Synchrotron Self-Absorption in SN 1993J

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The standard interaction model for radio supernovae considers the synchrotron radio emission to be optically thin and partially absorbed due to ionized thermal electrons in the circumstellar wind of the progenitor star. We have written a numerical radiative transfer code to study the synchrotron radio emission from supernovae, that takes into account both synchrotron and expansion losses. Here, we present the results obtained on SN 1993J, which take into account all observational data. We show that synchrotron self-absorption plays a role at all wavelengths, becoming the dominant absorption mechanism at current epochs at wavelengths longer than about 90cm.

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1. INTRODUCTION

Radio emission from supernovae has been previously interpreted in terms of an optically-thin shell, whose emission is partially suppressed by external free-free absorption (Chevalier 1982a; Weiler *et al.* 1989; Weiler, Panagia & Sramek 1990) In this model—known as the standard interaction model (Chevalier 1982a), hereafter SIM—a strong interaction between the density profiles of the supernova ejecta ($\rho_{\rm ej} \propto r^{-n}$) and of the circumstellar material ($\rho_{\rm cs} \propto r^{-s}$) is expected. In the SIM, this interaction causes the formation of a self-similarly expanding ($R_{\rm sh} \propto t^m; m = (n-3)/(n-s)$) shell-like structure (Chevalier 1982b), from which the observed synchrotron radio emission arises. In addition, it is assumed (Chevalier 1982a) that (i) both magnetic energy density, $\epsilon_{\rm B}$, and relativistic energy density, $\epsilon_{\rm rel}$, evolve with time as the post-shock thermal energy density ($\propto \rho_{\rm sh} v_{\rm sh}^2$); (ii) the synchrotron emission is optically thin; and (iii) the external absorbing medium has a power-law dependence $s = 2$. These assumptions have been shown to be good enough to reproduce the light curves of many supernovae. However, none of these supernovae were observed early enough to monitor the rising part of their light curves.

The discovery of SN 1993J (García 1993) on March 28, 1993 in the galaxy M81, brought an unprecedented opportunity to test the SIM for supernovae. The early discovery of hydrogen lines in its spectra (Fillipenko & Matheson 1993) classified this supernova as Type II. Marcaide *et al.* (1995a) showed the radio emission to arise from a shell-like structure, that expands self-similarly (Marcaide *et al.* 1995b), thus giving strong support to the SIM. It has been shown (Marcaide *et al.* 1997) that the expansion is decelerating with expansion index $m = 0.86 \pm 0.02$ and that there is strong evidence that the circumstellar medium density is of the form $\rho_{\rm cs} \propto r^{-s}$, with $s = 1.66$, in good agreement with previous modeling of both radio and X-ray observations (Fransson, Lundqvist & Chevalier 1996, hereafter FLC96), which require $1.5 \leq s \leq 1.7$. More recently, it has been claimed (Bartel *et al.* 2000) that the expansion of SN 1993J is not well described by a single self-similar expansion with a constant deceleration parameter, m, but rather by two different values of m. Our own VLBI monitoring, however, does not show evidence for two different slopes in the expansion of SN 1993J. Therefore, we present here calculations corresponding to a single, constant value for m. Attempts to fit

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the radio light curves of SN 1993J using the SIM have been unsuccessful so far, and have led several authors (Lundqvist 1994; Van Dyk *et al.* 1994; FLC96; Marcaide *et al.* 1997) to consider alternative power-laws for the circumstellar medium around SN 1993J, or to include synchrotron self-absorption as an additional absorbing mechanism (Fransson & Björnsson 1998)

2. SN 1993J RADIO LIGHT CURVES

We have written (Pérez-Torres 1999) a numerical code that computes the synchrotron radio emission from an expanding Type II supernova. We solve the synchrotron radiative transfer equation throughout the shell (including both synchrotron emission *and* self-absorption), and take into account both synchrotron losses and expansion losses. We assume a (modified) standard SIM scenario, in which the supernova synchrotron radio emission comes from the interaction shell that forms shortly after shock breakout. The SIM scenario is modified in the sense that we do not assume the synchrotron emission to be optically thin. As usual, we assume that the emission from inside the shell is due to the existence of relativistic electrons, $N(E,r)$, orbiting in a random magnetic field, $B(r)$. We also assume an initially injected relativistic electron distribution with a power-law energy dependence, $N(E,r) = N_0(r)\, E^{-p}$.

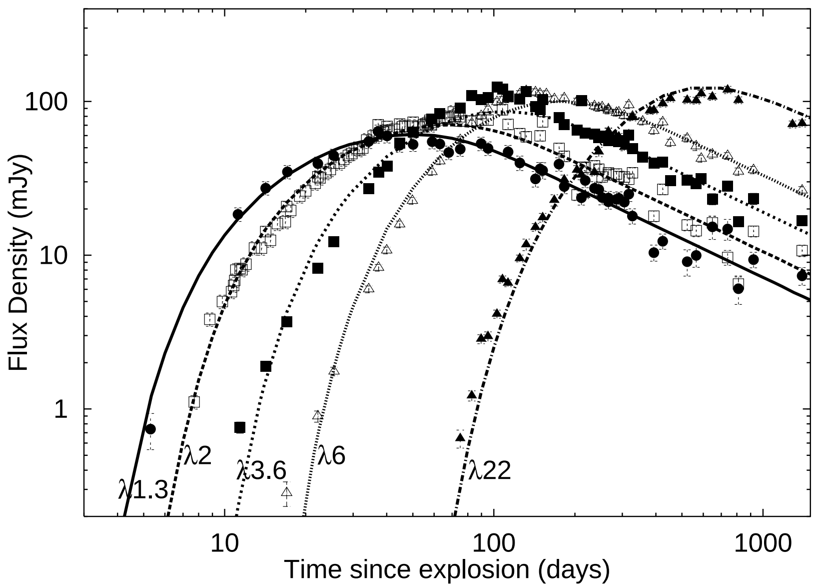

FIGURE 1. Radio light curves for SN 1993J at λ1.3 cm (filled circles), λ2 cm (open squares), λ3.6 cm (filled squares), λ6 cm (open triangles), and λ21 cm (filled triangles), from measurements made using the VLA and, at 2 cm, also the the Ryle Telescope. The lines represent our best fit model as described in the text.

We use our code to simulate the radio light curves from SN 1993J, with the aim of gaining insight into the physical conditions of this supernova. As in the SIM, we assume that both B and N_0 evolve with time as the post-shock thermal energy density, $\rho_{\rm sh} v_{\rm sh}^2$. With $m = 0.86$ and $s = 1.66$ from our VLBI observations, we then have the following evolution laws for magnetic field and relativistic particles, respectively: $B \propto r^{1-s/2-1/m} = r^{-0.99}$, $N_0 \propto r^{2(1-s/2-1/m)} = r^{-1.99}$, that is, $B \propto r^{-1}$, and $N_0 \propto r^{-2}$.

3. RESULTS AND DISCUSSION

We fit all the available radio data using five free parameters: (1) the spectral index of the injected electron distribution, p; (2) the wind parameter, M_W; (3) the initial magnetic field, $B(r_0)$; (4) the initial value of the injected function of relativistic electrons, $N_0(r_0)$; and (5) the low-energy cut-off for the relativistic electrons, $E_{\rm min}$. We use throughout our computations $r_0 = 6.35 \times 10^{14}$ cm, corresponding to an outer shell radius at our first epoch ($t_0 = 2.34$ days). Figure 1 shows the multi-wavelength radio data for SN 1993J along with our best fit model curves.

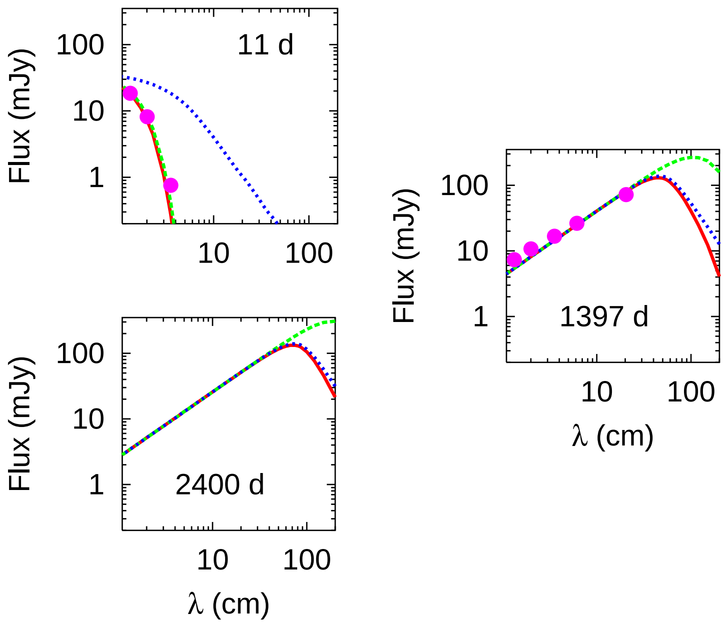

FIGURE 2. Fits to spectra at 11 and 237 days after explosion, and predicted spectrum at 2400 days, considering external free-free absorption (dashed lines), synchrotron self-absorption (dotted lines), and both external free-free absorption and synchrotron self-absorption (solid lines). The filled circles represent the available observational data for each epoch. At early epochs, the radio spectrum of SN 1993J (upper plot) is well explained by the solely effect of free-free absorption from the external medium. At late epochs (middle plot), however, free-free absorption and synchrotron self-absorption predict a similar spectral behavior for the observed wavelength range, but a different one at wavelengths around and above λ40 cm, at which observations are not available. The lower plot shows the predicted spectrum at current epochs. This prediction can be tested to discriminate between the free-free and self-absorption mechanisms described in the text.

Our results show that the radio emission from SN 1993J requires the existence, at very early epochs, of a highly-relativistic ($E_{\rm min} \approx 100\, m_e\, c$) population of electrons in the presence of a large magnetic field ($\approx$ 30 G). The existence of such a high-energy population of relativistic electrons is needed—at very early epochs—to account for the flattening of the radio light curves at the shortest wavelengths, and has been previously invoked in other astrophysical scenarios (e.g., radio emission from hot spots in lobes of radio galaxies (Carilli *et al.* 1991)). The unexpectedly large (initially) magnetic field of about 30 G argues strongly for turbulent amplification in the shell (Gull 1973; Chevalier 1982a; Chevalier & Blondin 1995), and rules out any hypothesis based on a magnetic field which arises from the compression of the circumstellar wind field. Furthermore, the assumption that the magnetic energy density evolves as the post-shock thermal energy results in a dependence of the magnetic field with radius of r^{-1}. Our best-fit value of $M_W = 1.7$ implies a mass-loss rate of $\dot{M} = 8.5\, M_{\odot}^{-5}\,\mathrm{yr}^{-1}$ for $v_w = 10\,\mathrm{km\,s}^{-1}$, and is in agreement within a factor of two with previous estimates (FLC96), thus confirming that the progenitor of SN 1993J intensively lost material in the form of a strong, slow wind, typical of red supergiant progenitors.

Our simulated spectra for SN 1993J up to a supernova age about 1400 days agree well with the observed spectra (Fig. 2). The supernova spectrum changes from a mainly inverted spectrum at early epochs to a more typical optically thin ($\alpha = -1, S_\nu \propto \nu^\alpha$) spectrum at late epochs and for an increasingly wide wavelength range. As shown in Fig. 2, external free-free absorption is dominant at early times ($t \leq 100$ days), but synchrotron self-absorption becomes increasingly important with time for longer wavelengths. Thus, the standard interaction model is incomplete, at least for SN 1993J, in that it ignores synchrotron self-absorption, which according to our model is the most relevant absorption mechanism—as the supernova ages—for the longer wavelengths. At the present epoch, the expected flux at this wavelength is $\sim$100 mJy for the synchrotron self-absorption dominated model, and $\sim$200 mJy for the free-free absorption dominated model. This prediction can be checked using $\lambda \sim$90 cm observations of SN 1993J with a sensitive radio telescope.

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REFERENCES

Bartel N., Bietenholz M.F., Rupen M.R., *et al.* 2000 *Science* **287**, 112.

Carilli, C.L., Perley, R.A., Dreher, *et al.* 1991, ApJ, **383**, 554

Chevalier, R.A. 1982a, ApJ, **259**, 302

Chevalier, R.A. 1982b, ApJ, **258**, 790

Chevalier, R.A. & Blondin, J.M. 1995, ApJ, **442**, 312

Fransson, C. & Björnsson, C.-I. 1998, ApJ, **509**, 861 (FB98)

Fransson C., Lundqvist P., & Chevalier R.A. 1996, ApJ, **461**, 993 (FLC96)

Freedman W.L., Hughes S.M., Madore B.F., *et al.* 1994, ApJ, **427**, 628

García, F. 1993, IAUC, 5731

Gull, S.F. 1973, MNRAS, **162**, 135

Lundqvist P. 1994, in *Circumstellar Media in the Late Stages of Stellar Evolution*, (Cambridge: Cambridge University Press), 213

Marcaide J.M., Alberdi A., Ros E., *et al.* 1995a, Nature, **373**, 44

Marcaide J.M., Alberdi A., Ros E., *et al.* 1995b, Science, **270**, 1475

Marcaide J.M., Alberdi A., Ros E., *et al.* 1997, ApJ, **486**, L31

Pérez-Torres, M.A. 1999, Ph.D. Thesis, University of Valencia, Spain

Van Dyk, S.D., Weiler, K.W., Sramek, R.A., *et al.* 1994, ApJ, **432**, L115

Weiler, K.W., Panagia, N., Sramek, R.A., *et al.* 1989, ApJ, **336**, 421

Weiler, K.W., Panagia, N. & Sramek. R.A. 1990, ApJ, **364**, 611