Galaxies and Their Constituents at the Highest Angular Resolutions
IAU Symposium, Vol. 205, 2001
R.T. Schilizzi, S. Vogel, F. Paresce and M. Elvis

Late Radio Emission from SN 1993J: Evidence for Synchrotron Self-Absorption

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Abstract. The standard model for radio supernovae considers the synchrotron radio emission to be only partially absorbed by ionized thermal electrons in the circumstellar wind of the progenitor star. However, for the best studied radio supernova, SN 1993J, we present evidence of synchrotron self-absorption based on modelfits to all available radio data. We show that while external absorption is the main absorption mechanism at early times, synchrotron self-absorption is the dominant mechanism at late epochs.

1. Introduction

The standard interaction model for radio supernovae, hereafter SIM, considers a strong interaction between the density profiles of the (Type II) supernova ejecta ($\rho_{\rm ej} \propto r^{-n}$) and of the circumstellar material ($\rho_{\rm cs} \propto r^{-s}$). This interaction causes the formation of a self-similarly expanding ($R_{\rm sh} \propto t^m; m = (n-3)/(n-s)$) shell-like structure, from which the observed synchrotron radio emission arises. In addition, it is assumed 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 $s = 2$. Although these assumptions have been shown to be good enough to reproduce the light curves of many supernovae, none of them were observed early enough to monitor the rising part of their light curves. The discovery of SN 1993J soon after its explosion in the galaxy M81, brought an unprecedented opportunity to test the SIM for supernovae. However, attempts to fit the radio light curves of SN 1993J using the SIM have been unsuccessful so far, and have led several authors to consider alternative power-law profiles for the circumstellar medium around SN 1993J, or to include synchrotron self-absorption as an additional absorbing mechanism.

2. Modeling the radio emission from SN 19993J

We have written 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

https://doi.org/10.1017/S0074180900221530 Published online by Cambridge University Press

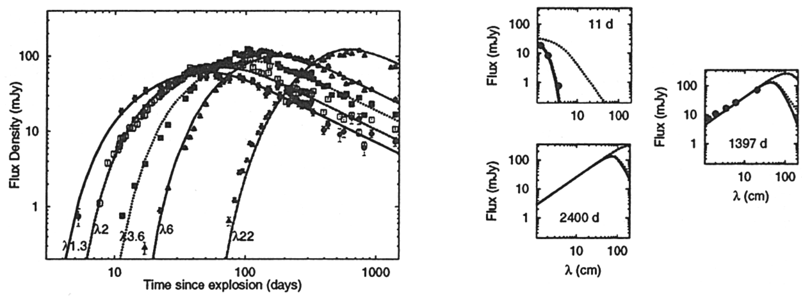

Figure 1. **Left:** fits to the radio light curves of SN1993J at different wavelengths, along with the observed data. **Right:** fits to spectra at 11 and 1397 days after explosion, and predicted spectrum at 2400 days, considering external free-free absorption (dashed lines), synchrotron self-absorption (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 and lower plots), however, free-free absorption and synchrotron self-absorption predict a similar spectral behavior for the observed wavelength range, but a different one at longer wavelengths.

losses. We assume a standard SIM scenario, where the emission from 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 initial relativistic electron distribution with a power-law energy dependence, $N(E,r) = N_0(r)\,E^{-p}$. We model the available radio data using the following parameters: (1) the spectral index of the injected electron distribution, p; (2) the initial magnetic field, $B(r_0)$; (3) the initial value of the injected function of relativistic electrons, $N_0(r_0)$; and (4) a low-energy cut-off for the relativistic electrons, $\gamma_{\rm min}(r_0)$. We fit the above parameters at the reference radius $r_0 = 6.35 \times 10^{14}$ cm ($\equiv t_0 = 2.34$ days), and find that the multi-wavelength radio data for SN 1993J (Figure 1) are best reproduced by a model with $p = 3$, $B(r_0) = 27$ G, $N_0(r_0) = 6.7 \times 10^{-7} {\rm erg}^{\rm p-1}\,{\rm cm}^{-3}$, and $\gamma_{\rm min}(r_0) \approx 90$. Fig. 1 (left) shows our best-fit to the radio data of SN 1993J. Note the (unexpectedly) large magnetic field inferred from the modeling, and the existence of a low-energy cutoff in the electron distribution, to account for the early radio emission.

Our simulated spectra for SN 1993J up to a supernova age about 1400 days agree well with the observed spectra (Fig. 1 right). 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. Though external free-free absorption is dominant at early times ($t \leq 100$ days), synchrotron self-absorption becomes increasingly important with time for longer wavelengths. Therefore, the standard interaction model is incomplete, at least for SN 1993J, in that it ignores synchrotron self-absorption, which according to our modeling is the most relevant absorption mechanism—as the supernova ages—for the longer wavelengths. At current epochs, the expected flux at $\lambda \approx 90$cm is $\sim$120 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 interferometer. If SN 1993J is not a bizarre radio supernova, our results indicate that synchrotron self-absorption is likely to play an important role in most supernovae, especially as they age.

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