1.3 $\times$ 0.9 mas^2 at a position angle of -13°.4).

for the first 5.74 yr. However, this velocity applies only to the protrusions found by Bartel et al. (1991), not to the shell. Indeed, the velocities reported by Bartel et al. (1991) were calculated for the protrusions, and assuming that these originated in the center at the time of the explosion. These authors also pointed out that the protrusions extended from the center to twice the radius of the shell, i.e., the protrusions were *outside* the shell. Therefore, a value of ~1.85 mas ($\approx$ 2.66 $\times$ 10^{17} cm $\approx$ 0.087 pc) for the angular diameter of SN 1986J at epoch 1998.74 is indicated, and a mean linear velocity of the radio shell of ~7,400 km s^{-1} is more appropriate to characterize the first 5.74 yr of the expansion of SN 1986J, as has been previously noticed by Chevalier (1998) and Houck et al. (1998). Chevalier (1998) also pointed out that such a velocity at roughly the time of the peak flux is evidence against the synchrotron self-absorption mechanism acting in SN 1986J.

The angular size of the supernova (at the 5-rms noise level) is $\theta \approx 4.7 \pm 0.3$ mas, equivalent to $\approx 6.8 \times 10^{17}$ cm $\approx$ 0.22 pc. Combining this angular size measurement with that obtained by Bartel et al. (1991) for epoch 1988.74 ($\theta \approx 1.85$ mas), we then obtain a mean angular expansion velocity of the shell between 29 September 1988 (1988.74) and 21 February 1999 (1999.14) of ≈ 0.14 mas yr^{-1}, which corresponds to a linear velocity of $\sim$ 6300 km s^{-1}. If we assume that SN 1986J freely expanded for the first 5.74 yr of its life ($m = 1, r \propto t^m$) and then started to decelerate, the expansion between the two epochs of VLBI observations is characterized by $m = 0.90 \pm 0.06$, a mild deceleration that contrasts with the other known radio supernovae which have shown a strong deceleration in the first years of their expansion (SN1979C: Marcaide et al. 2002; SN1987A: Staveley-Smith et al. 1993, Gaensler et al. 1997; SN1993J: Marcaide et al. 1997, Bartel et al. 2000). The angular size that we obtain for the shell of SN 1986J seems to rule out the possibility that the bulk of the shell structure expanded for the first 5.74 yr at the velocity of $\sim 15,000$ km s^{-1} (see above and Chevalier 1998). On the other hand, since the mass loss rate of SN 1986J seems to have been $\gtrsim 2 \times 10^{-4}$ $M_{\odot}\,\mathrm{yr}^{-1}$ (Weiler, Panagia & Sramek 1990), the implied swept-up mass at epoch t=16.14 yr is $M_{\rm sw} \approx 2.2\,M_{\odot}$ (for a wind velocity of v_w=10 km s^{-1}), and the thermal electron density $\sim 8{\times}10^3\,\mathrm{cm}^{-3}$. The mild deceleration, together with the high swept-up mass, seems to indicate that the hydrogen-rich envelope ejected mass, $M_{\rm env} \gtrsim 12\,M_{\odot}$. Such a large mass for the hydrogen-rich envelope strongly hints that the progenitor of SN 1986J was probably a single, massive Red Super Giant (RSG), as also suggested by Weiler et al. (1990).

4. Summary

We used 5 GHz global VLBI observations of SN 1986J taken on 21 February 1999 to obtain a high-resolution radio image of the supernova about 16 yr after its explosion (assumed to have occurred on 1983.0). Our main results can be summarized as follows:

– The radio structure of SN 1986J is shell-like, even after more than 16 yr after its explosion. However, the shell is highly distorted, which can be interpreted as evidence for clumpiness or filamentary structure in the pre-supernova wind.
– The radio flux of SN 1986J at 5 GHz is ≈ 7 mJy, which results in a spectral luminosity of about $1.4 \times 10^{37}\,\mathrm{erg\,s^{-1}\,Hz^{-1}}$.
– There are three "spots" outside the shell at the 3-rms noise level. These could be protrusions alike those found by Bartel et al. (1991). Such clumps are expected in some models of radio supernovae (Chugai 1993), where the supernova shock collides with a clumpy distribution of material, instead of a smooth one. We cannot rule out, however, the possibility that the spots are mere artifacts of the image reconstruction procedure.
– The expansion of SN 1986J between 1988.74 and 1991.14 has decelerated from ~7,400 km s^{-1} down to ~6,300 km s^{-1}. This mild deceleration can be characterized by a power-law ($r \propto t^m$), with a deceleration parameter $m = 0.90 \pm 0.06$. Since the swept-up mass must be $\approx 2.2\,M_{\odot}$ (for $\dot{M} = 2 \times 10^{-4}$ $M_{\odot}\,\mathrm{yr}^{-1}$ and $v_w = 10\,\mathrm{km\ s^{-1}}$), this mild deceleration seems to indicate a mass of the hydrogen-rich envelope ejected at explosion of $\gtrsim 12$ $M_{\odot}$. In this case, the supernova progenitor kept almost intact its hydrogen-rich envelope, in spite of its strong mass-loss wind rate, and is a strong hint that the progenitor of SN 1986J was a single, massive RSG.

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