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RADIO-SIZE ESTIMATES OF SN 1993J

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ABSTRACT

Supernova 1993J (SN 1993J) in M81, now classified as Type IIb, is a strongly emitting radio supernova whose size can be resolved and whose growth can be monitored with the technique of very long baseline interferometry (VLBI). The results could provide important information about the circumstellar matter and the degree of asymmetry of the explosion. For several models of the emission of the radio supernova, we report estimates of its angular sizes 29 and 36 days after explosion at the wavelengths of 3.6 and 1.3 cm, respectively. These results, which correspond to our first epochs in an ongoing effort to determine the supernova structure and its growth, slightly favor an optically thick uniform disk model, given the recently derived Cepheid distance to M81 and the estimated maximum supernova expansion speed. Further VLBI observations, combined with the expansion-speed data, may yield an independent estimate of the distance to M81.

Subject headings: galaxies: individual (NGC 3031, M81) — radio continuum: stars — supernovae: individual (SN 1993J) — techniques: interferometric

1. INTRODUCTION

SN 1993J was discovered on 1993 March 28 in M81 (NGC 3031) (Ripero & García 1993), most likely 2 days after the explosion (Schmidt et al. 1993). The supernova was initially classified (Filippenko et al. 1993) as Type II due to its broad Hα emission line. Its optical light curve peaked less than 2 days after discovery and passed through a second maximum about 2 weeks later (Schmidt et al. 1993; Wheeler et al. 1993). Based on detailed modeling of the optical light curves, several groups (Nomoto et al. 1993; Podsiadlowski et al. 1993) suggested that SN 1993J might be similar to Type Ib supernovae, such as SN 1983N. These suggestions were supported by the (later) appearance of strong He I lines in the supernova spectrum, which seemed to indicate that the supernova had begun to transform into a type similar to Ib (Filippenko & Matheson 1993; Schmidt et al. 1993; Swartz et al. 1993), such as reported earlier for SN 1987K (Filippenko 1988). Now SN 1993J is classified as Type IIb (Filippenko 1988; Woosley 1991).

Compared to many previous supernovae, the radio emission of SN 1993J was detected quite early (Weiler et al. 1993; Pooley & Green 1993) and increased rather rapidly (Weiler et al. 1994). Although the details of how, where, and when radio emission originates in supernovae are incompletely known, it is thought (Chevalier 1982, 1990; Weiler et al. 1986, 1990) that the emission is generated by the outgoing shock produced by the supernova blast wave interacting with the circumstellar matter, enhancing the magnetic field and energizing the relativistic electrons responsible for the radio synchrotron radiation. The early detection of the radio emission indicates that the circumstellar material, presumably ejected by the progenitor as a wind, has less optical depth than in radio-bright Type II supernovae such as SN 1979C or SN 1986J, according to the circumstellar interaction model (Chevalier 1990). On the other hand, the flux density of the radio emission at wavelengths longer than 3.6 cm continues to grow even 180 days after the explosion (Weiler et al. 1994), thus indicating denser circumstellar material than that surrounding SN 1983N but similar to the material around SN 1980K.

Asymmetry in the shape of the supernova explosion has been suggested, based on the unusual shape of the absorption troughs observed in the He I and Hα lines (Schmidt et al. 1993) and on the detection of strong linear optical polarization (Trammell et al. 1993). The radio structure could also be asymmetric due to some combination of an intrinsic asymmetry of the geometry of the interaction shell, of its magnetic field distribution, and of its relativistic electron-density distribution. Using very long baseline (radio)interferometry (VLBI), we should be able to detect any such asymmetry: combining the estimated distance to M81 of 3.6 Mpc (Freedman et al. 1994) and the maximum supernova gas expansion velocity of about 20,000 km s^{-1}, estimated from the extent of the blue wing in the Hα line absorption (Schmidt et al. 1993), suggests that the radio supernova should grow at an angular rate of about 0.20 milliarcseconds (mas) $month^{-1}$, which is well matched to the beam sizes (point-spread functions) of worldwide VLBI arrays operating at centimeter wavelengths. Thus, a detection of a possible asymmetry in radio structure should be within reach after a few months of observations and might help to determine whether the explosion was asymmetric or not. A detection and measurement of such an asymmetry might, in turn, help understand whether the progenitor was a single star or part of a multiple-star system (Nomoto et al. 1993; Podsiadlowski et al. 1993; Höflich et al. 1993). Further, the circumstellar interaction model (Chevalier 1990) predicts that the radio supernova should have a shell structure; with SN 1993J, we have the opportunity to test this prediction.

VLBI measurements can also be used to estimate the distance to M81, in much the same way as they were used to estimate the distance to SN 1979C in M100 (Bartel et al. 1985), by comparing the evolution of the angular size of the supernova, as observed by VLBI, to the maximum radial expansion rate measured from optical lines. For SN 1979C the lack of a

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detailed knowledge of the radio structure was an important source of systematic error, which may be greatly reduced for SN 1993J.

2. OBSERVATIONS AND DATA REDUCTION

We carried out VLBI observations of the supernova on 1993 April 24 (day 29 after the explosion) and on May 1 (day 36) at the wavelengths of 3.6 and 1.3 cm, respectively. On April 24 we used two radio telescopes, one each in Robledo de Chavela (M, 70 m diameter), near Madrid, Spain, and in Westford (E, 18 m), Massachusetts, USA. At M and at E we had system temperatures of about 20 and 50 K, respectively. We observed from 21:30 UT on April 24 through 01:30 UT on April 25 with a fringe spacing of 1.4 mas. We alternated 5.5 minute observations of SN 1993J ($\alpha = 9^h55^m24^s.774$, $\delta = +69°01'13''.70$, J2000.0 [Marcaide et al. 1993]) with 1 minute observations of the calibrator source 0917+624 in a 10 minute cycle. We also observed the calibrators 0923+392 (4C 39.25) and 0954+658 several times each. On May 1, we used M, another radiotelescope (K, 37 m) in Westford, Massachusetts, and one in Medicina (L, 32 m), near Bologna, Italy. Typical system temperatures were 70, 160, and 120 K, respectively. We observed alternately SN 1993J (5.5 minutes) and 0954+658 (1 minute) with a 15 minute cycle from 11:15 UT on May 1 through 01:15 UT on May 2, with fringe spacings of about 0.6 and 2.0 mas; for the remainder of our 24 hr session we observed the calibrators 0316+413 (3C 84), 0917+624, 0923+392, 1641+399 (3C 345), 1901+319 (3C 395), and 2200+420 (BL Lac).

The experiments were run with Mark IIIA recording equipment (Rogers et al. 1983) at 144 and 224 megabits s^{-1} sampling rates, corresponding to 72 and 112 MHz bandwidths, at 3.6 and 1.3 cm, respectively. The data were correlated at the Haystack Observatory, and fringes were detected for SN 1993J with signal-to-noise ratios in the range from 5–7 for the 3.6 cm data and in the range from 7–14 for the 1.3 cm data. The supernova flux densities at 3.6 cm on April 24 and at 1.3 cm on May 1 were 15.2 ± 0.8 and 55.6 ± 2.8 mJy, respectively (Weiler et al. 1994). We used the Caltech Package (Pearson 1991) to calibrate and fit a model to the data. In the first step of the calibration procedure, we used radiometric information obtained during the observations and a priori knowledge about the antenna gains. We then improved this calibration by incorporating antenna-gain corrections obtained from modeling the calibrator source 0917+624 for the April 24 data and the calibrator sources 0954+658 and 1901+319 for the May 1 data. At 3.6 cm we relied on knowledge of the structure of 0917+624 at 3.6 cm from three epochs in 1991 (K. Standke, 1993, private communication). However, one should notice that 0917+624 is the prototype of intraday variable sources (Quirrenbach et al. 1989), and its flux density may vary by almost 20% on hour timescales. For the 1.3 cm data, we relied for the calibration on flux density measurements, on published maps at 3.6 and 6 cm (Gabuzda et al. 1992; Lara et al. 1994), and on our inference of the 1.3 cm structures for 0954+658 and 1901+319 by extrapolating from the 3.6 cm maps using the spectral indices obtained from the 3.6 and 6 cm maps. From our amplitudes for the three baselines and corresponding closure phases, we were able to improve these brightness distributions. The data reduction for each calibrator source was carried out independently by different people to check for consistency of reduction. The resultant differences in antenna-gain corrections for both 0954+658 and 1901+319 were consistent with each other to 5%–10%. We adopted the average values and used them in the analysis of the SN 1993J data. Due to its low flux density, the supernova was not detected on the K-L baseline, and hence we have no closure phase available. From scans of 1901+319, we estimated that amplitude loss due to loss of coherence over the 5.5 minute integration time for SN 1993J was about 8%.

3. RESULTS

After correcting upward the visibility amplitudes at 1.3 cm by 8% to account for the coherence loss, we fitted three models to the resultant SN 1993J visibility data at both 3.6 and 1.3 cm: An optically thin uniform sphere, a uniform disk, and a uniform ring. To estimate the effects of calibration errors on the models, we scaled up and down our amplitudes at 3.6 and 1.3 cm by 15% (total range of 30%). The results are given in Table 1. The fits to the data are very similar for all models; hence, in Figure 1, a comparison with the data is shown only for the uniform disk model.

We turn now to using the estimate of the distance to M81 (Freedman et al. 1994) to distinguish among these radio supernova models. Let us assume that the maximum supernova gas speed equals the speed of the shock causing the radio emission and that the shock front does not decelerate appreciably during, at least, the first 40 days following the explosion of SN 1993J. Given the maximum inferred gas speed of about 20,000 km s^{-1} (Schmidt et al. 1993), the radius of the supernova gas sphere should be about 5.2×10^{10} and 6.4×10^{10}

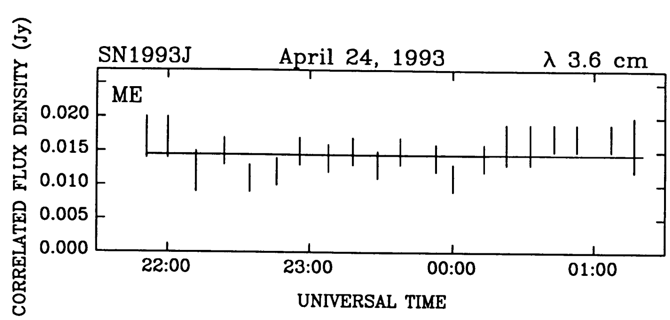

FIG. 1*a*

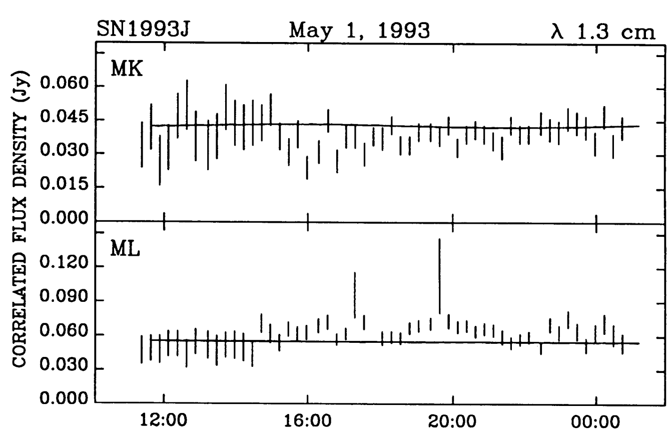

FIG. 1*b*

FIG. 1.—Fits of the uniform disk models given in Table 1 to the observed correlated flux densities at (*a*) 3.6 cm and (*b*) 1.3 cm.

TABLE 1

ESTIMATES OF SIZE OF SN 1993J

Model	Observing wavelength (cm) 3.6[a]	1.3[b]
	Diameter[c] (mas)	
Optically thin uniform sphere	$0.31^{+0.33}_{-0.31}$	0.31 ± 0.06
Uniform disk	$0.25^{+0.33}_{-0.25}$	0.28 ± 0.06
Uniform ring	$0.19^{+0.21}_{-0.19}$	0.20 ± 0.04

[a] Day 29 after explosion. Optically estimated size is 0.19 mas (see text).

[b] Day 36 after explosion. Optically estimated size is 0.24 mas (see text).

[c] Quoted errors cover diameter estimates obtained by scaling up and down the best calibrated data by 15% (see text).

km, 29 and 36 days after the explosion, respectively. At a distance to M81 of 3.6 Mpc (Freedman et al. 1994), the angular diameter of such spheres would be about 0.19 and 0.24 mas, respectively. Our estimates in Table 1 for day 29 after explosion are too uncertain to be useful. The estimates for day 36 after explosion, however, favor slightly the uniform disk model. This conclusion is not in contradiction with the circumstellar interaction model—a shell model—because if the shell emission were optically thick during the early times, as suggested by measurements of the spectral index α [$S(\nu) \propto \nu^{\alpha}$] of 1.17 ± 0.15 and 0.76 ± 0.15, on April 24 and May 1, respectively (Weiler et al. 1994), the radio emission would appear to emanate from a uniform disk. Thus, while the present stage of VLBI data accumulation and analysis for SN 1993J does not allow us to obtain a useful independent estimate of the distance to M81, the currently accepted distance to M81 proves useful in constraining the models of SN 1993J.

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