RADIO OBSERVATIONS OF SN 1979C: EVIDENCE FOR RAPID PRESUPERNOVA EVOLUTION

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ABSTRACT

We present new radio observations of the supernova SN 1979C made with the Very Large Array (VLA) at 20, 6, 3.6, and 2 cm from 1991 July to 1998 October, which extend our previously published observations (Weiler et al.), which began 8 days after optical maximum in 1979 April and continued through 1990 December. We find that the radio emission from SN 1979C has stopped declining in flux density in the manner described by Weiler et al. and has apparently entered a new stage of evolution. The observed “flattening,” or possible brightening, of the radio light curves for SN 1979C is interpreted as due to the supernova shock wave entering a denser region of material near the progenitor star and may be indicative of complex structure in the circumstellar medium established by the stellar wind from the red supergiant (RSG) progenitor.

Subject headings: radio continuum: stars — shock waves — stars: evolution — supernovae: individual (SN 1979C)

1. INTRODUCTION

The study of supernovae (SNe) that are significant sources of radio emission, known as “radio supernovae” (RSNe), provides unique information on the properties of the progenitor stellar systems and their immediate circumstellar environments. In particular, changes in the density of the presupernova stellar wind—established circumstellar material (CSM) alter the intensity of the radio emission and allow us to probe the mass-loss history of the supernova’s progenitor, structures in the CSM, and the nature and evolution of the SN progenitor.

Significant deviation of the radio emission of SNe from standard models has previously been noted and interpreted as due to a complex CSM density structure. SN 1979C (Weiler et al. 1986, 1991) has shown a quasi-periodic variation in its radio emission, which may be due to modulation of the CSM density by a binary companion (Weiler et al. 1992; Schwartz & Pringle 1996). SN 1987A, after an initial, faint radio outburst and rapid decline until 1990 June, is now increasing in radio flux density because of the SN shock starting to impinge on the inner edges of the well-known, much higher density central ring (Turtle et al. 1990; Staveley-Smith et al. 1992, 1993, 1995; Ball et al. 1995; Gaensler et al. 1997). SN 1980K (Montes et al. 1998), at an age of ~10 yr, has experienced a sharp drop in its radio emission far beyond that expected from models of its previous evolution. More recently, SN 1988Z has also shown a sharp drop in its radio emission similar to that of SN 1980K (Lacey et al. 1999).

Recent observations of SN 1979C imply that the shock from SN 1979C has entered a new, higher density CSM structure different from the modulated decline previously reported (Weiler et al. 1992). The radio emission has apparently stopped declining and has been constant, or perhaps increasing, for the past 8 yr.

We have monitored SN 1979C [R.A.(2000.0) = 12°52′58.67 ± 0.01; decl.(2000.0) = +15°47′51.8 ± 0.2] in NGC 4321 (M 100) since 1979 April 27, and the results through December 1990 are available in Weiler et al. (1986, 1991, 1992). Here we present new Very Large Array3 (VLA) radio measurements from between 1991 July 28 and 1998 October 19.

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2. OBSERVATIONS

Routine monitoring observations of SN 1979C have been carried out with the VLA at 20 cm (1.465 GHz) and 6 cm (4.885 GHz) a few times a year since 1991. On 1996 December 21 and 1998 February 10, observations were additionally made at 3.6 cm (8.435 GHz) and 2 cm (14.965 GHz). The techniques of observation, editing, calibration, and error estimation are described in previous publications on the radio emission from SNe (see, e.g., Weiler et al. 1986), with particular reference to SN 1979C in Weiler et al. (1991, 1992). The "primary" calibrator remains 3C 286 and is assumed to be constant in time with flux densities 14.45, 7.42, 5.20, and 3.45 Jy, at 20, 6, 3.6, and 2 cm, respectively. The "secondary" calibrator, 1252 + 119, was used as the phase (position) calibrator with a defined position of \( \text{R.A.}(1950) = 12^h 52^m 07^s .724, \) decl.\((1950) = +11^\circ 57' 20'' .82\) and, after calibration by 3C 286, as the actual flux density reference for the observations of SN 1979C. As expected for a "secondary" calibrator,\(^4\) the flux density of 1252 + 119 has been varying over the years, as can be seen in both Table 1 and Figure 1.

The flux density measurement error is a combination of the rms map error, which measures the contribution of small unresolved fluctuations in the background emission and random map fluctuations due to receiver noise, and a basic fractional error \( \epsilon \) included to account for the normal inaccuracy of VLA flux density calibration (see, for example, Weiler et al. 1986) and possible deviations of the primary calibrator from an absolute flux density scale. The final errors \( (\sigma_f) \) as listed in Table 2 are taken as

\[
\sigma_f^2 = (\epsilon S_0)^2 + \sigma_0^2,
\]

where \( S_0 \) is the measured flux density, \( \sigma_0 \) is the map rms for each observation, and \( \epsilon = 0.05 \) for 20, 6, and 3.6 cm and \( \epsilon = 0.075 \) for 2 cm.

3. RESULTS

Table 2 shows the new flux density measurements from 1991 July 28 through 1998 October 19, while Figure 2 shows a plot of all the available 20 and 6 cm data for SN 1979C from 1979 April 27 through 1998 October 19, along with the best-fit model through 1990 December (day \( \sim 4300; \) Weiler et al. 1992). Figure 3 shows the evolution of the spectral index between 20 and 6 cm, \( \alpha_{20} \), for all the available data through 1998 October 19, and Figure 4 shows the spectrum at four frequencies for the 1996 December 21, 1998 February 10, and 1998 February 13 observations.

\(^4\) Secondary calibrators are chosen to be compact and unresolved by the longest VLA baselines. Such compact objects are usually extragalactic and variable so their flux density must be recalibrated from the primary calibrators for each observing session.

| Observation Date | Time since SN 1979C Optical Maximum (days) | \( S_{20} \) (Jy) | \( S_6 \) (Jy) | \( S_{3.6} \) (Jy) | \( S_2 \) (Jy) |
|------------------|------------------------------------------|-----------------|----------------|-----------------|----------------|
| 1979 Apr 19      | \( \equiv 0 \)                            | ...             | ...            | ...             | ...             |
| 1991 Jul 28      | 4483                                     | 0.770           | 0.607          | ...             | ...             |
| 1991 Oct 31      | 4578                                     | 0.834           | 0.717          | ...             | ...             |
| 1992 Mar 01      | 4700                                     | 0.776           | 0.628          | ...             | ...             |
| 1992 Oct 13      | 4926                                     | 0.757           | 0.674          | ...             | ...             |
| 1993 Jan 28      | 5033                                     | 0.795           | 0.672          | ...             | ...             |
| 1993 May 07      | 5132                                     | ...             | 0.673          | ...             | ...             |
| 1993 Oct 17      | 5295                                     | 0.771           | 0.717          | ...             | ...             |
| 1994 Feb 18      | 5419                                     | 0.789           | 0.738          | ...             | ...             |
| 1994 Apr 25      | 5485                                     | 0.753           | 0.721          | ...             | ...             |
| 1995 Jun 15      | 5901                                     | 0.752           | 0.677          | ...             | ...             |
| 1995 Dec 12      | 6081                                     | 0.771           | 0.746          | ...             | ...             |
| 1996 Oct 06      | 6380                                     | 0.772           | 0.772          | ...             | ...             |
| 1996 Dec 21      | 6456                                     | 0.736           | 0.791          | 0.753           | 0.704           |
| 1997 Sep 23      | 6732                                     | 0.740           | 0.702          | ...             | ...             |
| 1998 Feb 10      | 6872                                     | ...             | ...            | 0.845           | 0.876           |
| 1998 Feb 13      | 6875                                     | 0.769           | 0.720          | ...             | ...             |
| 1998 Oct 19      | 7123                                     | 0.785           | 0.771          | ...             | ...             |
| Observation Date | Time since Optical Maximum<sup>b</sup> (days) | VLA Configuration | Flux Density (mJy) |
|------------------|----------------------------------------|------------------|-------------------|
|                  |                                        | S<sub>20</sub>   | σ<sub>20</sub>   | S<sub>6</sub>   | σ<sub>6</sub>   | S<sub>3.6</sub> | σ<sub>3.6</sub> | S<sub>2</sub>   | σ<sub>2</sub>   | S<sub>2</sub>   | σ<sub>2</sub>   | S<sub>2</sub>   | σ<sub>2</sub>   |
| 1979 Apr 19      | 0                                      |                 |                 |                 |                 |                 |                 |                 |                 |                 |                 |                 |                 |
| 1991 Jul 28      | 4483                                   | A               | 5.229           | 0.276           | 1.915           | 0.103           |                 |                 |                 |                 |                 |                 |                 |
| 1991 Oct 31      | 4578                                   | B               | 5.365           | 0.289           | 1.546           | 0.101           |                 |                 |                 |                 |                 |                 |                 |
| 1992 Mar 01      | 4700                                   | C               | 5.640           | 0.801           | 2.253           | 0.120           |                 |                 |                 |                 |                 |                 |                 |
| 1992 Oct 13      | 4926                                   | A               | 5.396           | 0.287           | 2.574           | 0.143           |                 |                 |                 |                 |                 |                 |                 |
| 1993 Jan 28      | 5033                                   | A               | 5.582           | 0.304           | 2.625           | 0.136           |                 |                 |                 |                 |                 |                 |                 |
| 1993 May 07      | 5132                                   | B               |                 |                 |                 |                 |                 |                 |                 |                 |                 |                 |                 |
| 1993 Oct 17      | 5295                                   | C/D             | 5.190           | 0.281           | 2.251           | 0.115           |                 |                 |                 |                 |                 |                 |                 |
| 1994 Feb 18      | 5419                                   | D/A             | 5.670           | 0.535           | 1.660           | 0.311           |                 |                 |                 |                 |                 |                 |                 |
| 1994 Apr 25      | 5485                                   | A               | 5.810           | 0.314           | 2.740           | 0.170           |                 |                 |                 |                 |                 |                 |                 |
| 1995 Jun 15      | 5901                                   | A               | 5.340           | 0.328           | 1.740           | 0.240           |                 |                 |                 |                 |                 |                 |                 |
| 1995 Dec 12      | 6081                                   | B               | 5.663           | 0.074           | 2.664           | 0.139           |                 |                 |                 |                 |                 |                 |                 |
| 1996 Oct 06      | 6380                                   | D/A             | 5.640           | 0.335           | 2.170           | 0.170           |                 |                 |                 |                 |                 |                 |                 |
| 1996 Dec 21      | 6456                                   | A               | 5.820           | 0.315           | 2.690           | 0.180           |                 |                 |                 |                 |                 |                 |                 |
| 1997 Sep 23      | 6732                                   | CnD             | 4.200           | 0.452           | 1.727           | 0.107           |                 |                 |                 |                 |                 |                 |                 |
| 1998 Feb 10      | 6872                                   | D               |                 |                 |                 |                 |                 |                 |                 |                 |                 |                 |                 |
| 1998 Feb 13      | 6875                                   | DnA             | 5.460           | 0.279           | 2.680           | 0.149           |                 |                 |                 |                 |                 |                 |                 |
| 1998 Oct 19      | 7123                                   | B               | 5.140           | 0.406           | 2.500           | 0.136           |                 |                 |                 |                 |                 |                 |                 |

<sup>a</sup> For previous measurements, cf. Weiler et al. 1986, 1991.

<sup>b</sup> The date of the explosion is taken to be 1979 April 4, 15 days before optical maximum (cf. Weiler et al. 1986).
The solid line in Figure 3 is calculated from the best-fit model to the data through 1990 December and is not adjusted for the change in evolution since that time. The solid line in Figure 4 is calculated from the best-fit theoretical light curves (solid line) and 20 cm (dashed line), including the quasi-periodic, or sinusoidal, term proposed by Weiler et al. (1992). The best-fit parameters were determined using only data through 1990 December (day ~4300).

The fluctuations seen in Figure 2 in the 6 cm data (relative to the fairly constant 20 cm data) after day ~4300 also appear to be real. These data were reduced independently by three (and in some cases four) of the authors, all with similar results. The fluctuations are not correlated with fluctuations in the secondary calibrator 1252+119 or VLA array configuration. Higher frequency observations that would assist in the interpretation of these data are, unfortunately, available on only two dates (1996 December 21 and 1998 February 13) and have no long-term monitoring values with which to compare.

4. PARAMETERIZED MODEL

Previous work on RSNe (see, e.g., Weiler et al. 1986, 1991) has shown that the radio emission can be reasonably parameterized in terms of a small number of free parameters. The table below gives the best-fit values of these parameters.

| Parameter | Value | Deviation Range |  
|-----------|-------|-----------------|
| $K_s$ (mJy) | 1710 | 1440-2060 |
| $\alpha$ | -0.75 | (-0.76-0.63) |
| $\beta$ | -0.80 | (-0.83-0.78) |
| $K_0$ | $3.38 \times 10^7$ | (2.97-3.82) $\times 10^7$ |
| $\delta \equiv \alpha - \beta - 3$ | -2.94 | (-2.96-2.92) |
| $A_0$ | $7.3 \times 10^{-2}$ | (6.7-8.1) $\times 10^{-2}$ |
| $B^{-1}$ (days) | 1570 | 1520-1610 |
| C | 0.90$\pi$ | (0.83-0.99)$\pi$ |
| $t_0$ | 1979 Apr 4 | ... |
| $x^2$/dof | 2.47 | ... |

* Only data through 1990 December are used in the fitting procedure.

b The error estimates for the parameter values are determined using the bootstrap method, which is described in § 4.
well described in its gross properties by a parameterized model of the form

\[
S(\text{mJy}) = K_1 \left( \frac{v}{5 \text{ GHz}} \right)^{\alpha \left( t - t_0 \right) / 1 \text{ day}} e^{-\tau},
\]

where

\[
\tau = K_2 \left( \frac{v}{5 \text{ GHz}} \right)^{-2.1 \left( t - t_0 \right) / 1 \text{ day}}.
\]

\(K_1 \) and \(K_2\) correspond formally to the flux density (in mJy) and uniform absorption, respectively, at 5 GHz one day after the explosion date, \(t_0\); \(\alpha\) is the nonthermal spectral index of the synchrotron emission; and \(\beta\) is the decline rate of the radio emission after maximum. The term \(e^{-\tau}\) describes the attenuation of a local, external medium that uniformly covers the emitting source (“uniform external absorption”) and is assumed to be purely thermal, ionized hydrogen with frequency dependence \(v^{-2.1}\). From the Chevalier (1982a, 1982b) model for radio emission from SNe, this CSM is assumed to have radial density dependence \(\rho \propto r^{-2}\) and to have been established by a constant mass-loss rate, \(M\), and constant-speed wind, \(w\), from a red supergiant progenitor. The parameter \(\delta\) describes the time dependence of the optical depth for this local, uniform medium, and \(\delta = \alpha - \beta - 3\) is specified in the Chevalier model (Chevalier 1984). For an unaccelerated SN shock, \(\delta = -3\) is appropriate (Chevalier 1982a).

Chevalier (1982a) also determined the dependence of the radio luminosity on the mass-loss rate \((M)\) and progenitor wind velocity \((w)\) or, equivalently, to the average CSM density \((\rho_{\text{CSM}} \propto M/w)\), as

\[
L \propto \left( \frac{M}{w} \right)^{(\gamma - 7 + 12m)/4},
\]

where \(\gamma = -2\alpha + 1\) is the power law of the relativistic electron energy distribution and \(m = -\delta/3\) describes the time dependence of the self-similar evolution of the shock radius, \(R \propto t^m\). In this model, the magnetic energy density and the relativistic energy density both scale as the total postshock energy \((\propto \rho_{\text{CSM}} V^2_{\text{shock}})\), where \(V_{\text{shock}} = dR/dt\), and both the magnetic field amplification efficiency and the particle acceleration efficiency remain constant as the SN evolves.

Weiler et al. (1992) noted periodic features in the radio light curves of SN 1979C. Since the spectral index was not affected by the observed flux density oscillations, they concluded that the variations were due to emission efficiency changes caused by modulations in the CSM density structure rather than being due to optical depth effects. They, therefore, introduced a modification to equation (2) by multiplying the emission term \(K_1\) by the sinusoidally varying modulation

\[
\left\{ 1 + A \sin \left[ 2\pi B \left( \frac{t - t_0}{1 \text{ day}} \right) + C \right] \right\}^{-(\alpha + 2\delta + 3)/2}.
\]

Since a radial density modulation of the CSM will also affect the optical depth \(\tau \propto \rho_{\text{CSM}} \propto (M/w)^2\), equation (3) was modified by multiplying the absorption term \(K_2\) by

\[
\left\{ 1 + A \sin \left[ 2\pi B \left( \frac{t - t_0}{1 \text{ day}} \right) + C \right] \right\}^2.
\]

In equations (5) and (6), the expression

\[
A \sin \left[ 2\pi B \left( \frac{t - t_0}{1 \text{ day}} \right) + C \right] + C
\]

represents the deviation of \(M/w\) from a constant pre-SN wind mass-loss rate.\(^5\) The parameters \(A, B, C\) and \(C\) define the sinusoidal variation of \(\rho_{\text{CSM}} \propto (M/w)\), where \(A\) represents the fractional amplitude of the density modulation, \(B\) represents its frequency (in cycles day\(^{-1}\)), and \(C\) represents its phase lag (in radians).

The best-fit model parameters to the pre-1991 data \((t - t_0 < 4300\) days) are listed in Table 3. This fit is slightly different from that of Weiler et al. (1992), because of improved fitting software, but agrees with that work to within the uncertainties. The errors in these new fitting parameters were estimated using a bootstrap procedure (Press et al. 1992). Bootstrap procedures use the actual data sets to generate thousands of synthetic data sets that have the same number of data points, but some fraction of the data is replaced by duplicated original points. The fitting parameters are then estimated for these synthetic data sets using the same algorithms that are used to determine the parameters from the actual data. The ensemble of parameter fits is then used to estimate errors for the parameters by examining number distributions for the parameter in question. The errors in the fitting parameters in Table 3 correspond to the values with 15.85% and 84.15% (i.e., \(\pm 1\) \(\sigma\) for a Gaussian distribution), respectively, of the cumulative distribution for each parameter.

5 While it is true that the optical depth is due to the integral along the line of sight to the radio emitting region, most of the absorption occurs close to the shock front where the density is the greatest. The fractional errors in \(\tau\) from using our equations (3) and (6) instead of the actual integrated expression for \(\tau\) vary roughly sinusoidally with a period \(\sim 1/B\) and a magnitude \(\sim 0.4\). Thus, as the epoch we are concerned with, \(\tau \ll 1\), the fractional errors in \(e^{-\tau}\) are much smaller than 2.4.
A denser CSM may either be an isotropic shell or be in the form of condensations that have a small combined magnetic field, with densities not decreasing but remaining fairly constant, which implies that the cloud properties are not strongly affected by the interaction with the expanding shock front. Since the flux density of the radio emission increases almost linearly with time, this suggests a significant density enhancement in the circumstellar medium that continues to evolve in the present manner, the amount of engulfed matter increases rapidly: for example, in another 8 yr (i.e., by the year 2007) the additional swept-up mass would be approximately 1.7 $M_\odot$, giving a total swept-up mass of $\sim 6.8 M_\odot$.

Such a swept-up mass is large, even for a red supergiant star, and it implies a very massive progenitor. Estimates of the mass of the envelope ejected by SN 1979C range from $M_{env} \sim 1 M_\odot$ (Chugai 1985) to $M_{env} \sim 6 M_\odot$ (Branch et al. 1981; Bartunov & Blinnikov 1992; Blinnikov & Bartunov 1993). In particular, in the models by Bartunov & Blinnikov (1992) for SN 1979C, the CSM has a reasonable density profile, matching the observed $B$ light curves of SN 1979C quite well. Adopting their value for $M_{env}$, assuming a stellar remnant mass of $M_{rem} \sim 1.4 M_\odot$, and using our above estimate for the current value of the swept-up mass, the initial mass of the progenitor must have been between $M_0 \gtrsim 11.3 M_\odot$. Assuming the current evolution of the flux density continues, by 2007 our estimate would rise to $M_0 \gtrsim 14.2 M_\odot$. While large, this is still consistent with the estimates of Van Dyk et al. (1999). From their Hubble Space Telescope (HST) imaging of the SN 1979C environment, they find that the stellar ages in that environment are consistent with the SN progenitor having an initial mass of $M_0 \approx 17–18 M_\odot$. 

### 5.2. Equatorial Wind or Disk

Alternatively, the increase in flux density could be an effect of the geometry of the CSM. It is conceivable that at small radii the CSM was distributed in a disk with constant solid angle. At a radius of $\sim 3.4 \times 10^{17}$ cm (0.11 pc), the radius reached by a 9250 km s$^{-1}$ shock after 4300 days, the disk thickness increases so it covers a larger solid angle, reaching about twice the initial solid angle by day 7100, while maintaining a $\rho \propto r^{-2}$ behavior. Such a flared...
geometry would ease the mass requirement if the original disk subtended a relatively small angle (Ω) and were at a large inclination angle, so as to be seen almost edge-on. In such a case the mass-loss rate determined by radio light-curve fitting (in which the rate is derived essentially from the free-free absorption of the CSM) would be valid only within the solid angle subtended by the disk, rather than over the full 4π sr. Then, the mass engulled by day 4300 would be reduced by a factor Ω/4π and could be as small as ~ 1/10 of the estimates in the previous section without making the requirement on the viewing inclination angle too severe. However, even in such a case, the flux density flattening observed since day 4300 requires an increase of the interacting surface, so that the mass engulled at later times increases at the same rate as the flux density does relative to the best-fit model. For example, if we take an initial solid angle of the disk to be Ω = 4π/3, the mass swept by day 4300 would be ~0.57 $M_\odot$ and the mass swept up by day 7100 would be an additional ~0.54 $M_\odot$. More generally, if we denote with φ the fraction of solid angle subtended by the disk in the inner region, the mass swept by day 4300 would be 1.71φ $M_\odot$ and the mass subsequently swept up by day 7100 would be ~1.44φ $M_\odot$, a large but much smaller amount than for the spherical shell case.

5.2.3. Model Discrimination

A possible discriminant between the two basic possibilities, an increase of CSM density or an increase of CSM coverage, is the measurement of free-free absorption at low frequencies. For the case of flattening flux density due to a less rapidly declining (as $ρ \propto r^{-1.4}$ rather than $ρ \propto r^{-2}$) CSM density, the emission measure (EM) will begin to decrease as EM $\propto r^{-1.8}$, while for the case of flattening flux density due to increasing coverage factor, the emission measure behavior will be either the same as or steeper than the canonical stellar wind $ρ \propto r^{-2}$ and could vary as much as EM $\propto r^{-3}$ or more. In temporal terms, the differing density dependence of the EM implies that, up to 4300 days, the emission measure decreased as EM $\propto r^{-3}$ and that, for $t - t_0 > 4300$ days, its behavior changed to EM $\propto r^{-1.8}$. However, this behavior can be tested only at those frequencies at which the optical depth was of the order of unity at 4300 days, so observations at lower frequencies than the 1.4 GHz will be required to distinguish between the two scenarios.

To estimate how low an observing frequency is required to see the difference, the best-fit model gives an optical depth of

$$\tau(v) = 1.45 \left(\frac{t}{1000 \text{ days}}\right)^{-3} \left(\frac{v}{1 \text{ GHz}}\right)^{-2.1},$$

so at 4300 days the free-free optical depth was of the order of unity at 148 MHz and ~0.3 at 250 MHz. Even 330 MHz observations at the VLA are insufficient as they would probe an optical depth of only ~0.2 at day 4300. Thus, testing these models may be impractical, since no high-resolution, high-sensitivity radio telescopes currently exist at such low frequencies.

5.3. The Possibility of a Clumpy CSM

We have previously postulated that the CSM around SN 1979C is highly structured (Weiler et al. 1991, 1992), and we and others have found evidence for a clumpy CSM in SN 1986J (Weiler, Panagia, & Sramek 1990) and SN 1988Z (Van Dyk et al. 1993; Chugai & Danziger 1994). We may also speculate that there is evidence for a dense clumpy medium surrounding SN 1979C from the fact that the 1.4 GHz flux densities at $t > 4300$ days remain relatively constant and consistently higher than predictions from the best-fit model, while the 5 GHz flux density values fluctuate from as low as the best-fit model extrapolation, to as high as 0.47 times the 1.4 GHz flux densities, with a range of spectral indices from about $-1 < \alpha_{50} < -0.6$ (as shown in Fig. 3). These fluctuations appear real in that they greatly exceed the estimated measurement errors and seem to have a timescale of ~1 yr. Unfortunately, the paucity of observations in the 4300–7100 day interval makes it hard to test this hypothesis in detail.

If real, this 5 GHz fluctuation and 1.4 GHz stability could indicate a “cooling” time of ~0.5 yr for the relativistic electrons responsible for the higher frequency emission and an appreciably greater time constant for lower energy electrons. This could be evidence for the presence of a relatively small number of dense clumps interspersed in the general, stellar wind-generated CSM, but requires a cooling effect that is a very strong function of frequency. Synchrotron and inverse Compton losses scale only as $v^{-1.2}$, and Coulomb losses, as $v^{1/2}$ (see, for example, the analysis of SN 1993J by Fransson & Björnsson 1998), so producing such a large variation in timescales over such a small frequency range by these mechanisms is very difficult. Additionally, in order to produce such losses at all, synchrotron cooling would require magnetic fields $H \sim 1$ G, much greater than the expected $B(1 \text{ mG})$ fields. Unfortunately, there are too few measurements at 8.4 and 14.96 GHz (only two at each frequency) to determine whether the fluctuations are also seen at higher frequencies.

Other evidence for dense clumps comes from the estimate of high densities ($n_e > 10^6 \text{ cm}^{-3}$) derived by Fesen et al. (1999) from optical and UV spectroscopy of SN 1979C. However, it is hard to assess the significance of their result, because their density estimate is based on a comparison of [O ii] and [O iii] line intensities measured at two epochs about 4 yr apart, with the unverified assumption that the line fluxes do not change with time. Additionally, the optical emission and radio emission probably arise from different physical media, making it difficult to compare the densities derived by Fesen et al. (1999) directly with the radio results. Chugai & Danziger (1994) discriminated between equatorial disk and clump models for the case of SN 1988Z by using the intermediate velocity component of the emission lines with FWHM of ~2000 km s$^{-1}$. Fesen et al. (1999) propose that the “spiky” profiles of several lines from SN 1979C are suggestive of clumpy emission regions, and individual spikes in the profiles of [O i] $\lambda$6300 and [O iii] $\lambda$5007 in their Figure 5 have roughly the same velocity width as the lines used by Chugai & Danziger (1994) for the case of SN 1988Z.

The possible presence of clumps in the CSM and the reality of high-frequency fluctuations should be tested. More frequent, multifrequency radio observations (approximately every three months) at a number of frequencies greater than 1.4 GHz might establish the nature of the apparent radio flux density fluctuations, and simultaneous optical/UV observations would permit an unambiguous determination of the gas density in the clumps. We have already begun more frequent monitoring of SN 1979C.
with the VLA, including both higher (8.4 and 14.9 GHz) and lower (330 MHz) frequencies.

6. CONCLUSIONS

Analysis of the radio emission from the Type II RSN 1979C at 20 and 6 cm from 1991 July 28 through 1998 October 19 has shown that its radio emission has unexpectedly stopped decreasing in flux density and has flattened, or perhaps begun increasing, while maintaining a relatively constant spectral index. Such behavior is in conflict with the best-fit model parameter predictions, based on an assumed $\rho \propto r^{-2}$ CSM established by a constant mass-loss rate, constant-velocity wind from the pre-SN star. We interpret this “flattening” as an indication that the SN shock wave has encountered a new region of CSM that was formed by the SN's progenitor $\sim 10,000$–$15,000$ yr before the SN explosion.

Interpretation of the data implies that this new region could either be a higher density shell, which should soon be crossed by the fast-moving shock, or a “flared” disklike structure in the CSM, if the mass loss were constrained to a narrow solid angle. Additionally, rapid radio flux density fluctuations at 5 GHz, which are not present at 1.4 GHz, are interpreted as possible evidence for clumps or large-scale density enhancements in the CSM.

Continued monitoring of SN 1979C at multiple radio frequencies—which is ongoing—is needed in order to determine the form and duration of this new phase in the evolution of the radio light curves and, correspondingly, the structure of this new component of the CSM. With the longest relatively complete multifrequency data set available for the emission from any supernova, SN 1979C serves as a unique laboratory for understanding the evolution of Type II supernova progenitors, their pre-SN mass-loss history, and their interactions with their local environments.

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