Low-Metallicity Star Formation:
From the First Stars to Dwarf Galaxies
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First Stars – Type Ib Supernovae Connection

Ken'ichi Nomoto[1,2]**, Masaomi Tanaka**[2]**, Yasuomi Kamiya**[2]**,**
Nozomu Tominaga[3] **and Keiichi Maeda**[1]

[1]Institute for the Physics and Mathematics of the Universe, University of Tokyo, Kashiwa, Chiba 277-8568, Japan
email: nomoto@astron.s.u-tokyo.ac.jp

[2]Department of Astronomy, University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan
[3]National Astronomical Observatory, Mitaka, Tokyo 113-0033, Japan

Abstract. The very peculiar abundance patterns observed in extremely metal-poor (EMP) stars can not be explained by conventional normal supernova nucleosynthesis but can be well-reproduced by nucleosynthesis in hyper-energetic and hyper-aspherical explosions, i.e., Hypernovae (HNe). Previously, such HNe have been observed only as Type Ic supernovae. Here, we examine the properties of recent Type Ib supernovae (SNe Ib). In particular, SN Ib 2008D associated with the luminous X-ray transient 080109 is found to be a more energetic explosion than normal core-collapse supernovae. We estimate that the progenitor's main sequence mass is $M_{\rm MS} = 20 - 25 M_\odot$ with an explosion of kinetic energy of $E_{\rm K} \sim 6.0 \times 10^{51}$ erg. These properties are intermediate between those of normal SNe and hypernovae associated with gamma-ray bursts. Therefore, such energetic SNe Ib could also make an important contribution to the chemical enrichment in the early Universe.

Keywords. Galaxy: halo, gamma rays: bursts, nuclear reactions, nucleosynthesis, abundances, stars: abundances, stars: Population II, supernovae: general

1. Metal Poor Stars – Hypernovae – GRB Connections

The abundance patterns of the extremely metal-poor (EMP) stars are good indicators of supernova (SN) nucleosynthesis, because the Galaxy was effectively unmixed at [Fe/H] < -3. Thus they could provide useful constraints on the nature of First Supernovae and thus First Stars.

The EMP stars are classified into three groups according to [C/Fe] (e.g., Hill, François, & Primas 2005, Beers & Christlieb 2005):

(1) [C/Fe] ~ 0, normal EMP stars ($-4 <$ [Fe/H] < -3);

(2) [C/Fe] $\gtrsim +1$, Carbon-enhanced EMP (CEMP) stars ($-4 <$ [Fe/H] < -3);

(3) [C/Fe] $\sim +4$, hyper metal-poor (HMP) stars ([Fe/H] < -5, e.g., HE 0107–5240, Christlieb *et al.* 2002, Bessell & Christlieb 2005; HE 1327–2326, Frebel *et al.* 2005).

Table 1 summarizes other abundance features of various EMP stars. Many of these EMP stars have high [Co/Fe].

We have shown that such peculiar abundance patterns can not be explained by conventional normal supernova nucleosynthesis but can be reproduced by nucleosynthesis in hyper-energetic and hyper-aspherical explosions, i.e., Hypernovae (HNe) (e.g., Maeda *et al.* 2002, Maeda & Nomoto 2003, Tominaga *et al.* 2007, Tominaga 2007).

The abundance pattern of the Ultra Metal-Poor (UMP) star (HE 0557–4840: Norris *et al.* 2007) is shown in Figure 1 and compared with the HN ($E_{51} = 20$) and SN ($E_{51} = 1$) models of $25 M_\odot$ stars. The Co/Fe ratio ([Co/Fe]~ 0) requires a high energy explosion and the high [Sc/Ti] and [Ti/Fe] ratios require a high-entropy explosion. The HN model is

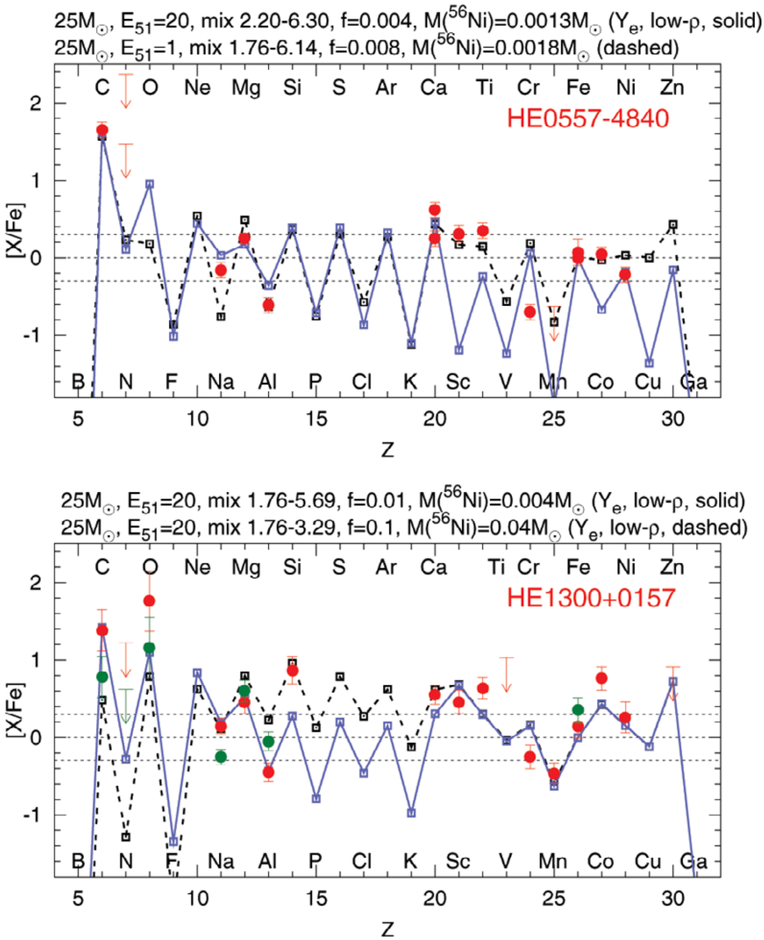

Figure 1. Comparisons of the abundance patterns between the mixing-fallback models and the UMP star HE0557–4840 (upper: Norris *et al.* 2007), and the CEP star HE1300+0157 (lower: Frebel *et al.* 2007).

in a good agreement with the abundance pattern of HE 0557–4840. The model indicates $M(^{56}\mathrm{Ni}) \sim 10^{-3} M_{\odot}$ being similar to faint SN models for CEMP stars.

The abundance pattern of the CEMP-no star (i.e., CEMP with no neutron capture elements) HE 1300+0157 (Frebel *et al.* 2007) is shown in Figure 1 (lower) and marginally reproduced by the hypernova model with $M_{\mathrm{MS}} = 25 M_{\odot}$ and $E_{51} = 20$. The large [Co/Fe] particularly requires the high explosion energy.

Previously, Hypernova-like explosions with $E_{51} > 10$ have been found only in Type Ic supernovae (SNe Ic), which are core-collapse supernovae characterized by the lack of hydrogen and helium.

Recently, several interesting Type Ib supernovae (SNe Ib) have been observed to show quite peculiar features. SNe Ib are another type of envelope-stripped core collapse SN but characterized by the presence of prominent He lines. Thus it is interesting to examine the explosion energy and other properties of SNe Ib in comparison with Hypernovae and normal SNe.

Here we present our analysis of peculiar SNe Ib 2008D and 2006jc.

Table 1. Metal-poor stars.

Name	[Fe/H]	Features	Reference
HE 0107–5240	−5.3	C-rich, Co-rich?, [Mg/Fe]$\sim$ 0	Christlieb *et al.* 2002
HE 1327–2326	−5.5	C, O, Mg-rich	Frebel *et al.* 2005, Aoki *et al.* 2006
HE 0557–4840	−4.8	C, Ca, Sc, Ti-rich, [Co/Fe]$\sim$ 0	Norris *et al.* 2007
HE 1300+0157	−3.9	C, Si, Ca,Sc,Ti, Co-rich	Frebel *et al.* 2007
HE 1424–0241	−4.0	Co,Mn-rich, Si,Ca,Cu-poor	Cohen *et al.* 2007
CS 22949–37	−4.0	C,N,O,Mg,Co,Zn-rich	Depagne *et al.* 2002
CS 29498–43	−3.5	C,N,O,Mg-rich, [Co/Fe]$\sim$ 0	Aoki *et al.* 2004
BS 16934–002	−2.8	O,Mg-rich, C-poor	Aoki *et al.* 2007

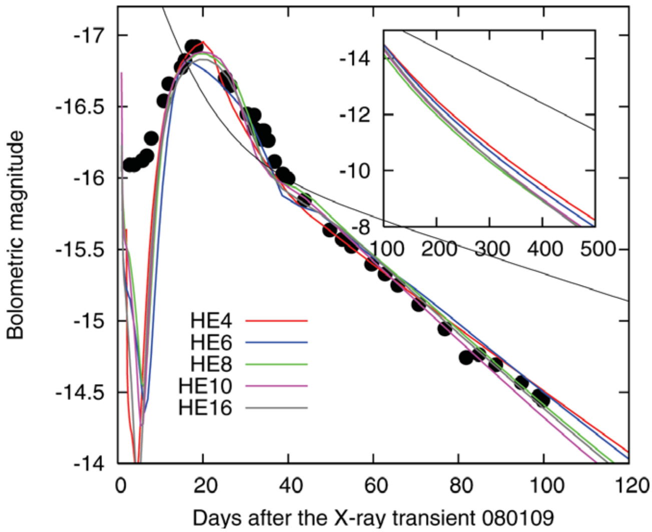

Figure 2. The pseudo-bolometric ($UBVRIJHK$) light curve (LC) of SN 2008D compared with the results of LC calculations with the models HE4 (red), HE6(blue), HE8 (green), HE10 (magenta) and HE16 (gray). The pseudo-bolometric LC is shown in filled (left) and open (right) circles. The thin black line shows the decay energy from ^{56}Ni and ^{56}Co [$M(^{56}\mathrm{Ni}) = 0.07\ M_{\odot}$]. At late epochs, it is roughly equal to the optical luminosity under the assumption that γ-rays are fully trapped. The bolometric magnitude at $t \sim 4$ days after the X-ray transient is brighter by ~ 0.25 mag than that shown by other papers (Soderberg *et al.* 2008; Malesani et al. 2008; Modjaz *et al.* 2008b; Mazzali *et al.* 2008), which is shown by the thin arrow in the left panel.

2. Energetic Type Ib Supernova SN 2008D

SN 2008D was discovered as a luminous X-ray transient in NGC 2770. The X-ray emission of the transient reached a peak $\sim$ 65 seconds, lasting $\sim$ 600 seconds, after the observation started. The X-ray spectrum is soft, and no γ-ray counterpart was detected by the *Swift* BAT. The optical counterpart was discovered at the position of the X-ray transient, confirming the presence of a SN 2008D (see, e.g., Soderberg *et al.* 2008).

SN 2008D showed a broad-line optical spectrum at early epochs ($t \lesssim 10$ days, hereafter t denotes time after the transient, 2008 Jan 9.57 UT, Soderberg *et al.* 2008). However, the spectrum changed to that of a normal Type Ib SN, i.e., a SN with He absorption lines and without H lines (Modjaz *et al.* 2008). To date, the SNe associated with GRBs or XRFs are all Type Ic, i.e., SNe without H and He absorption.

The pseudo-bolometric ($UBVRIJHK$) light curve (LC) is compared with the theoretical models of He star models HE4, HE6, HE8, HE10, and HE16, whose masses are

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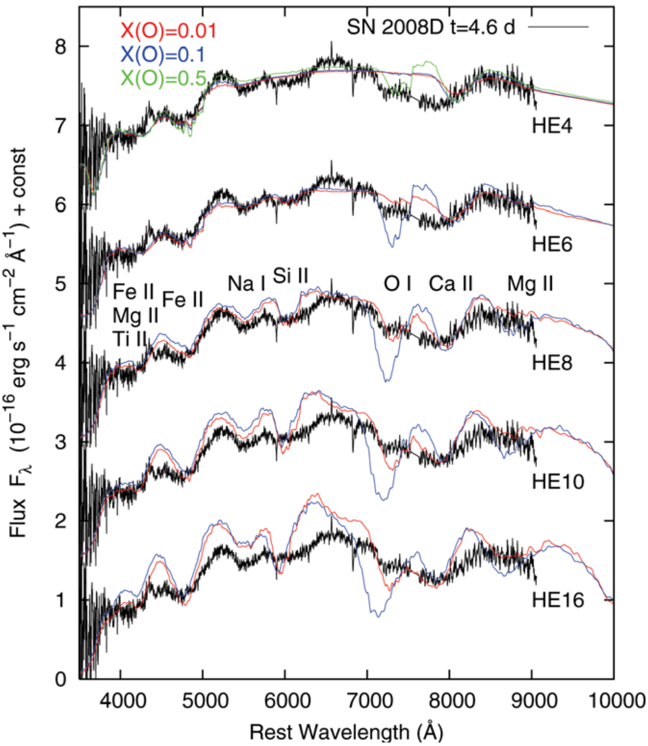

Figure 3. The spectrum of SN 2008D at $t = 4.6$ days from the X-ray transient (black line, Mazzali *et al.* 2008) compared with synthetic spectra (color lines). The spectra are shifted by 6.0, 4.5, 3.0, 1.5, 0.0 from top to bottom. The model spectra are reddened with $E(B-V) = 0.65$ mag. From top to bottom, the synthetic spectra calculated with HE4, H46, HE8, HE10 and HE16 are shown. The red, blue and green lines show the synthetic spectra with oxygen mass fraction $X(\mathrm{O}) = 0.01$, 0.1, and 0.5, respectively. Since the synthetic spectra with $X(\mathrm{O}) = 0.1$ for more massive models than HE4 already show too strong O I line, the spectra with $X(\mathrm{O}) = 0.5$ are not shown for these models.

$M_\alpha = 4, 6, 8, 10$, and $16 M_\odot$, respectively. These He stars correspond to the main-sequence stellar masses of $M_{\rm ms} \sim 15$, 20, 25, 30, and 40 $M_\odot$.

Since the timescale around the peak depends on both $M_{\rm ej}$ and $E_{\rm K}$ as $\propto \kappa^{1/2} M_{\rm ej}^{3/4} E_{\rm K}^{-1/4}$, where κ is the optical opacity (Arnett 1982), a specific kinetic energy is required for each model to reproduce the observed timescale. The derived set of ejecta parameters are ($M_{\rm ej}/M_\odot$, $E_{\rm K}/10^{51}$ erg) = (2.7, 1.1), (4.4, 3.7), (6.2, 8.4), (7.7, 13.0) and (12.5, 26.5) for the case of HE4, HE6, HE8, HE10 and HE16, respectively. The ejected ^{56}Ni mass is $\sim 0.07 M_\odot$ in all models.

We have done a detailed theoretical study of emission from SN 2008D. The bolometric LC and optical spectra are modeled based on realistic progenitor models and the explosion models obtained from hydrodynamic/nucleosynthetic calculations (Tanaka *et al.* 2008).

We have found that HE4, HE10 and HE16 are not consistent with SN 2008D. Both HE6 and HE8 have a small inconsistency related to the boundary between the He-rich and O-rich layers. It seems that a model between HE6 and HE8 may be preferable.

We thus conclude that the progenitor star of SN 2008D had a He core mass $M_\alpha = 6 - 8 M_\odot$ prior to the explosion. This corresponds to a main sequence mass of $M_{\rm MS} = 20 - 25 M_\odot$. We find that SN 2008D is an explosion with $M_{\rm ej} = 5.3 \pm 1.0 M_\odot$ and $E_{\rm K} = 6.0 \pm 2.5 \times 10^{51}$ erg. The mass of the central remnant is $1.6 - 1.8 M_\odot$, which is near the

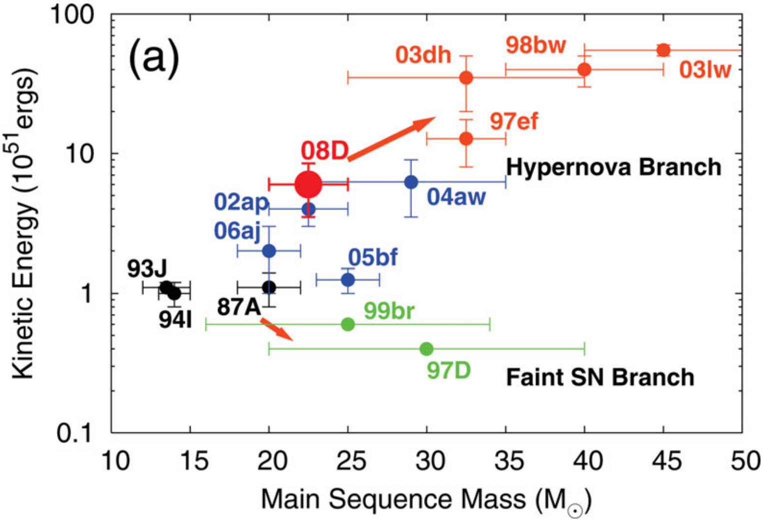

Figure 4. The kinetic explosion energy E as a function of the main sequence mass M of the progenitors for several supernovae/hypernovae. Hypernovae are the SNe with $E_{51} > 10$.

boundary mass between a neutron star and a black hole. Note that the error bars reflect just the uncertainty of the LC and spectral modeling.

Figure 4 shows the kinetic energy of the ejecta and the ejected ^{56}Ni mass as a function of the estimated main sequence mass for several core-collapse SNe (see, e.g., Nomoto *et al.* 2007). SN 2008D is shown by a red circle.

Comparison with other Type Ib SNe shown in Figure 4 is possible only for SN 2005bf although SN 2005bf is a very peculiar SN that shows a double peak LC with a very steep decline after the maximum, and increasing He line velocities (Anupama et al. 2005; Tominaga *et al.* 2005; Folatelli *et al.* 2006; Maeda et al. 2007). The LC of SN 2005bf is broader than that of SN 2008D, while the expansion velocity of SN 2005bf is lower than that of SN 2008D. These facts suggest that SN 2005bf is the explosion with a lower E_K/M_{ej} ratio.

The spectra of SN 2008D and SN 1999ex are very similar (Valenti et al. 2008b), while SN 2005bf has lower He velocities. The He lines in SN 1993J are very weak at this epoch. The Fe features at 4500-5000Å are similar in these four SNe, but those in SN 2005bf are narrower. Malesani *et al.* (2008) suggested that the bolometric LCs of SNe 1999ex and 2008D are similar. The similarity in both the LC and the spectra suggests that SN 1999ex is located close to SN 2008D in the $E_K - M_{MS}$ and $M(^{56}\mathrm{Ni}) - M_{MS}$ diagrams.

Malesani *et al.* (2008) also pointed the similarity of the LCs of SNe 1993J and 2008D. But the expansion velocity is higher in SN 2008D (see, e.g. Prabhu *et al.* 1995). Thus, both the mass and the kinetic energy of the ejecta are expected to be smaller in SN 1993J. In fact, SN 1993J is explained by the explosion of a $4M_\odot$ He core with a small mass H-rich envelope (Nomoto *et al.* 1993; Shigeyama *et al.* 1994; Woosley *et al.* 1994).

3. Dust-Forming Type Ib Supernova SN 2006jc

Another recent event, SN Ib 2006jc, is characterized by dust formation in the ejecta as found from NIR and MIR observations.

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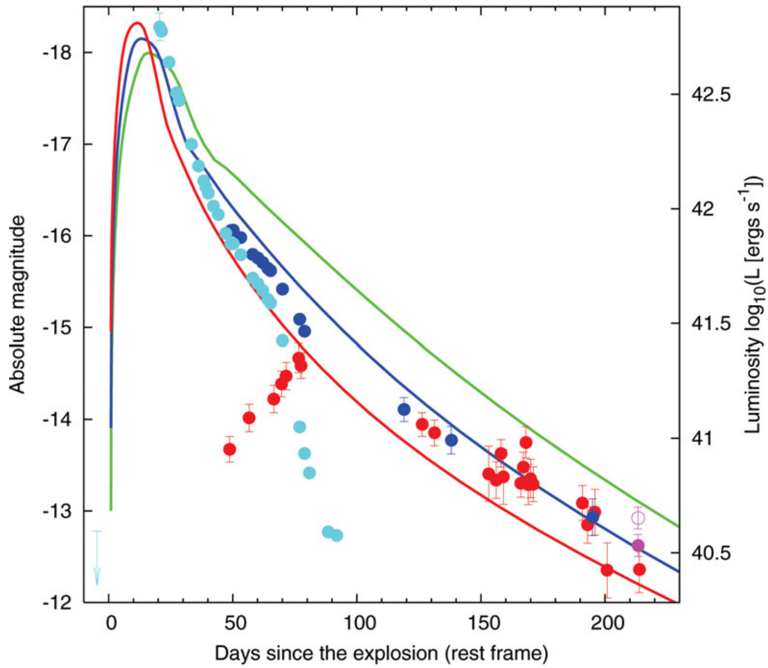

Figure 5. Comparison between the synthetic LCs for the models with $E_{51} = 5$ and $M_{\rm ej} = 5.1 M_{\odot}$, $E_{51} = 10$ and $M_{\rm ej} = 4.9 M_{\odot}$, and $E_{51} = 20$ and $M_{\rm ej} = 4.6 M_{\odot}$, and the LCs of SN 2006jc ($L_{\rm UV} + L_{\rm opt}$, $L_{\rm IR,est}(\nu < 3 \times 10^{14}{\rm Hz})$, $L_{\rm bol}$, $L_{\rm IR,hot}(\nu < 3 \times 10^{14}{\rm Hz})$, $L_{\rm IR}(\nu < 3 \times 10^{14}{\rm Hz})$).

We present a theoretical model for Type Ib supernova (SN) 2006jc. We calculate the evolution of the progenitor star, hydrodynamics and nucleosynthesis of the SN explosion, and the SN bolometric LC. The synthetic bolometric LC is compared with the observed bolometric LC constructed by integrating the UV, optical, near-infrared (NIR), and mid-infrared (MIR) fluxes.

The progenitor is assumed to be as massive as $40 M_{\odot}$ on the zero-age main-sequence. The star undergoes extensive mass loss to reduce its mass down to as small as $6.9 M_{\odot}$, thus becoming a WCO Wolf-Rayet star. The WCO star model has a thick carbon-rich layer, in which amorphous carbon grains can be formed. This could explain the NIR brightening and the dust feature seen in the MIR spectrum. We suggest that the progenitor of SN 2006jc is a WCO Wolf-Rayet star having undergone strong mass loss and such massive stars are the important sites of dust formation. We derive the parameters of the explosion model in order to reproduce the bolometric LC of SN 2006jc by the radioactive decays: the ejecta mass $4.9 M_{\odot}$, hypernova-like explosion energy 10^{52} ergs, and ejected ^{56}Ni mass $0.22 M_{\odot}$.

We also calculate the circumstellar interaction and find that a CSM with a flat density structure is required to reproduce the X-ray LC of SN 2006jc. This suggests a drastic change of the mass-loss rate and/or the wind velocity that is consistent with the past luminous blue variable (LBV)-like event.

We have thus found SN Ib 2006jc is almost a HN-like energetic explosion. This is suggestive for the SN Ib contribution to the early enrichment in the Universe. Also dust formation in a WCO star seems to be quite important.

4. Concluding Remarks

We presented a theoretical model for SN 2008D associated with the luminous X-ray transient 080109. These models are tested against the bolometric LC and optical spectra. This is the first detailed model calculation for the Type Ib SN that is discovered shortly after the explosion.

The main sequence mass of the progenitor of SN 2008D is estimated to be $M_{\rm MS} = 20 - 25 M_{\odot}$, between normal SNe and GRB-SNe (or hypernovae). The kinetic energy of SN 2008D is also intermediate. Thus, SN 2008D is located between the normal SNe and the "hypernovae branch" in the $E_{\rm K} - M_{\rm MS}$ diagram (upper panel of Fig. 4). The ejected ^{56}Ni mass in SN 2008D ($\sim 0.07 M_{\odot}$) is similar to the ^{56}Ni masses ejected by normal SNe but much smaller than those in GRB-SNe.

These energetic SNe Ib, as indicated from both 2008D and 2006jc, could make an important contribution to the chemical enrichment in the early Universe, although the explosions are not as extreme as Hypernovae. Dust formation in WCO stars could also be important.

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