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Unusual Supernovae, Pop III Gamma-Ray Bursts, and First Chemical Enrichment

Ken'ichi Nomoto*
Institute for the Physics and Mathematics of the Universe (IPMU), University of Tokyo
E-mail: nomoto@astron.s.u-tokyo.ac.jp

Takashi Moriya
Institute for the Physics and Mathematics of the Universe (IPMU), University of Tokyo
E-mail: takashi.moriya@ipmu.jp

Masaomi Tanaka
Institute for the Physics and Mathematics of the Universe (IPMU), University of Tokyo
E-mail: masaomi.tanaka@ipmu.jp

Keiichi Maeda
Institute for the Physics and Mathematics of the Universe (IPMU), University of Tokyo
E-mail: keiichi.maeda@ipmu.jp

Nozomu Tominaga
Department of Physics, Konan University
E-mail: tominaga@konan-u.ac.jp

Tomoharu Suzuki
Department of Astronomy, University of Tokyo
E-mail: suzuki@astron.s.u-tokyo.ac.jp

It is remarkable that large diversities of supernova properties such as brightness and explosion energy have been observed. It is challenging to explore the origin of unusual supernovae, e.g., extremely faint and extremely luminous supernovae, and the extremely energetic explosions (hypernovae) associated with the Gamma-Ray Bursts. In particular, we present a core-collapse hypernova model for extremely luminous type Ic SN 2007bi as an alternative to the pair-instability model. We discuss how nucleosynthetic properties resulted from unusual supernovae are connected with the unusual abundance patterns of extremely metal-poor stars. Such connections may provide important constraints on the properties of first stars.

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*Speaker.

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1. Faint Supernovae, Luminous Supernovae, and Hypernovae

The final stages of massive star evolution, supernova properties, and their chemical yields depend on the progenitor's main-sequence masses M (e.g., [1, 34]). Here we call some specific supernovae (SNe) as follows. In terms of the kinetic explosion energy E, we use "Hypernovae" for such energetic SNe as $E_{51} = E/10^{51}$erg > 10. In terms of brightness, we use "Faint SNe (FSNe)" for low luminosity SNe, and "Luminous SNe (LSNe)" for SNe brighter than, say, -20 mag at maximum. The following mass ranges are set by various types of criteria, based on some combinations of observations and models. But the criteria and critical masses are not quite systematic yet, and should still be regarded as working hypothesis.

(1) **$M_{\rm up}$ - 10 $M_\odot$ stars: Faint supernovae**: These stars become electron capture SNe because their degenerate O+Ne+Mg cores collapse due to electron capture. $M_{\rm up} \sim 9 \pm 0.5 M_\odot$ depending on the mass loss rate on the super-AGB phase thus on the metallicity (e.g., [33]).

(2) **10 - 13 $M_\odot$ stars: Faint Supernovae**: These stars undergo Fe-core collapse to form a neutron star (NS) after the phase of strong Neon shell-flashes [24]. Their Fe core is relatively small, and the resultant SNe tend to be faint [34].

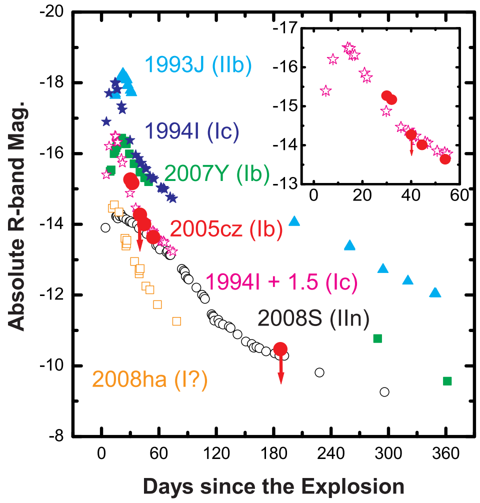
(3) **13 $M_\odot$ - $M_{\rm BN}$ stars: Normal Supernovae**: These stars undergo Fe-core collapse to form a NS, and produce significant amount of heavy elements from α-elements and Fe-peak elements. The boundary mass between the NS and black hole (BH) formation, $M_{\rm BN} \sim 25 M_\odot$, is only tentative.

(4) **$M_{\rm BN}$ - 90 $M_\odot$ stars: Hypernovae and Faint Supernovae**: These stars undergo Fe-core collapse to form a BH. SNe seem to be bifurcate into two branches, Hypernovae and Faint SNe. If the BH has little angular momentum, little mass ejection would take place and be observed as Faint SNe. On the other hand, a rotating BH could eject a matter in a form of jets to make a Hypernova. The latter explosions produce a large amount of heavy elements from α-elements and Fe-peak elements. Nucleosynthesis in these jet-induced explosions is in good agreement with the abundance patterns observed in extremely metal-poor stars.

(5) **90 - 140 $M_\odot$ stars: Luminous SNe (LSNe)**: These massive stars undergo nuclear instabilities and associated pulsations (ε-mechanism) at various nuclear burning stages depending on the mass loss and thus metallicity. Eventually, these stars undergo Fe-core collapse. Depending on the angular momentum, Hypernova-like energetic SNe could occur to produce large amount ^{56}Ni. (Because of the large ejecta mass, the expansion velocities may not be high enough to form a broad line features.) Thanks to the large E and ^{56}Ni mass, the SNe could be a LSNe. The possible presence of circumstellar matter (CM) leads to energetic SN IIn. Pulsation could also cause luminous event.

(6) **140 - 300 $M_\odot$ stars: LSNe**: If these very massive stars (VMS) do not lose much mass, they become pair-instability supernovae (PISN). The star is completely disrupted without forming a BH and thus ejects a large amount of heavy elements, especially ^{56}Ni. Radioactive decays could produce LSNe.

(7) **Stars with $M \gtrsim 300 M_\odot$: LSNe**: These VMSs are too massive to be disrupted by PISN but undergo core collapse (CVMS), forming intermediate-mass black holes (IMBHs). Some mass ejection could be possible, associated with the possible jet-induced explosion, which becomes a very luminous SNe (LSNe).



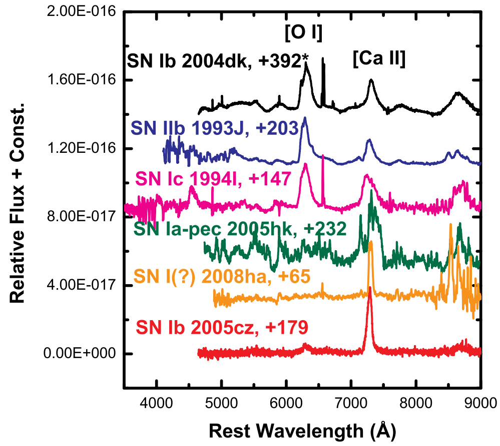


Figure 1: *(Left)*: The absolute R-band light curve of faint supernovae: SN IIn 2008S (black open circles), SN Ib 2005cz (red circles), SN I 2008ha (orange open squares), and SN Ib 2007Y (green squares) as compared with those of SN IIb 1993J (cyan triangles) and SN Ic 1994I (blue stars). Also shown is the light curve of SN 1994I, but dimmed by 1.5 magnitudes (magenta open stars) [15].

Figure 2: *(Right)*: The late-time spectrum of SN Ib 2005cz ($t = +179$ days). Also shown are SN Ib 2004dk at $t \sim 390$ days, SN IIb 1993J at $t = +203$ days, SN Ic 1994I at $t = +147$ days, peculiar SN Ia 2005hk at $t = +232$ days, and peculiar SN I 2008ha at $t = +65$ days. It is very unique that SN 2005cz shows only weak [O I] $\lambda\lambda$6300, 6364 and much stronger [Ca II] $\lambda\lambda$7291, 7323 than [O I] [15].

In the following sections, we summarize the properties of the above supernovae in some detail. See also [25, 26, 27, 28, 29].

2. 8 - 10 $M_\odot$ Super-AGB Progenitors and Faint Supernovae

An O+Ne+Mg white dwarf is formed from 8 $M_\odot$ - M_{up} stars, where $M_{up} \sim 9 \pm 0.5 M_\odot$ being smaller for smaller metallicity [33].

For M_{up} - 10 $M_\odot$ stars, the core mass grows to 1.38 $M_\odot$ and electron captures ^{24}Mg(e$^-$, ν) ^{24}Na (e$^-$, ν) ^{20}Ne and ^{20}Ne (e$^-$, ν) ^{20}F (e$^-$, ν) ^{20}O induce collapse [23].

The resultant explosion is induced by neutrino heating, and weak with the kinetic energy of as low as $E \sim 10^{50}$ erg [16]. These stars produce little α-elements and Fe-peak elements, but are important sources of Zn and light p-nuclei. These AGB supernovae may constitute an SN 2008S-like sub-class of Type IIn supernovae.

Nucleosynthesis in the supernova explosion of the $9 M_\odot$ star is as follows [41]. The largest overproduction is shared by ^{64}Zn, ^{70}Se, and ^{78}Kr. The ^{64}Zn production provides an upper limit to the occurrence of exploding O-Ne-Mg cores at about 20% of all core-collapse supernovae. The ejecta mass of ^{56}Ni is $0.002 - 0.004 M_\odot$, much smaller than $\sim 0.1 M_\odot$ in more massive progenitors.

The expected small amount of ^{56}Ni as well as the low explosion energy of electron capture supernovae have been proposed as an explanation of the observed properties of Faint SNe of type IIn, such as SN 2008S and similar transients [32, 35]. The envelope of the AGB star is carbon-enhanced [23]. Then dust could easily be formed in mass loss. This may result in a deeply dust-enshrouded object such as the progenitor of SN 2008S [32, 35].

3. Faint Supernovae from 10 - 13 $M_\odot$ Stars

Kawabata et al. (2010) reported the unique properties of SN 2005cz, which provide a new clue to the understanding of the SN property-progenitor connection. SN 2005cz is a He-rich Type Ib SN (SN Ib) and appeared in the elliptical galaxy. This is peculiar because SN Ib is a core-collapse explosion of a He star and usually does not appear in elliptical galaxies that contain only old low-mass stars.

Further, SN 2005cz is unusually faint and rapidly fading (Fig. 1). The mass of ^{56}Ni is estimated to be $M(^{56}\mathrm{Ni}) \sim 0.018\mathrm{M}_\odot$. The late-time spectrum of SN 2005cz at $t = +179$ days is very unique; unlike most of other SNe Ibc/IIb SN 2005cz shows much stronger [Ca II] than [O I] (Fig. 2) [15, 40, 7].

Oxygen is ejected mostly from the oxygen layer formed during the hydrostatic burning phase. Thus its mass depends sensitively on the progenitor mass and is smaller for lower-mass progenitors. On the other hand, Ca is explosively synthesized during the explosion. Theoretical models predict that the stars having main-sequence masses of $M_{\mathrm{ms}} = 13M_\odot$ and $18M_\odot$ produce 0.2 and $0.8M_\odot$ of O, and 0.005 and $0.004M_\odot$ of Ca, respectively [26]. Therefore, the Ca/O ratio in the SN ejecta is sensitive to the progenitor mass. To produce the extremely large Ca/O ratio, the mass of the progenitor star of SN 2005cz should be smaller than any other SNe Ib reported to date.

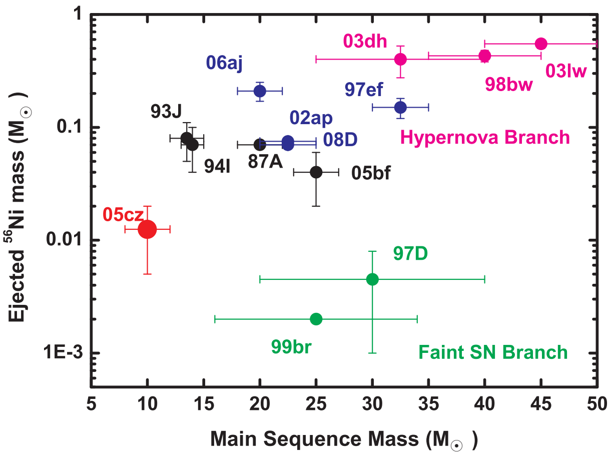
Kawabata et al. (2010) illustrate these unusual facts of SN 2005cz with the properties of SNe from the low-mass end of the core-collapse progenitors (i.e., either 8 - 10 $M_\odot$ or 10 - 13 $M_\odot$) in close binaries.

As for the host galaxy problem, the $\sim 10M_\odot$ star model is found to be consistent with the properties recently-inferred for the host galaxy of SN 2005cz. It is still a genuine E2 galaxy, but has a relatively young stellar population with life times of $10^7 - 10^8$ years and SN Ib 2005cz is likely the end product of one of these young stars (see [15] and references therein).

4. Supernovae from 13 $M_\odot$ - M_{BN} Stars

The supernova yields (including the mass of ^{56}Ni) depend on the progenitor's mass M, metallicity, and the explosion energy E (e.g., [18]). From the comparison between the observed and calculated spectra and light curves of supernovae, we can estimate M, E, and the mass of ^{56}Ni as shown in Figure 3 [26, 15]. From this figure, the boundary mass between the NS and BH formation has been estimated to be $M_{\mathrm{BN}} \sim 25M_\odot$. As shown in [27], the yields between the three groups [26, 19, 12] are in good agreement for $M = 15 - 25M_\odot$, $E = 1 \times 10^{51}$ erg and $Z = 0.00$ - 0.02.

However, theoretical predictions of Zn, Co, Ti/Fe are much smaller than those observed in extremely metal-poor (EMP) stars. The underproduction of these elements relative to Fe is much improved in the hypernova models (Fig. 5).



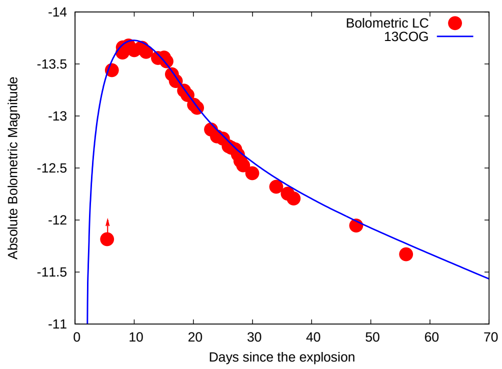


Figure 3: *(Left)*: The ejected mass of ^{56}Ni as a function of the main sequence mass M of the progenitors for several supernovae/hypernovae [15].

Figure 4: *(Right:)* The bolometric light curves of SN 2008ha and the model with $M = 13M_\odot$, $E = 1.2\times10^{48}$ erg, $M_{ej} = 0.074M_\odot$, and 0.003 $M_\odot$ ^{56}Ni [22].

The abundance pattern of EMP stars in the Hercules dwarf spheroidal galaxy is very peculiar [17], but can be reproduced by yields of Hypernova model with $M = 25M_\odot$ and $E_{51} = 20$ (Fig. 6; Tominaga et al. in prep.). These agreements suggest that hypernovae play an important role in the chemical enrichment during early galactic evolution.

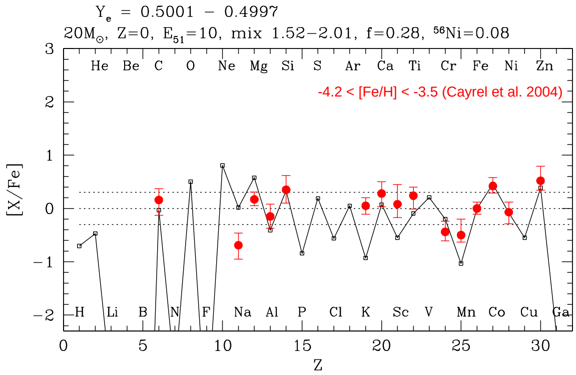
5. Hypernovae and Faint Supernovae from M_{BN} - 90 $M_\odot$ Stars

SNe in this mass range form BHs and seem to bifurcate into the Hypernova branch and the Faint SNe branch (Fig. 3). The Hypernova branch include three SNe (1998bw, 2003dh, and 2003lw) that are associated with long Gamma-Ray Bursts (GRBs) (Fig. 3).

Among the Faint SNe, one of the faintest example is SN 2008ha [40, 7]. This SN is of type I and the peak V magnitude is only -14.2 mag. The rise and decline of the LC is quite fast. Line velocities are such low as $\sim 2,000$ km s^{-1}. Moriya et al. (2010b) have shown that these features can be reproduced by the core-collapse supernova model. Figure 4 shows the bolometric LC of the model with $M = 13M_\odot$, $E = 1.2\times10^{48}$ erg, and 0.003 $M_\odot$ ^{56}Ni. The ejecta of this explosion model undergoes large fallback because of low E, so that the ejecta mass is only 0.074 $M_\odot$. The LC of this model well-reproduces SN 2008ha. (Although the $13M_\odot$ model is shown here, more massive star models may also reproduce SN 2008ha [22]).

The fallback SN (e.g., [14, 9]) should also undergo mixing of ^{56}Ni before the occurrence of fallback in order to reproduce the observed light curve. Tominaga (2009) has shown that such "mixing and fallback" in spherical explosion is equivalent to the jet-induced nucleosynthesis.

In the jet-induced nucleosynthesis and mass ejection, the important parameter is the energy deposition rate $\dot{E}_{dep}$ [36]. The variation of $\dot{E}_{dep}$ in the range of $\dot{E}_{dep,51} \equiv \dot{E}_{dep}/10^{51}\mathrm{ergs\,s^{-1}} = 0.3 - 1500$ leads to the following variation of the properties of GRBs and associated SNe. For low energy deposition rates ($\dot{E}_{dep,51} < 3$), the ejected ^{56}Ni masses ($M(^{56}\mathrm{Ni}) < 10^{-3}M_\odot$) are smaller than



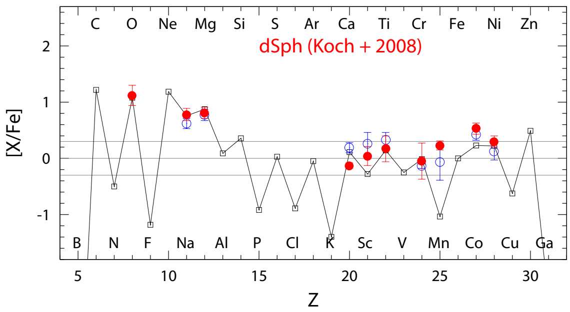


Figure 5: *(Left)*: Averaged elemental abundances of stars with [Fe/H] $= -3.7$ [4] compared with the hypernova yield (20 $M_\odot$, $E_{51} = 10$).

Figure 6: *(Right)*: The peculiar abundance pattern of the EMP stars in the Hercules dwarf spheroidal galaxy [17] is compared with the Hypernova yield (Tominaga et al. in prep.).

the upper limits for non-SN GRBs 060505 and 060614 [14]. For intermediate energy deposition rates ($3 \lesssim \dot{E}_{\rm dep,51} < 60$), the explosions eject $10^{-3} M_\odot \lesssim M(^{56}{\rm Ni}) < 0.1 M_\odot$, and the final BH masses are $10.8 M_\odot \lesssim M_{\rm BH} < 15.1 M_\odot$. The resulting SN is faint ($M(^{56}{\rm Ni}) < 0.01 M_\odot$) or sub-luminous ($0.01 M_\odot \lesssim M(^{56}{\rm Ni}) < 0.1 M_\odot$).

Faint SN as a result of large fallback has been suggested to be responsible to produce the peculiar abundance patterns of extremely metal-poor (EMP) stars [38, 14]. In the jet-induced explosion model, the abundance patterns of EMP stars (esp. [C/Fe]) are related to $\dot{E}_{\rm dep}$ as follows. Lower $\dot{E}_{\rm dep}$ yields larger $M_{\rm BH}$ and thus larger [C/Fe], because the infall reduces the amount of inner core material (Fe) relative to that of outer material (C).

The observed abundance patterns of extremely metal-poor (EMP) stars are classified into three groups according to [C/Fe]:

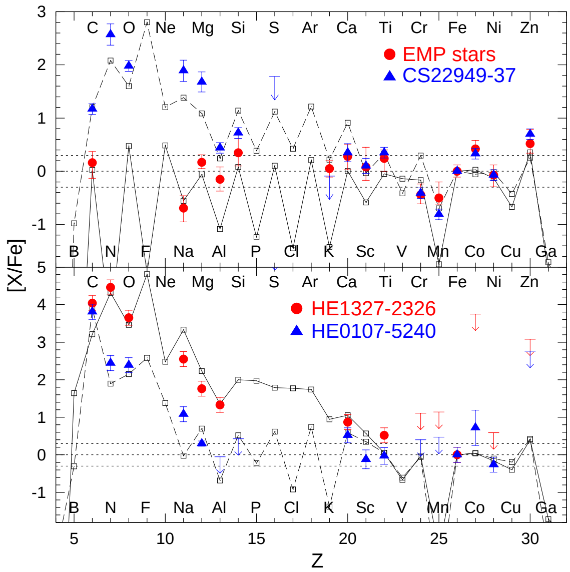
(1) [C/Fe] ~ 0, normal EMP stars ($-4 <$ [Fe/H] < -3, e.g., [4]);

(2) [C/Fe] $\gtrsim +1$, Carbon-enhanced EMP (CEMP) stars ($-4 <$ [Fe/H] < -3, e.g., CS 22949–37 [6]);

(3) [C/Fe] $\sim +4$, hyper metal-poor (HMP) stars ([Fe/H] < -5, e.g., HE 0107–5240 [5, 3]; HE 1327–2326 [8]).

Figure 7 shows that the abundance patterns of the averaged normal EMP stars, the CEMP star CS 22949–37, and the two HMP stars (HE 0107–5240 and HE 1327–2326) are well reproduced by the models with $\dot{E}_{\rm dep,51} = 120$, 3.0, 1.5, and 0.5, respectively. The model for the normal EMP stars ejects $M(^{56}{\rm Ni}) \sim 0.2 M_\odot$, i.e., a factor of 2 less than SN 1998bw. On the other hand, the models for the CEMP and the HMP stars eject $M(^{56}{\rm Ni}) \sim 8 \times 10^{-4} M_\odot$ and $4 \times 10^{-6} M_\odot$, respectively.

To summarize, (1) the explosions with large energy deposition rate, $\dot{E}_{\rm dep}$, are observed as GRB-HNe, and their yields can explain the abundances of normal EMP stars, and (2) the explosions with small $\dot{E}_{\rm dep}$ are observed as GRBs without bright SNe and can be responsible for the formation of the CEMP and the HMP stars. We thus propose that GRB-HNe and GRBs without bright SNe belong to a continuous series of BH-forming massive stellar deaths with relativistic jets of different $\dot{E}_{\rm dep}$.



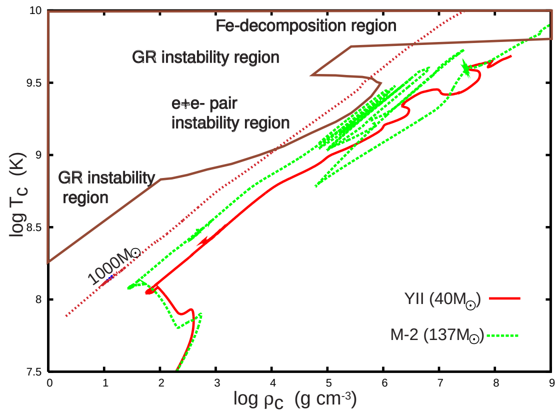


Figure 7: *(Left)*: A comparison of the abundance patterns between metal-poor stars and models [36]. *Upper*: typical EMP stars (*red dots*, [4]) and CEMP (*blue triangles*, CS 22949–37, [6]) and models with $\dot{E}_{\rm dep,51} = 120$ (*solid line*) and $= 3.0$ (*dashed line*). *Lower*: HMP stars: HE 1327–2326, (*red dots*, e.g., [8]), and HE 0107–5240, (*blue triangles*, [5, 3]) and models with $\dot{E}_{\rm dep,51} = 1.5$ (*solid line*) and $= 0.5$ (*dashed line*).

Figure 8: *(Right)*: Evolutionary tracks of the central temperature and central density of very massive stars [31]. The numbers in brackets are the final masses for models YII and M-2. The $1000M_\odot$ stars [30] are also shown.

6. Luminous Supernovae from $90-140M_\odot$ Stars

Massive Pop III stars are formed through mass accretion, starting from a tiny core through collapse (e.g., [44]). Such an evolution with mass accretion starting from $M \sim 1M_\odot$ has recently been studied by [30, 31]. Figure 8 shows the evolutionary tracks of the central density and temperature in the later phases.

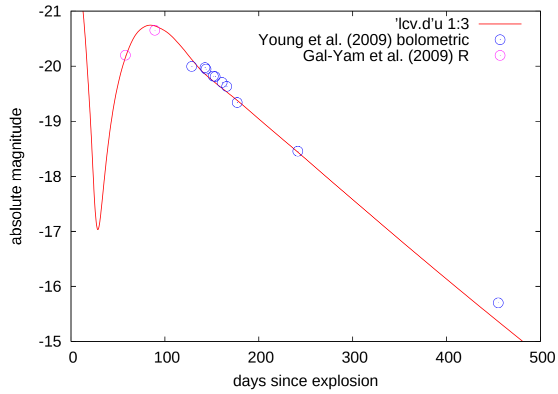
The star M-2, whose final mass is $137M_\odot$, undergoes nuclear instability due to oxygen and silicon burning and pulsates [25, 42, 39, 31]. In the extreme case, the pulsation could induce dynamical mass ejection and optical brightening as might be observed in the brightest SN 2006gy [42].

After pulsations, these stars eventually undergo core-collapse to form BHs, which could lead to Pop III GRBs.

If the explosion energy in forming Pop III GRBs is large enough, the mass of ^{56}Ni can be as large as $\sim 6M_\odot$ [39]. The resultant light curve can be consistent with Luminous Supernovae such as SNe 2006gy and 2007bi (Figs. 9 and 10: [22]).

7. Pair-Instability Supernovae from 140 - 300 $M_\odot$ Stars

These very massive stars (VMS) undergo pair-creation instability and are disrupted completely by explosive oxygen burning, as pair-instability supernovae (PISNe) (e.g., [2, 1, 38, 11]). Their LCs



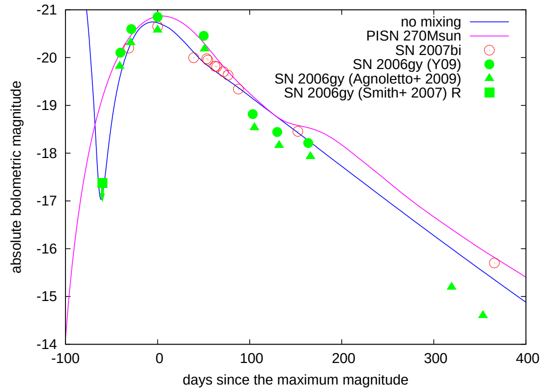


Figure 9: *(Left)*: The bolometric light curve of the C+O core SN models ($M_{\rm ej} = 39\ M_\odot, E_{\rm kin} = 3.3\times10^{52}$ erg, and $M(^{56}{\rm Ni}) = 6.1\ M_\odot$) compared with the bolometric LC of SN 2007bi [22].

Figure 10: *(Right)*: The PISN model ($M = 270 M_\odot$) for the LC of SNe 2006gy and 2007bi [22].

can be consistent with LSNe 2007bi and 2006gy [10] as seen in Figs. 9 and 10 [22].

However the abundance patterns of the ejected material for the 200 $M_\odot$ star [38] are compared with EMP stars. It is clear that PISN ejecta cannot be consistent with the large C/Fe observed in HMP stars and other C-rich EMP stars. Also, the abundance ratios of iron-peak elements ([Zn/Fe] < -0.8 and [Co/Fe] < -0.2) in the PISN ejecta cannot explain the large Zn/Fe and Co/Fe ratios in typical EMP stars.

8. Very Massive Stars ($> 300 M_\odot$) and Intermediate Mass Black Holes

It is possible that the First Stars were even more massive than $\sim 300 M_\odot$, if rapid mass accretion continues during the whole main-sequence phase of Pop III stars [30, 31].

Such massive stars undergo core-collapse (CVMS: core-collapse VMS) as seen from the 1000 $M_\odot$ star track in Figure 8. If such stars formed rapidly rotating black holes, jet-like mass ejection could produce processed material [30]. In fact, for moderately aspherical explosions, the patterns of nucleosynthesis match the observational data of both intracluster medium and M82 [30].

It is also possible that LSNe 2006gy and/or 2007bi can be the explosion of the above CVMS. This result suggests that explosions of CVMS contribute significantly to the chemical evolution of gases in clusters of galaxies. This result may support the view that Pop III CVMS could be responsible for the origin of intermediate mass black holes (IMBH) and Pop III GRBs.

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