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RADIO EMISSION FROM SUPERNOVA SN 1986J IN NGC 891

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ABSTRACT

We report radio detection at 90 cm of supernova SN 1986J in the edge-on galaxy NGC 891, and several prediscovery radio observations of the same object at 20 cm and 6 cm. These observations have been made over the past few years with the Westerbork Synthesis Radio Telescope and the Very Large Array.

In approximately 1984, a discrete radio continuum source appeared above the extended radio disk emission from the galaxy NGC 891 at a position about 1′ southeast of the nucleus. The flux density at 20 cm increased from 7.5 to 11.7 mJy between 1984 August and 1985 January. Later, during 1987 September to 1988 March, the flux density at 90 cm was also observed to increase from $\sim$9 to 14 mJy. On the other hand at 6 cm the flux density of this discrete source has been decreasing through mid-1988, after reaching a peak of more than 128 mJy at some time between mid-1984 and mid-1986.

We compare these results with models of radio supernova. The radio characteristics are indicative of Type II, and free-free absorption by thermal electrons in the emitting region as well as in an external medium could be important. The radio spectral index between 6 and 20 cm varied from 1.5 to 0.4 over a period of two years (1984–1986), suggesting free-free absorption in a hot, optically thick thermal region surrounding the supernova which is slowly becoming optically thin at low frequencies. This circumstellar interaction model adequately fits the 6 cm radio data, but the fit at 90 cm is only marginally acceptable and at 20 cm the model does not fit the data well at all.

A unique feature of SN 1986J is its high radio luminosity. It has been suggested that the precursor was an extremely massive star and that the surrounding medium was unusually dense.

In a few years, the supernova could be as bright as 350 mJy at 90 cm and may be a prominent feature in the radio morphology of NGC 891 for several years thereafter.

Subject headings: galaxies: individual (NGC 891) — interferometry — radio sources: identifications — stars: individual (SN 1986J) — stars: supernovae

I. INTRODUCTION

Many optically identified supernovae in nearby galaxies have been later detected as time-variable radio sources at centimeter wavelengths. For instance, SN 1979C in NGC 4321, SN 1980K in NGC 6946 (Weiler *et al.* 1981, 1982), SN 1983N in NGC 5236 (Sramek, Panagia, and Weiler 1984), and SN 1987A in the LMC (Manchester 1987) were first detected optically and later monitored to obtain their radio "light" curves. In contrast, SN 1986J was first detected at radio wavelengths in NGC 891 by van Gorkom *et al.* (1986), and later identified with a 20th mag optical object (Rupen *et al.* 1987). Searches were subsequently made for evidence of variable radio emission in earlier radio observations of the galaxy (Fabbiano, and Gioia 1986; Wehrle 1986; Sukumar 1986). SN 1986J is now the second confirmed supernova to be detected first at radio wavelengths; the first was SN 1981K detected in NGC 4258 by van der Hulst *et al.* (1983).

Previous observations of extragalactic Type II supernovae have shown them to be powerful radio sources brighter than Galactic supernova remnant Cas A by one to three orders of magnitude. Their growth and decay times have been measured in months rather than days, the exception being SN 1987A in the LMC where the peak radio emission was detected within three days of the supernova event. Also, the radio emission from the Type I supernova SN 1983N in the face-on spiral galaxy NGC 5236 could even be detected 11 days before optical maximum.

The nonthermal radio emission from supernova remnants can be modeled in terms of the interaction of the outer parts of a supernova envelope with the circumstellar matter, creating a region wherein magnetic fields can be amplified and relativistic electrons accelerated (Chevalier 1977; Cowsik 1979; Chevalier 1982; Manchester 1987). This model has been used to explain the observed radio emission from Type II supernovae such as SN 1979C, SN 1980K, and SN 1987A as well as the Type I supernova SN 1983N; the differences being attributed to a flatter supernova radial density profile and a steeper relativistic electron spectrum for a Type I supernova. For SN 1986J, Chevalier (1987) has shown that the circumstellar interaction model adequately fits the radio data available to him at that time. The optical line and continuum emission were modeled with a central pulsar nebula as the energy source.

Cowsik and Sarkar (1984) have presented an alternative model of the evolution of the radio emission from supernovae where the interaction with an external medium may become important. Sramek *et al.* have noted that, although the physical mechanisms for generating nonthermal radio emission from Type I and II supernovae are similar, the local conditions under which the radiation is generated could be quite different. This seems to be the most probable scenario for supernova SN 1986J where, as we describe later, the radio luminosity exceeds that of any other radio supernova by a factor of at least 5.

We compare all observations presently available with the existing models for the radio emission and thereby determine

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the physical conditions of the medium surrounding the supernova. We then estimate the expected increase in luminosity during the initial phase of its evolution as a radio source at low frequencies.

II. RADIO OBSERVATIONS AND RESULTS

The galaxy NGC 891 was observed on 1984 August 29 at 20 and 6 cm with the Very Large Array (VLA) of the National Radio Astronomy Observatory (NRAO) operating in its D-configuration. The observations were made in the "snapshot" mode for about 10 minutes at each frequency, and the calibrated data were analyzed using the AIPS software package of the NRAO. Initially, a region of $\sim 1° \times 1°$ around the galaxy was mapped and an inner $0.^{\circ}5 \times 0.^{\circ}5$ area was CLEANed. The CLEAN components with positive amplitudes were used to self-calibrate the data in order to reduce the instrumental variations in the visibility phase; the self-calibrated data were then used to produce the final maps. The CLEAN components were restored with a Gaussian beam of size $40'' \times 40''$ at 20 cm and $14'' \times 14''$ at 6 cm. The rms noise levels in the final maps were about 1.0 and 0.7 mJy per beam at 20 and 6 cm, respectively.

As part of a new observing program to obtain high-resolution maps of spiral galaxies at low frequencies, we have observed NGC 891 with the VLA at 90 cm in its A-, B-, and C-configurations between 1987 September and 1988 March. The galaxy was also observed at 6 cm with the VLA in the D-configuration during 1988 August. These observations have been done for at least 6 hours in each configuration in order to obtain adequate sensitivity to the extended disk emission. The analysis procedures are similar to those described above, but special computer programs have been developed in order to detect and delete data suffering from interference at 90 cm. This interference is locally generated at the VLA site and is particularly severe at the shorter interferometer baselines. Also, the large field of view at 90 cm is dominated by the radio galaxies 3C 66.A and 3C 66.B situated $\sim 50'$ north of NGC 891, and hence maps of very large size are required in order to CLEAN away the effects of these sources on NGC 891. The rms noise levels in the final maps are typically about 3 and 0.02 mJy per beam at 90 cm and 6 cm, respectively. Sample VLA maps showing radio emission from the galactic disk and the supernova at 6 cm and 90 cm are shown in Figures 1*a* and 1*b*.

The galaxy NGC 891 was also observed with the Westerbork Synthesis Radio Telescope (WSRT) from 1984 September to 1985 January for the purpose of examining carefully the detailed distribution of radio surface brightness and its relation to the optical image. The observations were conducted after the installation of a new back-end receiver in which correlations between the fixed antennas of the WSRT could be obtained, resulting in a significant increase in the sensitivity and the addition of many redundant baselines. A much-improved calibration of the data is therefore possible, permitting the identification and removal of most of the variations in the amplitude and phase of the interferometer fringes which are due to instrumental effects. The observations were carried out in five sessions, four of them lasting about 12 hours each in four different configurations of interferometer baselines. An additional observing session lasting about 10 hours was obtained in order to compensate for data lost due to malfunctioning antennas in the earlier sessions. At each configuration, the observing bandwidth was split into eight channels of 5 or 10 MHz, and the correlations obtained separately. This allowed us to isolate the contamination by H I emission from the galaxy which appeared in one of the channels near 1418 MHz, and the remaining data in seven channels were used for making the maps. The elaborate data editing and calibration procedures followed will be described elsewhere; they are less relevant to the present topic of point-source detection of the supernova, although the dynamic range of better than 1000:1 which has been achieved on the final map of NGC 891 is essential to the accuracy with which we can determine the supernova flux density. The 20 cm WSRT map of NGC 891 for each day of observation in one configuration has a Gaussian beam size of $16'' \times 12''$ at PA = 0°, and a noise level of 0.075 mJy, which is nearly the theoretically expected value. A typical map of the galaxy at one of the frequency channels for a single day is shown in Figure 1*c*, with the position of the supernova marked on it.

From cross-cuts through the maps along the major axis of the galaxy near the supernova, we determined and subtracted an estimate of the emission from the underlying disk. The radio position for the supernova was determined by fitting a Gaussian-source model to the emission. In Table 1 we have listed our estimates of the supernova position at 90, 20, and 6 cm, along with some optical parameters of the galaxy NGC 891. We have also listed our estimates for the flux densities of the supernova in Table 2 along with other observations reported in the literature. These data are shown graphically in Figure 2, where the steep rise of the radio emission at 6, 20, and 90 cm is evident. The radio spectral index ($S \propto \nu^{\alpha}$) between 6 and 20 cm varied from 1.5 to 0.4 over a period of two years (1984–1986). The spectral index between 6 and 90 cm is currently estimated to be 0.7.

From the observations at different frequencies and at different epochs, the expected variation of the radio flux density owing to the decreasing optical depth of the medium surrounding the supernova can be estimated. Using the circumstellar interaction model (Chevalier 1982) for the radio emission from several radio supernovae, Weiler *et al.* (1986) have successfully fitted a power-law relationship to the observed radio flux density S as a function of frequency ν and the supernova age $t - t_0$, where t_0 is the time of the explosion. This relationship is expressed as

$$S(\mathrm{mJy}) = K_1(\nu/5\ \mathrm{GHz})^{\alpha}[(t - t_0)/1\ \mathrm{day}]^{\beta}e^{-\tau}\ ,$$

where the optical depth τ also has a power-law dependence on frequency and the supernova age as

$$\tau = K_2(\nu/5\ \mathrm{GHz})^{-2.1}[(t - t_0)/1\ \mathrm{day}]^{\delta}\ .$$

In these relationships, K_1 and K_2 are the scaling parameters corresponding respectively to the flux density and optical depth one day after the supernova explosion. Based on the circumstellar interaction model, Chevalier (1987) has estimated the occurrence of the SN 1986J event to be around 1983 January, and we have used that estimate to fit the observed radio "light-curves." The data set is most complete at 6 cm; the best fit at this wavelength is obtained by assuming that the time interval from the initial event until the optical depth of the circumstellar free-free absorption material becomes unity at 6 cm is 700 days. Assuming this age, we estimate the spectral index $\alpha = -1.0$; the temporal growth indices (β, δ) for the flux density $\beta = -1.2$, and for the optical depth, $\delta = -4.3$. The corresponding values for $K_1 = 7.05 \times 10^5$ and $K_2 = 1.71 \times 10^{12}$.

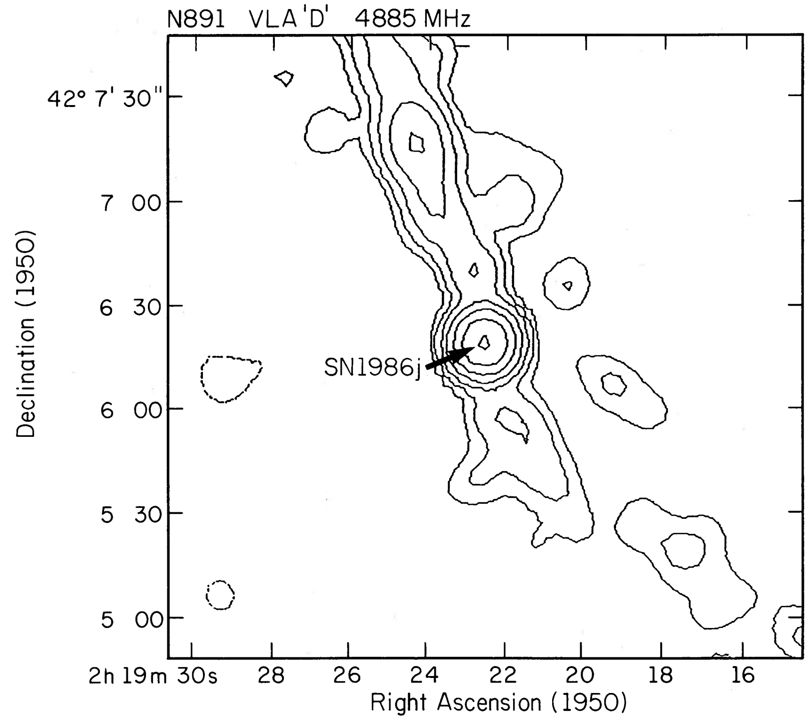

FIG. 1*a*

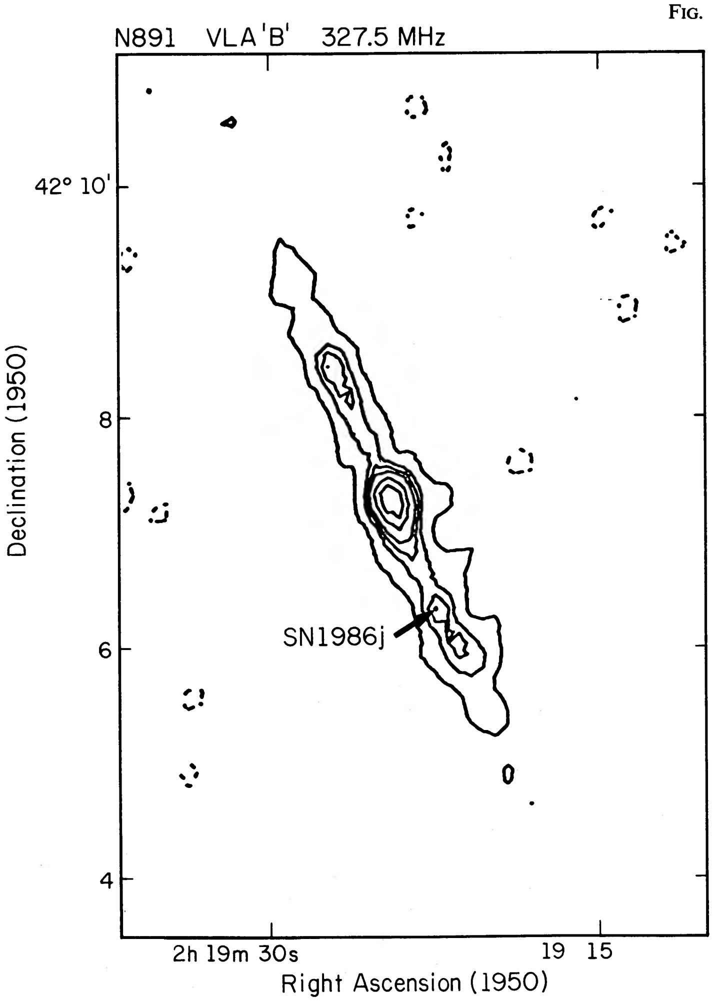

FIG. 1*b*

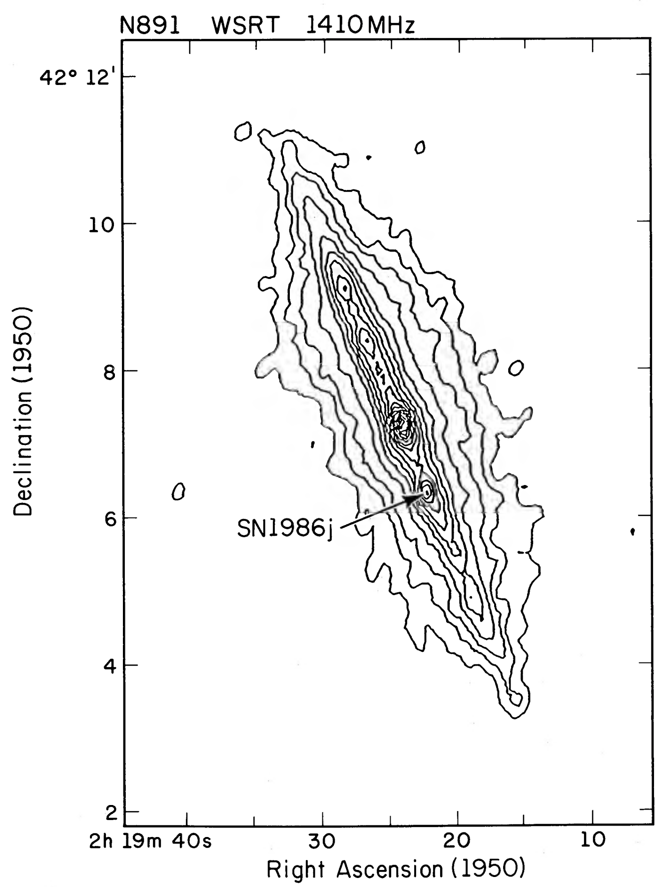

FIG. 1*c*

FIG. 1.—(*a*) VLA map showing radio emission from SN 1986J at 6 cm. The contours are −0.5 (*dashed*), 0.5, 1, 2, 4, 8, 16, and 32 mJy per beam. The restoring beam size is 14″ × 14″. (*b*) A typical VLA map obtained with partial spatial frequency coverage showing radio emission from SN 1986J at 90 cm. The contours are −10 (*dashed*), 10, 20, 25, 30, 40, and 50 mJy per beam. The restoring beam size is 14″ × 12″ at PA = 0°. (*c*) A typical WSRT map showing radio emission from SN 1986J at 20 cm. The contours are 0.5, 1, 1.5, 2.5, 4, 5.5, 7.5, 10, 12.5, 15, 17.5, 20, 22.5, 25, 27.5, and 30 mJy per beam. The restoring beam size is 16″ × 12″ at PA = 0°.

TABLE 1

OPTICAL AND RADIO PARAMETERS OF NGC 891 AND SN 1986J

PARAMETER	VALUE	
NGC 891		
Galaxy type	Sc	
Inclination angle	>88° (edge-on)	
Radio nucleus position (Allen *et al.* 1978)		
Right ascension (1950)	$02^{h}19^{m}24^{s}.3$	
Declination (1950)	$+42°07'17''.0$	
Assumed distance	7.6 Mpc	
SN 1986J		
Supernova type	Type II	
Radio position (1950)	R.A.	Decl.
WSRT 20 cm	$02^{h}19^{m}22^{s}.3 \pm 0^{s}.2$	$+42°06'20'' \pm 2''$
VLA(D) 6 cm	02 19 22.5 0.1	42 06 19 1
VLA(B) 90 cm	02 19 22.5 0.1	42 06 18 1
Estimated Properties at the maximum of the 6 cm emission		
Age	960 days	
Flux density	140 mJy	
Spectral luminosity	$\sim 10^{28}$ ergs s^{-1} Hz^{-1}	
Ratio to Cas A	1200	
Radio spectral index (6–20 cm) in optically thin region $\alpha = -1.0$		
Power law index for flux density decline $\beta = -1.2$		
Power law index for optical depth decline $\delta = -4.3$		

TABLE 2

FLUX DENSITIES OF SN 1986J AT VARIOUS RADIO WAVELENGTHS

	WAVELENGTH				
UT DATE	λ90 cm (mJy)	λ20 cm (mJy)	λ6 cm (mJy)	λ2 cm (mJy)	REFERENCE
1973 Jul/Nov	...	...	<2.5	...	Allen *et al.* 1978
1975 Jun/Aug	...	<10	...	...	Allen *et al.* 1978
1979 May/Jun	...	...	<3	...	This paper
1984 May 1	...	...	25	...	Rupen *et al.* 1986
1984 Aug 29	...	7.5 ± 2.2	37	...	This paper; Sukumar 1986
1984 Sep 8	...	...	60	...	Fabbiano, and Gioia, 1986
1984 Sep 8	...	≤10	...	...	Rupen *et al.* 1987
1984 Sep 23	...	9.73 ± 0.13	...	...	This paper
1984 Oct 21	...	<3	...	...	Condon 1986
1984 Oct 25	...	10.34 ± 0.14	...	...	This paper
1984 Dec 4	...	11.56 ± 0.12	...	...	This paper
1984 Dec 6	...	...	65	...	Wehrle 1986
1985 Jan 6	...	11.71 ± 0.11	...	...	This paper
1985 Jun 7	...	...	...	58	Wehrle 1986
1986 May 1	...	...	128	...	Wehrle 1986
1986 Aug 21	...	64 ± 2	...	...	Rupen *et al.* 1987
1986 Aug 22	...	64 ± 2	...	...	Rupen *et al.* 1987
1986 Aug 24	...	76	112	53	van Gorkom *et al.* 1986
1986 Aug 25	...	75	124	50	van Gorkom *et al.* 1986
1986 Aug 25	...	80 ± 2	...	...	Rupen *et al.* 1987
1986 Aug 25	...	...	...	52 ± 2	Rupen *et al.* 1987
1986 Sep	...	...	110	...	Rupen *et al.* 1987
1986 Sep 22	...	69 ± 3	...	...	Rupen *et al.* 1987
1986 Sep 22	...	77 ± 3	...	...	Rupen *et al.* 1987
1986 Sep 22	...	83 ± 3	...	...	Rupen *et al.* 1987
1986 Sep 22	...	...	124 ± 5	...	Rupen *et al.* 1987
1986 Sep 22	...	...	...	50 ± 2	Rupen *et al.* 1987
1987 Sep 13	8.7 ± 2.5	...	...	...	This paper; Allen *et al.* 1988
1987 Nov 24	11.4 ± 2.5	...	...	...	This paper; Allen *et al.* 1988
1988 Jan 23	12.0 ± 2.5	...	...	...	This paper; Allen *et al.* 1988
1988 Mar 12	14.3 ± 2.5	...	...	...	This paper; Allen *et al.* 1988
1988 Aug 28	...	...	69 ± 2	...	This paper

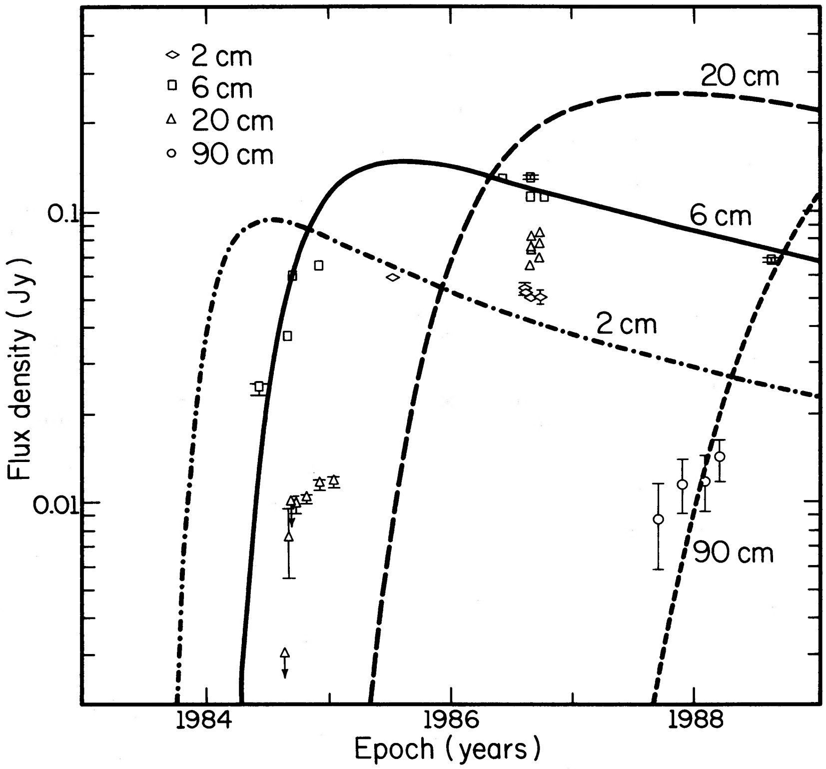

FIG. 2.—Time dependence of the radio emission from SN 1986J at 2, 6, 20, and 90 cm. The scatter in the 20 cm data seen around epoch 1986.8 may be due in part to slightly different observing frequencies. The curves are fits to the data using the circumstellar interaction model.

As can be seen from Figure 2, the model fits the 6 cm data very well. The 90 and 2 cm data are marginally in agreement with the model, although the data are very sparse at these wavelengths. However, the agreement with the 20 cm data is quite poor. Chevalier (1987) has assumed an age of 1600 days for the optical depth to reach unity at 20 cm; we find that such an age will not simultaneously fit the 20 cm measurements for epoch 1984.8 and also the 90 cm measurements for epoch 1988. The final model parameters differ considerably from those of SN 1979C, SN 1980K, SN 1981K, and SN 1983N (Weiler *et al.* 1986) for which the circumstellar interaction model has been successfully applied to fit the data both at 20 and 6 cm. In particular, K_1 and K_2 are several orders of magnitude larger for SN 1986J, and the temporal dependence of optical depth is steeper.

III. DISCUSSION

The estimated maximum radio emission at 6 cm of ~ 140 mJy in mid-1985 makes SN 1986J the most luminous radio supernovae known; it was at that time more than 1200 times brighter than Cas A. Note that our assumed distance of 7.6 Mpc to NGC 891 may be low; increasing the distance to 12 or 14 Mpc will, of course, further increase the luminosity of SN 1986J.

Since Type I supernovae are not expected to be such strong radio emitters, we assume that SN 1986J must be of Type II. From features in the optical spectrum (notably the He I recombination lines), Rupen *et al.* (1987) have suggested that the supernova may actually be of Type V; however, for the purposes of the following comparison, we will continue to assume that SN 1986J is of Type II, similar to the extragalactic supernovae SN 1979C and SN 1980K and to the Galactic supernova Cas A. Radio emission from both Type I and Type II supernovae has been modeled as arising from the interaction of the outer parts of a shocked supernova envelope with the circumstellar matter left by a massive progenitor star in its red-giant phase (Chevalier 1982, 1984). The density and structure of the expanding circumstellar shell are crucial in determining the nature of radio emission. It has been proposed that the emission from typical extragalactic radio supernovae is powered by a rapidly spinning pulsar (Marscher and Brown 1978; Pacini and Salvati 1981). Most of the extragalactic supernovae are short-lived, and the radio emission rapidly fades in a few years. Compared to them, however, the evolution of radio emission from SN 1986J has taken rather a long time, particularly at 20 and 90 cm. Since SN 1986J is exceptionally luminous at radio frequencies, conditions in the supernova are likely to be unusual; for instance, the magnetic field strength may be much stronger than in the case of a typical supernova like Cas A, or the surrounding medium may be much more dense, or both. The high optical luminosity of SN 1986J has been attributed to a central pulsar nebula (Chevalier 1987); this pulsar may contribute energetic particles over a longer period of time, and shocks at the interface between the supernova envelope and a dense circumstellar medium could accelerate these particles further. Alternatively, the high luminosity may also be explained if the fast outer layer of the expanding supernova envelope interacts with a dense interstellar medium, generating hydromagnetic turbulence and accelerating electrons to cosmic-ray energies (Cowsik and Sarkar 1984).

The circumstellar interaction model adequately fits the observed variation of the radio flux density at 6 cm but does not agree very well with the flux density variation at 20 cm. The growth rate of the radio emission at 90 cm also differs considerably from that predicted by the model. Also, it seems that the temporal dependence of the optical depth ($\delta = -4.3$) is steeper than a variation $\propto t^{-3}$ which is expected from the circumstellar interaction model (Chevalier 1981). In order to corroborate the steep variation of the optical depth since the supernova explosion, and to confirm the event date of 1983 January, we need flux density measurements prior to 1984 when the radio emission would have increased steeply with time at short centimeter wavelengths. From an examination of observations at 2695 and 8085 MHz made around 1976 by Seaquist and Bignell (1976), Rupen *et al.* (1987) derived upper limits of 4 and 6 mJy, respectively. From unpublished observations with the WSRT (R. J. Allen and F. X. Hu, private communication), an upper limit of ~ 3 mJy could be obtained at 6 cm for the epoch 1979.

The fit of the circumstellar interaction model at 6 cm provides an estimate of 2.5 yr from the SN 1986J supernova event to maximum radio emission at 6 cm. This interval is the longest known for radio supernovae; at 6 cm the corresponding time intervals are about 1.6 yr for SN 1979C, 0.4 yr for SN 1980K, and 15 days for SN 1983N (cf. Figs. 2, 4, and 7 in Weiler *et al.* 1986). SN 1986J shows a slower increase, but reaches a higher luminosity. At the time of maximum in the 6 cm radio emission, the model predicts very high optical depths of about 4 at 20 cm and greater than 25 at 90 cm, supporting the picture of the supernova embedded in a thick dense external medium. Cowsik and Sarkar (1984) present a model of the evolution of the radio emission from supernovae where the interaction with the interstellar medium and the acceleration of relativistic electrons by hydromagnetic turbulence are examined. These mechanisms are best invoked to study the evolution of synchrotron radio emission a few decades after the supernova event; in objects where such mechanisms may be useful, Gull (1975) suggests that the magnetic field and relativistic electrons are generated toward the end of the initial free-expansion phase. However, if the outer layer of the expanding supernova envelope is decelerated by a dense medium then turbulence may be generated earlier in the evolution. Such an interaction with an external medium could be important for SN 1986J, at least in influencing the low-frequency radio emission. In that case, the radio luminosity $S_{\max}$ of a Type II supernova is strongly dependent on the total energy release E_{tot} and the density of the interstellar medium ρ_0, according to (Cowsik and Sarkar 1984)

$$S_{\max} \propto E_{\text{tot}}^{(5\alpha+1)/2} \rho_0^{(\alpha+1)/2} M_{\text{ej}}^{-(\alpha+1)/2} ,$$

where M_{ej} is the ejected mass ($\sim 10^{33}$ g of matter). In order to account for the higher luminosity of SN 1986J for which the radio spectral index is steeper than that of Cas A at "turn on" ($\alpha \approx 1.0$; $S \propto \nu^{-\alpha}$, in conformity with the sign convention of Cowsik and Sarkar 1984), E_{tot} must exceed that of Cas A by about a factor of 10. This is uncomfortable, since the total radiated energies for both Type I and Type II supernovae are thought to be comparable at about 1.3×10^{51} ergs (Chevalier 1984). Alternatively, for a typical ejected mass of $\approx 5\ M_\odot$, the progenitor may be located in a dense star-forming H II region with an electron density of about 100 cm^{-3}; E_{tot} would then exceed that of a typical Type II supernova by only a factor of 2, which is not excessive. Such a region will also be optically thick for radio emission at low frequencies until it is rapidly forced to a lower optical depth by the expanding supernova shock. In fact, the steep temporal dependence ($\delta = -4.3$) suggests such rapid decrease in the optical depth of the medium surrounding the supernova. As the supernova evolves in its synchrotron radio emission while interacting with the interstellar medium, a shell-like source morphology is expected for the remnant.

IV. CONCLUSIONS

SN 1986J in the edge-on spiral galaxy NGC 891 has presented some of the most perplexing observational results among the extragalactic radio supernova studied so far. Its location in a heavily obscured part of the galaxy has undoubtedly prevented early optical detection, and thus deprived us of arriving at an accurate epoch for the supernova explosion. We have presented some prediscovery radio detections of the supernova both at 20 and 6 cm and shown the following.

1. Assuming the supernova exploded in 1983 January, the 6 cm radio data can be fitted very well with the circumstellar interaction model for a time interval of 700 days between the explosion and the time at which the optical depth for free-free absorption decreases to unity at 6 cm. However, this model fits the sparse data at 90 cm and 2 cm only marginally and does not adequately fit the 20 cm data at all. It may be necessary to consider additional mechanisms in the expansion phase, such as free-free and synchrotron self-absorption in the emitting gas itself (see e.g., Manchester 1987). Further observations especially at 20 and 90 cm are needed in order to investigate the role of these mechanisms. If a more satisfactory model can be found, it may be possible to determine the supernova explosion date from the radio data alone.

2. If we nevertheless adopt the circumstellar interaction model, we derive a rate of decrease of optical depth which is significantly faster than the values for other extragalactic supernova remnants such as SN 1979C, SN 1980K, and SN 1983N. Also, the scaling parameters for the flux density and optical depth are larger by several orders of magnitude. These differences make a detailed comparison of SN 1986J with other radio supernova questionable.

3. We note finally that one of the remarkable features of SN 1986J is its extremely high radio luminosity. Although a model involving a central pulsar energy source could possibly be constructed in order to explain this, alternate mechanisms such as interaction with a dense interstellar medium occurring after the initial expansion phase may also account for the high radio luminosity, especially at low frequencies.

In a few years the supernova could be as bright as 350 mJy at 90 cm and may be a prominent addition to the radio morphology of NGC 891 for several years thereafter. We strongly encourage periodic monitoring of the radio emission from this supernova at various radio frequencies.

We thank the staff of the Westerbork Synthesis Radio Telescope (WSRT) and of the Very Large Array (VLA) for their assistance with the observations. The WSRT is operated by the Netherlands Foundation for Radio Astronomy with the financial support of the Netherlands Organization for Scientific Research (NWO). The VLA is operated by the National Radio Astronomy Observatory (NRAO) through Associated Universities, Inc., under contract to the National Science Foundation. The calibrated WSRT data were transferred to the Gray XMP/48 supercomputer of the National Center for Supercomputing Applications (NCSA) at the University of Illinois, and further analysis was carried out using reconstruction software specially developed by R. Sault for that computer. For the analysis of the VLA data using the NRAO–AIPS software we are grateful to M. Norman, who arranged for access to the Alliant mini-supercomputer at NCSA. It is a pleasure to thank R. Cowsik for his critical comments and helpful discussions. J. M. van der Hulst, K. Weiler, and G. de Bruyn provided much useful advice. S. S. thanks the College of Liberal Arts and Sciences of the University of Illinois for financial support. This research has been supported in part by The National Science Foundation under grant AST 8715905.

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