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Baby supernovae through the looking glass at long wavelengths

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Abstract. We emphasize the importance of observations of young supernovae in wide radio band. We argue on the basis of observational results that only high- or only low-frequency data is not sufficient to get full physical picture of the shocked plasma. In SN 1993J, the composite spectrum obtained with Very Large Array (VLA) and Giant Metrewave Radio Telescope (GMRT), around day 3200, shows observational evidence of synchrotron cooling, which leads us to the direct determination of the magnetic field independent of the equipartition assumption, as well as the relative strengths of the magnetic field and relativistic particle energy densities. The GMRT low-frequency light curves of SN 1993J suggest the modification in the radio emission models developed on the basis of VLA data alone. The composite radio spectrum of SN 2003bg on day 350 obtained with GMRT plus VLA strongly supports internal synchrotron self absorption as the dominant absorption mechanism.

Keywords : magnetic fields – radiation mechanisms: non-thermal – radio continuum: stars – supernovae: individual (SN 1993J, SN 2003bg)

1. Introduction

Radio emission from supernovae is argued to be due to the synchrotron emission from the forward shocked shell due to the relativistic electrons in presence of magnetic field. The radio emission is initially absorbed from the external medium (free-free absorption i.e. FFA) or through synchrotron self absorption (SSA), i.e. an internal process.

The most critical parameter which affects the synchrotron emission is the magnetic field. The magnetic fields in a few supernovae have been estimated indirectly by assuming equipartition between relativistic energy density and the magnetic energy density. The magnetic field in the shocked plasma in supernovae is enhanced due to hydrodynamic instabilities in the plasma. While it is plausible, there is no convincing argument for the equipartition assumption. In many classical radio sources, such as supernova remnants (SNRs) 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). 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 due to 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*.

We emphasize here the need for broad-band radio observations of SNe to address the above issues. Combining radio data from a high frequency VLA and low frequency GMRT can offer such opportunities. We discuss two supernovae in this context - an eleven years old type IIb supernova SN 1993J and a one year old type Ic supernova SN 2003bg.

2. SN 1993J in M81

SN 1993J exploded on March 28, 1993 in M81 (3.6 Mpc). The early spectrum of SN1993J showed the characteristic hydrogen line signature of type II SNe, but subsequently made a transition to hydrogen-free, He-dominated type Ib SNe, hence classified as type IIb SN.

2.1 Observations

We observed SN 1993J with the GMRT in 610 and 235 MHz wavebands on 2001 Dec 30 and in 1420 MHz band on 2001 Oct 15. We combined this dataset with the high frequency VLA observations provided by C. Stockdale, K. Weiler et al. in 22.5, 14.9, 8.4, 4.8 and 1.4 GHz wavebands observed on 2002 Jan 13 (See Table 1). The data was analyzed using Astronomical Image Processing System (AIPS). More details of observations, data analysis are described in Chandra et al. (2004a).

2.2 Modeling the composite radio spectrum

The GMRT and VLA combined spectrum on day 3200 suggests the break in the spectral index in the optically thin part of the spectrum (Fig. 1). The break in the spectrum occurs at 4.02 ± 0.19 GHz with the steepening of spectral index by 0.6. This variation in spectral index is consistent with that predicted from the synchrotron cooling effect with continuous injection (Kardashev 1962). If we were to model the low frequency data with

Table 1. Observations of the spectrum of SN 1993J on day 3200

Date of Observation	Telescope	Days since explosion	Frequency in GHz	Flux density mJy	rms mJy
Dec 31,01	GMRT	3199	0.239	57.8 ±7.6	2.5
Dec 30,01	GMRT	3198	0.619	47.8 ±5.5	1.9
Oct 15,01	GMRT	3123	1.396	33.9 ±3.5	0.3
Jan 13,02	VLA	3212	1.465	31.44±4.28	2.9
Jan 13,02	VLA	3212	4.885	15 ±0.77	0.19
Jan 13,02	VLA	3212	8.44	7.88 ±0.46	0.24
Jan 13,02	VLA	3212	14.965	4.49 ±0.48	0.34
Jan 13,02	VLA	3212	22.485	2.50 ±0.28	0.13

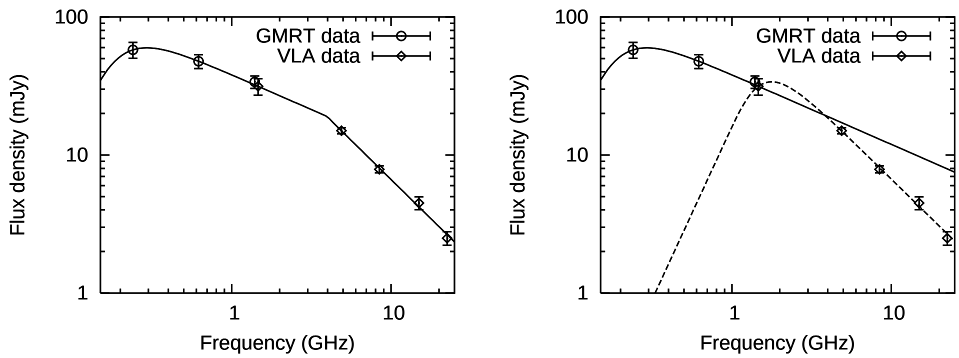

Figure 1. *Left panel*: Combined GMRT plus VLA spectrum of SN 1993J on day 3200 with SSA model (solid line) with a break in the spectral index at 4 GHz. At low frequencies, the spectral emission index α is 0.51 before break and after the break, in high frequency regime, it is 1.13. *Right panel*: Wide band spectrum of SN 1993J. Synchrotron self absorption fit to "only" low frequency data (solid line) and "only" high frequency data (dashed line).

a turnover due to SSA, then *under the assumption of equipartition* we would obtain a field of $B_{eq} = 38.3 \pm 17.1$ mG (see, however next section).

2.3 Synchrotron aging and determination of the magnetic field

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

$$\tau = E/[-(dE/dt)_{Sync}] = 1.43 \times 10^{12} B^{-3/2} \nu^{-1/2} \text{ sec} \tag{1}$$

Here we use ${B_\perp}^2 = (B\,\text{Sin}\theta)^2 = (2/3)B^2$. 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: $\tau = t$, whence,

$$\nu_{break} = (t/1.43\times 10^{12})^{-2} B^{-3} = 2\times 10^{24} B_0^{-3}\, t \text{ Hz} \tag{2}$$

Here we use $B = B_0/t$ (Fransson & Bjornsson 1998). From the above eqn. (and using $\nu_{break} = 5.12\times 10^{18} B E^2_{break}$ Hz (Pacholczyk 1969)) and with break frequency 4 GHz, we get magnetic field $B = 0.19$ G for $t = 3200$ days. However this estimate of the B does not account for other processes like diffusive shock acceleration (Fermi mechanism) and adiabatic losses, likely to be important for a young supernova.

We derive below the magnetic field under cumulative effect of all these processes. The adiabatic losses will be given by $dE/dt_{adia} = -(V/R)E = -E/t$. Here V is the expansion velocity, i.e. the ejecta velocity and R is the radius of the spherical shell.

In supernovae, 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), $t_c = 4\kappa_\perp(1/v_1 + 1/v_2)/v$. 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 shock front, $v_1 = V$ and $v_2 = v_1/4 = V/4$ (for compression factor of 4). The break in the spectrum will occur for those electron energies for which the time scales for the cumulative rate of change of electron energy due to synchrotron cooling plus adiabatic losses and gain through diffusive acceleration becomes comparable to the life time of the supernova (Kardashev 1962). Lifetime of electrons for the cumulative energy loss rate is

$$\tau = \frac{E}{(dE/dt)_{Total}} = \frac{E}{(R^2 t^{-2}/20\kappa_\perp)E - bB^2E^2 - t^{-1}E} \tag{3}$$

where the first term in the denominator is the acceleration term, the second term is the familiar synchrotron loss term with $b = 1.58\times 10^{-3}$ and the third term is due to adiabatic losses. Setting the life time $\tau = t$, break frequency can be derived as:

$$\nu_{break} = \frac{2\times 10^{24}}{{B_0}^3}\left[\frac{R^2}{20\kappa_\perp} t^{-1/2} - 2\, t^{1/2}\right]^2 \text{Hz} \tag{4}$$

The value of $\kappa_\perp$ is used as 2.96×10^{24} cm^{2}s^{-1} (see Chandra et al. 2004b). Using size of the supernova $R = 2.65\times 10^{17}$ cm from VLBI observations (Bartel et al. 2002), we obtain magnetic field $B = 0.33 \pm 0.01$ Gauss, from the observationally determined break. On the other hand, from the best fit in SSA, the magnetic field under equipartition assumption is $B_{eq} = 38 \pm 17$ mG. Comparison of the two magnetic field determines the value of the equipartition fraction between relativistic energy of particles and magnetic field energy. Equipartition fraction $a = U_{rel}/U_{mag}$ varies with magnetic field B as $a = (B/B_{eq})^{-(2\gamma+13)/4}$ (Chevalier 1998). Therefore, the fraction a ranges between $8.5\times10^{-6} - 4.0 \times 10^{-4}$ with a central value (corresponding to $B_{eq} = 38$ mG) of $a = 1.0 \times 10^{-4}$ on day 3200. This very low value of the equipartition fraction suggests that the plasma is heavily dominated by the magnetic energy density, and electron acceleration to relativistic energies is inefficient.

2.4 Role of acceleration

It is argued here that acceleration may play a role in determination of magnetic field from the synchrotron cooling break when the acceleration region and the synchrotron loss regions are overlapping. However, the extent to which these two regions overlap near the interaction shell strongly distorted by fingers of hydrodynamic instability is not a priori clear. The experimental trend of shift in the break frequency with time may determine this issue. If acceleration processes are important then break frequency will tend to shift to lower frequency with time ($\nu_{break} \propto t^{-1}$), whereas break frequency will shift to higher frequency with time ($\nu_{break} \propto t$) if they are not important (Eq. 4). In any case, our conclusion that the plasma is dominated by magnetic energy density remains unaffected.

3. SN 1993J light curves at low frequencies

Weiler et al. (2002) provided the detailed modeling of SN 1993J at all epochs based on high frequency VLA data. We extrapolate this model to 1420, 610, 325 and 243 MHz frequencies at GMRT observation epochs with the above parameters. Fig 2. shows this extrapolated light curves for the SN at 1420, 610, 325 and 243 MHz and our corresponding GMRT data points at the respective frequencies. It is evident that the free-free model described above overpredicts the flux densities at low frequencies. In fact lower the frequencies, more significant is the departure from the standard free-free model. This indicates that the optical depths fitted using high frequency datasets, simply extrapolated to low frequencies with the dependence $\tau \propto \nu^{-2.1}$ are not sufficient to account for the required absorption. One needs to incorporate some additional frequency dependent opacity at low frequencies, which can compensate for the difference between the model light curves and actual data.

4. SN 2003bg in MCG -05-10-015

SN 2003bg is type Ic supernova in MCG -05-10-015 (19 Mpc). It was discovered on 2003 Feb 25, most likely two weeks after the explosion (based on the spectral chronometers). It was devoid of Hydrogen and Helium in the optical spectra, hence classified as type Ic supernova.

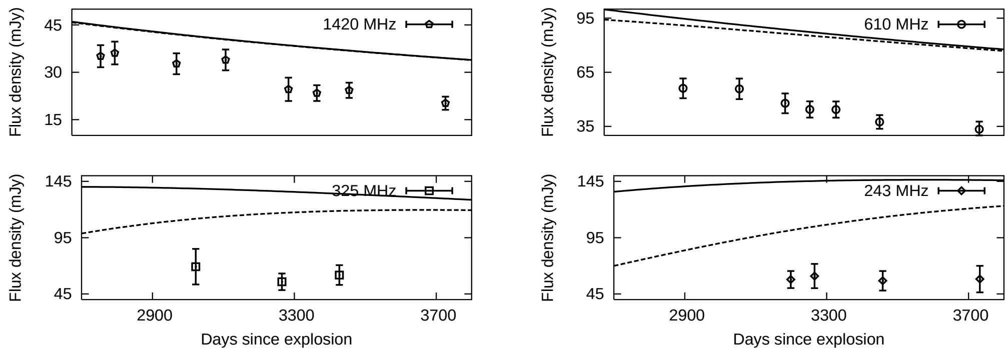

Figure 2. Comparison of low-frequency data to the predictions of the models obtained by fitting high-frequency fluxes of SN 1993J. The solid lines in all the three plots are Weiler et al.'s (2002) model extrapolated to lower frequencies. Dashed lines are the flux density plot after incorporating the SSA optical depth in Weiler's free-free model.

4.1 Observations

We observed SN 2003bg with GMRT in 1280 MHz band on 2003 Feb 2 and then in 610 MHz band on 2003 Feb 5 and in 325 MHz band on 2003 Feb 8. On our request A. Soderberg and S. Kulkarni observed the SN at high VLA frequencies on 2003 Feb 8, thus obtaining the wide band radio spectrum all the way from 0.3 GHz up to 44 GHz (Tab. 2). Fig. 3 shows the 1280 MHz band GMRT radio map of SN 2003bg.

4.2 Modeling the composite radio spectrum

Radio emission in SNe is usually absorbed in the early stages. It can be either due to FFA or SSA. The data in the optically thick part of the spectrum can distinguish between the two because of their varied dependence on frequency. We fit both homogeneous FFA and SSA models (Chevalier 1998) to the spectrum (see Fig. 3). The 610 MHz data point clearly discriminates the FFA model and favors SSA model. From the SSA fit to the data under equipartition assumption, we find the values of the following parameters: emission spectral index ($\alpha = 3$), size of SN 2003bg ($R = (9.98 \pm 0.43) \times 10^{16}$ cm), expansion speed ($v = 33,000\,\mathrm{km\,s^{-1}}$), and magnetic field ($B = 0.18 \pm 0.03$ G).

We notice that 44 GHz data point is not falling on the powerlaw in the optically thin part and it suggests a break somewhere between 22 GHz to 44 GHz. The break may be due to the synchrotron aging. Since we have only one data point, we cannot draw any conclusive evidence and it will be useful to have the spectrum extended beyond 44 GHz. If there is indeed a break due to synchrotron cooling, it will determine the magnetic field directly, independent of equipartition assumption, as was in the case of SN 1993J.

Table 2. Observations of the spectrum of SN 2003bg on day 350

Date of Observation	Telescope	Days since explosion	Frequency in GHz	Flux density mJy	rms mJy
Feb 08,04	GMRT	363	0.325	57.8 ±7.6	2.5
Feb 05,04	GMRT	360	0.619	47.8 ±5.5	1.9
Feb 02,04	GMRT	357	1.280	33.9 ±3.5	0.3
Feb 08,04	VLA	363	1.465	23.88±0.4	–
Feb 08,04	VLA	363	4.885	30.88 ±0.08	–
Feb 08,04	VLA	363	8.44	18.96 ±0.07	–
Feb 08,04	VLA	363	14.97	9.65 ±0.17	–
Feb 08,04	VLA	363	22.5	6.56 ±0.08	–
Feb 08,04	VLA	363	44.3	2.23 ±0.26	–

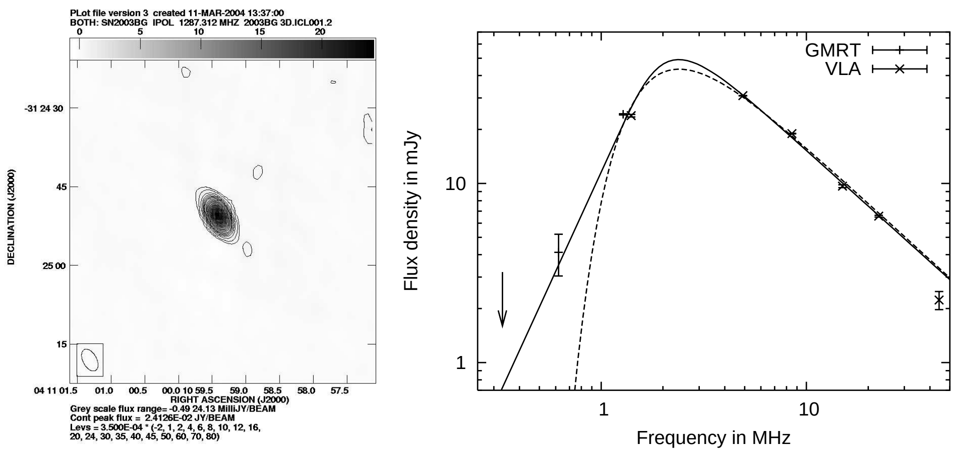

Figure 3. *Left panel*: GMRT radio map of SN 2003bg at 1280 MHz frequency observed on Feb 02, 2004. *Right panel*: Synchrotron self absorption (solid line) and free-free absorption (dashed line) fits to the SN 2003bg combined GMRT plus VLA spectrum.

5. Discussion and Conclusions

In right panel of Fig. 1 we show a comparison of SSA model (with a single optically-thin power-law index) fitted only to the low frequency data (0.22 GHz to 1.4 GHz) versus such a model fit obtained with only the higher frequency data (1.4 GHz to 22.5 GHz). This comparison shows that while the model fitted only to the low frequencies over-predicts the flux density at high frequencies, the model fitted only to high frequencies on the other hand fails to account for both synchrotron cooling break and seriously under-predicts the low frequency flux densities. The comparison underscores the importance of broad band observations for determining the physical processes taking place in the supernova.

The particle energy density is far below than the magnetic energy density (by a factor of 1/10000) for SN 1993J, although there are indications that in SNe like SN 1998bw/GRB980425, there may exist this equipartition (Kulkarni et al. 1998). Future studies of the equipartition factor for SN 1993J may indicate for the first time how particle acceleration efficiency in strongly turbulent magnetized plasma evolves with time in the large magnetic-Reynolds and Reynolds numbers limit. Light curves based on high frequency FFA models extrapolated to low frequencies overpredict the fluxes at low frequencies. Some extra opacity is needed to incorporate the difference. We added an extra opacity due to SSA which also could not account for the required absorption (Fig. 2). This suggests the low frequency opacity in SN 1993J is not the simple extrapolation of high frequency opacity and it is likely that hitherto unaccounted absorption mechanisms are at work at low frequencies.

There could be a break in the radio spectrum of SN 2003bg. We are planning simultaneous observations with GMRT along with VLA and ATCA. This will provide us the spectrum from 0.2 GHz to 80 GHz and will establish whether the break is real or due to data artifact. We also could discard the homogeneous free-free absorption model over the SSA model from the low-frequency optically thin part of the spectrum.

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