YOUNG SUPERNOVAE AS EXPERIMENTAL SITES FOR STUDYING
THE ELECTRON ACCELERATION MECHANISM

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ABSTRACT

Radio emissions from young supernovae (<1 year after the explosion) show a peculiar feature in the relativistic electron population at a shock wave, where their energy distribution is steeper than typically found in supernova remnants and than that predicted from the standard diffusive shock acceleration (DSA) mechanism. This has been especially established for the case of a class of stripped envelope supernovae (SNe IIb/Ib/Ic), where a combination of high shock velocity and low circumstellar material density makes it easier to derive the intrinsic energy distribution than in other classes of SNe. We suggest that this apparent discrepancy reflects a situation where the low energy electrons, before being accelerated by the DSA-like mechanism, are responsible for the radio synchrotron emission from young SNe, and that studying young SNe sheds light on the still-unresolved electron injection problem in the acceleration theory of cosmic rays. We suggest that the electron’s energy distribution could be flattened toward high energy, most likely around 100 MeV, which marks a transition from inefficient to efficient acceleration. Identifying this feature will be a major advance in understanding the electron acceleration mechanism. We suggest two further probes: (1) millimeter/submillimeter observations in the first year after the explosion and (2) X-ray observations at about one year and thereafter. We show that these are reachable by ALMA and Chandra for nearby SNe.

Key words: acceleration of particles – radiation mechanisms: non-thermal – shock waves – supernovae: general – supernovae: individual (SN 2011dh)

Online-only material: color figures

1. INTRODUCTION

The most promising cosmic-ray acceleration mechanism involves a strong shock wave. In the standard diffusive shock acceleration (DSA) scenario (Fermi 1949; Blandford & Ostriker 1978; Bell 1978), particles acquire energy through multiple shock crossings between upstream and downstream. Studying two acceleration sites—young supernova (SNe) and evolved supernova remnants (SNRs)—provides a seemingly controversial result. Young SNe expanding into circumstellar material (CSM) launch a strong shock wave. The shock wave generates/amplifies the magnetic field and accelerates electrons (Chevalier 1998; Chevalier & Fransson 2006), similar to SNRs. Stripped-envelope SNe, or SNe IIb/Ib/Ic, are well-studied in centimeter (cm) wavelengths (e.g., Chevalier & Fransson 2006; Soderberg et al. 2012; Krauss et al. 2012; Maeda 2012, 2013; Horesh et al. 2012). They are characterized by a combination of high shock velocity and relatively low CSM density, thus providing an ideal site for studying the intrinsic energy distribution of relativistic electrons, which are less affected by absorption or cooling than other classes of SNe (Chevalier 1998; Chevalier & Fransson 2006). The intrinsic power-law index is typically found to be $p \sim 3$ (where $N(E)/dE \propto E^{-p}$; Chevalier & Fransson 2006), which is not as efficient as predicted by the DSA mechanism ($p = 2$; Blandford & Ostriker 1978; Bell 1978; Ellison et al. 2000; Morlino & Caprioli 2012). On the other hand, the cm emission from SNRs is generally consistent with the DSA prediction (e.g., Bamba et al. 2003; Uchiyama et al. 2007).

In this Letter, we suggest that this apparent discrepancy indeed provides a strong indication of how electrons are injected into the DSA mechanism (Section 2). We suggest a scenario that explains the different properties of the radio-emitting electrons in a unified scheme. Our interpretation provides (at least) two observational signatures: (1) millimeter (mm) emissions in the first year after the explosion (Section 3) and (2) X-ray synchrotron emissions at about one year after the explosion and thereafter (Section 4). Section 5 presents concluding remarks.

2. ELECTRON ACCELERATION TOWARD THE DSA MECHANISM

A major issue remains concerning the acceleration of electrons. For the standard DSA mechanism (Fermi 1949; Blandford & Ostriker 1978; Bell 1978) to work effectively, the particles must already have enough kinetic energy (at least $\gamma \gtrsim 200$ for electrons in SNe IIb/Ib/Ic, where $\gamma$ is the Lorentz factor; see below). Numerical simulations predict that the energy distribution in the high energy regime follows the linear theory of DSA (with $p \sim 2$), while in the lower energy it can be steeper (Ellison et al. 2000; Morlino & Caprioli 2012). First, let us provide a simple argument on the energy above which the electrons are energetic enough to be accelerated by the efficient DSA-like mechanism. The width of the collisionless shock wave can be approximated by the gyroradius of downstream thermal protons, while the mean free path of relativistic electrons can be approximated by the gyroradius of the relativistic electrons. Therefore, the condition in which the electron’s mean free path exceeds the shock wave width is expressed as

$$E \gtrsim m_e c^2 \left(\frac{m_p}{m_e}\right) \left(\frac{V}{c}\right) \sim 100 \text{ MeV} \ (\text{i.e., } \gamma \gtrsim 200),$$

where $V \sim 0.1c$ is the shock wave velocity typically seen in young SNe IIb/Ib/Ic. The same criterion is $\gamma \gtrsim 20$ for SNRs with $V \sim 0.01c$. This assumes the Bohm limit for the strength of the random magnetic field turbulence, which is likely realized in the SN–CSM interaction, but if
this is not the case, the above criterion will decrease. Above this energy electrons can experience the whole compression ($r = 4$), therefore $p = (r + 2)/(r - 1) = 2$ in the test particle limit. On the other hand, the acceleration of electrons below this energy can be totally different: either the non-DSA pre-acceleration mechanism dominates or these electrons are partially accelerated by the DSA in the nonlinear regime (Ellison et al. 2000) where the subshock compression ratio is reduced by the feedback of the proton acceleration (Tatischeff 2009). These processes, which are expected for these low energy electrons, could result in a steep distribution with $p > 2$.

Now, we compare this critical energy scale to the energy of radio-synchrotron emitting electrons (in cm wavelengths). The electron's energy and the corresponding synchrotron emission frequency are connected by

$$\nu \sim 80 \gamma^{0.5} B^{-0.5},$$

where $\nu \equiv 10^{10} \nu_0$ Hz and $B$ is the magnetic field strength behind the shock in Gauss. Observationally, $B \sim 1$ G in SNe IIb/Ib/Ic and $B \sim 100 \mu$G in evolved SNRs. We note that this is consistent with an expectation from equipartition. In equipartition ($B^2/4\pi \equiv \epsilon_B \rho_{\text{CSM}} V^2$) and for the same reference value of $\epsilon_B \sim 0.1$, we expect $B \sim 1$ G for young SNe ($n_{\text{CSM}} \sim 10^6$ cm$^{-3}$ and $V \sim 0.1$c) and $B \sim 100$ G for SNRs ($n_{\text{ISM}} \sim 1$ cm$^{-3}$ and $V \sim 0.01$c). At 10 GHz, which is typical of cm wavelengths, the electrons’ energy, which is responsible for the emission, is $\gamma \sim 80$ in SNe IIb/Ib/Ic and $\gamma \sim 8000$ in SNRs.

Following the above estimate, it is clear that the electrons emitting in cm wavelengths are in totally different energy regimes in young SNe and SNRs. The electrons’ energy, which is responsible for the radio emission, is certainly much higher than the DSA requirement for SNRs, so they are likely efficiently accelerated. On the other hand, the radio-emitting electrons in young SNe are unlikely to satisfy the efficient DSA condition, i.e., the electrons do not feel the shock wave as infinitesimal discontinuity. We suggest that this is a reason why different intrinsic slopes are obtained for young SNe and SNRs.

This interpretation offers a unique opportunity for studying the electron acceleration mechanism, or the injection problem, through the SN–CSM interaction signals from young SNe. Our model curves are compared to the 5$\sigma$ detection limit in the continuum observation mode of ALMA with a 1 hr exposure in each band (Brown et al. 2004). Figure 1 shows that ALMA can detect the synchrotron signal from nearby SNe, and that the possible spectral flattening can be investigated. If we take $\gamma_{\text{fl}} \sim 200$ as our reference value (Section 2), this will be clearly identified in 100–345 GHz. For ALMA’s Cycle-1 and an exposure of 1 hr, this is reachable for typical SNe IIb/Ib/Ic up to $\sim 10$ Mpc and to $\sim 25$ Mpc or even more for SNe eIIb and the intermediate case. For the larger value of $\gamma_{\text{fl}}$, the beginning of this light curve flattening is delayed at the lower flux level.

Figure 2 shows the evolution of the synthesized spectrum as a function of time for $\gamma_{\text{fl}} = 200$. The spectral break frequency (corresponding to $\gamma_{\text{fl}}$) moves toward the lower frequency as time goes by. The break appears within the ALMA bands at $\sim 20$–100 day, and later enters into the lower frequency bands.

1 Peak radio date and luminosity of SNe IIb/Ib/Ic following the expectation that CSM density is varied when similar explosion properties are applied (Maeda 2013).

2 We have used the Cycle 1 ALMA Observing Tool for the sensitivity calculation (http://www.almaobservatory.org/).
Thus, the multi-epoch follow-up is crucial, and coordinated follow-up in cm wavelengths is strongly encouraged.

In these models, the synchrotron cooling is the dominant process in the energy range of interest here (Maeda 2012). The cooling frequency evolves toward the higher energy. For the "cIIb" model, it is initially below the ALMA bands, and later moves into the ALMA bands, and then it moves to even higher energy. This evolution is in the direction opposite of the one caused by the intrinsic spectral flattening, thus these two effects are distinguishable. An independent estimate of the magnetic field strength is gained through the relation \( t \sim 110(50.5 B^{-1.5}) \) days, providing a rare case to test different scenarios for magnetic field generation/amplification.

4. X-RAY EMISSION (e.g., CHANDRA)

Another suggestion for determining the spectral flattening is to examine a late-phase X-ray property (see also Chevalier & Fransson 2006). Figure 3 shows an expected X-ray light curve evolution \( (\nu L_\nu, \gamma) \sim 1 \keV \). This model assumes an additional low energy relativistic electron population at \( \gamma \sim 50 \) to account for the X-ray luminosity at \( \gamma \sim 50 \) to account for the X-ray luminosity at \( \sim 40 \) day via inverse Compton (IC) scattering, together with the power-law synchrotron-emitting electrons at \( \gamma \sim 50 \). For the IC, we assume that the SN bolometric light curve follows the \(^{56}\text{Co} \) decay after 100 days. This would overestimate the IC scattering effect there, so the IC contribution could decrease more quickly than shown in Figure 3 after 100 days. In addition to this reference model, Maeda (2012) provided another possibility, where the CSM density is as high as \( A_\nu \sim 30 \) and the early phase X-ray was dominated by the free–free emission from the thermal electrons (see also Campana & Immler 2012; Sasaki & Ducci 2012). While Maeda (2012; see also Soderberg et al. 2012) preferred the low-density solution in view of a connection to other SNe Ib/c, the early-phase observation of SN 2011dh itself did not discriminate between these two possibilities.

The synchrotron contribution is small compared to other mechanisms if we extrapolate the intrinsic electron energy distribution derived for the radio-emitting electrons \( (\nu L_\nu, \gamma) \sim 10 \) to the X-ray synchrotron-emitting electrons (i.e., without the flattening). With spectral flattening the synchrotron X-ray is enhanced, and can dominate the free–free emission at \( \leq 100 \) days if \( \gamma_0 \sim 200 \) (if \( A_\nu = 4 \)). It further dominates the IC X-ray at \( \leq 300 \) days. On the other hand, the free–free emission always dominates the X-ray emission if the CSM density is as high as \( A_\nu = 30 \). This provides a test for the origin of the X-ray emission from SN 2011dh. If the early-phase X-ray was due to the high density CSM and the free–free emission, then the late-phase X-ray luminosity should stay as luminous as \( 10^{37} \) erg s\(^{-1} \) even at a few years after the explosion. Otherwise, it should be below \( 10^{36} \) erg s\(^{-1} \).

The free–free emission follows the temporal evolution of \( \nu L_\nu \propto r^{-1} \) (Chevalier et al. 2006; Chevalier & Fransson 2006). The synchrotron X-ray is in the cooling regime and roughly follows \( \nu L_\nu \propto r^{-0.3} \) without flattening (Chevalier & Fransson...
According to this interpretation, we suggest that the relativistic electron’s energy distribution could be flattened toward high energy. We provide an estimate of the energy scale of electrons where this could most likely happen, at $\sim 100$ MeV (i.e., $\gamma_{\text{fl}} \sim 200$). We suggest that identifying (or constraining) this feature can provide an important clue for the still-unresolved electron injection problem, and propose two practically accessible diagnostics on this issue, (1) mm/sub-mm observations in the first year and (2) later X-ray observations around one year after the explosion or thereafter. The mm/sub-mm emission from stripped-envelope SNe is detectable up to $\sim 25$ Mpc by ALMA. The second is applicable up to $\sim 10$ Mpc by Chandra, and is currently testable for SN Ib 2011dh in M51.

Besides investigating the possible flattening of relativistic electrons’ distribution, these methods will provide additional information. The mm/sub-mm observation can be used to place an independent constraint on the magnetic field strength behind the shock wave. The later X-ray observation is able to distinguish the X-ray production mechanism in the early phase. Also, we emphasize the additional uniqueness of the mm/sub-mm observation—the transparency even for SNe Ib and possibly SNe Iip within dense CSM. By combining the cm and mm observations, both optically thick and thin emissions can be traced to derive the physical quantities behind the shock wave (see, e.g., Maeda 2012). We also note that this transparency increases the applicability of the method for studying the shock breakout using the early-phase synchrotron emission (Maeda 2013) of SNe with a denser CSM than in cm.

Our model prediction is based on the model that explains the cm emission from nearby SN cIIb 2011dh (Maeda 2012). SN 2011dh is typical among SNe cIIb/Ib/Ic in its radio properties (Soderberg et al. 2012), and there is a wide distribution of SNe Ib/Ib/Ic in the synchrotron luminosity (Chevalier et al. 2006; Chevalier & Soderberg 2010). There are radio-strong SNe Ib/Ib/Ic, more luminous than SN 2011dh by an order of magnitude or even more, including “engine-driven” SNe sometimes associated with GRBs (Soderberg et al. 2010). For these especially radio strong SNe, the ALMA detectable horizon extends to even greater distances, i.e., $\sim 100$ Mpc.

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5. CONCLUDING REMARKS

In this Letter, we have proposed new approaches to investigating the injection and acceleration problem of relativistic electrons at a strong shock wave. A peculiar feature derived from synchrotron radio emissions (in cm wavelengths) from nearby young SNe, especially established for stripped-envelope SNe (Ib/Ib/Ic), is the steepness in the intrinsic energy distribution of the radio-emitting relativistic electrons. We suggest that this steep distribution could result from a pre-acceleration mechanism, which is able to energize electrons up to the energy threshold needed to start the DSA, as the cm emission is produced by electrons whose mean free path is smaller than the shock wave width under the physical conditions realized in young SNe.

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