DISCOVERY OF SHELL-LIKE RADIO-STRUCTURE IN SN 1993J

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The radio-luminous supernova SN 1993J in M81 offers an unprecedented opportunity to study with high linear resolution the details of the growth of a supernova radio structure by means of the VLBI technique. Here we report the discovery of shell-like radio-structure eight months after explosion, when the source had turned partially optically thin to emission at 8.4 GHz. A radio map from that epoch shows a circularly symmetric structure with a shell thickness of ~30% of the shell outer radius. The emission around the shell is not uniform. The average expansion rate of the shell's outer radius during the eight months is 2.43±0.15μas d^{-1}. Spectroscopic observations of SN 1993J in the visible[1] indicate maximum supernova gas speeds of 16,000±3,000 km s^{-1}. These two results yield a distance to M81 of 3.8±0.8 Mpc, in good agreement with the more accurate result of 3.63±0.34 Mpc determined from Hubble Space Telescope observations of Cepheids[2]. This radio-shell in SN 1993J is the first discovered in a young supernova, and the monitoring of its growth offers a unique oportunity to understand the details of the emission of radio supernovae.

Our observations were part of a continuing VLBI effort[3,4] to monitor the expansion of the radio supernova SN 1993J. Here we discuss the data obtained on 26 September 1993 and on 22 November 1993 with especial emphasis on the latter. We observed at 8.4 GHz with global VLBI arrays (see Table 1). For the November 1993 data only a few iterations and minor self-calibration, all with the CLEAN option in the California Institute of Technology VLBI Package[5], were needed to obtain the image shown in Figure 1. The corresponding postfit residuals for the visibility amplitudes and closure phases yield a χ^2 per degree of freedom (χ^2_ν) of 1.0. Also good (χ^2_ν ~2.5) is the fit obtained with a model composed of two slightly-elliptical concentric uniform-disks (one of positive flux density and the other of negative flux density) which simulate a shell structure of noncircularly symmetric radio emission (Table 1). However, the data are incompatible with single uniform-disk models which yield $\chi^2_\nu \geq 6$. For the September 1993 data, we can not distinguish between a shell and a disk model. The source size at that epoch and the available resolution of the array do not allow us to make this distinction.

The radio shell in Figure 1 is almost spherically symmetric. Its detection and the relative uniformity of its brightness distribution excludes, at least for this supernova, models like the pulsar-driven model[6,7,8]. Other models[9,10,11,12,13,14] predict supernova radio shells of approximate spherical symmetry. Nonetheless, the observed closeness of SN 1993J to spherical symmetry is somewhat surprising in view of the asphericity implied by optical spectropolarimetric observations[15], by line asymmetries[16], and by suggestions that the progenitor was a member of a binary system[17,18]. Binarity could cause nonspherically symmetric density profiles of the supernova gas and the circumstellar material, and hence affect similarly the structure of the shock front responsible for the observed radio emission. We cannot at this time, however, make a quantitative comparison between predictions based on this inference and the asphericity of our model.

Asymmetry is definitely present in the radio shell emission, although some of the small scale features in Figure 1 might be artifacts of the CLEAN deconvolution method, since for illustrative purposes we show the map convolved with a beam size half that of the main beam of the array. The enhanced emission in the southeast part of the ring is clearly implied by the visibility amplitudes which yield an image of nearly bilateral symmetry about an axis of PA$\sim$135°. Remarkably, and perhaps importantly, PA$\sim$45° (perpendicular to PA$\sim$135°) is nearly identical to that reported[15] for the polarization intrinsic to the source and attributed to electron scattering in an aspherical geometry. What could cause such a preferred direction? One possibility is an asymmetric effect on presupernova outflow of a companion star in a (slowly precessing) elliptical orbit. Perhaps also the optical spectropolarimetric results could be reinterpreted as due to a spherically symmetric geometry with an asymmetric emission.

Key information on the supernova phenomenon is provided by the growth with time of the radio shell. One must be careful, however, in comparing the apparent sizes of the supernova at different epochs. Previous papers[3,4] have analyzed the visibilities with a circular disk model which was perhaps appropriate only for the very early phases of the supernova expansion. However, if some time after explosion, but before the source could be well resolved spatially, the correct characterization was not as a uniform disk but rather as a shell with variable shell-thickness, then the radius estimates would have to be lowered by factors between 0.85 and 1 (refs. 19 and 3). This size correction as a function of the epoch of observation would yield an expansion rate lower than previously estimated[3].

Using our radio-shell radius estimate for 22 November 1993 (day 239 after explosion), which is unaffected by these modeling problems, and a zero-size at explosion, we obtain an average shell-radius expansion rate of $2.43\pm0.15\mu$as d^{-1}, somewhat lower than the estimate of $2.98\pm0.08\mu$as d^{-1} based on data from the first three months after explosion and on the uniform-disk model[3]. The value quoted for the standard error for our expansion-rate estimate is based on measurements of a set of our images, made with various sizes of the restoring beam, and is 40% larger than the statistical standard error from our modelfit.

The "mini-shell models"[9,10,11,13,14] predict shell-like radio-emission from a region which contains shocked supernova ejecta and shocked ambient gas. The determination of the gas density profile in the steep gradient region of the ejecta is important because it may tell us about the pre-explosion hydrodynamic conditions in the progenitor and the details of the explosion. Such a determination depends on (1) the deceleration in the growth rate of the supernova's angular size, and (2) the density profile of the circumstellar material. The first depends crucially on the unambiguous characterization of the radio structure. Hence the importance of the discovery of shell structure which will enable us to determine the growth rate unambiguously. The second has been determined by Van Dyk *et al.*[20] who find a circumstellar material density profile proportional to $r^{-1.5}$, where r is the radial distance from the center of explosion, by fitting a model of two external absorbers surrounding an optically-thin spherically-symmetric synchrotron emitting expanding source to the observed multi-frequency radio light curves. We should expect improvements in both determinations in the future. At present we can combine only ill-defined source sizes from previous epochs with our present result to conclude that in the angular size vs. time law[9], $\theta \propto t^m$, a deceleration characterized by m=0.90±0.05 is favoured. Combined further with the results of Van Dyk *et al.*[20] –and highly dependent on the latter– we infer a very steep SN-ejecta density profile.

From our estimate of the angular expansion rate and an estimate of the maximum gas expansion speed, we could determine the distance to M81[21,3]. What is this expansion speed? Prior estimates[3] from analysis of optical spectra indicated that this speed was 18,000±1,000 km s^{-1}. However, we note that a "kink" in the Hα absorption profile at ~15,000 km s^{-1} is likely due to contamination from another line, perhaps Fe II 6415 or Si II 6355. Such a contamination line was observed earlier in SN 1990E[22]. Removing its contribution yields a maximum expansion speed of 16,000±3,000 km s^{-1}. Other strong lines in our spectra, such as He 5876, give the same maximum expansion speeds and uncertainties. Combining this result with our estimate of the average angular expansion rate (thus ignoring the minor effect of the deceleration), and allowing for a 10% difference in the optical and radio shell growth rates[21], we obtain 3.8±0.8 Mpc for the distance to M81. This result is consistent with the value 3.63±0.34 Mpc (ref. 2) obtained from the Hubble Space Telescope observations of Cepheids in M81.

To summarize: in this paper we show the first image ever made of a very young (eight months old) supernova radio-shell, which favours the "mini-shell model"[11,14] over all other previously proposed models[6,7,8]. This shell whose thickness in November 1993 was $\sim$ 30% of its outer radius is nearly circular, with enhanced emission in the southeast part near PA$\sim$135°. The size of the radio shell is significantly smaller than expected from estimates of the expansion of the radio source, based on observations at earlier epochs[3] and uniform disk models. Further, we obtain an improved, almost model-free, estimate of the average expansion rate of the radio shell for the first $\sim$240 days following explosion. The result here reported, combined with further monitoring of the radio shell and of the radio light curves, should allow a precise characterization of the supernova ejecta density profile and other relevant physical parameters of the "mini-shell model". It will also be extremely interesting to see which instabilities, if any, develop in the shell because their type and detail would characterize the interaction of the supernova gas with the circumstellar material.

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FIGURE CAPTION

Figure 1. Grey-scale and contour map of SN 1993J from 8.4 GHz observations 239 days after explosion. Since the visibility amplitudes are insensitive to a 180° rotation of the image, the (small) structure in the closure phases is required to resolve this ambiguity and favors slightly the enhanced emission being in the southeast part rather than the northwest part of the ring. The contours are at 2,4,8,16,32,64, and 90% of the peak surface brightness. The gaussian beam used in the convolution of the delta-function-component model to obtain this CLEAN map is shown as a filled circle (at lower left) and has a full-width at half-maximum (FWHM) of 0.25 mas, half the value of the FWHM of the interferometer's main beam. 1 mas is equivalent to 5.25×10^{16} cm (0.05 ly) for a distance of 3.5 Mpc.

TABLE 1 SN 1993J: 8.4 GHz Observations and model parameters

Date of Observation	Age* (d)	Measured Total Flux Density† (mJy)	Model# Component Flux Density (mJy)	Semi-major Axis‡ (μas)	Axis Ratio‡	Position Angle of Major Axis‡ (°)
26 Sep 1993	182	78 ± 4	78.8	478 ± 8	1	
22 Nov 1993	239	59 ± 3	82.2	612^{+20}_{-26}	0.91 ± 0.03	117 ± 13
			−24.3	423^{+59}_{-14}	0.81 ± 0.10	81 ± 14

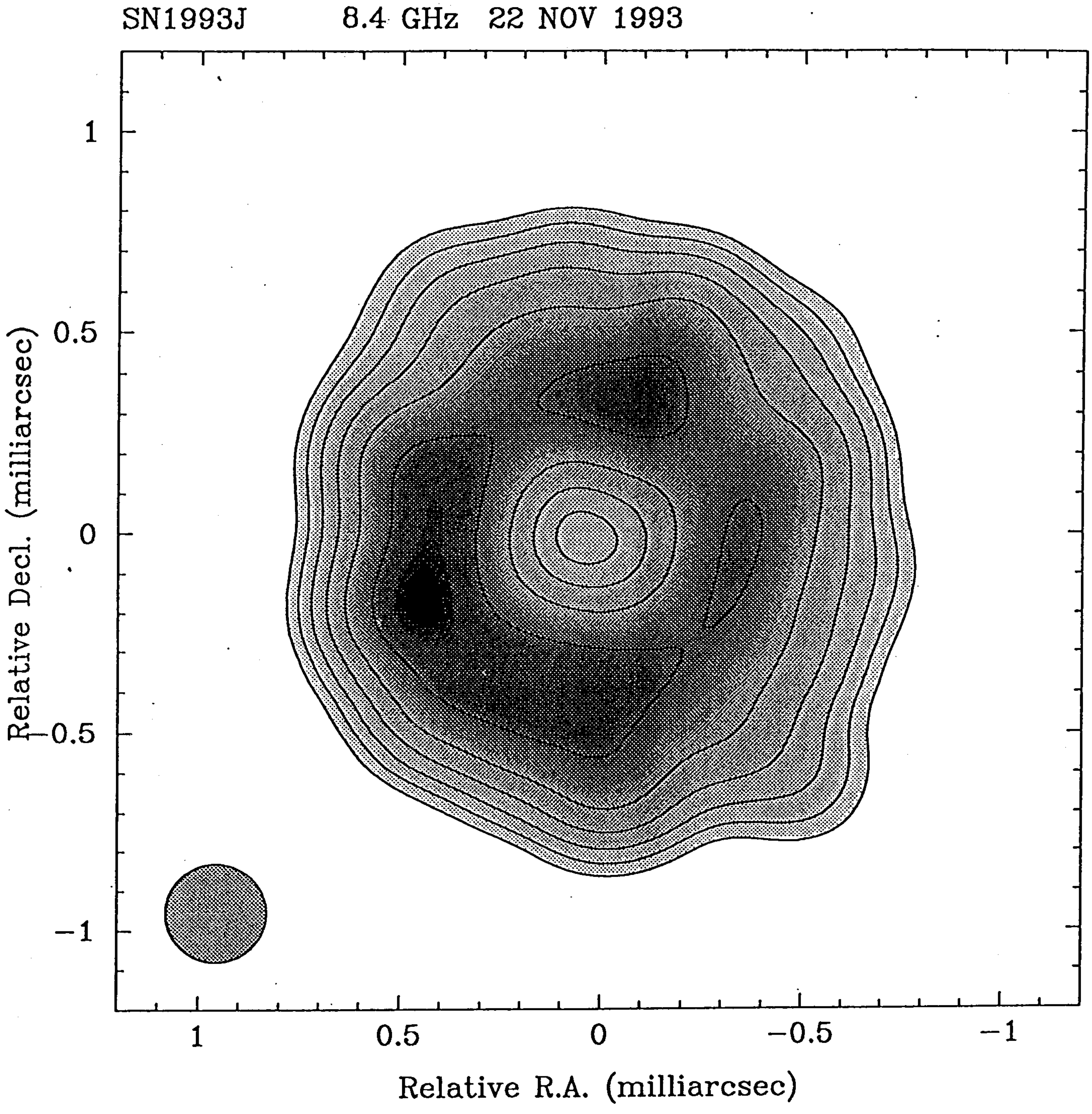
On 26 September 1993 the observations were made with the following antennas (symbols, diameters, affiliations and locations in parentheses): VLA (Y, equivalent diameter 130m, NRAO, near Socorro, New Mexico, USA); Effelsberg (B, 100m, MPIfR, Effelsberg, Germany); DSS63 (M, 70m, NASA, Robledo, Spain); DSS15 (V, 34m, NASA, Goldstone, California, USA); Medicina (L, 32m, CNR, Medicina, Italy). On 22 November 1993 instead of the DSS15 antenna, DSS14 (D, 70m, NASA, Goldstone, California, USA) was used. At each station a hydrogen maser frequency standard was used to govern the local oscillator chain and the 'time tagging' of the recorded data. The data were recorded with the Mark IIIA or compatible system, in mode B double speed, yielding bandwidths of 56MHz. Right-hand circular polarization (IEEE convention) was recorded. The data were correlated at the Max Planck Institut für Radioastronomie, Bonn, Germany.

* Age of the supernova with respect to estimated explosion date of 28 March 1993.

† Obtained from observations with the VLA[6].

Uniform-disk models used.

‡ Errors quoted are about 3 times the statistical standard deviations and include a 2% standard error in the amplitude scale calibration.



MARCAIDE ET AL : FIG 1