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SYNCHROTRON AGING AND THE RADIO SPECTRUM OF SN 1993J

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ABSTRACT

We combine the Giant Metrewave Radio Telescope low-frequency radio observations of SN 1993J with the Very Large Array high-frequency radio data to get a near-simultaneous spectrum around day 3200 since explosion. The low-frequency measurements of the supernova determine the turnover frequency and flux scale of the composite spectrum and help reveal a steepening in the spectral index, $\Delta\alpha \sim 0.6$, in the optically thin part of the spectrum. This is the first observational evidence of a break in the radio spectrum of a young supernova. We associate this break with the phenomenon of synchrotron aging of radiating electrons. From the break in the spectrum we calculate the magnetic field in the shocked region independent of the equipartition assumption between energy density of relativistic particles and magnetic energy density. We determine the ratio of these two energy densities and find that this ratio is in the range 8.5×10^{-6} to 5×10^{-4}. We also predict the nature of the evolution of the synchrotron break frequency with time, with competing effects due to diffusive Fermi acceleration and adiabatic expansion of the radiative electron plasma.

Subject headings: magnetic fields — radiation mechanisms: nonthermal — radio continuum: stars — supernovae: individual (SN 1993J)

1. INTRODUCTION

With the radio spectrum of a young supernova, we probe the conditions in the magnetized plasma where this radiation originates from relativistic electrons. These electrons are believed to be accelerated in the interface region of the supernova blast wave shock and the circumstellar medium. The radio emission from the nearby supernova SN 1993J is clearly of a nonthermal nature and is argued to be due to synchrotron radiation in a magnetic field amplified in the interaction region and affected by synchrotron self-absorption (SSA) and external free-free absorption (see, e.g., Fransson & Bjornsson 1998 and references therein). The most critical parameter of the plasma that affects the synchrotron radiation spectrum is the strength of the magnetic field. This is often estimated indirectly under assumptions of equipartition of energy between the magnetic fields and that of relativistic particles or by fitting the radio flux density and turnover wavelength. In many classical radio sources, such as supernova remnants like the Crab or Cassiopeia A, or in luminous radio galaxies, the radio spectral index is found to steepen at high frequencies (see, e.g., Kardashev 1962; Eilek et al. 1997; Myers & Spangler 1985). This is due to the so-called synchrotron aging of the source, as during the lifetime of the source, electrons with high-enough energies in a homogeneous magnetic field will be depleted because of efficient synchrotron radiation compared with the ones with lower energies. An observation of a synchrotron break can yield a measurement of the magnetic field *independent of the equipartition argument* if the age of the source is known (the magnetic field in the Crab Nebula was measured by Pikelner 1956, as quoted in Shklovskii 1960 using this technique).

Multifrequency radio studies of a supernova such as SN 1993J, which is bright enough in the radio bands, can offer such a possibility. SN 1993J exploded on 1993 March 28. It was the archetypal Type IIb supernova and provided a good opportunity to study the extragalactic supernovae in detail for being the nearest extragalactic supernova (3.6 Mpc). In this Letter, we discuss the near-simultaneous spectrum of SN 1993J obtained by combining the Giant Metrewave Radio Telescope (GMRT) low-frequency data with the Very Large Array (VLA) high-frequency data around day 3200 since explosion. We find a steepening of the spectrum by $\Delta\alpha = 0.6$ at a radio frequency of 4 GHz. We associate this break with the synchrotron cooling. Synchrotron aging of young supernovae has been discussed by Fransson & Bjornsson (1998) and also mentioned by Perez-Torres et al. (2002). However, we find the first clear observational signature of a spectral break in radio bands of the young supernova SN 1993J. With this break frequency and the independently known age of SN 1993J, we determine the magnetic field in the supernova. Moreover, we predict how this break frequency will evolve with time, based on a quasi-static evolution of the electron spectrum under the combined effect of acceleration processes, synchrotron losses, and adiabatic expansion of the shell where the electrons are confined. We compare this observationally determined field with the best-fit magnetic field under equipartition assumption and hence derive the fraction by which relativistic energy density deviates from magnetic energy density.

We briefly describe the observations of SN 1993J in § 2. In § 3 we combine the data with the VLA data and explore spectral fits with and without synchrotron cooling breaks. In § 4 we explore the cumulative effects of adiabatic expansion of the supernova envelope and energy gain undergone by electrons under diffusive particle acceleration on the synchrotron cooling affected particle spectrum. In § 5 we discuss the evolution of

TABLE 1
Observations of the Spectrum of SN 1993J

Date of Observation	Days since Explosion	Frequency (GHz)	Flux Density (mJy)	rms (mJy)
2001 Dec 31	3199	0.239	57.8 ± 7.6	2.5
	3198	0.619	47.8 ± 5.5	1.9
2001 Oct 15	3123	1.396	33.9 ± 3.5	0.3
2002 Jan 13[a]	3212	1.465	31.44 ± 4.28	2.9
	3212	4.885	15 ± 0.77	0.19
	3212	8.44	7.88 ± 0.46	0.24
	3212	14.965	4.49 ± 0.48	0.34
	3212	22.485	2.50 ± 0.28	0.13

[a] VLA data points (K. Weiler, C. Stockdale, & collaboration 2003, private communication).

the break frequency with time and the importance of wideband spectra for modeling.

2. GMRT OBSERVATIONS

We observed SN 1993J with the GMRT in 610 and 235 MHz wave bands on 2001 December 30 and in a 1420 MHz band on 2001 October 15. We combined this data set with the high-frequency VLA observations (kindly provided by K. Weiler, C. Stockdale, & collaboration 2003, private communication) in 22.5, 14.9, 8.4, 4.8, and 1.4 GHz wave bands observed on 2002 January 13 (see Table 1 for details). Since the supernova is 10 years old, we do not expect the flux density to change by a significant amount in a timescale of a couple of months. For example, using time dependence of the flux density as $F \propto t^{-0.64}$ (van Dyk et al. 1994), we find that the flux density of the supernova will change by only 1.6% from 2001 October 15 to December 30, i.e., the flux density of the supernova at 1.4 GHz, which was 33.9 mJy on 2001 October 15, scaled to 33.4 mJy on 2001 December 30. The difference is well within the errors quoted. Flux calibrators 3C 48 and 3C 147 were observed at the beginning and at the end of the observations. In 1420 MHz observations, we used 1034+565 as a phase calibrator, whereas 0834+555 was used as a phase calibrator for 610 and 235 MHz band observations. The phase calibrator was observed for 6 minutes after every 25 minutes of observation on the supernova. The total time spent on the supernova varied from 2 to 4 hr. The data were analyzed using Astronomical Image Processing Software (AIPS). The flux density errors quoted in our GMRT data sets are

$$\sqrt{[(\text{map rms})^2 + (10\% \text{ of the peak flux of SN})^2]}.$$

The 10% of the peak flux takes into account any possible systematic errors in GMRT as well as the variation in flux in the short time difference in the near simultaneous spectrum. More details of observations, data analysis, and low-frequency spectra of SN 1993J at other epochs are described elsewhere (Chandra et al. 2003).

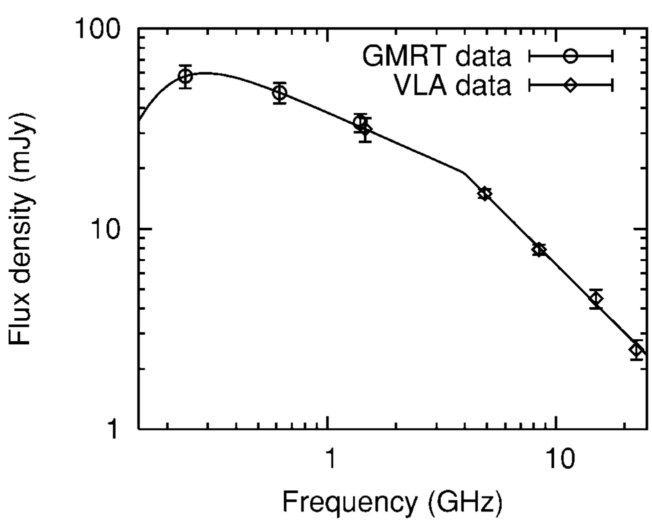

Fig. 1.—Spectrum of SN 1993J with SSA with a break in the spectral index at high frequencies. At low frequencies, the spectral emission index α is 0.51 before the break; in a high-frequency regime (after the break), it is 1.13.

3. MODELING THE COMPOSITE RADIO SPECTRUM

When we try to fit the combined GMRT plus VLA spectrum using SSA (Chevalier 1998) or free-free absorption (van Dyk et al. 1994) models, we find that the optically thin part of the spectrum cannot be fitted with a single power law. The data suggest a steepening of the spectrum toward the higher frequency end, and two power laws are required to fit the optically thin part of the spectrum. The normalized $\chi^2 = 7.3$ per 5 degrees of freedom (dof) for SSA with a single power law improves significantly to $\chi^2 = 0.1$ per 3 dof with SSA with a power law with a break. We use the SSA model to derive the magnetic field from the turnover in the spectrum.[1] The best-fit magnetic field at the peak of the spectrum under equipartition assumption is 38.3 ± 17.1 mG, and the radius is $(1.81 \pm 0.07) \times 10^{17}$ cm. The break in the spectrum occurs at 4.02 ± 0.19 GHz. Figure 1 shows the spectrum with the SSA fit with a break in the spectrum. We see that the emission spectral index α for the frequency region below 4.02 GHz is $\alpha = 0.51 \pm 0.01$ (or $\gamma = 2.01 \pm 0.02$, where γ is the particle spectral index related to α as $\gamma = 2\alpha + 1$). The spectral index at 4.02 GHz toward the higher frequency end changes by $\Delta\alpha = 0.62 \pm 0.04$, hence the emission spectral index after the break toward the higher frequency region is $\alpha = 1.13 \pm 0.05$.

This variation in spectral index is roughly consistent with that predicted from the synchrotron cooling effect with continuous injection (see Kardashev 1962), and we attribute the break in the spectrum of SN 1993J to synchrotron cooling.

[1] On the basis of the observational data for various radio supernovae, Slysh (1990) had argued that for all considered supernovae, SSA is responsible for the turnover in the spectrum, even though other absorption processes are at work.

4. SYNCHROTRON AGING AND EFFECT OF OTHER ENERGY LOSS/GAIN PROCESSES

The lifetime of the relativistic electrons undergoing synchrotron losses is given as

$$\tau = E/[-(dE/dt)_{\rm sync}] = 1.43 \times 10^{12} B^{-3/2} \nu^{-1/2}\ {\rm s}. \quad (1)$$

Here we use $B_\perp^2 = (B \sin\theta)^2 = \frac{2}{3}B^2$. The above expression is implicitly a function of time, since the magnetic field in the region of emission itself changes with time as the supernova shock moves out farther into the circumstellar plasma. The time variation of the synchrotron break frequency can be obtained by setting $\tau = t$, where

$$\nu_{\rm break} = (t/1.43 \times 10^{12})^{-2} B^{-3} = 2 \times 10^{24} B_0^{-3} t\ {\rm Hz}. \quad (2)$$

Here we use $B = B_0/t$ (Fransson & Bjornsson 1998). From the above equation (and using $\nu_{\rm break} = 5.12 \times 10^{18} B E_{\rm break}^2$ Hz; Pacholczyk 1970) and with break frequency 4 GHz, we get magnetic field $B = 0.19$ G for $t = 3200$ days. However, this estimate of the magnetic field does not account for other processes such as diffusive Fermi acceleration and adiabatic losses, likely to be important for a young supernova and affecting the break frequency. Diffusive Fermi acceleration and adiabatic expansion processes do not result in a change of slope of the energy spectrum from what it was in the case of pure synchrotron losses, but the frequency where the synchrotron cooling break occurs gets shifted depending on the strength of these two competing processes (Kardashev 1962). Adiabatic losses shift the "break" frequency toward lower frequency with time, whereas acceleration processes shift the cooling break to higher frequencies. We derive below the magnetic field under the cumulative effect of all these processes. Since the supernova is young and expanding rapidly, the adiabatic losses will be given by $dE/dt_{\rm adia} = -(V/R)E = -E/t$. Here V is the expansion velocity, i.e., the ejecta velocity, and R is the radius of the spherical shell.

In supernovae, the diffusive mechanism is assumed to be the main acceleration mechanism (Fransson & Bjornsson 1998; Ball & Kirk 1992). In this process electrons gain energy every time they cross the shock front, either from upstream to downstream or vice versa. The average fractional momentum gain per shock crossing or recrossing is $\Delta = [4(v_1 - v_2)/3v]$, and the average time taken to perform one such cycle is (Ball & Kirk 1992; Drury 1983)

$$t_c = \frac{4\kappa_\perp}{v}\left(\frac{1}{v_1} + \frac{1}{v_2}\right). \quad (3)$$

Here v is the test particle velocity, v_1 is the upstream velocity and v_2 is the downstream velocity, and $\kappa_\perp$ is the spatial diffusion coefficient of the test particles across the ambient magnetic field, when the shock front is quasi-perpendicular to the field. In the rest frame of the shock front, $v_1 = V$ and $v_2 = v_1/4 = V/4$ (for a compression factor of 4). Hence the rate of energy gain will be

$$\left(\frac{dE}{dt}\right)_{\rm Fermi} = \frac{\Delta E}{t_c} = \frac{EV^2}{20\kappa_\perp} = \frac{E(R/t)^2}{20\kappa_\perp}. \quad (4)$$

The break in the spectrum will occur for those electron energies for which the timescales for the cumulative rate of change of electron energy due to synchrotron cooling plus adiabatic losses and gain through diffusive shock acceleration become comparable to the lifetime of the supernova (Kardashev 1962). The lifetime of electrons for the cumulative energy loss rate is

$$\tau = \frac{E}{(dE/dt)_{\rm total}} = \frac{E}{(R^2 t^{-2}/20\kappa_\perp)E - bB^2E^2 - t^{-1}E}, \quad (5)$$

where the second term in the denominator is the synchrotron loss term with $b = 1.58 \times 10^{-3}$. Setting the lifetime $\tau = t$, the break frequency can be derived as

$$\nu_{\rm break} = \frac{2 \times 10^{24}}{B_0^3}\left(\frac{R^2}{20\kappa_\perp} t^{-1/2} - 2t^{1/2}\right)^2\ {\rm Hz}. \quad (6)$$

We do not yet have an observational determination of $\kappa_\perp$ for SN 1993J. However, in the case of SN 1987A, from the delay in the switch-on of the emission between 843 MHz and 4.8 GHz, this parameter was estimated to be $\kappa_\perp = 2 \times 10^{24}$ cm^2 s^{-1} (Ball & Kirk 1992). This is relatively independent of the density and magnetic field of the two clumps in the circumstellar medium into which the SN 1987A shock was running in the first 1500–1600 days. We use a slightly different $\kappa_\perp$ for SN 1993J, since there is evidence that the compression ratio ρ of gas or plasma across the shock in SN 1993J is higher than that of SN 1987A.[2] Therefore, we estimate that $\kappa_\perp$ for SN 1993J (scaled by the higher compression ratio in SN 1993J) is $\kappa_\perp = (4/2.7) \times 2 \times 10^{24}$ cm^2 s^{-1}, i.e., 2.96×10^{24} cm^2 s^{-1}. From VLBI observations (Bartel et al. 2002), the extrapolated angular radius of SN 1993J on day 3200 is ~5012 μas, i.e., ~2.65×10^{17} cm. Using $\kappa_\perp$ and R in equation (6) we find the magnetic field $B = 0.33 \pm 0.01$ G, from the observationally determined break.

From our SSA best fit to the radio spectrum, we have a value of the best-fit equipartition magnetic field $B_{\rm eq} = 38.2 \pm 17.1$ mG. If a is the ratio between relativistic electron energy density, $U_{\rm rel}$, to magnetic energy density, $U_{\rm mag}$ ($a = U_{\rm rel}/U_{\rm mag}$), then magnetic field B depends on equipartition factor a as $B \propto a^{-4/(2\gamma+13)}$ (see Chevalier 1998). Hence, we get equipartition fraction a, i.e., $U_{\rm rel}/U_{\rm mag} = 8.5 \times 10^{-6}$ to 5.0×10^{-4}. This small value of the ratio of particle energy density versus magnetic energy density indicates that the plasma kinetics is dominated by magnetic field and associated turbulence.

5. DISCUSSION AND CONCLUSIONS

We see in the last section that the magnetic field calculated from the break in the spectral index is 0.33 G, which is ~1.4 times higher than that expected from an extrapolation of Fransson & Bjornsson (1998; $B = 0.24$ G at day 3200). If we took only the synchrotron cooling effect and neglected adiabatic expansion and diffusive Fermi acceleration, we get magnetic field $B = 0.19$ G, which is in closer agreement with that of Fransson & Bjornsson (1998). However, at this young age of the supernova, the effects of adiabatic expansion and diffusive Fermi acceleration are likely to be significant, as seen in SN 1987A (Ball & Kirk 1992), and hence these effects should not be neglected.

One can estimate the importance of the diffusive acceleration term, if one is able to follow how the break frequency evolves

[2] Diffusive acceleration predicts a flattening of the spectrum at a spectral index $\alpha = 3/[2(\rho - 1)]$, which gives $\rho = 4$ in the case of SN 1993J, in contrast to $\rho = 2.7$ for SN 1987A (Ball & Kirk 1992).

with time. In equation (6), the first term is the contribution of the acceleration and the second term is the contribution of adiabatic expansion and synchrotron losses. We note that for the estimated value of $\kappa_\perp$ at the present epoch, diffusive Fermi acceleration dominates and will continue to dominate over the adiabatic losses until about 20 years since explosion. Therefore, at the present epoch the break frequency evolves as $\nu_{\rm break} \propto t^{-1}$. After 20 years, the acceleration will cease to dominate over adiabatic expansion and the break frequency will increase as $\nu_{\rm break} \propto t$.

Since we do not have an independent method to estimate the spatial diffusion coefficient $\kappa_\perp$ for SN 1993J, we have used the linearly scaled (by the respective compression ratios, ρ) value of $\kappa_\perp$ measured for SN 1987A from direct radio observations (see Ball & Kirk 1992). However, we can directly calculate the value of $\kappa_\perp$ from the (measurable) rate of change of $\nu_{\rm break}$, i.e., from the expression

$$\frac{d\nu_{\rm break}}{dt} = \frac{2\times 10^{24}}{B_0^3}\left(\frac{R^2}{20\kappa_\perp}t^{-1/2} - 2t^{1/2}\right) \times \left(-\frac{R^2}{20\kappa_\perp}t^{-3/2} - 2t^{-1/2}\right)\ \text{Hz s}^{-1}. \quad (7)$$

For the present epoch and with the estimated parameters as above, we calculate that the break frequency is changing at the rate of 1.2 GHz yr^{-1}. Thus a few more multifrequency spectral observations across GMRT and VLA bands, separated by a few years, will observationally determine the temporal variation in the break frequency and underline the importance of the diffusive acceleration effects.

The combination of multifrequency radio spectrum across GMRT and VLA bands is critical for deriving the above results. In Figure 2 we show a comparison of the SSA model (with a single optically thin power-law index) fitted only to the low-frequency data (0.22–1.4 GHz) versus such a model fit obtained with only the higher frequency data (1.4–22.5 GHz). This comparison shows that while the model fitted only to the low frequencies overpredicts the flux density at high frequencies, the model fitted only to high frequencies, on the other hand, fails to account for the high-frequency synchrotron cooling break and seriously underpredicts the low-frequency flux densities. The comparison underscores the importance of broadband observations for determining the physical processes taking place in the supernova.

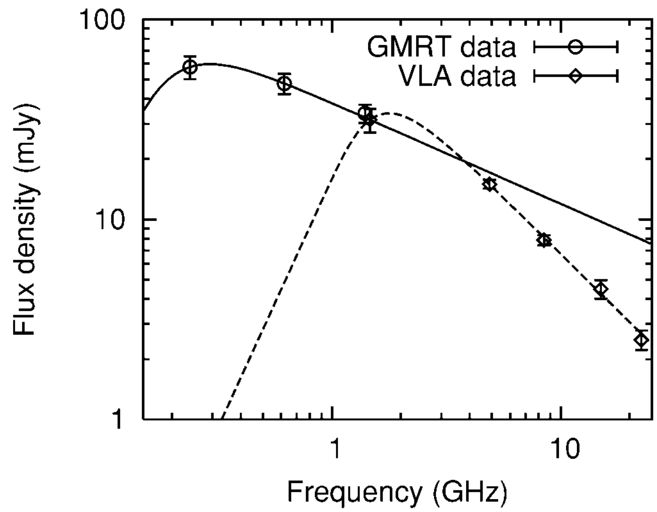

FIG. 2.—Wideband spectrum of SN 1993J. SSA fit to "only" low-frequency data (*solid line*) and "only" high-frequency data (*dashed line*).

We note the uncertainty in $\kappa_\perp$ for SN 1993J as also emphasized by the referee, who suggests that $\kappa_\perp$ may not be a constant and points out a paper by Reynolds (1998). Reynolds *assumes* that $\kappa_\perp$ is proportional to the particle energy. This dependence may affect the determination of the magnetic field (see eq. [6]). Only future observations of the break frequency evolution with time will directly put constraints on $\kappa_\perp$ for SN 1993J. We also note that our results are based on the assumption that the acceleration and synchrotron losses are taking place in the same region. However, if the regions of the two processes are not substantially overlapping, the synchrotron break frequency will not be affected by acceleration. Even in that case, the magnetic field is much higher than the equipartiton magnetic field and the plasma is still dominated by the magnetic energy density.

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