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SN 1993J: THE EARLY RADIO EMISSION AND EVIDENCE FOR A CHANGING PRESUPERNOVA MASS-LOSS RATE

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ABSTRACT

We present daily-to-weekly monitoring of the first 8 months of radio emission from supernova (SN) 1993J using the Very Large Array at five wavelengths, providing the most detailed radio light curves ever established for an SN. While the radio emission evolves regularly in both time and frequency, the usual form of the SN shock/circumstellar medium interaction model does not adequately describe the observations. In particular, for a spherically symmetric geometry, the circumstellar density profile is flatter ($\rho_{\rm CSM} \propto r^{-1.5}$) than that ($\rho_{\rm CSM} \propto r^{-2}$) generally assumed for a constant mass-loss rate, constant-velocity stellar wind. This is interpreted as a decrease in the pre-SN mass-loss rate (or increase in wind velocity) immediately prior to explosion. Additionally, the rate of increase in the early radio emission at each frequency cannot simply be described as due to decreasing external absorption by a uniform medium, but requires the presence of higher density "clumps" or "filaments" embedded in the stellar wind.

Subject headings: galaxies: individual (NGC 3031) — radio continuum: stars — stars: mass loss — supernovae: general — supernovae: individual (SN 1993J)

1. INTRODUCTION

SN 1993J in M81 (NGC 3031) was discovered at magnitude $V = 11.8$ mag on 1993 March 28.91 (Ripero 1993), and, by March 30, at maximum magnitude $V = 10.7$ mag, had become the brightest SN in the northern hemisphere in almost 60 years. Due to its proximity (3.63 ± 0.34 Mpc; Freedman et al. 1994) and the fact that all Type II SNs are expected to be strong radio emitters (Weiler et al. 1989), we made very early attempts with the Very Large Array (VLA)[3] to detect radio emission. Observations taken on March 31 at 3.6 and 20 cm yielded only upper limits of less than 0.14 and less than 0.16 mJy (3 σ), respectively (Sramek et al. 1993), but on April 2 the first detection of radio emission was obtained, 0.75 mJy at 1.3 cm (Weiler et al. 1993). This was confirmed at 2 cm by Pooley & Green (1993a) with the Ryle Telescope in Cambridge, UK, on April 5 and again by the VLA at 1.3, 2, and 3.6 cm on April 8 (Van Dyk et al. 1993b). Emission at 6 cm was detected on April 13 by both Strom (1993) and Rupen et al. (1993), and at 20 cm on June 11 by Van Dyk et al. (1993a).

Regular monitoring of SN 1993J with the VLA at 1.3 cm (22.5 GHz), 2 cm (14.9 GHz), 3.6 cm (8.4 GHz), 6 cm (4.9 GHz), and 20 cm (1.4 GHz) continues. Pooley & Green (1993b) are also monitoring the SN at 2 cm with the Ryle telescope. Additional observations at 3 mm with the French-German IRAM (Radford et al. 1993) and Caltech OVRO (Phillips & Kulkarni 1993a, b; J. A. Phillips 1993, private communication) mm interferometers, and at 0.9 cm with the Effelsberg 100 cm telescope of MPIfR in Bonn, Germany (W. Reich 1993, private communication), are also available. SN 1993J's radio structure is being measured with VLBI observations at 18, 13, 3.6, 2, and 1.3 cm by Bartel et al. (1994) and Marcaide et al. (1994). We consider here only data from the VLA, the OVRO and Ryle telescopes, and VLBI observations by Bartel et al. (1994).

2. RADIO OBSERVATIONS

The VLA radio observations reported here were made between March 31 and November 28. Results from a few epochs are still unavailable, but the smooth radio evolution implies that their absence is unlikely to affect our modeling or conclusions. VLA phase and flux density calibration and data reduction followed standard procedures (e.g., Weiler et al. 1986; Weiler, Panagia, & Sramek 1990), using 3C 286 as the primary flux density calibrator and 1044+719 as the main secondary flux density and phase calibrator. At 20 cm in the more compact "D" configuration, 0945+664 was the secondary calibrator.

Figure 1 shows the flux density evolution for SN 1993J. All data were taken with the VLA, except at 2 cm, where additional data from Pooley & Green (1993b) are also displayed. The agreement between the VLA and Ryle telescope measure-

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ments at 2 cm is excellent. The solid lines are the best-fit model light curves, discussed below.

3. DISCUSSION

Weiler et al. (1986) discuss the common properties of radio SNs (RSNs), including nonthermal synchrotron emission with high brightness temperature, turn-on delay at longer wavelengths, power-law decline after maximum with index β, and spectral index α asymptotically decreasing to an optically thin value. Weiler et al. (1986) have shown that the "mini-shell" model of Chevalier (1982a, b), with modifications by Weiler et al. (1990), adequately describes previously known RSNs. In this model, the relativistic electrons and enhanced magnetic fields necessary for synchrotron emission are generated by the SN shock interacting with a relatively high-density ionized circumstellar envelope. This dense cocoon is presumed to have been established by a constant mass-loss rate, constant-velocity wind from a red supergiant (RSG) SN progenitor or companion (i.e., $\rho_{\mathrm{CSM}} \propto r^{-2}$), and ionized and heated by the initial SN optical/UV/X-ray flash. The rapid rise in radio flux density results from the shock overtaking progressively more of the wind matter, leaving less of it along the line of sight to absorb the emission from the shock region.

3.1. *Model Radio Light Curves for SN 1993J*

Following Weiler et al. (1986, 1990), we adopt the model

$$S(\mathrm{mJy}) = K_1\left(\frac{\nu}{5\ \mathrm{GHz}}\right)^{\alpha}\left(\frac{t-t_0}{1\ \mathrm{day}}\right)^{\beta} e^{-\tau}(1-e^{-\tau'})\tau'^{-1}\,, \tag{1}$$

where

$$\tau = K_2\left(\frac{\nu}{5\ \mathrm{GHz}}\right)^{-2.1}\left(\frac{t-t_0}{1\ \mathrm{day}}\right)^{\delta}\,, \tag{2}$$

and

$$\tau' = K_3\left(\frac{\nu}{5\ \mathrm{GHz}}\right)^{-2.1}\left(\frac{t-t_0}{1\ \mathrm{day}}\right)^{\delta'}\,, \tag{3}$$

with K_1, K_2, and K_3 corresponding, formally, to the flux density, uniform, and nonuniform external absorption, respectively, at 5 GHz 1 day after the explosion date t_0. The term $e^{-\tau}$ describes the attenuation of a medium that uniformly covers the emitting source ("uniform external absorption"), and the $(1-e^{-\tau'})\tau'^{-1}$ term describes the attenuation produced by an inhomogeneous medium with optical depths distributed between 0 and τ' ("clumpy external absorption"; Natta & Panagia 1984). Both absorption components are assumed to be purely thermal, ionized hydrogen with frequency dependence $\nu^{-2.1}$. The parameters δ and δ' describe, respectively, the time dependence of the optical depths for the uniform and nonuniform media.[4]

The model by Chevalier (1982a, b) relates β and δ to the energy spectrum of the relativistic particles γ ($\gamma = 2\alpha - 1$) by

$$\delta = \alpha - \beta - 3\,. \tag{4}$$

Weiler et al. (1990), for SN 1986J, and Van Dyk et al. (1993c), for SN 1988Z, also proposed a relation between δ' and δ, i.e.,

$$\delta' = 5\delta/3\,. \tag{5}$$

A search for the best parameter fit to equations (1)–(3) was carried out by minimizing the reduced χ-squared (χ^2_{red}). *However*, no parameter fitting, with the constraints of equations (4) and (5), could produce a satisfactory description of SN 1993J. The sharp early turn-on of the 1.3 and 2 cm emission, the flat, slow decline after peak flux density, and the well-established explosion date clearly required that δ and δ' be allowed to vary freely and independently. Permitting this, the best-fit parameter values are listed in Table 1, with the resulting model curves plotted in Figure 1.

From Figure 1 the deviations from the model appear systematic, not random. The very earliest, highest frequency data are too low, perhaps indicating a turn-on process for the nonthermal emission not described by the purely thermal optical depth effects of equations (2) and (3). Also, the peak flux density at lower frequencies is generally underestimated, and the most recent data indicate that β may be steepening beyond the currently best-fit value.

3.2. *Interpretation of Results*

Two major differences exist between the best-fit model for SN 1993J and those for previous RSNs: (1) δ' does not follow equation (5) (i.e., $\delta' \approx \delta$; $\delta' \neq 5\delta/3$), and (2) δ does not follow equation (4) (i.e., $\delta \simeq -2 \neq \alpha - \beta - 3$). We interpret these differences as: (1) $\delta' \sim \delta$ implies that the uniform and clumpy absorption components are coincident in space, i.e., the circumstellar cocoon is inhomogeneous with lines of sight having equal probabilities for optical depths between $\tau_{\min} = \tau$ and $\tau_{\max} = \tau + \tau'$; (2) since VLBI measurements (Bartel et al. 1994) show that the outgoing shock is still undecelerated ($R \sim t$) as of late 1993 June, $\delta \simeq -2$ implies a density profile of the circumstellar matter $\rho_{\mathrm{CSM}} \propto r^{-3/2}$, much flatter than that expected from the standard Chevalier model. A RSG star can establish such a profile if: (1) the stellar wind has a velocity exactly equal to the escape velocity from the star, or (2) the mass-loss rate $\dot{M}$ for the star decreases (or the wind velocity w increases; radio

TABLE 1

BEST-FIT PARAMETERS FOR THE RADIO EMISSION FROM SN 1993J[a]

Parameter	Value	Deviation Range[b]
K_1	4.14×10^3	$(1.81 - 6.25) \times 10^3$
α	-0.99	$-(1.60 - 0.67)$
β	-0.64	$-(0.89 - 0.53)$
K_2	1.35×10^3	$(0.72 - 4.65) \times 10^3$
δ	-1.99	$-(2.15 - 1.61)$
K_3	2.54×10^4	$(1.46 - 7.65) \times 10^4$
δ'	-2.02	$-(2.18 - 1.71)$
t_0[c]	-0.50	$-3.25 - +5.33$
χ^2_{red}	5.6[d]	—

[a] Parameters are determined by a minimum χ^2_{red} fit to eqs. (1), (2), and (3).

[b] The deviation range is the range in which there is a 67% probability that the true value lies; this is equivalent to a 1 σ uncertainty for a one-parameter fit (see Abramowitz & Stegun 1965).

[c] The explosion date, t_0, is measured from the estimated date of shock breakout (Wheeler et al. 1993) on 1993 March 28.0.

[d] An additional error of 18% per measured point would be required to bring χ^2_{red} to 1.0.

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[4] Weiler et al. (1990) discuss the physical interpretation of the absorbing media described by eqs. (2) and (3) and suggest that eq. (3) represents thermal absorbing/nonthermal emitting matter statistically mixed along the line of sight via an irregular shock preceding the SN ejecta. They also point out that a high level of clumping or filamentation in the external absorbing medium could give rise to the same mathematical form. With $\delta \sim \delta'$ for SN 1993J (see § 3.2), we feel that the latter interpretation is more likely correct for this SN.

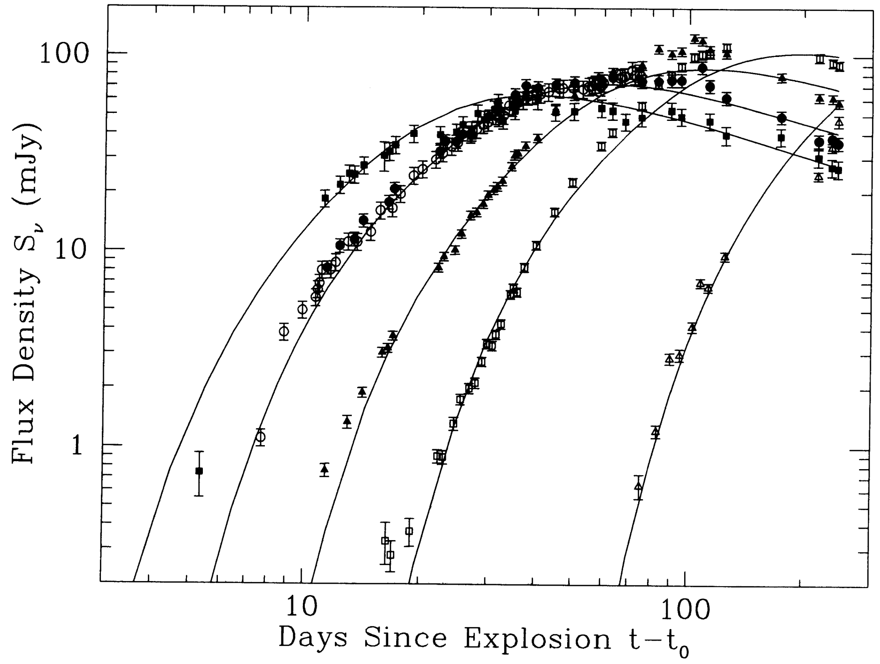

FIG. 1.—Radio light curves for SN 1993J at 1.3 cm (*filled squares*), 2 cm (VLA data: *filled circles*; Ryle telescope data: *open circles*), 3.6 cm (*filled triangles*), 6 cm (*open squares*), and 20 cm (*open triangles*). The lines represent the best-fit model as described in the text with the parameters listed in Table 1.

observations are only sensitive to $\dot{M}/w$) prior to explosion. Possibility (1) is less feasible, since a wind at precisely the escape speed appears unlikely. Possibility (2) is more plausible.

3.3. *Estimation of the Presupernova Mass-Loss Rate*

In a uniform medium with density $\rho \propto r^{-3/2}$, the free-free optical depth outward from a radius R can be written as $\tau = (\kappa_{\rm ff} \bar{Z} n_e^2 R)/2$, where n_e is the thermal electron density, $\bar{Z}$ is the average ionic charge, and $\kappa_{\rm ff}$ is the free-free opacity (see Panagia & Felli 1975; Weiler et al. 1986). The density is $n_e = \dot{M}/(4\pi R^2 w \mu_e m_{\rm H})$, where μ_e is the average molecular weight per electron and $m_{\rm H}$ is the hydrogen atomic mass. The mass-loss rate for the uniform component of the RSG wind beyond a radius from the star's center $R = vt$, having been lost at time

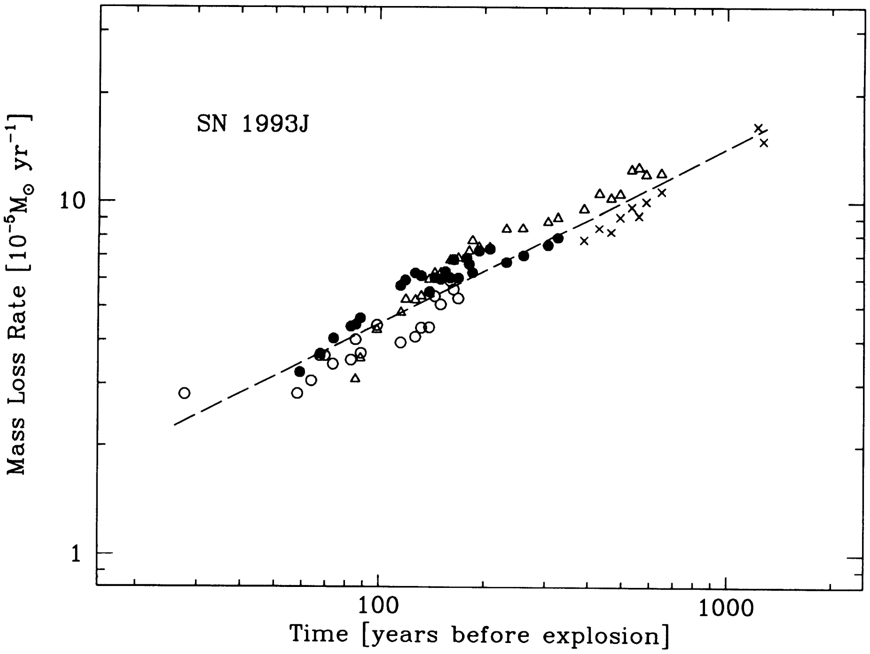

FIG. 2.—Mass-loss rate of the presumed red supergiant progenitor to SN 1993J vs. time before the explosion. The mass-loss rates are from the free-free optical depths derived for the flux density ratios S(22.5 GHz)/S(14.9 GHz) (*open circles*), S(14.9 GHz)/S(8.4 GHz) (*filled circles*), S(8.4 GHz)/S(4.9 GHz) (*triangles*), and S(4.9 GHz)/S(1.4 GHz) (*crosses*). The average solution from eq. (7) is plotted as a dashed line.

$t' = R/w = (v/w)t \approx 2000t$ prior to explosion,[5] is then

$$\dot{M} = \left[\frac{2(4\pi)^2 \tau w^2 \mu_e^2 m_{\rm H}^2 (vt)^3}{\bar{Z}\kappa_{\rm ff}}\right]^{0.5} , \qquad (6)$$

where τ is the optical depth at 5 GHz at time t when the SN shock is at radius R (see Weiler et al. 1986).

The total mass-loss rate must also include the clumpy matter. Since all values between τ and $\tau + \tau'$ are equally probable, and the mass-loss rate is proportional to the square root of the optical depth, the total mass-loss rate will be a factor $\frac{2}{3}[(\tau'/\tau + 1)^{1.5} - 1]/[\tau'/\tau] = \frac{2}{3}[(K_3/K_2 + 1)^{1.5} - 1]/[K_3/K_2] = 2.942$ (see Table 1) greater than that due to τ alone. Assuming singly ionized circumstellar matter with electron temperature $T_e = 10^5$ K (Lundqvist & Fransson 1988), $\mu_e = 1.3$, and average ionic charge $\bar{Z} = 1$, the total mass-loss rate is

$$\dot{M}_{\rm tot} \simeq 4.74 \times 10^{-5} \tau_{5\,\rm GHz}^{0.5} \left[\frac{w}{10\ {\rm km\ s^{-1}}}\right] \left[\frac{v}{18{,}900\ {\rm km\ s^{-1}}}\right]^{1.5}$$

$$\times \left[\frac{t}{30\ {\rm days}}\right]^{1.5} \left[\frac{\mu_e}{1.3}\right] \bar{Z}^{-0.5} \left[\frac{T_e}{10^5\ {\rm K}}\right]^{0.68} M_\odot\ {\rm yr}^{-1} . \qquad (7)$$

We have estimated the total optical depth at 5 GHz at different epochs from the ratios of flux density pairs at adjacent frequencies, under the assumption that the nonthermal emission has $\alpha = -0.85$. The values of $\dot{M}_{\rm tot}$ deduced in this way, as well as the average relationship obtained from equation (7), are shown in Figure 2. At the oldest presently determinable epoch (~ 1300 yr before explosion, or $\sim 4.1 \times 10^{16}$ cm from the RSG), $\dot{M}_{\rm tot} \sim 1.5 \times 10^{-4}\ M_\odot\ {\rm yr}^{-1}$, which is quite high; it decreased to $\sim 2 \times 10^{-5}\ M_\odot\ {\rm yr}^{-1}$ just prior to explosion. If this interpretation is correct, we expect $\dot{M}_{\rm tot}$ at even older epochs to flatten and the radio emission evolution to steepen to the canonical RSN behavior of $\delta \sim -3$, $\beta = \alpha - \delta - 3 \sim -0.85$.

4. CONCLUSIONS

We present detailed radio observations of SN 1993J at multiple wavelengths for the first few months after explosion. The standard Chevalier model does not adequately describe SN 1993J's early radio evolution. Two modifications are required: (1) The radio absorbing medium is entirely external and significantly inhomogeneous, consisting of clumps or filaments embedded in a uniform wind, and (2) the circumstellar density profile is flatter ($\rho_{\rm CSM} \propto r^{-1.5}$) than the $\rho_{\rm CSM} \propto r^{-2}$ expected for a constant mass-loss rate, constant-velocity RSG wind. We interpret this flatter density profile as due to a decreasing mass-loss rate (or increasing wind velocity) from the SN progenitor in the last stages of evolution.

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[5] VLBI measurements indicate the radio-emitting region is expanding steadily at 0.18 ± 0.03 mas month^{-1} (Bartel et al. 1994). Assuming the M81 Cepheid distance of 3.63 ± 0.34 Mpc (Freedman et al. 1994), the expansion velocity is then 18,900 ± 3600 km s^{-1}. The wind velocity is assumed to be $w = 10$ km s^{-1}.

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