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EVIDENCE FOR PERIODIC MODULATION OF PRESUPERNOVA MASS LOSS FROM THE PROGENITOR OF SN 1979C

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ABSTRACT

Examination of the short-term deviations from the best-fit model light curves for 10 years of measurements on the radio supernova SN 1979C at 20 and 6 cm shows periodic behavior. With an observed period of ~1575 days, model interpretations imply an ~8% modulation of the presupernova stellar wind density on a time scale of ~4000 yr. These observations therefore provide the first direct evidence for the periodic modulation of stellar winds on long time scales. Although any interpretations remain tentative at this point, the mechanism may involve modulation of the mass loss in a stellar wind from the presupernova red supergiant either as a result of pulsational instability or, more likely, by interaction with a massive companion star in a highly eccentric binary orbit, similar to the conditions in the VV Cephei star systems.

Subject headings: binaries: close — stars: mass loss — supernovae: individual (SN 1979C)

1. INTRODUCTION

A recent paper (Weiler et al. 1991) presented the 10 yr radio light curves at 20, 6, and 2 cm of the radio supernova (RSN) SN 1979C [$\alpha(1950.0) = 12^h20^m26^s.71 \pm 0^s.01$; $\delta(1950.0) = +16°04'29''.5 \pm 0''.2$] in NGC 4321 (M 100). SN 1979C, being a relatively bright RSN with an accurate data set over a long time interval, provides the best currently available example for studying any short-term deviations from the well-established Chevalier (1981a, b, 1984a, b) model for the gross, long-term radio light curve behavior. Figure 1*a* shows the Weiler et al. (1991) data set with the solid lines determined from the best model found by them. Examination of Figure 1*a* shows seemingly periodic deviations from this model at both wavelengths. Subtracting the model from the data points and plotting the percentage deviation in Figure 1*b* strengthens this impression by showing both wavelengths to be systematically too high at ~1200 and ~2800 days since explosion and systematically too low at ~650, ~2100, and ~3700 days since explosion. Such evidence appears strong enough to warrant further study.

2. PERIOD ANALYSIS

To establish the nature and reality of this apparent periodicity we applied the period analysis for unevently sampled time series discussed in Horne & Baliunas (1986) to the deviations at each wavelength to determine their power spectra $P_X(\omega)$, where $\omega = 2\pi/T$, with T being the period in days. The power spectra were normalized by the total variance of the data for each wavelength band, σ^2, such that

$$P_N(\omega) = P_X(\omega)/\sigma^2 \ . \quad (1)$$

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These normalized power spectra, $P_N(\omega)$, for 20 and 6 cm, are shown together in Figure 2. Also shown in Figure 2 are indications of the significance of the periods obtained in the analysis, i.e., the "false alarm probabilities," at the 10%, 50%, and 90% levels. The false alarm probability, F, as discussed in Horne & Baliunas (1986; see also Scargle 1982), is calculated from

$$F = 1 - (1 - \exp^{-z})^{N_i} \ , \quad (2)$$

where z is height of the highest peak in the power spectrum for each wavelength band and N_i is the number of sampled independent frequencies in the analysis. The numbers N_i are calculated from the numbers N_0 of measured 20 and 6 cm data points using equation (13) of Horne & Baliunas (1986); these are $N_i \simeq 67$ ($N_0 = 59$) and $N_i \simeq 82$ ($N_0 = 70$), respectively. The false alarm probability levels are not independently shown in Figure 2 for the 20 and 6 cm data. The calculated false alarm probabilities are so similar for the two wavelengths that only the average value for each probability is shown.

Examination of Figure 2 shows a number of peaks in the power spectrum at each wavelength band, but only one peak at both bands approaches or exceeds the 10% false alarm probability and is additionally well-correlated at both wavelengths. That peak is at a frequency $\omega = 3.989 \times 10^{-3}$ day^{-1}, or $T(=2\pi/\omega) = 1574.8$ days. The formal uncertainty in this frequency, determined using equation (14) of Horne & Baliunas (1986), is $\delta\omega \simeq 1.4 \times 10^{-4}$ day^{-1}, or ~4% of the frequency (this corresponds to $\delta T \simeq 55$ days). While the power spectrum peak is relatively less prominent at 20 cm, this can partly be explained by the fact that, for at least some of the initial part of the variation at 20 cm, the emission was still partly optically thick, significantly modifying the early modulations. In any case, it is clear that the SN 1979C data at 20 and 6 cm show a significant periodic component with a period ~1575 days in the deviation of the radio radiation from the best-fit mini-shell model.

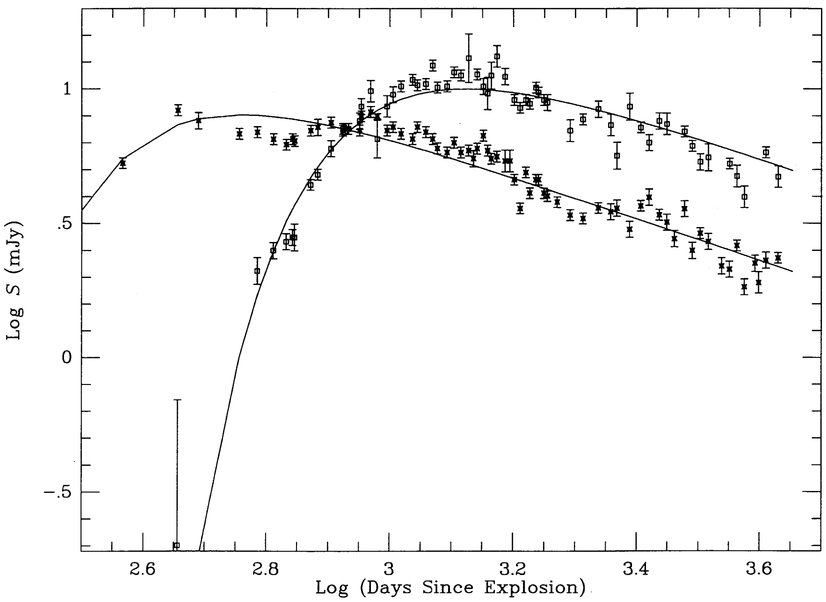

FIG. 1*a*

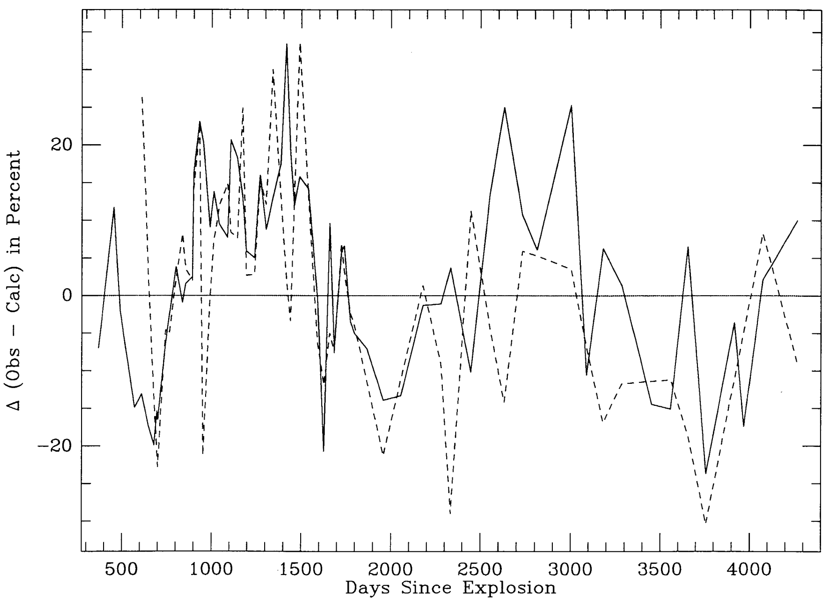

FIG. 1*b*

FIG. 1.—(*a*) Radio "light curves" for SN 1979C in NGC 4321 (M 100) reproduced from Weiler et al. (1991). Two wavelengths, 20 cm (*open squares*) and 6 cm (*four-sided stars*) are shown together; the 2 cm data included in Fig. 1 of Weiler et al. is excluded here. The data represent more than 10 yr of observations for this object. The age of the supernova $(t - t_0)$ is measured in days from the estimated date of explosion of $t_0 \equiv$ 1979 April 4 (15 days before optical maximum). The solid lines represent the best-fit light curves of the form

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

where

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

and $\delta \equiv \alpha - \beta - 3$. The best-fit parameter values from Weiler et al. (1991) are $\alpha = -0.74$, $\beta = -0.78$, $K_1 = 1446$, and $K_2 = 3.64 \times 10^7$, with t_0 given above and δ defined by the Chevalier model (Chevalier 1984b) to be $\delta \equiv \alpha - b - 3 = -2.96$ (cf. col. [4] of Table 1). (*b*) Deviations in percent, $([S_{\mathrm{obs}} - S_{\mathrm{model}}]/S_{\mathrm{model}}) \times 100$, of the observed flux density values for SN 1979C in NGC 4321 (M 100) from the best-fit model values, as calculated by Weiler et al. (1991) and shown in Fig. 1*a*, at both 6 cm (*solid line*) and 20 cm (*dashed line*).

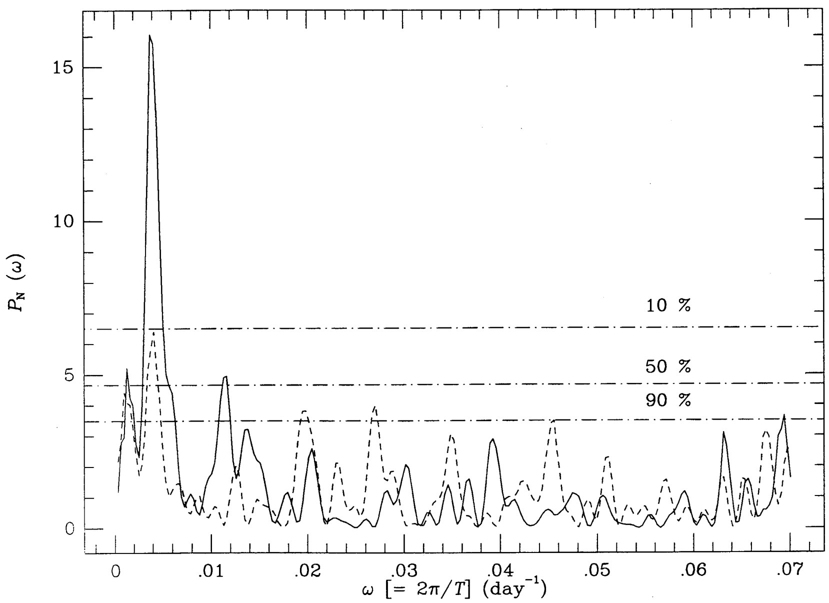

FIG. 2.—Power spectra, $P_N(\omega)$, of the deviations (Fig. 1*b*) from the best-fit models (solid lines in Fig. 1*a*) for the SN 1979C radio light curves at 6 and 20 cm. The power spectrum for the 6 cm deviations is shown as a solid line, while that for the 20 cm deviations is a dashed line. Also shown in the figure are the power levels for "false alarm probabilities" of 10%, 50%, and 90%, computed from the expression given by Scargle (1982) and Horne & Baliunas (1986). Because they are so similar, the false alarm probability levels shown are averages of the values calculated separately for the 20 cm data and the 6 cm data.

3. REVISED MODEL RADIO LIGHT CURVES

Previous work on radio supernovae (see, e.g., Weiler et al. 1986, 1991) has shown that the Chevalier mini-shell model (Chevalier 1981a, b; 1984a, b) provides a good fit to the gross properties of the radio light curves. This model is described by

$$S(\mathrm{mJy}) = K_1\left(\frac{\nu}{5\ \mathrm{GHz}}\right)^{\alpha}\left(\frac{t-t_0}{1\ \mathrm{day}}\right)^{\beta} e^{-\tau}\,, \qquad (3)$$

where

$$\tau = K_2\left(\frac{\nu}{5\ \mathrm{GHz}}\right)^{-2.1}\left(\frac{t-t_0}{1\ \mathrm{day}}\right)^{\delta}\,, \qquad (4)$$

with $S(\mathrm{mJy})$ being the observed flux density at frequency ν with spectral index α at epoch $t - t_0$ days after the supernova explosion on day t_0. The parameter β describes the decline of the flux density with time and parameters K_1 and K_2 formally represent, respectively, the flux density and optical depth at 5 GHz one day after explosion. The optical depth τ is assumed to be purely of a thermal, free-free nature in an ionized medium (frequency dependence $\nu^{-2.1}$) external to the emitting region with radial density dependence $\rho \propto r^{-2}$ from a red supergiant (RSG) wind of constant speed. Because of the success of the Chevalier model (see Weiler et al. 1986; Weiler, Panagia, & Sramek 1990), δ is not solved for but is taken to be

$$\delta \equiv \alpha - \beta - 3\,. \qquad (5)$$

For SN 1979C this model provides a good fit to the gross properties of the radio emission and is the origin of the curves shown in Figures 1*a* with the parameters listed in column (4) of Table 1 (which is repeated from Table 4 in Weiler et al. 1991). However, Weiler et al. (1991) found that even with the best possible fit of equations (3), (4), and (5) to the 20, 6, and 2 cm data, a reduced $\chi^2_{\mathrm{red}} \simeq 5.6$ remained, where χ^2_{red} is calculated for N observed data points by

$$\chi^2_{\mathrm{red}} = \frac{1}{N}\frac{(S_{\mathrm{obs}} - S_{\mathrm{model}})^2}{[\sigma_f^2 + (\epsilon S_{\mathrm{obs}})^2]}\,, \qquad (6)$$

with σ_f^2 defined as (see Weiler et al. 1991)

$$\sigma_f^2 \equiv (0.05 S_{\mathrm{obs}})^2 + \sigma_{\mathrm{obs}}^2\,. \qquad (7)$$

The term σ_{obs} in equation (7) is the observed rms map error measured by Weiler et al. (1991) from the observations of SN 1979C, and $0.05S_{\mathrm{obs}}$ is a basic 5% error introduced into all measurements to account for the normal inaccuracy of Very Large Array (VLA)[3] flux density measurements and any absolute scale error for the primary calibrator 3C 286. The term ϵ in equation (6) is an additional "minimum measurement error" necessary to give a $\chi^2_{\mathrm{red}} \sim 1$ per degree of freedom. Weiler et al. (1991; see § 4.1 of that paper) found that an ϵ of 10.5% had to be introduced into the fitting procedure to give a $\chi^2_{\mathrm{red}} \sim 1$. This need to increase the data errors beyond the measurement level of $\sim$5% in order to obtain $\chi^2_{\mathrm{red}} \sim 1$ implies, not unexpectedly, that the model of equations (3), (4), and (5) is not sufficiently complex to describe the details of short-term fluctuations in the light curves.

With such strong evidence for short-period fluctuations in the radio light curves for SN 1979C from χ^2_{red} and Figures 1*a*, 1*b*, and 2, we can modify equations (3) and (4) to include time-dependent sinusoidal modulations of both emission and absorption. Because the amplitude of the modulation is roughly the same at both 6 and 20 cm (see Fig. 1*b*), and because the fluctuations are not apparent in the spectral index determinations (see Fig. 2 in Weiler et al. 1991), we conclude that they

[3] The VLA is operated by the National Radio Astronomy Observatory of Associated Universities, Inc., under a cooperative agreement with the National Science Foundation.

TABLE 1

FITTING PARAMETERS FOR SN 1979C

Parameter (1)	New Value[a] (2)	Deviation Range[b] (3)	Previous Value[c] (4)	Deviation Range[b] (5)
K_1	1448	1065–1780	1446	1080–1770
α	−0.74	−(0.65–0.79)	−0.74	−(0.66–0.79)
β	−0.78	−(0.76–0.81)	−0.78	−(0.76–0.81)
K_2	3.67×10^7	$(2.37–7.02) \times 10^7$	3.64×10^7	$(2.40–6.83) \times 10^7$
$\delta(\equiv \alpha - \beta - 3)$	−2.96	−(2.84–3.03)	−2.96	−(2.85–3.03)
A	0.078	−0.157–+0.298	...	...
B	$\equiv(1574.8)^{-1}$			
C	0.92π	-0.14π–$+1.86\pi$	...	...
t_0^d	≡1979 Apr 4			

[a] The radio light curves are assumed to fit a curve of the form

$$S(\mathrm{mJy}) = K_1\left\{1 + A\sin\left[2\pi B\left(\frac{t-t_0}{1\ \mathrm{day}}\right) + C\right]\right\}^{1.83}\left(\frac{\nu}{5\ \mathrm{GHz}}\right)^{\alpha}\left(\frac{t-t_0}{1\ \mathrm{day}}\right)^{\beta}e^{-\tau},$$

where

$$\tau = K_2\left\{1 + A\sin\left[2\pi B\left(\frac{t-t_0}{1\ \mathrm{day}}\right) + C\right]\right\}^{2}\left(\frac{\nu}{5\ \mathrm{GHz}}\right)^{-2.1}\left(\frac{t-t_0}{1\ \mathrm{day}}\right)^{\delta},$$

and $\delta \equiv \alpha - \beta - 3$ is assumed (from Chevalier 1984b).

[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 range for a one-parameter solution. For the four-parameter fit (col. [4]) by Weiler et al. (1991), this is the amount that a parameter must deviate from the best-fit value in order to increase χ^2_{red} from ~1 to ~5. For the six-parameter fit (col. [2]) done in this paper, it is the amount necessary to increase χ^2_{red} from ~1 to ~7.

[c] From the Weiler et al. (1991) fit to the data with a formulation equal to that of Footnote "a" above, but with no sinusoidal term (i.e., $A \equiv 0$).

[d] The data of the explosion is taken to be 1979 April 4, following Weiler et al. (1986).

are primarily circumstellar matter density-related emission efficiency modulations rather than optical depth changes. However, since density variations in the circumstellar matter will have some effect on the optical depth as well, we also must include an appropriate modulation of absorption.

The radial density of the circumstellar matter, ρ_{circum}, is proportional to the ratio of the mass-loss rate, $\dot{M}$, to the wind velocity, w, of the presupernova star (i.e., $\rho_{\mathrm{circum}} \propto \dot{M}/w$). For emission, Chevalier (1982) in his equation (26) relates the radio luminosity of a SN, L, with the radial density as

$$L \propto (\dot{M}/w)^{(\gamma - 7 + 12m)/4}, \tag{8}$$

where m characterizes the power-law increase of the SN radius, R, with time t (i.e., $R \propto t^m$) and γ is the exponent of the power-law relativistic electron energy spectrum. The value of m is also related to the density distribution index, n, within the SN ejecta (i.e., $\rho_{\mathrm{ejecta}} \propto r^{-n}$) and to δ of equation (5) by

$$m = -\delta/3 = (n-3)/(n-2). \tag{9}$$

The value of γ is related to the radio spectral index α by

$$\alpha = (1-\gamma)/2. \tag{10}$$

For the values of α and β, and, therefore, of δ and m, found by Weiler et al. (1991) and given in column (4) of Table 1, we find that equation (8) becomes

$$L \propto (\dot{M}/w)^{1.83}. \tag{11}$$

Any radial density modulation of the circumstellar matter will also affect the optical depth τ by

$$\tau \propto (\dot{M}/w)^2 \tag{12}$$

(see eq. [9] of Weiler et al. 1986).

Therefore, a periodic modulation of the radial density, $\dot{M}/w$, of the circumstellar matter around the presupernova star can be introduced into equations (3) and (4) as

$$S(\mathrm{mJy}) = K_1\left\{1 + A\sin\left[2\pi B\left(\frac{t-t_0}{1\ \mathrm{day}}\right) + C\right]\right\}^{1.83} \times \left(\frac{\nu}{5\ \mathrm{GHz}}\right)^{\alpha}\left(\frac{t-t_0}{1\ \mathrm{day}}\right)^{\beta}e^{-\tau}, \tag{13}$$

where

$$\tau = K_2\left\{1 + A\sin\left[2\pi B\left(\frac{t-t_0}{1\ \mathrm{day}}\right) + C\right]\right\}^{2} \left(\frac{\nu}{5\ \mathrm{GHz}}\right)^{-2.1}\left(\frac{t-t_0}{1\ \mathrm{day}}\right)^{\delta}, \tag{14}$$

with

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

representing the modulation of $\dot{M}/w$ around a steady presupernova mass-loss rate. The new parameters A, B, and C define the sinusoidal modulation of $\dot{M}/w$, where A represents the amplitude of the modulation, B represents its frequency (in cycles day^{-1}), and C represents its phase lag. From the power spectrum analysis described in § 2, we take

$$B \equiv 1/T \equiv 1/1574.8\ \mathrm{day}^{-1}. \tag{15}$$

Applying equations (5), (13), (14), and (15) to the available data sets for SN 1979C at 20 and 6 cm (the 2 cm data was excluded from the fitting procedure because of its sparseness and poor quality), and using a fitting procedure similar to that of Weiler et al. (1991), a minimum χ^2_{red} was found by varying the six free parameters α, β, K_1, K_2, A, and C. The explosion data t_0 was fixed as 1979 April 4 (see Weiler et al. 1986).

The best-fit values for α, β, K_1, K_2, A, and C are listed in column (2) of Table 1 along with the values (col. [4]) for these parameters found by Weiler et al. (1991) without inclusion of the sinusoidal term (i.e., $A \equiv 0$). This new fit to the data for SN 1979C yields a best-fit curve with a minimum $\chi^2_{\rm red} \sim 3.3$ per degree of freedom when no additional "minimum measurement error," ϵ, is included. This is a substantial improvement over the minimum $\chi^2_{\rm red} \sim 5.6$ found by Weiler et al. (1991) under similar constraints for the model without a sinusoidal term (eqs. [3] and [4]). An additional "minimum measurement error" of $\epsilon \sim 8.5\%$ brings $\chi^2_{\rm red}$ down to ~ 1 for the fit to equations (13) and (14), while an $\epsilon \sim 10.5\%$ was required to bring $\chi^2_{\rm red}$ to ~ 1 for the fit to equations (3) and (4) without the sinusoidal term. Thus, the addition of a periodic modulation to the radial density of the presupernova wind significantly improves our description of the radio emission from SN 1979C. It is interesting to note that this modulation is superposed onto a much more steady stellar mass loss described by the simpler model of Weiler et al. (1991), since examination of Table 1 shows that the four fitting parameters α, β, K_1, and K_2 are identical to those from the fit obtained by Weiler et al. (1991) to equations (3), (4), and (5).

The model curves calculated from equations (5), (13), and (14) for the parameter values of column (2) in Table 1 are shown as the solid lines in Figure 3, together with the 20 and 6 cm data sets from Weiler et al. (1986, 1991). Clearly the new model light curves shown in Figure 3, which include a sinusoidal modulation of the presupernova wind radial density, provide not only a lower value of $\chi^2_{\rm red}$, but also a substantially better "visual" fit than the model light curves from Weiler et al. (1991) shown in Figure 1*a*. The higher-frequency fluctuations of the data points at both wavelengths following day ~ 1260 (log day ~ 3.10) are quite well-described by the model light curves. The rise in the most recent data points at both wavelengths beginning at day ~ 3760 (log day ~ 3.58) implies that this periodic variation is still in progress and should become even better defined as monitoring of SN 1979C continues.

Closer examination of Figure 3 shows that the new model light curves still do not well describe the initial peak in the observed 6 cm light curve at day ~ 437 (log day ~ 2.64) and the following dip at day ~ 700 (log day ~ 2.90) with its coincident "knee" in the rapidly rising 20 cm flux density. Weiler et al. (1986) also noted this early fluctuation and concluded that it may be an optical depth change unrelated to the sinusoidal variation of equations (13) and (14). This is likely, since the optical depth is still quite high at 20 cm at that time and the spectral index variation (see Fig. 2 in Weiler et al. 1991) appears to show a "knee" at the same time.

4. POSSIBLE MODEL INTERPRETATIONS OF THE SHORT-PERIOD RADIO VARIATIONS

As discussed above, it appears that the observed deviations of the radio data for SN 1979C at 20 and 6 cm from a simple radio supernova model are real and are periodic in nature.

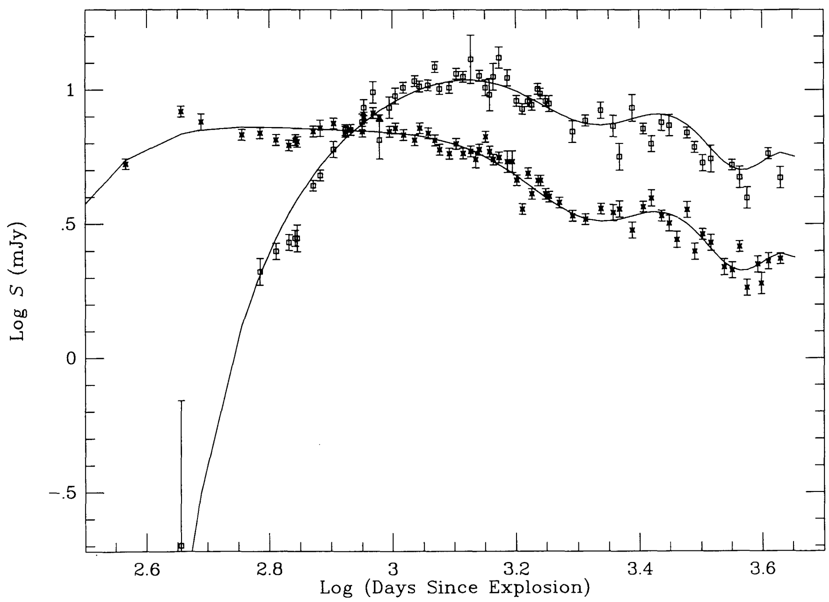

FIG. 3.—Radio "light curves" for SN 1979C at 20 cm (*open squares*) and 6 cm (*four-sided stars*), with the data at both wavelength bands from Weiler et al. (1986, 1991). Age of the supernova ($t - t_0$) is measured in days from the estimated date of explosion on 1979 April 4 (15 days before optical maximum). The solid lines represent the best-fit curves of the form

$$S({\rm mJy}) = K_1\left\{1 + A \sin\left[2\pi B\left(\frac{t - t_0}{1\ {\rm day}}\right) + C\right]^{1.83}\left(\frac{\nu}{5\ {\rm GHz}}\right)^{\alpha}\left(\frac{t - t_0}{1\ {\rm day}}\right)^{\beta} e^{-\tau}\right.,$$

where

$$\tau = K_2\left\{1 + A \sin\left[2\pi B\left(\frac{t - t_0}{1\ {\rm day}}\right) + C\right]\right\}^2\left(\frac{\nu}{5\ {\rm GHz}}\right)^{-2.1}\left(\frac{t - t_0}{1\ {\rm day}}\right)^{\delta}$$

and $\delta \equiv \alpha - \beta - 3$. The parameter B is taken from the power spectrum analysis (see § 2) to be 1/1574.8 day^{-1}. The values of the parameters α, β, K_1, K_2, A, and C are derived from the fit and are given in col. (2) of Table 1.

Also, it appears that these periodic fluctuations are not primarily due to optical depth changes in a mixed or even intervening medium but are due to variations of the radio emission efficiency caused by a radial density structure in the circumstellar matter, which we assume was established by mass loss from the RSG progenitor star. If we assume a RSG stellar wind velocity of $w \sim 10$ km s^{-1} and a supernova shock (which excites this stellar wind to emit centimeter radio radiation) velocity of $v_s \simeq 9.2 \times 10^3$ km s^{-1} (Weiler et al. 1986), then the observed radio flux density modulation with a period of 1575 days (4.3 yr) suggests a radial density modulation in the wind with a period of $P \sim 4000$ yr, which continued for at least 2.5 cycles, or $\sim 10^4$ yr. What mechanisms are available to produce such regular density fluctuations in the presupernova stellar wind on such time scales?

Since the exciting shock wave is presumably almost spherical and traveling at nearly constant speed, the regularity and the relatively small amplitude ($\sim 15\%$) of the radio flux density variations implies that the circumstellar matter density variations must be evenly spaced, somewhat concentric about the SN, and produced as a minor ($\sim 8\%$) density modulation on a larger, relatively constant, presupernova stellar mass-loss rate. Two possible mechanisms which could account for such regularity are a pulsational instability of the RSG progenitor star or a dynamical modulation of the RSG wind by a binary companion in a highly eccentric orbit. The long time scale and small amplitude of the mass-loss modulation make it unlikely that intrinsic stellar interior oscillations could be the cause.

4.1. *Pulsational Instability in the Red Supergiant Envelope*

An obvious way of producing a density modulation in the circumstellar matter established by the presupernova RSG wind is to require that the RSG progenitor star pulsate on a time scale of ~ 4000 yr. The problem is that a RSG with a mass of ~ 10–$30\ M_\odot$ and radius of ~ 1000–$3000\ R_\odot$ has a much, much shorter dynamical time scale of only a few years. Thus, a fundamental mode pulsation of the supergiant cannot produce the required time scale. However, given our lack of knowledge about how a RSG wind is actually powered (cf. Pijpers 1990), some periodic instability may be present in the wind itself. The time scale for such a process might be on the order of the ratio of the radius at which the wind exceeds the escape velocity from the star to the wind velocity itself, which, for a 20 $M_\odot$ star and a wind velocity of 10 km s^{-1}, is only ~ 200 yr. Unfortunately, this is much too short. Thus, at the limit of current knowledge about RSG stars, it seems difficult, if not impossible, to achieve the required wind density modulation by stellar pulsations.

4.2. *Thermal Pulses and C/He Flashes*

Thermal pulses and carbon or helium flashes occur in asymptotic giant branch stars between 5 and 10 $M_\odot$ and have characteristic periods of hundreds to thousands of years (see, e.g., Iben 1974; Iben & Renzini 1983). The expected modulation of luminosity by such pulses is up to $\Delta \log L \simeq 0.1$–0.2, which implies a modulation of the mass-loss rate of up to a factor of 2 (see, e.g., Chiosi & Maeder 1986). Therefore, such phenomenon look promising to account for the observed modulation in the SN 1979C pre-supernova wind.

However, more quantitative considerations lead us to have reservations about such a possibility for the case of SN 1979C. In a previous paper (Weiler et al. 1991), from a lower limit to the mass lost by the progenitor in the RSG phase, we argued that the progenitor of SN 1979C must have been more massive than 13 $M_\odot$. A similar argument can be made by comparing the RSG mass-loss rate of SN 1979C with that of SN 1980K: they both were Type II-L SNs, but the mass-loss rate of SN 1979C was a factor of ~ 20 higher than that of SN 1980K (Weiler et al. 1986). From the stellar evolution models of Maeder (1990), this implies that the mass of the SN 1979C progenitor was at least twice that of the SN 1980K progenitor. Adopting 8 $M_\odot$ as a lower limit to the mass of *any* Type II supernova, this implies that the zero-age main sequence (ZAMS) mass of the SN 1979C progenitor is likely to have been $\gtrsim 16\ M_\odot$. A relatively high-mass SN progenitor is also favored based on *IUE* observations showing a very large nitrogen enhancement relative to carbon in the outer layers of the SN ejecta (presumably the presupernova atmosphere), implying that the presupernova star was a supergiant which had undergone a long period of mass loss (Fransson et al. 1984). With a mass of $\gtrsim 16\ M_\odot$ for the progenitor of SN 1979C, one would expect thermal pulses to occur at intervals of only a few hundred years, if they occur at all, and, therefore are too rapid to account for the observed ~ 4000 yr modulation period.

It is interesting to note that the effects of thermal pulses in the RSG phase should be more important for the case of less powerful RSNs such as SN 1980K and SN 1981K, whose progenitors are expected to be closer to the lower limit of 8 $M_\odot$. We have analyzed the radio light curve of SN 1980K to search for such variations (Weiler et al. 1992) but, unfortunately, the relative weakness of the radio emission from this RSN makes it impossible to detect any periodic variation.

4.3. *Dynamical Modulation of the Mass Loss from a High-Eccentricity Binary System*

Podsiadlowski, Joss, & Hsu (1992) find that the evolution of a large fraction of all massive stars is affected by interactions with close binary companions. For example, the VV Cephei stars are spectroscopic binaries typically containing an early M supergiant and a hot companion B star (Cowley 1969). Although most observed examples have typical separations of a few times 10^{14} cm and measured orbital periods of 10–50 yr, the system α Sco AB appears to have a period of greater than 800 yr (Buss & Snow 1988).

4.3.1. *A Simple Model*

As an illustration, let us consider a binary system with a period of $P = 4000$ yr, consisting of a B1 main-sequence star with mass $M_B \sim 10\ M_\odot$ and a RSG of mass $M_R \sim 15\ M_\odot$. Such a system has an orbital semi-major axis $a = 1.1 \times 10^{16}$ cm (~ 700 AU) and for a *circular* orbit, an orbital velocity for the RSG of $v_{\rm circ} \sim 2.2$ km s^{-1}, which is comparable to the RSG wind velocity of $w \sim 10$ km s^{-1}. If we make the simplifying assumption that the wind spherically emanates from the RSG in its own rest frame independent of position in the binary orbit, then purely dynamical effects from having $v_{\rm circ} \sim w$ ensure that the wind from the RSG has significant density variations in the form of an equiangular spiral centered on the center-of-gravity of the system. Unfortunately, a spherically symmetric supernova shock, with velocity $v_{\rm shock} \simeq 10^4$ km s^{-1}, progressing outward through such a uniform spiral density configuration produces no observable emission modulations until light-travel time effects became important. This occurs only when the shock radius, $R_{\rm shock}$, becomes comparable to $cP/2\pi \sim 6.5 \times 10^{17}$ cm, or only ~ 20 yr after the supernova event, which is much later than our observed intensity variations.

However, such a widely separated massive binary is unlikely to be in a circular orbit, since most long-period binaries are observed to have eccentric orbits, with median eccentricity $e \sim 0.5$ (Duquennoy & Mayor 1991). In an *eccentric* orbit, the maximum orbital velocity is reached at periastron and is given by

$$v_{\rm max} = v_{\rm circ}\left[\frac{(1+e)}{(1-e)}\right]^{0.5} , \quad (16)$$

while the minimum orbital velocity is reached at apastron and is given by

$$v_{\rm min} = v_{\rm circ}\left[\frac{(1-e)}{(1+e)}\right]^{0.5} . \quad (17)$$

For our proposed stellar system and $e = 0.5$, this gives for the RSG star, $v_{\rm max} \sim 4$ km s^{-1} and $v_{\rm min} \sim 1.3$ km s^{-1}. Again, considering only purely dynamical effects, the RSG wind density will be modulated, but now in a strongly asymmetric fashion, with the strongest density enhancements being roughly in the direction of travel of the RSG star at periastron (see Fig. 4). At least qualitatively, such an asymmetric density structure could give rise to a modulation of the radio emission from a supernova, such as that observed for SN 1979C, even when excited in a spherical shock wave.

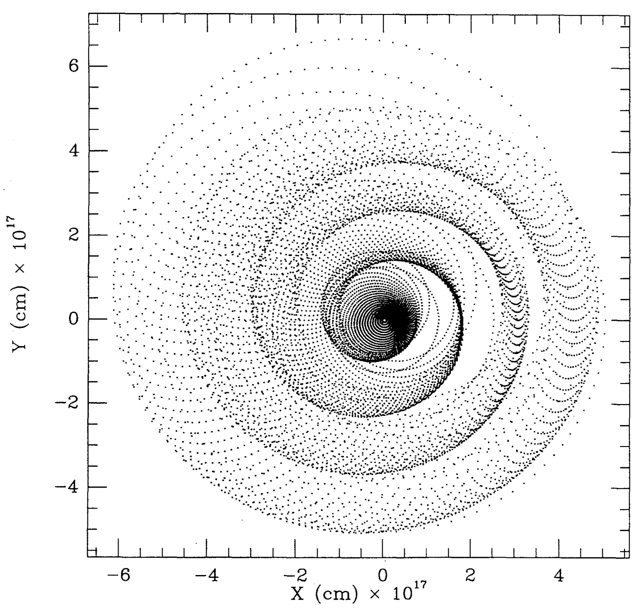

FIG. 4.—Illustration of possible asymmetric density enhancements in a presupernova stellar wind. At the center of the figure is an invisible binary system consisting of stars with ZAMS masses of 10 and 15 $M_\odot$ with an orbital period $P = 4000$ years and an eccentricity $e = 0.5$ (see § 4.3.1). The 15 $M_\odot$ star sends off a shell of particles every ~ 160 yr, and these particles travel out from the star with a constant velocity of 10 km s^{-1} relative to the star at the time of release. The effect here is purely dynamical; no attempt has been made to include hydrodynamical effects by stopping the shells from passing through each other. The figure shows a cut through the wind in the plane of the binary. A supernova shock, such as that for SN 1979C, would currently be at $\sim 3 \times 10^{17}$ cm for a shock velocity of $\sim 10^4$ km s^{-1} and a time since supernova explosion of ~ 10 yr.

4.3.2. *Limitations of the Simple Model*

In the above analysis, we have assumed for simplicity that the interaction of the wind from the RSG with the companion B star can be neglected. After all, the radius of a RSG such as that found in VV Cep is ~ 2000–3000 $R_\odot$ (Cowley 1969; Pijpers 1990), which is about an order of magnitude less than the periastron separation for the parameters we consider. However, the RSG stellar wind is affected by the B star out to a radius from the B star of

$$R_{\rm grav} = GM_{\rm B}/w^2 = 2 \times 10^{15}\ {\rm cm} , \quad (18)$$

which is about half of the periastron separation, so that the gravitational effect of the B star on the wind should strictly be taken into account at some level. Some of the wind is likely to be accreted by the B star, especially near periastron (cf. Podsiadlowski et al. 1992), and the rest will probably be gravitationally focused to some extent toward the orbital plane of the binary (cf. Morris 1981), again preferentially at periastron. The net effect of this interaction would be to increase the density structure modulation in the wind.

Another consideration is that the wind from the hot main-sequence B1 star will have some impact on the wind from the RSG presupernova star. Weiler et al. (1991) estimate the dense wind of the precursor to SN 1979C to have had a mass-loss rate of $\sim 6 \times 10^{-5}$ $M_\odot$ yr^{-1} for a wind velocity $w = 10$ km s^{-1}. The momentum from the wind of a 10 $M_\odot$ B1 ZAMS star (e.g., Maeder 1990) would have little effect on this, but a more massive companion, such as a 30 $M_\odot$ O6.5 ZAMS star like that present in VV Cep itself, could have a mass-loss rate of $\sim 10^{-7}$–10^{-6} $M_\odot$ yr^{-1} at a wind velocity $w \sim 3 \times 10^3$ km s^{-1} (Conti & Underhill 1988), which would severely impact the RSG wind. It is possible that such considerations can be used, together with more detailed modeling, to further constrain the precursor binary system for SN 1979C.

A further complication is that the RSG wind velocity of $w = 10$ km s^{-1} is equal to the escape velocity only at a radius of $\sim 3 \times 10^{15}$ cm, which is comparable to the periastron separation. Thus, the binary companion may also have some effects on the acceleration process within the wind (cf. Eggleton & Tout 1989; Tout & Hall 1991).

Finally, a more sophisticated model for a SN 1979C binary precursor system will need to involve three-dimensional numerical hydrodynamics. In particular, the fact that internal shocks occur within the wind at an interaction distance, $R_{\rm int}$, from the system given approximately by

$$R_{\rm int} = 0.5P\,\frac{(w - v_{\rm min})(w + v_{\rm max})}{(v_{\rm max} + v_{\rm min})} = 1.5 \times 10^{17}\ {\rm cm} , \quad (19)$$

which is about half the present radius of the supernova shock, must be included. These internal shocks are caused by the faster wind elements emitted at periastron catching up with the slower wind elements emitted at the previous apastron. The net effect of such internal interactions in the wind would tend to smooth out the density variations.

5. CONCLUSIONS

We find that short-period fluctuations in the radio light curves of SN 1979C first suggested in Weiler et al. (1991) are indeed significant and are most likely due to variations in emission efficiency caused by systematic density fluctuations of $\sim 8\%$ in the presupernova stellar wind. A detailed analysis reveals that these fluctuations have a period of ~ 1575 days, have now been observed for more than two full periods, and appear to be continuing. With reasonable estimates for the presupernova stellar wind velocity and the supernova shock velocity, this 1575 day radio emission variation implies a periodic stellar wind density modulation with a period of $\sim$4000 yr. This provides the first direct evidence for periodic density modulation in a stellar wind, in this case for a presumed RSG presupernova star. Although model interpretation requires more careful analysis, it appears that a possible origin for such a density variation is wind modulation by a binary companion to the SN progenitor, although other pulsational instabilities cannot be entirely excluded. If the binary hypothesis can be confirmed, it modifies the generally accepted concept of Type II SNs originating as the endpoint of the evolution of isolated, massive stars.

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