

CONSTRAINTS ON THE MASSIVE SUPERNOVA PROGENITORS

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The generally-accepted scheme distinguishes two main classes of supernovae (SNe): Ia resulting from the old stellar population (deflagration of a white dwarf in close binary systems), and SNe of type II and Ib/c whose ancestors are young massive stars (died in a core-collapse explosion). Concerning the latter, there are suggestions that the SNe II are connected to early B stars, and SNe Ib/c to isolated O or Wolf-Rayet (W–R) stars. However, little or no effort was made to further separate SNe Ib from Ic. We have used assumed SN rates for different SN types in spiral galaxies in an attempt to perform this task. If the isolated progenitor hypothesis is correct, our analysis indicates that SNe Ib result from stars of main-sequence mass $23M_{\odot} \lesssim \mathcal{M} \lesssim 30M_{\odot}$, while the progenitors of SNe Ic are more massive stars with $\mathcal{M} \gtrsim 30M_{\odot}$. Alternatively, if the majority of SNe Ib/c appear in close binary systems (CBs) then they would result from the same progenitor population as most of the SNe II, i.e. early B stars with initial masses of order $\mathcal{M} \sim 10M_{\odot}$. Future observations of SNe at high-redshift (z) and their rate will provide us with unique information on SN progenitors and the star-formation history of galaxies. At higher- z (deeper in the cosmic past), we expect to see the lack of type Ia events, i.e. the dominance of core-collapse SNe. Better understanding of the stripped-envelope SNe (Ib/c), and their potential use as distance indicators at high- z , would therefore be of great practical importance.

Keywords: General supernovae; star formation; star evolution; galaxies; stellar content.

1. Introduction

Interest in the study of supernovae (SNe) has been significantly increased following the renewed searches for SNe in recent years. Now more than 3000 SNe have been discovered since 1885, many of them at cosmological distances. Much effort has been invested in the classification of SNe, in understanding their progenitors and determining their SN rate (and rates for different SN and parent galaxy types). Consequently, we arrived at the generally-accepted scheme with two distinctive classes of SNe: Ia resulting from the old stellar population (deflagration of a C-O

white dwarf in close binary systems), and SNe of type II and Ib/c whose ancestors are young massive stars (died in a core-collapse explosion).

Historically, classification of SNe, according to their optical spectra, began by recognizing SNe I, with no hydrogen lines, and SNe II which do show hydrogen in their spectra. In addition, SNe II were shown to exhibit much wider photometric behavior than SNe I, which seemed to be a rather homogeneous class of objects. Nevertheless, it was shown later that there are actually two spectroscopically and photometrically distinct subclasses of SNe I: Ia which were only located in ellipticals, and Ib which were found in H II regions and spiral arms, which strongly suggested that their progenitors were massive young stars with their hydrogen envelopes stripped. The third subclass, SNe Ic, discovered later, show no helium lines either, and thus corresponds to the massive stars stripped of their H and He envelopes. For a more detailed review, see Refs. 1–4.

There are suggestions that the SNe II are connected to early B stars, and SNe Ib/c to isolated O or Wolf–Rayet (W–R) stars. However, little or no effort was made to further separate SNe Ib from Ic. In the subsequent analysis, we will use assumed SN rates for different SN types in spiral galaxies in an attempt to perform this task. An alternative, according to which all core-collapse SNe result from the same progenitor population is also discussed.

2. Analysis

2.1. *Masses of supernova progenitors*

The first constraints on the masses of supernova progenitors were put by Kennicutt,⁵ and later by van den Bergh,⁶ from the assumed supernova and star formation rates (SNR and SFR, respectively) for the core-collapse supernovae and their progenitors. Because of the short life of massive stars, the number of core-collapse events per century should be equal to the number of new born stars in the same time period, within the appropriate mass range,

$$\text{SNR} = \text{SFR}, \quad (1)$$

when converted to appropriate units. Star formation rate for the stars in the mass range from \mathcal{M}_L to \mathcal{M}_U is given with

$$\text{SFR} \propto \int_{\mathcal{M}_L}^{\mathcal{M}_U} f(\mathcal{M}) d\mathcal{M}, \quad (2)$$

where f is the initial mass function (IMF), $f(\mathcal{M}) = A\mathcal{M}^{-\beta}$ in Salpeter's form.⁷

According to Ref. 6, progenitors of SN II have masses $8\mathcal{M}_\odot \lesssim \mathcal{M}_{\text{II}} \lesssim 18\mathcal{M}_\odot$, corresponding to early B stars, whereas isolated O or W–R stars with $\mathcal{M}_{\text{Ib}} \gtrsim 18\mathcal{M}_\odot$ become SN Ib. SN Ic were not recognized separately from Ib at that time.^a

^aIn his study, van den Bergh used the stripped-envelope (Ib) to total core-collapse (Ib+II) ratio $\nu_{\text{se}}/\nu_{\text{cc}} \approx 0.26$.⁶

In order to calculate the limiting masses for SN Ib/c progenitors from the mass spectrum of star formation, we need to know the IMF and the SNRs for these particular classes of SNe. We will adopt, as the authors cited, the Miller–Scalo mass function with $\beta = 2.5$,⁸ the upper mass limit for the core-collapse SN progenitors of $\mathcal{M}_U = 100\mathcal{M}_\odot$, and the fixed predetermined lower limit of $\mathcal{M}_L = 8\mathcal{M}_\odot$, as is consistent with theory.^{1,9} Recently-determined supernova rates, i.e relative numbers that we are interested in, are given in Table 1.

SNRs for a given SN and galaxy type is defined as:

$$\nu = \frac{N}{T} [\text{SNu}], \quad (3)$$

where N is the number of SNe discovered in a given sample of galaxies during the total control time T , and supernova unit is $1 \text{ SNu} = \text{SNe per } 10^{10} L_\odot \text{ per century}$. The total control time incorporates galaxy luminosity as a normalization factor, since it has been shown that it correlates with the SNR, and the probability of SN detection, depending on the photometric properties of the SN type in question (see Refs. 3 and 10).

Our intent was to use entirely the study given in Ref. 10 since it provides a well-defined control time. Control time is of utmost importance for the correct determination of the SNR, which implies exclusion of all SNe discovered by chance for which T is undefinable. However, statistics were not large enough to separate stripped-envelope SNe, that, for this reason, were lumped together as Ib/c in Refs. 10 and 11.

Nonetheless, the majority of SNe Ib/c, as new types, were discovered in systematic SN searches, which means that, although unknown to us, there is a control time calculable. The crucial thing is that this control time is the same for SNe Ib and Ic, which are photometrically indistinguishable (or, at least, very much alike)!

Table 1. Supernova rates in SNu for different galaxies and SN types from Ref. 10. h is the Hubble parameter $h = H_o/(75 \text{ km s}^{-1} \text{ Mpc}^{-1})$. Last but one column is the stripped-envelope (Ib/c) relative to the total core-collapse SN rate (Ib/c+II). The last column shows the SN Ib to Ic ratio found in this study.

Galaxy type	$\nu[\text{SNu}]$		$\nu_{\text{se}}/\nu_{\text{cc}}$	$\tilde{N}_{\text{Ib}}/\tilde{N}_{\text{Ic}}$
	Ib/c	II		
E–S0	$< 0.01h^2$	$< 0.02h^2$	—	—
S0a–Sb	$0.11 \pm 0.06h^2$	$0.42 \pm 0.19h^2$	0.21	0.92 ^e
Sbc–Sd	$0.14 \pm 0.07h^2$	$0.86 \pm 0.35h^2$	0.14	0.45
Others ^c	$0.22 \pm 0.16h^2$	$0.65 \pm 0.39h^2$	0.25	0.42
All	$0.08 \pm 0.04h^2$	$0.40 \pm 0.19h^2$	0.17	0.53 ^d

^c Others include types Sm, Irregulars and Peculiars.

^d The ratio for $i \leq 45^\circ$ is 0.51, and 0.55 for $i > 45^\circ$, and thus it is not effected by galaxy inclination.

^e This high value is probably a consequence of the small-number statistics.

In other words, the selection effects acting on SNe Ib/c would be the same and therefore, for this initial study, we can assume

$$\frac{\nu_{\text{Ib}}}{\nu_{\text{Ic}}} = \frac{N_{\text{Ib}}}{N_{\text{Ic}}} \approx \frac{\bar{N}_{\text{Ib}}}{\bar{N}_{\text{Ic}}}, \quad (4)$$

where \bar{N} is the total number of recorded SNe. As a database, we used the October 2004 version of the Asiago Supernova Catalogue (hereafter ASC).¹² A cutoff at redshift $z = 0.03$ has been induced to make the results consistent with the rates in the local universe. The resulting numbers are given in the last column of Table 1.

If we adopt that approximately 83 per cent of all core-collapse events are SNe II and only 6 and 11 per cent are SNe Ib and Ic respectively, from

$$\frac{\int_{\mathcal{M}_L}^{\bar{\mathcal{M}}_{\text{Ib}}} \mathcal{M}^{-\beta} d\mathcal{M}}{\int_{\mathcal{M}_L}^{\mathcal{M}_U} \mathcal{M}^{-\beta} d\mathcal{M}} = \frac{\nu_{\text{II}}}{\nu_{\text{cc}}}, \quad (5)$$

$$\frac{\int_{\mathcal{M}_L}^{\mathcal{M}_U} \mathcal{M}^{-\beta} d\mathcal{M}}{\int_{\mathcal{M}_L}^{\bar{\mathcal{M}}_{\text{Ic}}} \mathcal{M}^{-\beta} d\mathcal{M}} = \frac{\nu_{\text{Ic}}}{\nu_{\text{cc}}}, \quad (6)$$

we obtain $\bar{\mathcal{M}}_{\text{Ib}} \approx 24\mathcal{M}_{\odot}$ and $\bar{\mathcal{M}}_{\text{Ic}} \approx 31\mathcal{M}_{\odot}$.

If one uses near infrared (K band) instead of B luminosity of a galaxy as a better tracer of its stellar mass, then the supernova rate per unit mass (SNum) can be calculated.¹³ Initial mass values for the progenitors of different types of core-collapse SNe as a function of the host galaxy's Hubble type, obtained by using rates in SNum from Ref. 13, are given in Table 2. The numbers in Table 2 are probably too limited by a small number statistics to be useful, but the mean values $\bar{\mathcal{M}}_{\text{Ib}} \approx 22\mathcal{M}_{\odot}$, $\bar{\mathcal{M}}_{\text{Ic}} \approx 29\mathcal{M}_{\odot}$, roughly match those obtained previously.

These initial mass values correspond to the massive short-lived O stars. If these are truly progenitors of SNe Ib/c they will die not far from the place where they were born. Table 3 gives the number of O stars of different subclass out of, or in the H II regions. It shows that early O stars are more likely to be located in H II regions than the late O stars, with O8 being the intermediate class. The explanation of

Table 2. Initial mass values for the progenitors of different types of core-collapse SNe as a function of the host galaxy's Hubble type, obtained by using rates from Ref. 13.

Galaxy type	$\nu_{\text{se}}/\nu_{\text{cc}}$	$\mathcal{M}_{\text{II}} [\mathcal{M}_{\odot}]$	$\mathcal{M}_{\text{Ib}} [\mathcal{M}_{\odot}]$	$\mathcal{M}_{\text{Ic}} [\mathcal{M}_{\odot}]$	
E-S0	0.23	8	20	30	100
S0a-Sb	0.14	8	27	34	100
Sbc-Sd	0.24	8	20	24	100

Table 3. Bright O stars and nebulosity from Ref. 6.

Location	Spectral type					
	O5	O6	O7	O8	O9	O9.5
In bright H II region	4	8	8	14	3	2
In faint H II region	2	2	2	6	6	3
Not in H II region	2	6	3	15	16	12

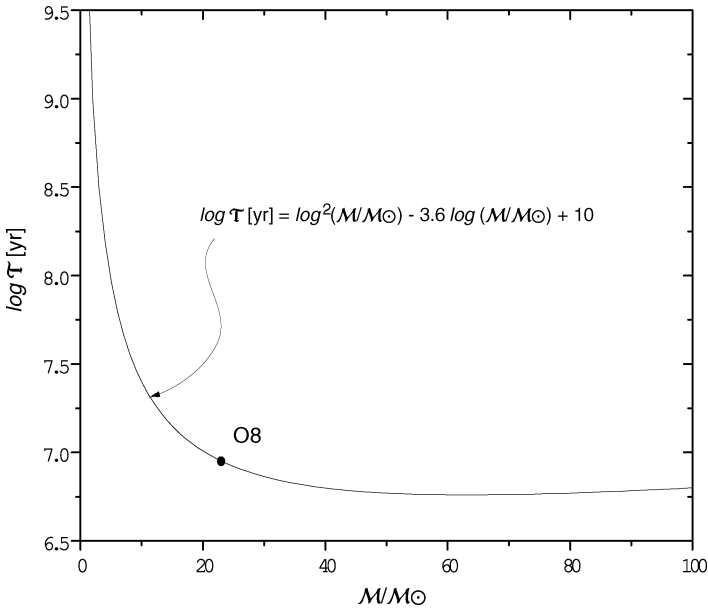


Fig. 1. Stellar lifetime versus initial mass in the range 1–100 M_{\odot} . For the relation adopted, see Ref. 14.

why this transition-like occurrence happens at about class O8 is offered in Fig. 1. The figure gives the average lifetime of stars in the mass range 1–100 M_{\odot} . For classes later than O8, the lifetime τ starts to significantly increase, which gives them enough time to abandon their birthplace.

The closest match to the obtained value for \bar{M}_{Ib} are exactly O8 stars with $M = 23M_{\odot}$ (from *Allen’s Astrophysical Quantities*, Ref. 15). Given the uncertainties in the SNRs we may adopt the latter value as the lower limit for the stripped-envelope core-collapse progenitors. The Ic progenitors would then correspond to the stars earlier than O7 with masses $M_{\text{Ic}} \gtrsim 30M_{\odot}$.

Theoretical models for a single non-rotating star predict a much higher minimum SN Ib progenitor mass, $M_{\text{Ib}} \gtrsim 30M_{\odot}$.¹⁶ Rotation seems to lower this value, $M_{\text{Ib}} \lesssim 25M_{\odot}$,^{17,18} which is consistent with the empirical value obtained here. On the other hand, the amount of mass loss suffered during the star’s life, which will ultimately determine the type of supernova, depends also on metallicity, and so

does the minimum mass.¹⁷ These three parameters: mass, metallicity and rotation, are the most important in single star supernova models.

A stronger association of SNe Ib/c and H II regions, that might be expected if their progenitors are very massive stars, is, however, questionable,¹⁹ and along with it the single star scenario. Alternatively, stripped-envelope SNe may appear in close binary systems (CBs) as a consequence of the Roche lobe overflow and the process of mass transfer to the companion star.

According to Ref. 20, presupernovae of SNe Ic thus may be the C-O stars in CBs, formed after the two stages of mass transfer during which H and He envelopes, respectively, had been lost. Similarly, SNe Ib may have progenitors in the He stars in CBs (i.e. only the first stage of mass transfer had been invoked).²¹

Principally, SNe Ib/c would then result from the same progenitor population as most of the SNe II. Intuitively, however, Ic may again result from the more massive stars. Very provisionally we may assume that, if the mass range for core-collapse SNe 8–100 \mathcal{M}_\odot , is to be applied to the stripped-envelopes, from

$$\frac{\int_{\mathcal{M}_L}^{\tilde{\mathcal{M}}_{\text{Ib}}} \mathcal{M}^{-\beta} d\mathcal{M}}{\int_{\tilde{\mathcal{M}}_{\text{Ib}}}^{\mathcal{M}_U} \mathcal{M}^{-\beta} d\mathcal{M}} = \frac{\nu_{\text{Ib}}}{\nu_{\text{Ic}}}, \quad (7)$$

$\tilde{\mathcal{M}}_{\text{Ib}}$ would be around $\sim 10\mathcal{M}_\odot$ (about class B2).

This is highly uncertain since there are many other important parameters that must be taken into account for determining the presupernova formation rate in CBs, such as the proximity of the companion (and rotation and metallicity, important for a single star also). Consequently, there may be a considerable overlap in the initial masses for these events. Perhaps these additional parameters may also be related to the progenitor's mass. However, this demands a more detailed and rather complicated analysis dealing with the formation and evolution of CBs.

Whatever the exact supernova scenario is, only from the low Ib/c SNR and the slope of the IMF, it may be conjectured that these are quite rare events. We can simply follow the line of reasoning: (i) rare events, (ii) unique physics, (iii) tight constraints on progenitors.

2.2. *Supernova luminosities*

All supernovae, with the exception of some Ic (hypernovae), are commonly believed to release about $\sim 10^{51}$ ergs in the form of kinetic energy (excluding the neutrinos). In the case of the hypernovae, this number is believed to be larger, $\geq 10^{52}$ ergs. Only about 1 per cent of this energy is transformed into light and radiated in a SN event.

Since this energy can be regarded as the released gravitational potential energy of a star, it directly depends on the presupernova's mass. SNe of a wide-mass-range progenitors are thus likely to have a wider intrinsic luminosity distribution (such as

it is with SNe II). Tight constraints on progenitors (their mass, metallicity, binarity, etc.) and a unique physics of explosion means a smaller dispersion in observational properties. This may apply to the luminosity of SNe Ib and SNe Ic. A sample of the latter would, however, still comprise the true hypernovae of $> 40M_{\odot}$ stars.

For the absolute magnitude at maximum (blue) light we can generally write,

$$M_B^0 = m_B - \mu - A_G - A_g = M_B - A_g, \tag{8}$$

where m_B is the apparent magnitude, $\mu = 5 \log d[\text{Mpc}] + 25$ is the distance modulus, A_G and A_g are the Galactic extinction and extinction in parent galaxy, respectively. Reference 22 gives the peak magnitude for Ib, uncorrected for parent galaxy extinction $M_B = -17.11 \pm 0.14$. This is consistent with the mean magnitude,

$$\langle M_B \rangle = -16.92 \pm 0.71 \approx -17, \tag{9}$$

obtained from chosen sample of SNe Ib/c from the ASC (see Table 4). The mean error adopted in Ref. 22, however, seems too optimistic. Since no extinction corrections were made, this value, although it may be statistically useful, is surely fainter than the true (intrinsic) magnitude.

The problem of extinction is the most important issue to be dealt with, in the process of obtaining true SN luminosities (absolute magnitudes). The plane-parallel model which gives absorption dependent on galaxy inclination $A_g = A_o \sec i$, widely used in the past, was shown not to describe extinction adequately.¹¹ An alternative model which introduces radial dependence was given in Ref. 23.

Figure 2 shows peak magnitude uncorrected for parent-galaxy extinction against the radial position of SN r in the units of galactic radius $R = D/2$. The figure shows that there is a certain trend of dimmer SNe with decreasing radius. If we assume that at $r/R = 1$, extinction is negligible, intrinsic absolute magnitude for Ib/c SNe would be closer to $M_B^0 = -18.31 \pm 0.45$.

It can also be seen on Fig. 2 that SNe Ic do show larger dispersion.^b The SNe that show the largest deviations are 1994I, 1998bw and 2002ap. There are suggestions that SN 2002ap, together with 1997ef and 1998bw, might even form a new subclass Id (they may correspond to the hypernovae, connected to the gamma-ray bursts).²⁷ Probably the best studied SN Ic, 1994 I, on the other hand, may have incorrect distance which caused deviation.²⁸

3. Conclusion

The aim of this paper was to reanalyze the stripped-envelope core-collapse SNe (Ib/c) and to try to bring them in connection to their progenitors. If the isolated progenitor hypothesis is correct, our analysis indicates that SNe Ib result from stars of main-sequence mass $23M_{\odot} \lesssim M_{\text{Ib}} \lesssim 30M_{\odot}$, while the progenitors of SNe Ic

^bOne SN Ib with listed peak B magnitude in the ASC, namely 1954A, was, however, not included because of the unknown properties of SN, i.e. its parent galaxy. The SN is in the irregular galaxy NGC 4214. It is not near any H II region, and it is untypically bright.

Table 4. SNe Ib/c with listed B magnitude at the time of maximum from the Asiago Supernova Catalogue (ASC). The two SNe are excluded: SN 1954A because of the other unknown properties of SN, i.e. its parent galaxy, and 1966J since it was shown to be Ia.²⁴ All data are from ASC, except for the distance moduli (Nearby Galaxy Catalogue — NGC, Ref. 25) and the correction for Galactic absorption A_G which is from RC3 (Ref. 26). Parent galaxy extinction is omitted since we found significant discrepancy for A_0 in RC3 and NGC. M_B is the absolute magnitude uncorrected for extinction in the parent galaxy.

Supernova	SN type	Galaxy	Galaxy type	Distance modulus μ	Inclination i [°]	Diameter D [kpc]	SN radial position r [kpc]	Apparent magnitude m_B	Galactic absorption A_G	Absolute magnitude M_B
SN 1972R	Ib	NGC 2841	Sb	30.39	65	27	10.7	12.85	0	-17.54
SN 1983N	Ib	NGC 5236	SBc	28.35	21	18	3.8	11.70	0.15	-16.80
SN 1984I	Ib	ESO 393-99	SBcd	33.48	25	30	11.0	16.60	0.45	-17.33
SN 1984L	Ib	NGC 991	SBc	31.37	28	16	3.5	14.00	0	-17.37
SN 2000H	Ib	IC 454	SBab	33.89	58	30	9.1	17.90	1.44	-17.43
SN 1962L	Ic	NGC 1073	SBc	30.91	25	21	5.7	13.94	0.07	-17.04
SN 1983I	Ic	NGC 4051	SBbc	31.15	35	26	5.5	13.70	0	-17.45
SN 1983V	Ic	NGC 1365	SBb	31.14	58	54	6.8	14.67	0	-16.47
SN 1987M	Ic	NGC 2715	SBc	31.55	74	28	2.1	15.30	0.02	-16.27
SN 1991N	Ic	NGC 3310	SBbc	31.36	19	15	0.8	15.50	0	-15.86
SN 1994I	Ic	NGC 5194	Sbc	28.40	48	14	0.6	13.77	0	-14.63
SN 1998bw	Ic pec	ESO 184-82	SB	32.97	33	9	2.6	14.09	0	-18.88
SN 2002ap	Ic pec	NGC 628	Sc	29.93	24	30	13.7	13.10	0.13	-16.93

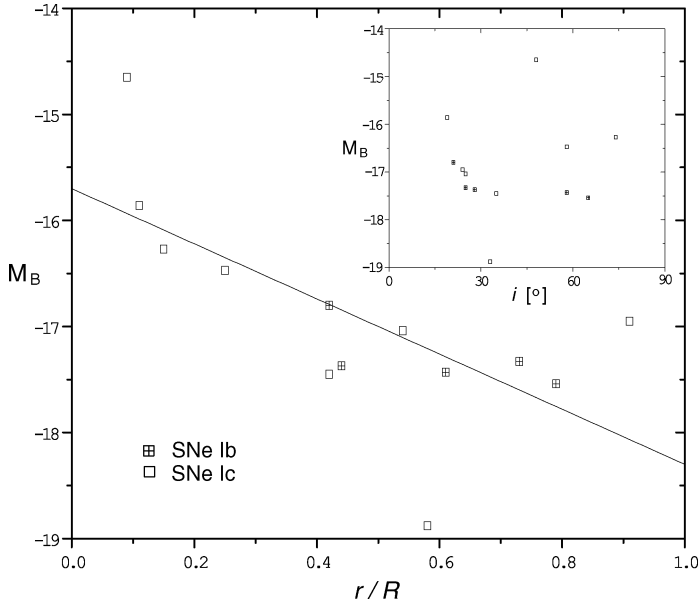


Fig. 2. SN absolute magnitude, uncorrected for the parent galaxy extinction, is plotted against the relative radial position of a SN in the galaxy. The straight line represents the least-squares fit. The inset in the upper-right corner of the plot shows, again, magnitude only now as the function of the galaxy inclination. There is no apparent dependence of M_B on i .

are more massive stars with $\mathcal{M}_{\text{Ic}} \gtrsim 30\mathcal{M}_{\odot}$. If a majority of SN Ib/c, alternatively, appear in close binary systems, then they would result from the same progenitor population as most of the SNe II, i.e. early B stars with initial masses of order $\mathcal{M} \sim 10\mathcal{M}_{\odot}$. Analysis of this scenario, however, would have to include more details and will be rather complicated, dealing with the formation and evolution of CBs.

The joint (Ib/c) intrinsic absolute magnitude obtained is

$$M_B^0 = -18.31 \pm 0.45 \approx -18, \quad (10)$$

whereas SNe Ic are likely to show larger dispersion from this value.

Future observations of SNe at high-redshift and their rate will provide us with unique information on SN progenitors and the star-formation history of galaxies. At higher- z (deeper in the cosmic past), we expect to see the lack of type Ia events, i.e. the dominance of core-collapse SNe. Better understanding of the stripped-envelope SNe (Ib/c), and their potential use as distance indicators at high- z , would therefore be of great practical importance.²⁹

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