PROBING SHOCK BREAKOUT AND PROGENITORS OF STRIPPED-ENVELOPE SUPERNOVAE THROUGH THEIR EARLY RADIO EMISSIONS

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ABSTRACT

We study properties of early radio emission from stripped-envelope supernovae (SNe; those of Type IIb/Ib/Ic). We suggest there is a sub-class of stripped-envelope SNe based on their radio properties, including the optically well-studied Type Ic SNe (SNe Ic) 2002ap and 2007gr, showing a rapid rise to a radio peak within ∼10 days and reaching a low luminosity (at least an order of magnitude fainter than a majority of SNe IIb/Ib/Ic). They show a decline after the peak that is shallower than that of other stripped-envelope SNe while their spectral index is similar. We show that all these properties are naturally explained if the circumstellar material (CSM) density is low and therefore the forward shock is expanding into the CSM without deceleration. Since the forward shock velocity in this situation, as estimated from the radio properties, still records the maximum velocity of the SN ejecta following the shock breakout, observing these SNe in radio wavelengths provides new diagnostics on the nature of both the breakout and the progenitor which otherwise require a quite rapid follow-up in other wavelengths. The inferred post-shock breakout velocities of SNe Ic 2002ap and 2007gr are sub-relativistic, ∼0.3c. These are higher than that inferred for SN II 1987A, in line with suggested compact progenitors. However, these are lower than expected for a Wolf–Rayet (W-R) progenitor. It may reflect an as yet unresolved nature of the progenitors just before the explosion, and we suggest that the W-R progenitor envelopes might have been inflated which could quickly reduce the maximum ejecta velocity from the initial shock breakout velocity.

Key words: circumstellar matter – radiation mechanisms: non-thermal – shock waves – supernovae: general – supernovae: individual (SNe 2002ap, 2007gr)

Online-only material: color figures

1. INTRODUCTION

Core-collapse supernovae (CC-SNe) are explosions of a massive star with a zero-age main-sequence mass ($M_{ms}$) exceeding ∼8 $M_{\odot}$. Their observational appearance is diverse, controlled by the nature of the progenitor star, the explosion, and the circumstellar environment. These are probably mutually connected through intrinsic controlling factors, including at least the progenitor mass, metallicity, and binarity. Clarifying these mutual relations is a key issue in the study of supernovae (SNe). For this reason, stripped-envelope SNe (SNe IIb/Ib/Ic; Filippenko 1997) have been a target of various studies. Being explosions of stars that have lost all or most of their hydrogen envelopes before the explosion (Nomoto et al. 1993), their origins are likely a mixture of different evolutionary paths (i.e., a single massive star with $M_{ms} \gtrsim 25 M_{\odot}$ or a binary evolution with $M_{ms} \lesssim 25 M_{\odot}$). They show diverse properties in explosion energies (Nomoto et al. 2010), with the most energetic ones linked to gamma-ray bursts (GRBs; see, e.g., Woosley & Bloom 2006 for a review). In this paper, we address the following three issues about their nature: (1) the nature of the shock breakout, (2) the progenitor structure and its relation to the shock breakout signal, and (3) radio emissions and the circumstellar material (CSM) environment.

The shock breakout emission is the first electromagnetic signal from SNe (Falk & Arnett 1977; Klein & Chevalier 1978). When the shock wave launched in the deepest part of the progenitor emerges from the stellar surface, an intensive UV/X-ray flash bursts out of the shock wave. The typical spectral energy of the emission is predicted to be sensitive to the progenitor radius, and for a Wolf–Rayet (W-R) progenitor it is mostly in X-rays. The shock breakout phenomenon was predicted theoretically more than a few decades ago, but so far its detection has been rare (Soderberg et al. 2008; Schavinski et al. 2008; Gezari et al. 2008; Modjaz et al. 2009) and was first inferred from the ionization structure around SN 1987A (Lundqvist & Fransson 1996). The shock breakout is essentially a very brief transient event. It is now an important target of time-domain astronomy, including future optical survey proposals to catch the shock breakout signals from high-z SNe (e.g., Tominga et al. 2011). However, such optical surveys are not optimized for SNe from a W-R progenitor (i.e., a leading progenitor scenario for SNe IIb/Ic, since it is an X-ray event lasting only for $\sim R_*/c \sim 10$ s (where $R_*$ is the progenitor radius and $c$ is the speed of light). The final stage of stellar evolution has not been clarified for stripped-envelope SNe. Estimating the radius of a progenitor star provides important insight here, highlighted by the direct detection of an unprecedented blue supergiant progenitor with $R_* \sim 50 R_\odot$ for SN II 1987A (see Arnett et al. 1989 for a review). So far, without direct progenitor detection (see Smartt 2009 for a recent review), the shock breakout signal and subsequent early optical emission have been used to estimate the size of the progenitors of SNe Ib/Ic (Soderberg et al. 2008; Chevalier & Fransson 2008; Modjaz et al. 2009; Rabinak & Waxman 2011). SN Ib 2008D is the only example where the shock breakout X-ray was convincingly detected (Soderberg et al. 2008; Chevalier & Fransson 2008; Rabinak & Waxman 2011). Any other independent information on the as yet unresolved nature of the progenitors is highly valuable.
Radio emissions have been detected from a number of nearby SNe Ib/Ib/Ic (see Chevalier & Fransson 2006 for a review). The radio emission is created through SN–CSM interaction, thus it is a strong tool with which to study the CSM environment. A relation between the time of the peak ($t_p$) and the luminosity at the peak ($L_p$) can be used to estimate the size of the emitting region (thus the velocity of the shock wave at the SN–CSM interaction), and the CSM density (Chevalier 1998). Generally SNe of different spectral sub-classes occupy different regions in the $t_p$–$L_p$ plot, and SNe Ib/c (plus a part of SNe Ib, i.e., “compact” SNe Ib; “cllb” hereafter) are characterized by relatively low $t_p$ and large $L_p$ for a given $t_p$ (Chevalier & Fransson 2006; Chevalier & Soderberg 2010). However, radio emission from SNe Ib/Ib/Ic is diverse in a sense that, even excluding outliers, they span more than an order of magnitude in both $t_p$ and $L_p$ for a majority of SNe Ib/c (Berger et al. 2003; Björnsson & Fransson 2004).

Among SNe IIb, SNe show features different from other SNe aside from just the radio spectral slope of $\frac{\alpha}{\beta}$ (Berger et al. 2003; Björnsson & Fransson 2004). While $L_p \sim 10^{27}$ erg s$^{-1}$ Hz$^{-1}$ and $t_p(\nu_p/5$ GHz) $\sim$ 30 days for a majority of SNe Ib/c, in SN 2002ap, $L_p \sim 10^{25}$ erg s$^{-1}$ Hz$^{-1}$ and $t_p(\nu_p/5$ GHz) $\sim$ 3 days, characterized by an extremely low luminosity and a fast rise to the peak. According to the SSA scaling relation, the CSM density is estimated to be lower than that of other SNe Ib/c at least by an order of magnitude. In the optically thin phase, a majority of SNe Ib/c show a radio spectral slope of $\alpha \sim -1$ and a temporal slope of $-1.5 \lesssim \beta \lesssim -1.3$ (where $L_p \propto \nu^{\alpha \beta}$; Chevalier & Fransson 2006). However, SN 2002ap showed a shallow decay with $\beta \sim -0.9$ while the spectral index was similar to that of other SNe ($\alpha \sim -0.9$; Berger et al. 2003; see also Björnsson & Fransson 2004; Chevalier & Fransson 2006). This peculiarity negates a standard interpretation for SN 2002ap. There has been only one theoretical interpretation suggested so far: the slope of the relativistic electrons’ energy distribution might have been different and flatter than in other SNe Ib/c (Björnsson & Fransson 2004; see also Chevalier & Fransson 2006).

We point out that SN Ic 2007gr has radio properties similar to SN 2002ap, despite its optical properties belonging to a “normal” (or non-broad-line) class (Hunter et al. 2008; Valenti et al. 2008). In Figure 1, we compare the multi-band radio light curves of SNe 2002ap and 2007gr.
SN 2007gr showed the temporal slopes of SNe 2002ap and 2007gr \( (\beta \lesssim -1) \) are different from other SNe Ib/c, placing this SN close to SN 2002ap in these properties. Furthermore, the radio spectral index and decay slope in optically thin phases are similar to those of SN 2002ap. Not only the \( \nu_p \) and \( \nu_m \), but also the temporal slopes of SNe 2002ap and 2007gr \( (\beta \lesssim -1) \) are different from other SNe Ib/c \( (\beta \lesssim -1.3) \), while their spectral indices are similar \( (\alpha \sim -1) \) to those of other SNe Ib/c.

The previous theoretical interpretation of the radio emission from SN 2002ap was based on the slow decay rate as mentioned above (Björnsson & Fransson 2004), and this is our motivation for investigating an alternative explanation for this behavior. However, it should be noted that the quality of the radio data of SN 2002ap, as well as that of SN 2007gr, does not allow for a very accurate determination of the decay rate. Fitting the radio light curve of SN 2002ap (Berger et al. 2003) during 4−50 days (eight points) by a function \( f_c \propto t^\beta \), we obtain \( \beta = -0.87 \pm 0.17 \) at 8.46 GHz. The error indicated here is 1σ. For SN 2007gr (Soderberg et al. 2010a), we obtain \( \beta = -0.85 \pm 0.12 \) (4−18 days, five points). For comparison, the “radio-normal” SN e11b 2011dh (Soderberg et al. 2012; Krauss et al. 2012) shows \( \beta = -1.13 \pm 0.16 \) at 29.0 GHz (30−100 days, four points). So, the preferred value of the decay rate \( (\beta) \) is flatter by \( \sim 0.3 \) in SNe 2002ap and 2007gr than in the canonical case. The deviation of SN 2002ap in the decay rate from the canonical value \( (\beta = -1.3) \) is therefore at the 2.5σ level, and for SN 2007gr it is above 3σ. Given the small number of data points, however, this nominal significance should be regarded as merely indicative. In any case, in this paper we will investigate the implications provided by this slow decay.

As summarized in this section, SNe 2002ap and 2007gr (seem to) share common properties, and we suggest that they form a sub-class of stripped-envelope SNe based on their radio properties. Observationally this class of objects is rare (about 10% of radio-detected stripped-envelope SNe), but may well intrinsically include a large fraction of stripped-envelope SNe: SNe 2002ap and 2007gr are among the nearest examples of stripped-envelope SNe, and they would not have been detectable at \( \sim 30 \) Mpc, i.e., the typical distance of most radio-detected SNe (Soderberg et al. 2010a). Future observations of nearby SNe in radio wavelengths will be critical to establish if the shallow decay is a common property of these radio low-luminosity stripped-envelope SNe.

3. HYDRODYNAMICS IN THE EARLY PHASE

One of the striking features of radio emission from SNe 2002ap and 2007gr is the short rise time, with timescales less than 10 days. In this section we discuss the hydrodynamic evolution of the shocked region in this early phase. In previous studies, the self-similar solution for the interaction between the expanding SN ejecta and CSM has been assumed (Chevalier 1982). However, the basic assumption in the formalism would not apply in the very early phase of the expansion and/or low CSM density. The effect of the interaction on the hydrodynamic evolution becomes important only after a sufficient amount of CSM is swept up by the forward shock, and then the ejecta begin to decelerate, following the self-similar solution that is eventually established. Before this phase, the ejecta feel the CSM almost as a vacuum, thus they are in the free-expansion phase.\(^2\)

The density structure at the outermost ejecta can be approximated by

\[
\rho_{SN} \sim 8.3 \times 10^{-18} E_{51}^{3.59} \left( \frac{M_{SN}}{M_\odot} \right)^{-2.59} \times \left( \frac{V}{0.3c} \right)^{-10.18} t_d^{-3} \text{ g cm}^{-3},
\]

where \( \rho_{SN} \) is the density of the SN ejecta at velocity \( V \), \( E_{51} \) is the kinetic energy of the SN ejecta (in unit of \( 10^{51} \) erg), \( M_{SN} \) is the ejecta mass, and \( t_d \) is the time since the explosion in days (Matzner & McKee 1999; Chevalier & Fransson 2008).

The maximum velocity of the SN ejecta is determined by the shock breakout set by the radiative losses due to the shock breakout flash, unless a process exists that could alter the dynamics at the highest velocity ejecta after the breakout. Although detailed radiation hydrodynamic modeling is required to obtain the exact value and the result depends on details in the treatment of the physics involved, the first-order estimate can be obtained by analytic considerations (Matzner & McKee 1999):

\[
V_{SN} \sim 0.48c \left( \frac{\kappa}{0.34 \text{ cm}^2 \text{ g}^{-1}} \right)^{0.16} E_{51}^{0.58} \left( \frac{M_{SN}}{M_\odot} \right)^{-0.42} \times \left( \frac{R_*}{10 R_\odot} \right)^{-0.32},
\]

where \( R_* \) is the radius of the progenitor (for that with a radiative envelope).

Let us assume that the density distribution of the CSM is expressed by the steady wind solution, \( \rho_{CSM} = M/4\pi v_w^2 \) (where \( M \) and \( v_w \) are the mass-loss rate and the wind velocity). Thus,

\[
\rho_{CSM} = 5 \times 10^{11} A_* v_w^{-2} \text{ g cm}^{-3},
\]

where \( A_* \approx 1 \) is a reference value corresponding to typical W-R mass-loss properties (i.e., \( M \sim 10^{-5} M_\odot \) yr\(^{-1} \) and \( v_w \sim 1000 \) km s\(^{-1} \)). Once the self-similar solution is established, the evolution of the velocity at the contact discontinuity follows the following form (Chevalier 1982; Chevalier & Fransson 2006):

\[
V_c \sim 8 \times 10^9 E_{51}^{0.43} \left( \frac{M_{SN}}{M_\odot} \right)^{-0.32} A_*^{-0.12} t_d^{-0.12} \text{ cm s}^{-1}.
\]

Since the self-similar solution describes the deceleration of the ejecta, the velocity here should be smaller than \( V_{SN} \). Thus, the self-similar solution does not apply if

\[
t \lesssim t_{dec} \approx 0.4 E_{51}^{3.58} \left( \frac{M_{SN}}{M_\odot} \right)^{-2.67} A_*^{-1} \left( \frac{V_{SN}}{0.3c} \right)^{-8.33} \text{ days}.
\]

Assuming \( V_{SN} \gg 0.1c \) and the typical value of a few \( M_\odot \) for the ejecta mass and \( A_* \sim 1 \), the strong interaction starts at the latest a few days after the explosion, and thus the free-expansion phase is negligible. This justifies the use of the

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\(^2\) The decelerated ejecta following the self-similar solution are frequently referred to as the “free expansion” in much of the literature since the deceleration is not large in the self-similar solution considered here (i.e., \( R \propto t^{1/2} \)) as compared to the Sedov phase (i.e., \( R \propto t^{1/3} \)) in CSM with constant density. In this paper, we refer to the “truly” free-expansion phase (i.e., \( R \propto t \)) before the establishment of the self-similar solution as the “free-expansion” phase.
A self-similar solution for most SNe. However, if $V_{\text{SN}} \lesssim 0.1c$, then even a typical W-R wind density is not enough to decelerate the ejecta to reach the self-similar solution within the timescale of $\sim 100$ days. Furthermore, a low CSM density prevents the SN ejecta from being decelerated, and with $A_*=0.01$ as inferred for the sub-class of SNe Ib/c (for example, the scaling relation of the SSA peaks implies that $A_*=0.04$ for SN 2002ap), the ejecta do not experience significant deceleration for $\sim 100$ days even with $V_{\text{SN}} \sim 0.2c$.

To confirm the above arguments, we have performed a series of hydrodynamic simulations for the early phase of the interaction. The ejecta structure is assumed to follow a power law up to the maximum ejecta velocity $V_{\text{SN}}$ (Equation (1)), with $E_1=1$ and $M_1=3M_\odot$. The CSM density distribution is assumed to be a power law as described by Equation (3). We have varied $V_{\text{SN}}$ and $A_*$ as parameters, choosing $V_{\text{SN}} = 0.1c, 0.2c, 0.3c$ and $A_* = 0.01, 1, 100$ (thus a total of nine models were investigated). The interaction starts at day 1 since explosion. Adiabatic Euler equations under spherical symmetry have been solved with the adiabatic index of 5/3, using the Harten–Lax–van-Leer Contact solver (Toro 1999) to treat the discontinuity and the shock waves (Maeda et al. 2002). The number of meshes is 8500, linearly covering up to $7.8 \times 10^{16}$ cm, so the spatial resolution is about $10^{15}$ cm which is sufficient to resolve the detailed structure of the interaction region throughout the computation.

Figures 2 and 3 show the evolution of the forward shock velocity and radius as a function of time. It is seen that the above analytical estimate roughly explains the behavior of the shock wave velocity: models with low $V_{\text{SN}}$ and/or low $A_*$ do not follow self-similar deceleration, but rather show an almost constant forward shock velocity. According to Equation (5), we expect $t_{\text{dec}}$ as follows: for $A_* = 100$, $t_{\text{dec}} < 2$ days for all values of $V_{\text{SN}}$, for $A_* = 1$, $t_{\text{dec}} < 1$ day for $V_{\text{SN}} > 0.2c$ but $\sim 200$ days for $V_{\text{SN}} = 0.1c$, and for $A_* = 0.01$, $t_{\text{dec}} \sim 2, 60, 20,000$ days for $V_{\text{SN}} = 0.3c, 0.2c, 0.1c$, respectively. In the simulations, for $A_* = 100$ the self-similar solution is approximately reached for all the cases. For $A_* = 1$ the high-velocity models with $V_{\text{SN}} \gtrsim 0.2c$ quickly follow the self-similar solution but the model with $V_{\text{SN}} = 0.1c$ starts to decelerate at $t \sim 100$ days. For $A_* = 0.01$, the model with $V_{\text{SN}} = 0.1c$ never experiences deceleration during the simulated period of time, and the model with $V_{\text{SN}} = 0.2c$ does not show signs of deceleration before $t \sim 40$ days.

Figure 4 shows the evolution of the velocity profiles for SN models expanding into the low-density CSM with $A_* = 0.01$, with the SN ejecta velocity $V_{\text{SN}} = 0.1c, 0.2c$, and $0.3c$. One immediately notices that all three models do not follow the self-similar solution in the early phase, since in such a case there must...
be no difference according to different $V_{SN}$. In our simulations, the velocity of the leading edge of the ejecta is not identical to the initial value (i.e., $V_{SN}$). At 6 days after the explosion (which may depend on the initial setup), the forward shock begins to develop, and the maximum velocity of the ejecta is $\sim 75,000$ km s$^{-1}$ for $V_{SN} = 0.3c$, 65,000 km s$^{-1}$ for $V_{SN} = 0.2c$, and 45,000 km s$^{-1}$ for $V_{SN} = 0.1c$. Thus, the kinetic energy is redistributed in such a way that it is decelerated for a large value of $V_{SN}$ and accelerated for a small value of $V_{SN}$. This kinetic energy redistribution may partly stem from a specific simulation setup, and details of this process could be dependent on the initial conditions. In any case, once the velocity profile is quickly adjusted, there is no further significant evolution, and the following arguments should not be sensitive to details in the numerical setup. The forward shock is formed with the velocity at roughly 80% of the (redistributed) maximum velocity of the ejecta, and the forward shock expands into the CSM at almost constant velocity without deceleration.

It has been argued that the free-expansion phase is negligible for SNe Ib/c, with the shock breakout velocity $V_{SN} > 0.3c$ estimated with Equation (2) or similar expressions, under the assumption that $R_e \sim R_\odot$ (Chevalier & Fransson 2006). However, it is not yet clear to what extent the analytic expression of the shock breakout physics is accurate: the expression is an order-of-magnitude estimate with various assumptions. The progenitor structure just before the explosion is under debate, without direct detection of the SNe Ib/c progenitors. For example, a peculiar SN Ib 2006jc showed a luminous-blue-variable-like eruption about two years before the SN explosion (Pastorello et al. 2007). The mechanism of such an outburst of the proposed WCO W-R progenitor (Tominaga et al. 2008) has not yet been clarified, highlighting our ignorance of the final evolution of W-R stars toward an SN explosion.

Considering all of these uncertainties in the shock breakout dynamics and progenitor scenarios, our motivation in this paper is to tackle these issues from the opposite direction: we first provide possible, observationally based information on these issues, then compare this with theoretical expectations. Our strategy is as follows. Rather than starting with the shock velocity based on Equation (2) (or similar expressions), we first compare the velocity of the forward shock estimated from the radio data and that predicted by the self-similar decelerating solution. The two should agree if the dynamics are in the self-similar phase, while the radio-derived velocity will be lower than the self-similar expectation if the ejecta are in the free-expansion phase. We then examine the radio spectra and light curve properties of these SNe to see if the free-expansion solution provides a consistent view. Once we obtain information on the free-expansion velocity through these analyses, then we could translate this information to the velocity of the shock breakout. This can then be used to calibrate the shock breakout physics (e.g., Equation (2)) and/or the nature of progenitors.

Useful diagnostics of the expansion of the forward shock, especially for stripped-envelope SNe, are provided by the observed $t_{\nu} - L_{\nu}$ relation. Figure 5 is a reproduction of the diagram from Soderberg et al. (2012; see also Chevalier 1998; Chevalier et al. 2006). The overplotted lines in the figure are the estimates that divide the (truly) free-expansion phase and the self-similar deceleration phase using Equation (5), for different choices of ejecta mass. Below these lines, the observationally derived velocity (through the SSA model) is smaller than the self-similar prediction; thus SNe in this range are very likely in the free-expansion phase.

![Figure 5](image_url)  
Figure 5. Radio properties of SNe Ib/Ib/Ic and SN II 1987A in the $t_{\nu} - L_{\nu}$ plot. The observed points are a reproduction of Soderberg et al. (2012) (see also Chevalier et al. 2006; Chevalier & Soderberg 2010), showing SNe Ic (cyan), Ib (green), cIIb (orange), clfb (red), "engine-driven" SNe Ic (including those associated with GRBs, blue), and 1987A (yellow). The velocity estimate with SSA scaling is shown by the dotted lines. The expectation from the self-similar hydrodynamic evolution is shown by the shaded area (blue, red, and green) for $\epsilon_b = 0.1$ and $\alpha = \epsilon_e/\epsilon_b = 0.1$–1, with $E_{51}$ and $M_{ej}$ given in the labels. The self-similar expectation for the specific cases of SNe 2002ap ($E_{51} = 5$, $M_{ej} = 3 M_\odot$), 2007gr ($E_{51} = 2$, $M_{ej} = 2 M_\odot$), and 1987A ($E_{51} = 1.4$, $M_{ej} = 14$) are shown by the red-filled area.

(A color version of this figure is available in the online journal.)

Figure 5 shows that SNe Ib/c as well as clfb generally follow the self-similar solution with $E_{51} \sim 1$ and $M_{ej} \sim 1–3 M_\odot$. An exception is SN 2002ap (as well as 1987A) which falls well below the self-similar prediction. Since different SNe have different properties in $E_{51}$ and $M_{ej}$, one has to compare the self-similar evolution and the radio properties on a case-by-case basis. With $E_{51} \sim 5$ and $M_{ej} \sim 3 M_\odot$ for SN 2002ap estimated through optical modeling (Mazzali et al. 2002), the discrepancy between the self-similar solution and the observed radio properties is even larger. The same argument applies to SNe 2007gr ($E_{51} \sim 2$, $M_{ej} \sim 2 M_\odot$; Hunter et al. 2008; Valenti et al. 2008) and 1987A ($E_{51} \sim 1.4$, $M_{ej} \sim 14 M_\odot$; e.g., Blinnnikov et al. 2000; Maeda et al. 2002), which showed that their radio properties are also below the self-similar case. Thus, we suggest that the shock wave evolution of SNe 2002ap and 2007gr (and 1987A) was in the free-expansion phase in these early epochs responsible for the early radio emission covering the SSA peak.

4. RADIO EMISSION FROM SNe WITHIN LOW-DENSITY CSM

Results from previous studies on the radio properties of SN 2002ap have been controversial. In the following, we show that a self-consistent picture can be obtained by considering the "free expansion" which was not taken into account in previous studies. We further show that the same solution could apply to SN 2007gr as well. In our scenario, the peculiar features of SNe 2002ap and 2007gr are natural consequences of SNe exploding within a relatively low-density CSM.

We calculate radio emissions from SNe Ib/c as follows. The basic formalisms have been developed by Fransson & Björnsson (1998) and Björnsson & Fransson (2004), and specific prescriptions used here are given by Maeda (2012; see also Chevalier
The synchrotron radio luminosity \(v L_v\) in the optically thin phase is given as
\[
v L_v \sim \pi R_{sh}^2 V_{sh} n_{rel} v v_{\nu}^{-2} \beta m_{e} c^2 \left[ 1 + \frac{t_{\text{sync}(v)}}{t} + \frac{t_{\text{sync}(v)}}{t_{\text{other}(v)}} \right]^{-1}.
\]  
(6)

Here \(R_{sh}\) and \(V_{sh}\) are the position and the velocity of the forward shock, and \(n_{rel}\) is the number density of the relativistic electrons. The relativistic electrons are assumed to follow a power-law distribution with index \(\beta\) as a function of energy (note that throughout this paper we use \(p\) as the intrinsic power-law index, before being altered by cooling effects). \(t_{\text{sync}}\) is the synchrotron cooling timescale. \(t_{\text{other}}\) is the timescale for other energy loss processes that do not emit at the radio frequency (i.e., inverse Compton (IC) scattering in the situation investigated here). The Lorentz factor of the electrons emitting at frequency \(v\) is \(\gamma_v \sim 80 v_{\nu}^{0.5} B^{-0.5}\) (here \(v_{\nu} = v / 10^{19}\) Hz and \(B\) is in Gauss).

In SNe Ib/Ib/Ic, the assumption of equipartition has been proven to work well (Fransson & Björnsson 1998; Soderberg et al. 2005; Chevalier & Fransson 2006). The energy densities of the relativistic electrons and the magnetic field behind the shock wave are proportional to the thermal energy density created by the shock wave, while the proportional coefficients \(\epsilon_e\) and \(\epsilon_B\) are generally found to be lower than the full equipartition: typically \(\epsilon_e = \epsilon_B = 0.1\) is assumed for simplicity, while Fransson & Björnsson (1998) and Maeda (2012) have suggested \(\epsilon_e \lesssim 0.01\) and \(\epsilon_B \sim 0.01-0.15\). Our general arguments are independent of the values of \(\epsilon_e\) and \(\epsilon_B\), a further discussion of which is given in the Appendix. The amplified magnetic field strength and the relativistic electron density are expressed as follows:
\[
B \sim 2.2 \times 10^6 \epsilon_B^{-0.5} A_{*}^{0.5} V_{sh} \text{ cm}^{-3} \text{ gauss},
\]  
(7)

\[
n_{rel} \sim 2.4 \times 10^{19} \frac{p - 2}{p - 1} \epsilon_{e, -1} A_{*} \left( \frac{V_{sh}}{R_{sh}} \right)^2 \text{ cm}^{-3}.
\]  
(8)

Substituting these expressions into Equation (6), the synchrotron emission is scaled as
\[
L_v \propto V_{sh}^{3} v^{-p/2} B^{p - 2/2} \left[ 1 + \frac{t_{\text{sync}(v)}}{t} + \frac{t_{\text{sync}(v)}}{t_{\text{other}(v)}} \right]^{-1}.
\]  
(9)

Note that so far no assumption has been made on the time dependence of the expansion of the interaction region.

In these SNe, the main cooling agencies are synchrotron cooling and IC scattering. These cooling timescales are estimated as
\[
t_{\text{sync}(v)} \sim 110 v_{\nu}^{-0.5} B^{-1.5} \text{ days},
\]  
(10)

\[
t_{\text{IC}(v)} \sim 1.7 v_{\nu}^{0.5} B^{0.5} \left( \frac{L_{\text{SN}}}{10^{42} \text{ erg s}^{-1}} \right)^{-1} \left( \frac{R_{sh}}{10^{15} \text{ cm}} \right)^2 \text{ days}.
\]  
(11)

Now, the spectral index \((\alpha)\) and the temporal slope \((\beta)\) of the synchrotron emission can be computed (here \(L_v \propto v^{\alpha} t^{\beta}\)). Describing the expansion dynamics as \(R_{sh} \propto t^{m}\) (therefore \(V_{sh} \propto t^{m-1}\)), the result is summarized in Table 1.

### Table 1

| Characteristics of the Synchrotron Emissiona |
|-----------------|-----------------|-----------------|
| \(\alpha\) | \(\beta\) | \(\gamma\) |
| \(\beta(p = 2)\) | \(\beta(p = 3)\) | \(\gamma(p = 3)\) |
| \((3m - 3) - \frac{1}{2}\) | \((3m - 3) - \frac{1}{2}\) | \((3m - 3) - \frac{1}{2}\) |
| \((5m - 5) + \frac{3}{2}\) | \((5m - 5) + \frac{3}{2}\) | \((5m - 5) + \frac{3}{2}\) |

Note. *The spectral index \((\alpha)\) and temporal slope \((\beta)\) are shown for different cooling regimes \((L_v \propto v^{\alpha} t^{\beta})\). These are characterized by the electron distribution power-law index \((p)\), the evolution of the forward shock \((m, \text{where } R_{sh} \propto t^m)\), and the evolution of the bolometric luminosity \((\gamma, \text{where } L_{bol} \propto t^{\gamma})\).*

A majority of SNe Ib/c show a spectral index \((\alpha) \sim -1\) and a temporal slope of \(-1.5 \lesssim \gamma \lesssim -1.3\) (Chevalier & Fransson 2006), consistent with the adiabatic expansion following the self-similar deceleration \((m \sim 0.9)\) with \(\gamma \sim 3\). The “low-density CSM” SNe Ic, 2002ap and 2007gr, differ from the other cases in temporal slope: they show a rather shallow decay, \(\beta \sim -1\), while the spectral index is similar to that of others \((\alpha \sim -1)\). One solution is to assume that the intrinsic slope of the relativistic electron distribution is flatter \((p \sim 2)\) than other SNe Ib/c \((p \sim 3)\) and that the electrons emitting in the radio frequency are in the IC cooling regime (Björnsson & Fransson 2004), while assuming self-similar dynamics \((m \sim 0.9)\). In this case, the spectral slope is reproduced (see Table 1). The temporal evolution of the (optical) bolometric luminosity of SN 2002ap was roughly \(\propto t^{0.8}\) before 10 days after the explosion, and \(\propto t^{-0.5}\) after that until 20 days after the explosion (Yoshii et al. 2003; Tomita et al. 2006). Thus, if the IC cooling dominates, then the radio temporal evolution will follow \(L_v \propto t^{0.3}\) and \(\propto t^{-1}\) before and after the optical peak (if the frequency of interest is optically thin). Well after the optical peak, the cooling will become less important as time goes by, so the radio light curve will be flattened until it reaches the temporal behavior of \(L_v \propto t^{-0.8}\) (for \(p = 2\)). Thus, this scenario roughly explains the radio flux evolution, \(\beta \sim -0.9\) as observed.

Although the scenario is consistent with the available observational data and can also explain the X-ray emission together with the radio (Björnsson & Fransson 2004), a drawback of the scenario is that it requires an electron distribution quite different from that of other SNe Ib/c. Note that for a magnetic field strength of \(B \sim 0.3\) Gauss (Björnsson & Fransson 2004), the radio emission is produced by electrons with an energy of \(\gamma \sim 50-150\), similar to those responsible for radio emission from other SNe eIIb/Ib/Ic (e.g., Maeda 2012). Thus, the different slopes cannot be attributed to the different energy regimes probed for different objects. If this is true, it might mean that being a broad-line SN Ic, SN 2002ap might have much more efficient electron acceleration (Chevalier & Fransson 2006), but as we show in Section 2 the same argument should apply to SN 2007gr, which is a non-broad-line canonical SN Ic, making this interpretation less appealing.

In this paper, we suggest another solution for radio emission from SN Ic 2002ap, which also naturally explains why the “canonical” SN Ic 2007gr shares similar properties. The analysis in the previous section suggests that the ejecta expansion of SNe 2002ap and 2007gr is approximated by the free expansion without any deceleration, rather than by the decelerating self-similar solution. In this case, \(\alpha \sim -1\) and \(\beta \sim -1\) are
In Figure 6, we also show the light curves with the IC cooling, the story is complicated by the effect of the IC cooling. Without the IC cooling, is ignored. The solid line in the figure), if the other cooling mechanism, i.e., the synchrotron cooling (e.g., Chevalier & Fransson 2006; Soderberg et al. 2012), is included. With the set of parameters adopted, the IC cooling is indeed important, confirming the claim made in previous works (Björnsson & Fransson 2004; Chevalier & Fransson 2006). With the standard $p = 3$, we predict that SNe in the low-density environment peak early in radio with a temporal index of $\beta \sim -1$, while in the higher density environment SNe peak later and show a temporal evolution of $\beta \sim -1.3$.

The radio light curves computed for the free-expansion case as compared to those of SN 2002ap are shown in Figure 6. The microphysics parameters are set as $\epsilon_B = \epsilon_e = 0.1$, as typically assumed for radio SNe. As expected from Figure 5, we require a relatively high forward shock velocity ($V_{sh} = 60,000 \text{ km s}^{-1}$) and low-density CSM ($A_e = 0.007$). The synchrotron cooling is included in the model, but its effect is negligible. Thus, the light curves show the temporal slope $\beta \sim -1$ as observed (red solid line in the figure), if the other cooling mechanism, i.e., the IC cooling, is ignored.

Although it looks like a simple and straightforward interpretation, the story is complicated by the effect of the IC cooling. In Figure 6, we also show the light curves with the IC cooling included. With the set of parameters adopted, the IC cooling is indeed important, confirming the claim made in previous works (Björnsson & Fransson 2004; Chevalier & Fransson 2006). With the standard $p = 3$, the model now fails to reproduce the spectral index.

Since the match between the observed radio behaviors and the prediction without the IC cooling is striking, we investigate what conditions are necessary to remedy this problem. The Compton cooling timescale is larger if $\epsilon_e$ is smaller to reproduce a given luminosity. Figure 7 shows an example where we adopt a low value for $\epsilon_e$. The model parameters are $V_{sh} = 80,000 \text{ km s}^{-1}$, $A_e = 0.05$, $\epsilon_B = 0.1$, and $\epsilon_e = 10^{-3}$. The required mass-loss parameter is now increased roughly following the SSA scaling, $\epsilon_B A_e (\epsilon_e/\epsilon_B)^{7/19}$, but it is still very low compared to other SNe Ib/c. The required velocity is also increased for the smaller value of $\epsilon_e$ roughly following the SSA scaling $V_{sh} \propto (\epsilon_e/\epsilon_B)^{-1/19}$. Not only the decrease in the relativistic electron density, but also the increase in the velocity, thus radius, has the effect of reducing the IC cooling effect. The light curve with low $\epsilon_e$ is similar to the standard case. The difference is that in this model, the IC cooling is now negligible. With the parameters for this “inefficient electron acceleration” model and $E_{51} = 5$ and $M_{ej} = 3 M_\odot$, Equation (5) predicts that $t_{\text{dec}} \sim 360$ days, justifying our assumption of free expansion.

For SN 2007gr, we have found a solution similar to that for SN 2002ap (Figures 8 and 9). The radio emission for the free-expansion evolution explains the multi-band light curves fairly well without the IC cooling. With $\epsilon_e = \epsilon_B = 0.1$, again the IC cooling alters the spectral index, and we require a low value of $\epsilon_e$ to fit the radio properties. For our fiducial model ($V_{sh} = 70,000 \text{ km s}^{-1}$, $A_e = 0.15$, $E_{51} = 2$, and $M_{ej} = 2 M_\odot$).
Figure 8. Radio emission from SN 2007gr compared with the “efficient electron acceleration” model. The model adopts $V_{sh} = 5.0 \times 10^9 \, \text{cm} \, \text{s}^{-1}$, $A_e = 0.022$, $p = 2.8$, $\epsilon_e = \epsilon_B = 0.1$. See the caption of Figure 6.

(A color version of this figure is available in the online journal.)

Figure 9. Radio emission from SN 2007gr compared with the “inefficient electron acceleration” model. The model adopts $V_{sh} = 7.0 \times 10^9 \, \text{cm} \, \text{s}^{-1}$, $A_e = 0.15$, $p = 2.8$, $\epsilon_e = 10^{-3}$, $\epsilon_B = 0.1$. See the caption of Figure 6.

(A color version of this figure is available in the online journal.)

dec $\sim 40$ days, which is long and roughly consistent with the observation.

We note that the low value of $\epsilon_e$ is not physically unreasonable. Indeed, detailed modeling of radio properties of SN eIIb 1993J (Fransson & Björnsson 1998) and SN cIIb 2011dh (Maeda 2012) points to $\epsilon_e \lesssim 0.01$, lower than generally assumed. No strong constraints have been placed on other SNe (e.g., Chevalier et al. 2006). We discuss a few issues from the previous works on $\epsilon_e$ in the Appendix. The low efficiency of the electron acceleration has an important consequence in interpreting the X-ray emission, which is also discussed in the Appendix.

We conclude that, so far, there is no strong observational indication against the low value of $\epsilon_e$ in stripped-envelope SNe (and we suggest that the low value of $\epsilon_e$ may be a generic feature).

5. IMPLICATIONS FOR SHOCK BREAKOUT AND PROGENITORS

5.1. SNe Ic 2002ap and 2007gr: Structure of W-R Stars at the End of Their Lives

Following our interpretation that the radio emission from SNe showing a short timescale for a low radio peak luminosity is described by the free expansion of the SN ejecta without deceleration, we can potentially connect properties of the shock breakout and the progenitor to these early radio properties.

In this early epoch, if the forward shock is still in the free-expansion phase, the characteristic velocity obtained through the radio properties is related to the maximum velocity of the SN ejecta following the shock breakout; thus, this important information can be obtained through the radio properties in the first month after the explosion, although in the other wavelengths it requires observing the very moment of the shock breakout. We emphasize that this is not possible for SNe already in the self-similar decelerating phase. Once the dynamics enter into the self-similar phase, the forward shock velocity is no longer related to the initial maximum velocity of the ejecta (and thus the shock breakout velocity; see Equation (4) and also Figure 2).3 If there would be two SNe which are exactly the same except for their maximum velocity ($V_{SN}$), distinguishing between them requires information at $t \lesssim t_{dec}$.

According to Section 2 (Figures 2–4), the freely expanding forward shock velocity is related to the maximum velocity of the SN ejecta after the shock breakout. Adopting the parameters derived by the free-expansion model for the SN 2002ap radio emission, we have performed the same hydrodynamic simulation as in Section 2. We thereby find that $V_{sh} = 80,000 \, \text{km} \, \text{s}^{-1}$ is obtained if $V_{SN} \sim 90,000 \, \text{km} \, \text{s}^{-1}$. In this simulation, the forward shock speed is constant until $t_d \sim 40$, thus being

3 It is much the same as the Sedov solution, where the information about the explosion is lost except for the explosion energy and the environment density.
consistent with the free-expansion model for the radio emission. We have performed the same experiment for SN 2007gr. Adopting $A_e = 0.15$, indeed we find it is not possible to obtain the constant forward shock velocity of $V_{th} \sim 70,000$ km s$^{-1}$ for more than 10 days; thus this model (with $\kappa = 10^{-3}$) for the radio emission is inconsistent with dynamic evolution. However, if we adopt $A_e = 0.05$ (which corresponds to the required parameters of $\kappa \sim 0.01$ and $V_{th} \sim 60,000$ km s$^{-1}$ for $\kappa = 0.1$), then the constant forward shock velocity of $V_{th} \sim 60,000$ km s$^{-1}$ is obtained for $\tau_d \sim 50$ for the maximum ejecta velocity of $V_{SN} \sim 75,000$ km s$^{-1}$, being roughly consistent with the radio observation.

Thus we infer a maximum ejecta velocity (or the “post-shock breakout velocity”) of $\sim 0.25$–$0.3c$ for SNe Ic 2002ap and 2007gr through their early radio emissions. This is greater than that inferred for SN 1987A, indicating that the progenitors of these SNe Ic are more compact than that of SN 1987A and/or their ejecta masses are smaller. However, the inferred velocity is smaller than the shock breakout velocity expected from the W-R progenitors of SNe Ib/c (especially the WO or WC progenitor for SNe Ic). If $R_e \sim 5 R_\odot$, one expects $V_{SN} \sim 0.35c$ for typical SNe Ib/c, $\sim 0.6c$ for the ejecta properties of SN 2003gr, and $\sim 0.8$–$0.9c$ for SN 2002ap (adopting $\kappa \sim 0.2$ cm$^2$ g$^{-1}$ for He or C/O composition). This could mean that there is still something missing in our understanding of the SN Ic progenitors and/or there is a missing part in our understanding of the shock breakout dynamics. In other words, the apparent discrepancy would provide a clue about these as yet unresolved issues, highlighting the importance of the independent information we could obtain through the early radio emission. We suggest that the apparent discrepancy does provide information on the progenitor structure just before the explosion.

A possible solution that we suggest is the following. While properties of typical Galactic W-R stars are assumed in studying the properties of SNe cIIb/Ib/Ic (including the shock breakout), we are not yet sure what the properties of a W-R star in the short period of time near the end of its life are. It has been suggested that the envelope would become expanded to a few to 10 times the original core radius, as a star approaches the Eddington luminosity (Gräfener et al. 2012). So far, studying SN properties has not provided any confirmation of this, and the new insight we obtain here could be the first indication that such an evolution may be the case.

Gräfener et al. (2012) showed that the typical density in such an envelope is $\sim 10^{-10}$ g cm$^{-3}$, and $\sim 10^{-8}$ M$_\odot$ is contained within $\sim 10 R_\odot$. The envelope can be more massive depending on the W-R mass and other parameters, reaching $\geq 10^{-6}$ M$_\odot$ in the model sequence studied by Gräfener et al. (2012). It is likely that this envelope would not affect the shock breakout itself—adopting $E_{51} = 1$, $M_d = 3$ M$_\odot$, and $R_e = 5 R_\odot$, the stellar density at the shock breakout is estimated to be $\sim 10^{-8}$ g cm$^{-3}$ using the formalisms from Rabinak & Waxman (2011). Thus, this would not dramatically affect basic predictions for the shock breakout high-energy signal and subsequent early optical/UV emission, consistent with a few constraints favoring compact progenitors through the shock breakout X-ray (SN Ib 2008D; Soderberg et al. 2008; Modjaz et al. 2009) and through the post-shock breakout optical emission (SN Ic PTF10vgv; Corsi et al. 2012).

However, the envelope could affect the dynamics just after the shock breakout. For typical parameters for SNe Ic, the shock breakout is estimated to take place when the mass above the shock (in the outer power-law part, thus excluding the envelope here) is $\sim 10^{-8}$ M$_\odot$. This is indeed comparable to the envelope mass, or can be even smaller. Then, the highest velocity ejecta will experience deceleration during penetration into the envelope, before the velocity profile is frozen when the shock emerges from the envelope. We suggest that this is what we can infer from the early radio emission. If the envelope mass is $\sim 10^{-8}$ M$_\odot$, it would decelerate the highest velocity to half of the original shock breakout velocity, following $V_{SN}/V_{SN,0} \propto (10^{-6} M_\odot/10^{-8} M_\odot)^{-0.15}$ (where $V_{SN,0}$ is the shock breakout velocity, while $V_{SN}$ is the maximum velocity after being affected by the envelope). This relation was obtained by combining the equations presented by Rabinak & Waxman (2011). The envelope would likely need to be He-rich to cause envelope inflation, but this amount of He is much smaller than the upper limit obtained by spectral modeling of SNe Ic (Hachinger et al. 2011).

5.2. Implications for Other Classes of SNe

The “engine-driven” SNe linked to GRBs (Kulkarni et al. 1998; Soderberg et al. 2006a, 2010b) are distinguished from other stripped-envelope SNe in radio properties (Berger et al. 2002; Soderberg et al. 2006b). According to Figure 5, these radio-strong SNe are roughly consistent with arising from the forward shock wave following the self-similar expansion with a highly energetic ($E_{51} \sim 50$) SN. The observed luminosity is larger than expected, by nearly an order of magnitude, but we note that in this regime a relativistic treatment is necessary for a quantitative comparison. The rough agreement suggests that the strong radio emission from these SNe may be understood in terms of the standard SN–CSM interaction scenario (with relativistic ejecta which would require a “central engine”), rather than invoking an additional relativistic jet component as long as the radio emission is concerned. The distinguishing feature in these engine-driven SNe is their large explosion energy, which has been derived through optical modeling (e.g., Iwamoto et al. 1998; Woosley et al. 1999; Maeda et al. 2006).

A majority of SNe Ib/c and cIIb are consistent with self-similar expansion in the $t_p$–$L_p$ plot. First, this indicates that their ejecta masses are mostly in the range of $M_d \approx 1$–$3$ M$_\odot$. An important implication of this is that a majority of them are likely an explosion of stars with $M_{ms} < 25$ M$_\odot$ and require a binary companion to strip off their H-rich envelopes: for example, if $M_{ms} \approx 25$ M$_\odot$ (roughly a lower limit for a single massive progenitor for SNe Ib/c), then the ejecta mass is expected to be $\sim 4.5$ M$_\odot$ if it explodes as an SN Ic and $\sim 6.5$ M$_\odot$ if it is an SN Ib. Next, this sets a rough upper limit for the size of the progenitors for these SNe cIIb/Ib/Ic. To enter into the self-similar phase, their shock breakout velocity must exceed at least 0.1c. For a reference value of $E_{51} = 1$ and $M_d = 3$ M$_\odot$, this means that the progenitor radius of most, if not all, SNe cIIb/Ib/Ic is $R_e \lesssim 250 R_\odot$. Thus, we reject a red supergiant (RSG) progenitor for SNe cIIb/Ib/Ic—they must come from a W-R star, or at most a yellow giant (the latter is a possible progenitor for SN cIIb 2011dh; Maund et al. 2011; Van Dyk et al. 2011; Bersten et al. 2012; Benvenuto et al. 2012).

4 However, the envelope could dilute and delay the shock breakout signal, similar to the situation expected for a shock breakout within a dense wind (Soderberg et al. 2008; Chevalier & Fransson 2008).

5 The upper limit here would further decline if the structure of the progenitors of these SNe is also similar to what we suggest for SNe 2002ap and 2007gr.
Another expectation is that some SNe eIIb (‘extended’ SNe Ib) may follow free expansion for a long time during the phases when the radio observations are performed because of the expected low shock breakout velocity. With \( R_e \sim 500 \, R_\odot \), \( E_{51} \sim 1 \), and \( M_{10} \sim 3 \, M_\odot \), SN eIIb 1993J is expected to have had a shock breakout velocity of 26,000 km s\(^{-1}\). Taking this at face value for SNe eIIb, we expect that \( t_{\text{dec}} \sim 600, 60, 6 \) days for \( A_\star = 1, 10, 100 \). If there are SNe eIIb within a relatively low CSM environment (e.g., \( A_\star = 10 \) for \( M = 10^{-6} \, M_\odot \) yr\(^{-1}\) and \( v_w = 10 \) km s\(^{-1}\)), then such SNe eIIb should show the free-expansion phase in radio, and high-frequency observations will be especially useful for capturing this feature. Indeed, SNe eIIb tend to be below the “self-similar expectation” in the \( t_{\text{exp}}-L_{\text{r}} \) plot, implying that some of them might indeed be in the free-expansion phase. However, a complication is that in these cases the free–free absorption may become important, and either a more detailed model including the free–free absorption or a direct measurement of the shock velocity via very long baseline interferometry is necessary.

6 CONCLUSIONS AND DISCUSSION

In this paper, we have investigated a consequence of SNe Ib/c exploding within low-density CSM (i.e., \( A_\star \lesssim 0.1 \), or \( M \lesssim 10^{-6} \, M_\odot \) yr\(^{-1}\) for a typical W-R wind velocity). Such an SN should show a “free-expansion” phase before entering into the self-similar deceleration phase if the post-shock breakout velocity is \( V_{\text{SN}} \lesssim 0.3c \). The predicted radio properties of such SNe are different from those of SNe in the self-similar phase, characterized by a shallow decline in the temporal evolution while the spectral index is the same, if all the other properties (i.e., the acceleration mechanism of electrons) are unchanged.

SNe exploding in a low-density CSM environment should be characterized in radio frequency by a fast rise to peak (within 10 days after the explosion) and a low luminosity at the peak. We have shown that all stripped-envelope SNe with these properties observed so far (SNe 2002ap and 2007gr, as well as SN 1987A from a blue giant progenitor) indeed have the expected properties in the temporal and spectral indices. The synthesized multi-band light curves show a good match to those observed for SNe 2002ap and 2007gr. We note that the other example, SN 1987A, was also well modeled by free expansion dynamics (Chevalier 1998). In our interpretation, the efficiency of the acceleration of electrons must be low in order to avoid the IC cooling in radio frequencies. This is the same conclusion we obtained for SN 2011dh (Maeda 2012), and we suggest that this may be a generic property of the SN–CSM interaction.

Understanding the radio properties from SNe in the \( t_{\text{free}}-L_{\text{r}} \) plot in terms of the dynamics of the shock propagation, we propose new diagnostics on the shock breakout and progenitor properties through early radio emission: the forward shock velocity in the free-expansion phase (\( V_{\text{sh}} \)) is closely related to the maximum velocity obtained at/after the shock breakout (\( V_{\text{SN}} \)). We suggest that the relatively low post-shock breakout velocity (\( \sim 0.3c \)) we have derived for SNe Ic 2002ap and 2007gr could indicate the existence of an envelope driven by a near-Eddington luminosity near the end of the W-R evolution (Gräfener et al. 2012). This highlights the usefulness/uniqueness of the proposed strategy as compared to other methods (e.g., breakout flash and/or subsequent optical emission) of probing the shock breakout and the progenitor: velocity information cannot be obtained using other methods. Also, for a majority of SNe eIIb/Ib/Ic, we reject an RSG progenitor through the radio properties.

The idea can, in principle, provide slightly different approaches to estimating the post-shock breakout maximum velocity and placing constraints on progenitor structures. Once one identifies the free-expansion phase (i.e., the transition from the free expansion to the self-similar dynamics in the decay slope), then one can estimate the post-shock breakout velocity using Equation (5) or a similar expression, adopting ejecta properties and the CSM density estimated independently. The expression, however, requires further calibrations, and does not provide a cross-check of the decay slope. For these reasons, we adopted a more detailed approach, in which we fitted the multi-band light curves and checked the assumed dynamic evolution with hydrodynamic simulations. Also, a stronger constraint than that used here could be placed on the progenitor radius when SNe do not show the free-expansion phase for most radio-detected SNe Ib/Ib/Ic (using the information at the radio peak), by using the earliest data points in which SNe are in the self-similar phase. A complication is that either the absorption (in the low frequency) or cooling (in the high frequency) can change the temporal slope in the early phase, thus distinguishing the different dynamics is generally difficult well before the radio peak. For this reason, we have placed a conservative upper limit on the progenitor radius using the radio information around the peak. Further study and calibration of these methods could be possible applications of the idea presented in this paper.

Future, large observational data sets in the radio frequency will be highly valuable. Such data have been increasingly accumulated recently thanks to great efforts of researchers working in the field (e.g., Soderberg et al. 2012). SNe in a low-density CSM environment, such as SNe 2002ap and 2007gr, will provide a new possibility for tackling properties of the shock breakout and the progenitor as mentioned above. A majority of radio-detected SNe Ib/Ib/Ic follow self-similar evolution, and thus their properties and distribution in the \( t_{\text{exp}}-L_{\text{r}} \) plot will reveal the general distribution of the progenitor mass and the energetics independently from optical wavelengths: so far, their distribution suggests that a majority of them (i.e., radio-detected stripped-envelope SNe) come from relatively low mass progenitors (\( \lesssim 25 \, M_\odot \)), indicating that a binary interaction path could be a dominant one, in line with other recent studies (e.g., Sana et al. 2012).

The low-density CSM around SNe Ic 2002ap and 2007gr may be related to the W-R progenitor structure just before the explosion. If the progenitor luminosity is larger, it would likely produce a higher-velocity wind, resulting in a lower value of \( A_\star \). This probably favors a massive WO star as a progenitor of these SNe Ic (e.g., Nugis & Lamers 2000). If this is true, we expect no SNe Ib/Ib would belong to the “rapid and faint” radio stripped-envelope SNe (i.e., SNe 2002ap and 2007gr are both of Type Ic), and future larger samples should be able to address this question. Searching for and observing these radio-faint stripped-envelope SNe will provide new clues about the progenitor scenario from this angle as well. Specifically, this will be best done by future observatories with better sensitivity than what is currently available. Because of the low radio luminosity of these objects, there may well be an observational bias in which we underestimate the frequency of these radio-weak SNe (Soderberg et al. 2010a). Once a volume-limited sample is constructed, it will hopefully connect the radio properties with different progenitor evolutionary paths.

6 SN II 1987A may well be an exception, due to its low-metallicity environment. This suggests that detailed analysis will require taking into account the metallicity of the local environment as well.
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APPENDIX

ELECTRON ACCELERATION EFFICIENCY (ε_e)

In our scenario, the acceleration of the relativistic electrons is required to be (relatively) inefficient (ε_e ≲ 0.01), as compared to frequently assumed (ε_e ∼ 0.1). As mentioned in the main text, so far there is no strong observational constraint against the low value of ε_e. Indeed, Fransson & Björnsson (1998) and Maeda (2012) suggested ε_e ≲ 0.01 for SN cIIb 1993J and SN cIIb 2011dh, respectively, based on detailed modeling of their radio properties. We discuss this issue in this appendix.

A.1. Previous Works

It has been stated that ε_e ≳ 0.1 for SNe Ib/c based on the equation ε_e m_e c^2 V_e^2 ≳ γ_m m_e c^2, where γ_m ≳ 1 is the characteristic Lorentz factor of relativistic electrons (Soderberg et al. 2005, 2010a). This is an analog of what is frequently adopted in the field of GRB non-thermal emission where a relativistic shock wave could accelerate all or most of the electrons into relativistic speed. The assumption that all the electrons are accelerated to relativistic speed, however, does not have to be the case in a non-relativistic shock wave in SNe. If only a fraction of ζ_e (in number) are accelerated from the thermal population to relativistic energy, then one has to multiply the right-hand side of the above equation by ζ_e, and therefore this limit on ε_e (by γ_m ≳ 1) becomes lower by the same factor of ζ_e. This is taken into account in our formalism (Equation (8)), and this is explicitly expressed as ζ_e ≈ 4ε_e − 1(V/0.1c)^2 (from Equations (3) and (8)) for a H-rich CSM (of course this applies only for ζ_e ≲ 1). For reference values of ε_e = 10^{-3} and V ∼ 0.2c, we have ζ_e ≈ 0.1–0.2, i.e., about 10% of thermal electrons are accelerated to the relativistic speed.

This value of ζ_e seems reasonable based on circumstantial evidence. (1) ζ_e has been typically found to be less than 1% in SN remnants where V_{sh} ∼ 0.01c (e.g., Bamba et al. 2003). Thus we do not expect that the condition ζ_e ∼ 1 must be met in the SN Ib/c shock wave which is also non-relativistic. (2) The X-ray emission from SN Ib 1993J (similar to SNe Ib/c in shock velocity) is believed to be emitted from the thermal electrons, and this requires that the thermal electrons be the main population at the shock front, while the relativistic electrons occupy only a small fraction (Fransson et al. 1996; Fransson & Björnsson 1998). In any case, the value of ζ_e is still open to debate (not only for SNe but also for other astrophysical acceleration sites).

Furthermore, the existence of thermal electrons as a bulk population would not produce inconsistency in terms of observed radio properties. The synchrotron radio emission is produced by electrons with γ ≳ 50 for the typical magnetic field strength seen in the SNe Ib/c shock front, leaving no observational signature for electrons with γ ≲ 50 (including the thermal population) in the radio band (see Maeda 2012 for a detailed discussion). Indeed, it is observationally forbidden to have γ_m ≳ 1: in this case, the radio emission should show a characteristic spectral break (Soderberg et al. 2005, 2010a; Chevalier & Fransson 2006), although such a break is not seen in observations. In this sense, the radio observation provides the upper limit for ε_e, not the lower limit.

A.2. X-Ray Production through the Inverse Compton Mechanism

The IC upscattering of SN optical photons has been proposed as an X-ray emission production mechanism, especially favored for stripped-envelope SNe with A_e ∼ 1 (e.g., Björnsson & Fransson 2004; Chevalier & Fransson 2006; Soderberg et al. 2012). The scenario requires a large population of relativistic electrons with γ ∼ 50, and thus a large value of ε_e (≳ 0.1) if these electrons’ energy distribution follows a power law extrapolated from the radio synchrotron-emitting electrons (typically with γ ∼ 50–200; see Maeda 2012 for a detailed discussion). In this section, we stress that having a large value of ε_e (≳ 0.1) is not a single solution for producing the IC X-rays, but there is an alternative interpretation in which the energy distribution of the IC-emitting electrons does not follow the extrapolation from the synchrotron-emitting electrons as suggested by Maeda (2012).

The low efficiency of the electron acceleration thus has an important consequence in interpreting the X-ray emission. Among several models suggested for the X-ray behavior of SN 2002ap, the IC scattering scenario seems the most plausible (Björnsson & Fransson 2004; Chevalier & Fransson 2006). However, if we adopt p ∼ 3, then we want to avoid the Compton cooling effect in the radio frequency (Section 4). We can estimate the IC X-ray luminosity in a form similar to the radio synchrotron emission:

\[ \nu L_\nu \sim \pi R^2 V_{ne} \nu^{2-p} m_e c^2 \left(1 + \frac{\nu}{\nu_c(\gamma)}\right), \]

where \( \nu_c \) is the IC cooling timescale. The typical electron energy (\( \gamma_c \)) where the Compton effect is significant is not sensitive to the value of \( \gamma_c \) since \( \gamma_c \propto L_{SN}^{-1} R_{sh} \) (not dependent on the microphysics parameters): at \( \nu = 5 \), \( \gamma_c \sim 140 \) and 250 for our models with \( \epsilon_e = 0.1 \) and \( 10^{-3} \), respectively. On the other hand, the electron energy responsible for the X-ray emission through the IC is \( \gamma_c \sim 30 \). Thus it is in the adiabatic phase, and the predicted X-ray luminosity is \( \nu L_\nu(1keV) \sim 6 \times 10^{35} \text{ erg s}^{-1} \) (for \( \epsilon_e = 0.1 \)) and \( \sim 6 \times 10^{35} \text{ erg s}^{-1} \) (for \( \epsilon_e = 10^{-3} \)) at day 5. The former is lower than the observed value only by a factor of two, but the latter is more than an order of magnitude lower than observed. The estimate is consistent with the previous work by Björnsson & Fransson (2004).

We note, however, that the similar situation is found in SN cIIb 2011dh, for which the extensive radio and X-ray data allowed detailed modeling of its properties (Soderberg et al. 2012; Krauss et al. 2012; Bietenholz et al. 2012; Horesh et al. 2012). For SN 2011dh, there is almost no doubt that the power-law index of the relativistic electrons emitting in the radio frequencies is \( p \sim 3 \), constrained by the late, optically thin light curves in multiple bands (Soderberg et al. 2012). While Soderberg et al. (2012) suggested a high value of \( \epsilon_e \) and Horesh et al. (2012) suggested even more efficient electron acceleration with \( \epsilon_e/\epsilon_B \sim 1000 \), Maeda (2012) pointed out that little change in the spectral index was observed once the radio emission became optically thin, and suggested that the IC cooling effect must be negligible in radio and that the acceleration of the...
relativistic electrons must be inefficient ($\epsilon_e \lesssim 0.01$). In this interpretation of Maeda (2012), the predicted IC emission in the X-ray was about one or two orders of magnitudes smaller than observed—this is the same situation we found for SNe 2002ap and 2007gr, but with the constraints on the spectral energy index of the electrons ($\gamma$) and on the effect of the IC cooling being much stronger than for SNe 2002ap and 2007gr.

To remedy this problem, Maeda (2012) suggested there is a distinct population of relativistic electrons below $\gamma \sim 50$, with a number density (per $\gamma$) more than an order of magnitude larger than the extrapolation from the power-law distribution for the radio-emitting, higher-energy electrons, in order to explain the X-rays from SN 2011dh by the IC mechanism while still being consistent with the radio behaviors. We expect that the acceleration mechanism is essentially the same in SN 2002ap, thus we suggest that the same argument for SN 2011dh applies to SN 2002ap as well and the X-ray properties of SN 2002ap could be explained in the same manner.

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