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Electron Acceleration in Supernovae and Millimeter Perspectives

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Abstract

Supernovae launch a strong shock wave by the interaction of the expanding ejecta and surrounding circumstellar matter (CSM). At the shock, electrons are accelerated to relativistic speed, creating observed synchrotron emissions in radio wavelengths. In this paper, I suggest that SNe (i.e., $\lesssim 1$ year since the explosion) provide a unique site to study the electron acceleration mechanism. I argue that the efficiency of the acceleration at the young SN shock is much lower than conventionally assumed, and that the electrons emitting in the *cm* wavelengths are *not* fully in the Diffusive Shock Acceleration (DSA) regime. Thus radio emissions from young SNe record information on the yet-unresolved 'injection' mechanism. I also present perspectives of millimeter (*mm*) observations of SNe – this will provide opportunities to uniquely determine the shock physics and the acceleration efficiency, to test the non-linear DSA mechanism and provide a characteristic electron energy scale with which the DSA start dominating the electron acceleration.

Keywords: acceleration of particles - radiation mechanism: non-thermal - supernovae: general.

1 Introduction

The most promising particle acceleration mechanisms require a strong shock wave, e.g., by the diffusive shock acceleration (DSA) mechanism where the particles acquire energy through repeated collisions between up- and down-streams of a shock wave (Fermi, 1949; Blandford & Ostriker, 1978; Bell, 1978). Supernova remnants (SNRs) are believed to be the origin of cosmic rays at least up to $\sim 10^{15}$eV (e.g., Bamba et al., 2003). There is one key issue in this picture for electrons – how the electrons are 'pre-accelerated'. For the DSA mechanism to work efficiently, a particle must already have an enough kinetic energy.

Supernovae (SNe), at the age of $\lesssim 1$ year, also produce emissions which are believed to be originated by relativistic electrons, accelerated at a strong shock created by the expanding SN ejecta running into circumstellar matter (CSM). Radio emissions from SNe are interpreted as the synchrotron emission, and X-rays from some SNe have been suggested to be emitted through the inverse Compton (IC) mechanism (e.g., Chevalier & Fransson, 2006 for a review). However, most of analyses on the non-thermal emissions from SNe have been focusing on deriving the CSM environment, rather than the acceleration mechanism (e.g., Soderberg et al., 2012). In this paper, I argue that young SNe provide a unique site to study the electron acceleration mechanism. I also suggest that millimeter (*mm*) observations, which are becoming feasible with new observatories like *ALMA*, can potentially provide essential information on this issue.

2 Non-Thermal Emissions

A situation around young SNe related to the non-thermal emission is similar to that for SNRs. Energy transfer from the shock wave kinetic energy to relativistic particles and that to magnetic field are roughly described by equipartition (Fransson et al., 1996). I adopt conventional notation – $\epsilon_{\rm e}$ and ϵ_B describe constant fractions of the shock wave energy transferred to the relativistic electrons and the magnetic field, respectively. Our arguments are based on modeling emissions from so-called striped envelope SNe (SE-SNe; or SNe IIb/Ib/Ic) that are believed to be explosions of He or CO stars (having lost at least the H envelope). In these SNe, the radio emission is well described by synchrotron emissions with the synchrotron self-absorption (SSA) at low frequencies (see, e.g., Chevalier & Fransson, 2006). Under some standard assumptions (Björnsson & Fransson, 2004; Chevalier & Fransson, 2006; Maeda et al. 2012, 2013a), the synchrotron properties can be described by the following parameters:

- p: Power law index of spectral energy distribution of injected relativistic electrons.
- m: Power law index of shock evolution in time ($R \propto t^{\rm m}$).

Table 1: Characteristics of the synchrotron emission from young SNe ($L_\nu \propto \nu^\alpha t^\beta$), for the adiabatic limit and for the synchrotron and IC cooling limits, respectively (Maeda, 2013a).

Indices	Adiabatic	Syn.	IC
α	$\frac{1-p}{2}$	$-\frac{p}{2}$	$-\frac{p}{2}$
β	$(3m-3)+\frac{1-p}{2}$	$(3m-3)+\frac{2-p}{2}$	$(5m-5)+\frac{2-p}{2}+\delta$
$\alpha(p=2)$	$-\frac{1}{2}$	-1	-1
$\beta(p=2)$	$(3m-3)-\frac{1}{2}$	$(3m-3)$	$(5m-5)+\delta$
$\alpha(p=3)$	-1	$-\frac{3}{2}$	$-\frac{3}{2}$
$\beta(p=3)$	$(3m-3)-1$	$(3m-3)-\frac{1}{2}$	$(5m-5)-\frac{1}{2}+\delta$

- δ: Power law index of optical/NIR SN emission in time ($L \propto t^\delta$).
- A_*: CSM density scale ($\rho_{\rm CSM} \propto A_* r^{-2}$; normalized as $A_* \sim 1$ for $\dot{M} \sim 10^{-5} M_\odot {\rm yr}^{-1}$ with the mass loss wind velocity of $1,000$ km s^{-1}).
- $\epsilon_{\rm e}$: Efficiency of the electron acceleration.
- ϵ_B: Efficiency of the magnetic field generation/amplification.

Note that the shock evolution (m) is mainly determined by the CSM density distribution, e.g., by a self-similar solution (Chevalier, 1982). Table 1 shows expected synchrotron properties, $L_\nu \propto \nu^\alpha t^\beta$. From the observed properties (α, β) one can almost uniquely determine the power law indices (p, m, δ). There is a degeneracy in the other parameters (i.e., in the 'scales'). Properties of the SSA-synchrotron are described by two characteristic observables (peak date and luminosity), while these are described by the three model parameters (i.e., A_*, $\epsilon_{\rm e}$, $\epsilon_{\rm B}$).

3 Efficiency of Electron Acceleration

Figure 1 shows how one can constrain the shock microphysics and CSM density. An example is given for intensively observed nearby SN IIb 2011dh. Thanks to detailed models of the optical emission (Bersten et al., 2012), the SN ejecta properties (mass and energy) have been strongly constrained – Model A adopts the shock wave dynamics expected from the optical emission model. Model B is shown for illustration, which *assumes* the dynamics so that $\epsilon_{\rm e} \sim 0.1$, but this fails to explain the optical behavior. Adopting Model A, $\epsilon_{\rm e}$ cannot be as large as ~ 0.1 which has been conventionally assumed, since such a situation requires extremely large mass loss rate (A_*). Then the expected thermal emission in X-rays would be much stronger than observed. Indeed, from the X-ray strength, $A_* \lesssim 30$, thus $\epsilon_{\rm e} \lesssim 0.01$ must apply. Also, from the energy conservation, $A_* \lesssim 2$ is rejected (otherwise $\epsilon_B > 0.3$). From these arguments, $0.005 \lesssim \epsilon_{\rm e} \lesssim 0.01$ and $\epsilon_B \gtrsim 0.001$ are obtained as robust constraints. This also indicates that $\alpha \equiv \epsilon_{\rm e}/\epsilon_B < 10$.

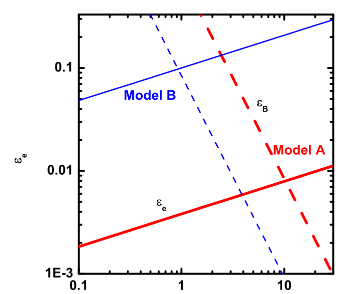

Figure 1: $\epsilon_{\rm e}$ and ϵ_B derived for SN 2011dh, as a function of A_* (Maeda, 2012).

So, a strong constraint can be placed on $\epsilon_{\rm e}$. There is another independent argument against a large value of $\epsilon_{\rm e}$. Figure 2 shows the models with small $\epsilon_{\rm e}$ and large $\epsilon_{\rm e}$. Large $\epsilon_{\rm e}$ should produce a detectable cooling effect in radio properties, which was however not detected. This argument on the IC cooling effect should apply to SNe in general. I note that sometimes a large value of $\epsilon_{\rm e}$ is introduced/suggested to explain X-ray luminosities by IC up-scattered photons (e.g., Chevalier & Fransson, 2006), but indeed I suggest here that one has to check if such a situation is consistent with the radio (*cm*) properties. For example, for SN 2011dh $\alpha \gtrsim 30$ (e.g., $\epsilon_{\rm e} \lesssim 0.3$ and $\epsilon_{\rm B} \sim 0.01$) has been suggested (e.g., Soderberg et al., 2012), but as shown above this should produce a detectable change in the radio light curves that was not observed (Maeda, 2012). Applying the same constraint to a few other SNe, it seems like that small $\epsilon_{\rm e}$ is a generic feature in SNe (Maeda, 2013a).

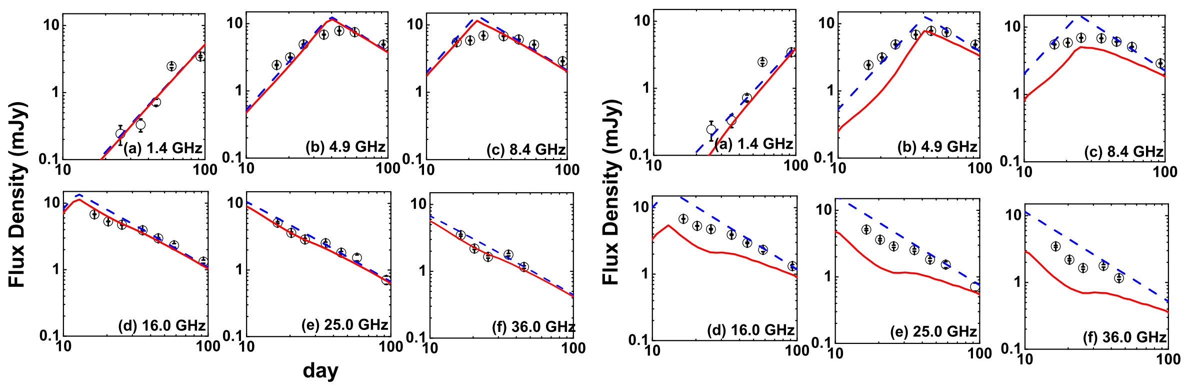

Figure 2: Left: Multi frequency radio light curves (red solid) as compared with those of SN 2011dh (Maeda, 2012). The parameters are $(A_*, \epsilon_e, \epsilon_B) = (4, 6\times10^{-3}, 5\times10^{-2})$ (left; adopting Model A) and $(20, 0.26, 2.5\times10^{-4})$ (right; Model B). The synthetic light curves without the IC cooling are also shown (blue dashed). Observational data are taken from Soderberg et al. (2012).

4 Injection and Acceleration Mechanisms

Since one can obtain both the spectral and temporal information for SNe, there is essentially no degeneracy in deriving the electrons' injected spectrum slope, p (Tab. 1). One interesting issue is found from such analyses – $p \sim 3$ is generally derived for young SNe, unlike more evolved SNRs (mostly $p \sim 2 - 2.4$; e.g., Bamba et al., 2003) and the standard DSA prediction in the test particle limit ($p \sim 2$; e.g., Ellison et al., 2000). A cause of the difference has not been clarified, and I propose that this is mainly due to totally different energies of the electrons emitting at *cm* wavelengths in young SNe and more evolved SNRs.

The argument here is based on that of Maeda (2013b). I note that a main difference between the synchrotron emission from SNe and that from SNRs is that the emitting electrons' energy is quite different for given frequency (Figure 3). Typical magnetic field strength is $B \sim 1$G for SNe (e.g., Chevalier & Fransson, 2006) and 100μG for SNRs (e.g., Bamba, et al., 2003). This is consistent with the equipartition expectation (Maeda, 2013b). At the observed frequency of $\sim$ 1 GHz, the emitting electrons' energies are $\sim$ 50 MeV and 5 GeV in SNe and SNRs, respectively. One can estimate if these electrons satisfy an essential condition required for DSA, namely the electron's mean free path is exceeding the shock wave width. This is satisfied by electrons with the energy $\gtrsim$ 100 MeV in SNe and 10 MeV in SNRs. Thus I suggest that the electrons emitting at GHz frequency are likely in the efficient DSA limit in SNRs, while they cannot be efficiently accelerated by DSA in SNe.

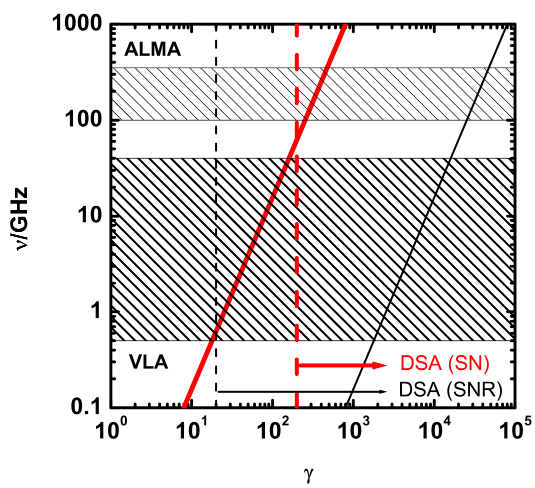

Figure 3: The relation between the electron's energy and the synchrotron frequency, for $B \sim 1$G typical of young SNe (red-thick-solid) and $\sim 100\mu$G typical of SNRs (black-thin-solid). Also shown is the *minimum* electron energy for the efficient DSA, adopting $V \sim 0.1c$ (SNe; red-thick-dashed) and $0.01c$ (SNRs; black-thin-dashed). The typical frequency coverage is shown by the shaded areas, for *cm* ('VLA') and *mm* ('ALMA') observations .

A unified scenario is proposed here – the steep energy spectrum of the electrons derived for young SNe reflects the inefficient DSA acceleration, or in other word, the 'injection' spectrum. This scenario makes young SNe interesting objects in studying the electron injection and acceleration mechanism, as one could directly probe the electron injection mechanism.

5 Perspectives for *mm* Observations

I propose that observations of nearby young SNe at *mm* wavelengths can potentially provide major advances in the issues discussed in this paper (see Maeda, 2013b for details). On the acceleration efficiency, the IC cooling effect is more important at higher frequencies, and thus at *mm* wavelengths one should be able to see this effect to determine $\epsilon_{\rm e}$, or at least place much stronger upper limit than at *cm* wavelengths. Alternatively, if $\epsilon_{\rm e}$ is very small, then the synchrotron cooling becomes important, and the cooling frequency would enter into the *mm* wavelength. If it happens, it will provide direct estimate of B. In either case, there is a good chance to obtain additional information, and then we can solve the degeneracy between the shock physics and the CSM environment (§2).

Another suggestion is on the electron injection. If the scenario suggested in §4 is correct, we should see the spectral flattening at high frequencies. This flattening could take place already at $\sim$ 100 MeV (§4), then one should be able to detect this signature at *mm* wavelengths (Fig. 3). If such a change in the electrons' energy spectral slope is detected, this could provide direct evidence of the non-liner acceleration theory where the particles' spectral slope is expected to become harder for higher energies (e.g., Ellison et al., 2004). The energy scale for the possible transition will provide strong constraints on the acceleration theory. For nearby objects (up to $\sim$ 25Mpc), such a signature should be detectable by *ALMA* (Maeda, 2013b).

6 Conclusions

In this paper, I have suggested to study electron acceleration mechanisms at a strong shock wave by radio observations of nearby young SNe. Especially, several ideas have been presented regarding (1) the acceleration efficiency and (2) injection problem and non-linear acceleration toward the efficient DSA. The ideas include (a) to constrain the efficiency by combining radio and optical data, (b) to place an independent constraint on the efficiency by the IC cooling effect, and (c) to probe propertis of 'injected' electrons before entering into the efficient DSA regime. I also propose that these issues can be further advanced by *mm* observations. Such observations are being planned – we have our ToO proposal of nearby SN follow-up observations by *ALMA* among the highest priority proposals in *ALMA* Cycle 1, which is currently active (until early 2014).

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References

[1] Bamba, A., et al.: 2003, ApJ, 589, 827 doi:10.1086/374687

[2] Bell, A.R.: 1978, MNRAS, 182, 147

[3] Bersten, M.C., et al.: 2012, ApJ, 757, 31 doi:10.1088/0004-637X/757/1/31

[4] Blandford, R.D., Ostriker, J.P.: 1978, ApJ, 221, L29 doi:10.1086/182658

[5] Björnsson, C.-I., Fransson. C.: 2004, ApJ, 605, 823

[6] Chevalier, R.A.: 1982, ApJ, 258, 790

[7] Chavalier, R.A., Fransson, C.: 2006, ApJ, 651, 381 doi:10.1086/507606

[8] Ellion, D.C., Berezhko, E.G., Baring, M.G.: 2000, ApJ, 540, 292 doi:10.1086/309324

[9] Fermi, E.: 1949, Phys. Rev. 75, 1169 doi:10.1103/PhysRev.75.1169

[10] Fransson, C., Lundqvist, P., Chevalier, R.A.: 1996, ApJ, 461, 993 doi:10.1086/177119

[11] Maeda, K.: 2012, ApJ, 758, 81

[12] Maeda, K.: 2013a, ApJ, 762, 14

[13] Maeda, K.: 2013b, ApJ, 762, L24

[14] Soderberg, A.M., et al.: 2012, ApJ, 752, 78 doi:10.1088/0004-637X/752/2/78

DISCUSSION

SERGIO COLAFRANCESCO: IC losses are dominant w.r.t. synchrotron loses if the B-field is low. How this can match with the expectation that the IC losses are important in high B-field regions in SNRs? What is a role of Coulomb heating effects?

KEIICHI MAEDA: On the IC cooling, I believe that we expect that in general the relative importance of the IC cooling is higher for lower B-field. Note that I am talking about cooling, not heating/emission. Here, the IC cooling rate is $L_{\rm IC} \propto u_{\rm ph}\gamma^2$ and the synchrotron cooling rate is $L_{\rm syn} \propto u_B\gamma^2$. Then, for given observed frequency ν, if one increases B then one should decrease γ (to emit at ν), leading to lower $L_{\rm IC}$. In this situation, $L_{\rm syn}$ can be large b/o the u_B term.

On the Coulomb heating. So far I have been focusing on SNe IIb/Ib/Ic, which are believed to have relatively low density CSM. I estimated the Coulomb effect, and at GHz or higher frequencies, the Coulomb heating is estimated to be negligible.