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Population III Supernovae and their Nucleosynthesis

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Abstract. Stars more massive than ~ 20 - 25 $M_\odot$ form a black hole at the end of their evolution. Stars with non-rotating black holes are likely to collapse "quietly" ejecting a small amount of heavy elements (Faint supernovae). In contrast, stars with rotating black holes are likely to give rise to very energetic supernovae (Hypernovae). We present distinct nucleosynthesis features of these two types of "black-hole-forming" supernovae. Nucleosynthesis in Hypernovae is characterized by larger abundance ratios (Zn,Co,V,Ti)/Fe and smaller (Mn,Cr)/Fe than normal supernovae, which can explain the observed trend of these ratios in extremely metal-poor stars. Nucleosynthesis in Faint supernovae is characterized by a large amount of fall-back. We show that the abundance pattern of the recently discovered most Fe-poor star, HE0107-5240, and other extremely metal-poor carbon-rich stars are in good accord with those of black-hole-forming supernovae, but not pair-instability supernovae. This suggests that black-hole-forming supernovae made important contributions to the early Galactic (and cosmic) chemical evolution. Finally we discuss the nature of First (Pop III) Stars.

Key words. supernovae – abundances – Population III stars

1. Introduction

Among the important developments in recent studies of core-collapse supernovae are the discoveries of two distinct types of supernovae (SNe): 1) very energetic SNe (Hypernovae), whose kinetic energy (KE) exceeds 10^{52} erg, about 10 times the KE of normal core-collapse SNe (hereafter $E_{51} = E/10^{51}$ erg), and 2) very faint and low energy SNe ($E_{51} \lesssim 0.5$; Faint supernovae). These two types of supernovae are likely to be "black-hole-forming" supernovae with rotating or non-rotating black holes. We compare their nucleosynthesis yields with the abundances of extremely metal-poor (EMP) stars to identify the Pop III (or first) supernovae. We show that the EMP stars, especially the C-rich class, are likely to be enriched by black-hole-forming supernovae.

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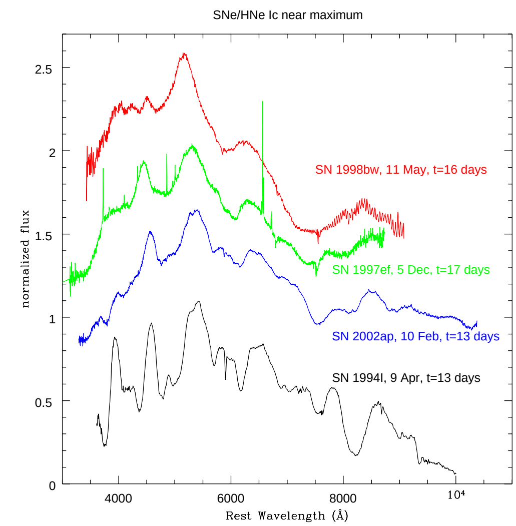

Fig. 1. The near-maximum spectra of Type Ic SNe and hypernovae: SNe 1998bw, 1997ef, 2002ap, and 1994I.

2. Hypernova Branch and Faint Supernova Branch

Type Ic Hypernova SN 1998bw was probably linked to GRB 980425 (Galama et al. 1998), thus establishing for the first time a connection between gamma-ray bursts (GRBs) and core-collapse SNe. However, SN 1998bw was exceptional for a SN Ic: it was as luminous at peak as a SN Ia, indicating that it synthesized $\sim 0.5\ M_\odot$ of ^{56}Ni, and its KE was estimated as $E \sim 3 \times 10^{52}$ erg (Iwamoto et al. 1998; Woosley, Eastman, & Schmidt 1999; Nakamura et al. 2001a).

Subsequently, other "hypernovae" have been recognized, such as SN 1997ef (Iwamoto et al. 2000; Mazzali, Iwamoto, & Nomoto 2000), SN 1999as (Knop et al. 1999; Hatano et al. 2001), and SN 2002ap (Mazzali et al. 2002). Figure 1 shows the near-maximum spectra of hypernovae. These hypernovae span a wide range of properties, although they all appear to be highly energetic compared to normal core-collapse SNe.

Figure 2 shows E and the mass of ^{56}Ni ejected $M(^{56}\mathrm{Ni})$ as a function of the main-sequence mass $M_{\rm ms}$ of the progenitor star obtained from fitting the optical light curves and spectra. These mass estimates place hypernovae at the high-mass end of SN progenitors.

In contrast, SNe II 1997D and 1999br were very faint SNe with very low KE (Turatto et al. 1998; Hamuy 2003; Zampieri et al. 2003). In Figure 2, therefore, we propose that SNe from stars with $M_{\rm ms} \gtrsim$ 20-25 $M_\odot$ have different E and $M(^{56}\mathrm{Ni})$, with a bright, energetic "hypernova branch" at one extreme and a faint, low-energy SN branch at the other (Nomoto et al. 2003ab). For the faint SNe, the explosion energy was so small that most ^{56}Ni fell back onto the compact remnant. Thus the faint SN branch may become a "failed" SN branch at larger $M_{\rm ms}$. Between the two branches, there may be a variety of SNe (Hamuy 2003).

This trend might be interpreted as follows. Stars with $M_{\rm ms} \lesssim$ 20-25 $M_\odot$ form a neutron star, producing $\sim 0.08 \pm 0.03\ M_\odot$ ^{56}Ni as in SNe 1993J, 1994I, and 1987A. Stars with $M_{\rm ms} \gtrsim$ 20-25 $M_\odot$ form a black hole; whether they become hypernovae or faint SNe may depend on the angular momentum in the collapsing core, which in turn depends on the stellar winds, metallicity, magnetic fields, and binarity. Hypernovae might have rapidly rotating cores owing possibly to the spiraling-in of a companion star in a binary system.

3. Nucleosynthesis in Hypernovae

In core-collapse supernovae/hypernovae, stellar material undergoes shock heating and subsequent explosive nucleosynthesis. Iron-peak elements are produced in two distinct regions, which are characterized by the peak temperature, $T_{\rm peak}$, of the shocked material. For $T_{\rm peak} > 5\times10^9$K, material undergoes complete Si burning whose products include Co, Zn, V, and some Cr after radioactive decays. For $4 \times 10^9\mathrm{K} < T_{\rm peak} < 5 \times 10^9$K, incomplete Si burning takes place and its after decay products include Cr and Mn (Hashimoto, Nomoto, & Shigeyama 1989; Thielemann, Nomoto, & Hashimoto 1996).

3.1. Supernovae vs. Hypernovae

The right panel of Figure 3 shows the composition in the ejecta of a 25 $M_\odot$ hypernova model

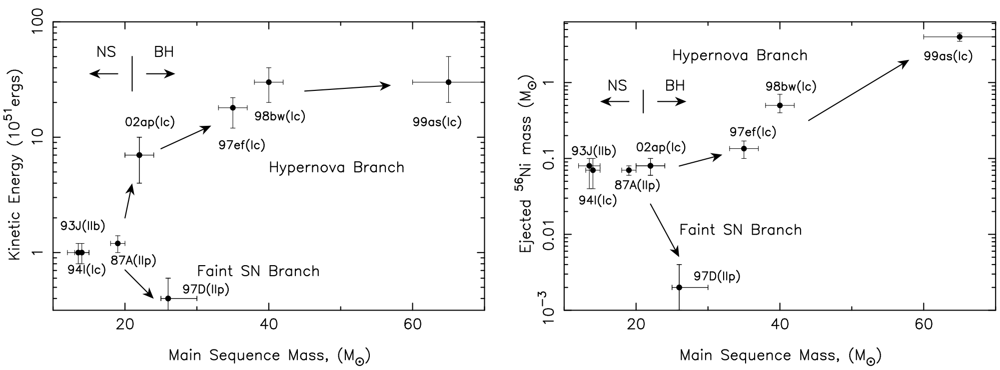

Fig. 2. The explosion energy and the ejected ^{56}Ni mass as a function of the main sequence mass of the progenitors for several supernovae/hypernovae (Nomoto et al. 2003ab).

(E_{51} = 10). The nucleosynthesis in a normal 25 $M_\odot$ SN model (E_{51} = 1) is also shown for comparison in the left panel of Figure 3 (Umeda & Nomoto 2002).

We note the following characteristics of nucleosynthesis with very large explosion energies (Nakamura et al. 2001b; Nomoto et al. 2001; Ohkubo et al. 2003):

(1) Both complete and incomplete Si-burning regions shift outward in mass compared with normal supernovae, so that the mass ratio between the complete and incomplete Si-burning regions becomes larger. As a result, higher energy explosions tend to produce larger [(Zn, Co, V)/Fe] and smaller [(Mn, Cr)/Fe], which can explain the trend observed in very metal-poor stars (Umeda & Nomoto 2003b).

(2) In the complete Si-burning region of hypernovae, elements produced by α-rich freezeout are enhanced. Hence, elements synthesized through capturing of α-particles, such as ^{44}Ti, ^{48}Cr, and ^{64}Ge (decaying into ^{44}Ca, ^{48}Ti, and ^{64}Zn, respectively) are more abundant.

(3) Oxygen burning takes place in more extended regions for the larger KE. Then more O, C, Al are burned to produce a larger amount of burning products such as Si, S, and Ar. Therefore, hypernova nucleosynthesis is characterized by large abundance ratios of [Si,S/O], which can explain the abundance feature of M82 (Umeda et al. 2002).

3.2. Hypernovae and Zn, Co, Mn, Cr

Hypernova nucleosynthesis may have made an important contribution to Galactic chemical evolution. In the early galactic epoch when the galaxy was not yet chemically well-mixed, [Fe/H] may well be determined by mostly a single SN event (Audouze & Silk 1995). The formation of metal-poor stars is supposed to be driven by a supernova shock, so that [Fe/H] is determined by the ejected Fe mass and the amount of circumstellar hydrogen swept-up by the shock wave (Ryan, Norris, & Beers 1996). Then, hypernovae with larger E are likely to induce the formation of stars with smaller [Fe/H], because the mass of interstellar hydrogen swept up by a hypernova is roughly proportional to E (Ryan et al. 1996; Shigeyama & Tsujimoto 1998) and the ratio of the ejected iron mass to E is smaller for hypernovae than for normal supernovae.

In the observed abundances of halo stars, there are significant differences between the abundance patterns in the iron-peak elements below and above [Fe/H]~ -2.5 - -3.

(1) For [Fe/H]$\lesssim -2.5$, the mean values of [Cr/Fe] and [Mn/Fe] decrease toward smaller metallicity, while [Co/Fe] increases (McWilliam et al. 1995; Ryan et al. 1996).

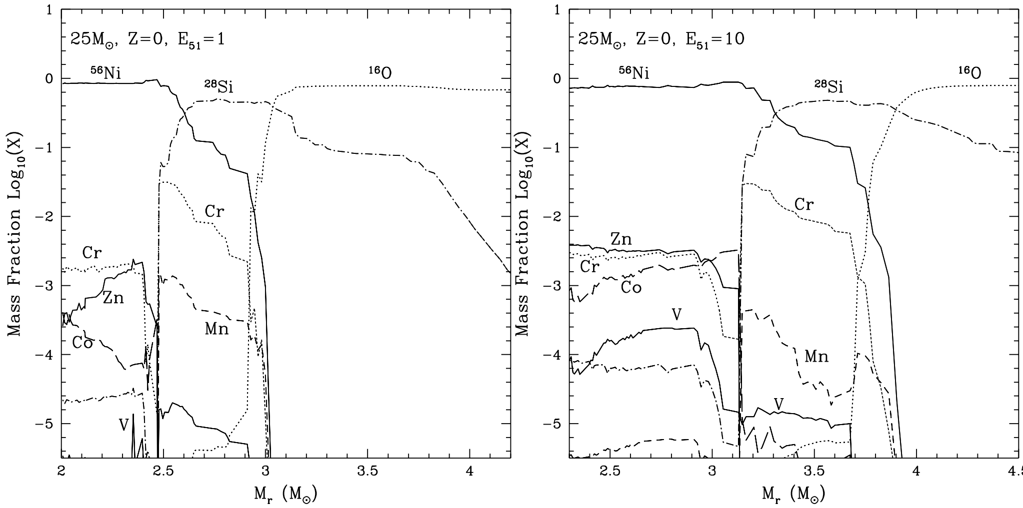

Fig. 3. Abundance distribution against the enclosed mass M_r after the explosion of Pop III 25 $M_\odot$ stars with $E_{51} = 1$ (left) and $E_{51} = 10$ (right) (Umeda & Nomoto 2002).

(2) [Zn/Fe]$\sim$ 0 for [Fe/H] $\simeq -3$ to 0 (Sneden, Gratton, & Crocker 1991), while at [Fe/H] < -3.3, [Zn/Fe] increases toward smaller metallicity (Primas et al. 2000; Blake et al. 2001).

The larger [(Zn, Co)/Fe] and smaller [(Mn, Cr)/Fe] in the supernova ejecta can be realized if the mass ratio between the complete Si burning region and the incomplete Si burning region is larger, or equivalently if deep material from the complete Si-burning region is ejected by mixing or aspherical effects. This can be realized if (1) the mass cut between the ejecta and the compact remnant is located at smaller M_r (Nakamura et al. 1999), (2) E is larger to move the outer edge of the complete Si burning region to larger M_r (Nakamura et al. 2001b), or (3) asphericity in the explosion is larger.

Among these possibilities, a large explosion energy E enhances α-rich freezeout, which results in an increase of the local mass fractions of Zn and Co, while Cr and Mn are not enhanced (Umeda & Nomoto 2002; Ohkubo et al. 2003). Models with $E_{51} = 1$ do not produce sufficiently large [Zn/Fe]. To be compatible with the observations of [Zn/Fe] $\sim$ 0.5, the explosion energy must be much larger, i.e., $E_{51} \gtrsim 20$ for $M \gtrsim 20 M_\odot$, i.e., hypernova-like explosions of massive stars ($M \gtrsim 25 M_\odot$) with $E_{51} > 10$ are responsible for the production of Zn.

In the hypernova models, the overproduction of Ni, as found in the simple "deep" mass-cut model, can be avoided (Ohkubo et al. 2003). Therefore, if hypernovae made significant contributions to the early Galactic chemical evolution, it could explain the large Zn and Co abundances and the small Mn and Cr abundances observed in very metal-poor stars (Fig. 4: Umeda & Nomoto 2003b).

4. Extremely Metal-Poor (EMP) Stars

Recently the most Fe deficient and C-rich low mass star, HE0107-5240, was discovered (Christlieb et al. 2002). This star has [Fe/H] $= -5.3$ but its mass is as low as 0.8 $M_\odot$. This would challenge the recent theoretical arguments that the formation of low mass stars, which should survive until today, is suppressed below [Fe/H] $= -4$ (Schneider et al. 2002).

The important clue to this problem is the observed abundance pattern of this star. This star is characterized by a very large ratios of [C/Fe] = 4.0 and [N/Fe] = 2.3, while the abundances of elements heavier than Mg are as low as Fe (Christlieb et al. 2002). Interestingly, this is not the only extremely metal poor (EMP)

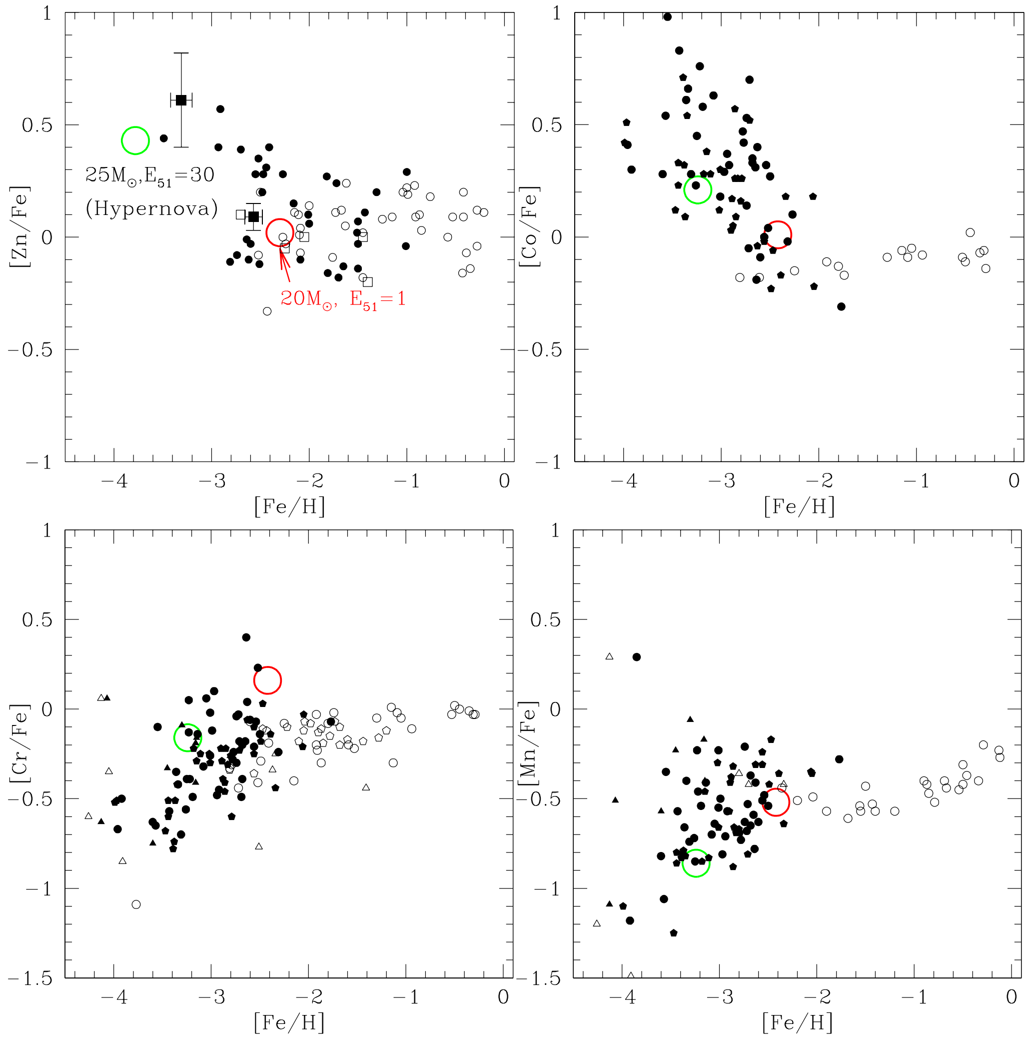

Fig. 4. Observed abundance ratios of [Zn, Co, Cr, Mn/Fe] vs [Fe/H] compared with (15M, E_{51} = 1) and (25M, E_{51}=30) models (Umeda & Nomoto 2003b).

stars that have the large C/Fe and N/Fe ratios, but several other such stars have been discovered (Ryan 2002). Therefore the reasonable explanation of the abundance pattern should explain other EMP stars as well. We show that the abundance pattern of C-rich EMP stars can be reasonably explained by the nucleosynthesis of 20 - 130 $M_{\odot}$ supernovae with various explosion energies and the degree of mixing and fallback of the ejecta.

4.1. The Most Fe-Poor Star HE0107-5240

We consider a model that C-rich EMP stars are produced in the ejecta of (almost) metal-free supernova mixed with extremely metal-poor interstellar matter. We use Pop III pre-supernova progenitor models, simulate the supernova explosion and calculate detailed nucleosynthesis (Umeda & Nomoto 2003a).

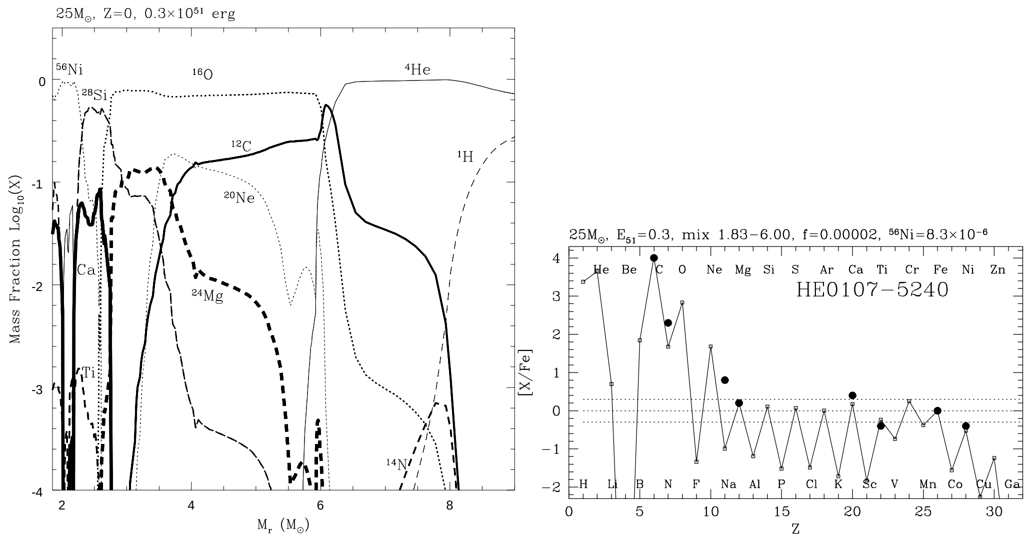

Fig. 5. (left) The post-explosion abundance distributions for the 25 $M_\odot$ model with the explosion energy $E_{51} = 0.3$ (Umeda & Nomoto 2003a). (right) Elemental abundances of the C-rich most Fe deficient star HE0107-5240 (filled circles), compared with a theoretical supernova yield (Umeda & Nomoto 2003a).

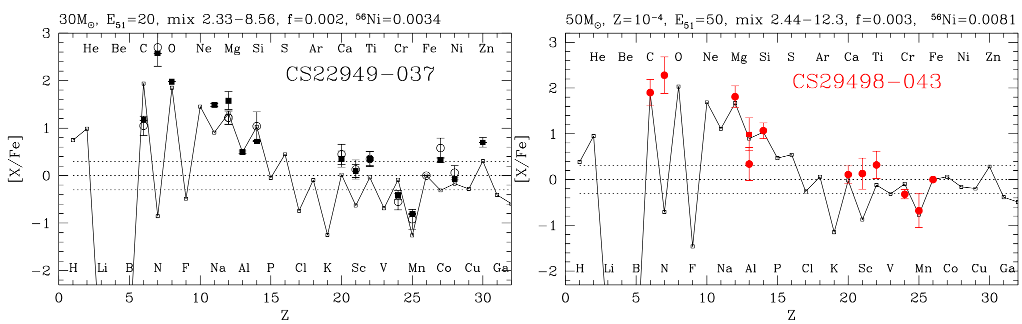

Fig. 6. (left) Elemental abundances of CS 22949-037 (open circles for Norris et al. 2001, and solid squares for Depagne et al. 2002), compared with a theoretical supernova yield (Umeda & Nomoto 2003ab). (right) Same as the left panel but for CS 29498-043 (Aoki et al. 2002).

In Figure 5 (right) we show that the elemental abundances of one of our models are in good agreement with HE0107-5240, where the progenitor mass is 25 $M_\odot$ and the explosion energy $E_{51} = 0.3$ (Umeda & Nomoto 2003a).

In this model, explosive nucleosynthesis takes place behind the shock wave that is generated at $M_r = 1.8\ M_\odot$ and propagates outward. The resultant abundance distribution is seen in Figure 5 (left), where M_r denotes the Lagrangian mass coordinate measured from the center of the pre-supernova model (Umeda & Nomoto 2003a). The processed material is assumed to mix uniformly in the region from $M_r = 1.8\ M_\odot$ and $6.0\ M_\odot$. Such a large scale mixing was found to take place in SN1987A and various explosion models (Hachisu et al. 1990; Kifonidis et al. 2000). Almost all materials below $M_r = 6.0\ M_\odot$ fall back to the central remnant and only a small fraction ($f = 2 \times 10^{-5}$) is ejected from this region. The ejected Fe mass is $8 \times 10^{-6}\ M_\odot$.

The CNO elements in the ejecta were produced by pre-collapse He shell burning in the He-layer, which contains 0.2 $M_\odot$ ^{12}C. Mixing of H into the He shell-burning region produces 4×10^{-4} $M_\odot$ ^{14}N. On the other hand, only a small amount of heavier elements (Mg, Ca, and Fe-peak elements) are ejected and their abundance ratios are the average in the region of M_r = 1.8 - 6.0 $M_\odot$. The sub-solar ratios of [Ti/Fe] = −0.4 and [Ni/Fe] = −0.4 are the results of the relatively small explosion energy (E_{51} = 0.3). With this "mixing and fallback", the large C/Fe and C/Mg ratios observed in HE0107-5240 are well reproduced (Umeda & Nomoto 2003a).

In this model, N/Fe appears to be underproduced. However, N can be produced inside the EMP stars through the C-N cycle, and brought up to the surface during the first dredge up stage while becoming a red-giant star (Boothroyd & Sackmann 1999).

4.2. Carbon-rich EMP stars: CS 22949-037 and CS 29498-043

The "mixing and fallback" is commonly required to reproduce the abundance pattern of typical EMP stars. In Figure 6 (left) we show a model, which is in good agreement with CS22949-037 (Umeda & Nomoto 2003a). This star has [Fe/H] = −4.0 and also C, N-rich (Norris, Ryan, & Beers 2001; Depagne et al. 2002), though C/Fe and N/Fe ratios are smaller than HE0107-5240. The model is the explosion of a 30 $M_\odot$ star with E_{51} = 20. In this model, the mixing region (M_r = 2.33 - 8.56 $M_\odot$) is chosen to be smaller than the entire He core (M_r = 13.1 $M_\odot$) in order to reproduce relatively large Mg/Fe and Si/Fe ratios.

Similar degree of the mixing, but for a more massive progenitor, would also reproduce the abundances of CS29498-043 (Aoki et al. 2002), which shows similar abundance pattern (Fig. 6: right).

We assume a larger fraction of ejection than HE0107-5240, 2%, from the mixed region for CS22949-037, because the C/Fe and N/Fe ratios are smaller. The ejected Fe mass is 0.003 $M_\odot$. The larger explosion energy model is favored for explaining the large Zn/Fe, Co/Fe and Ti/Fe ratios (Umeda & Nomoto 2002).

Without mixing, elements produced in the deep explosive burning regions, such as Zn, Co, and Ti, would be underproduced. Without fallback the abundance ratios of heavy elements to lighter elements, such as Fe/C, Fe/O, and Mg/C would be too large. In this model, Ti, Co, Zn and Sc are still underproduced. However, these elements may be enhanced efficiently in the aspherical explosions (Maeda et al. 2002; Maeda & Nomoto 2003ab).

4.3. EMP Stars with a Typical Abundance Pattern

Similarly, the "mixing and fall back" process can reproduce the abundance pattern of the typical EMP stars without enhancement of C and N. Figure 7 (left) shows that the averaged abundances of [Fe/H] = −3.7 stars in Norris et al. (2001) can be fitted well with the model of 25 $M_\odot$ and E_{51} = 20 but larger fraction (∼ 10%) of the processed materials in the ejecta. This yield (Umeda & Nomoto 2003b) is recommendable as averaged core-collapse SN yields for the use of chemical evolution models.

4.4. Aspherical Explosions

The "mixing and fall-back" effect may also be effectively realized in non-spherical explosions accompanying energetic jets (e.g., Maeda et al. 2002; Maeda & Nomoto 2003ab). Jet-like asphericity in hypernova explosions is anticipated both by theories and observations (e.g., Maeda et al. 2003). Compared with the spherical model with the same $M_{\rm cut}(i)$ and E, the shock is stronger (weaker) and thus temperatures are higher (lower) in the jet (equatorial) direction. As a result, a larger amount of complete Si-burning products are ejected in the jet direction, while only incomplete Si-burning products are ejected in the equatorial direction (Fig. 8). In total, complete Si-burning elements can be enhanced (Maeda & Nomoto 2003ab).

The jet-induced explosion results in angle-dependent distribution of nucleosynthetic products as shown in Figure 8. The distribution of ^{56}Ni (which decays into ^{56}Fe) is

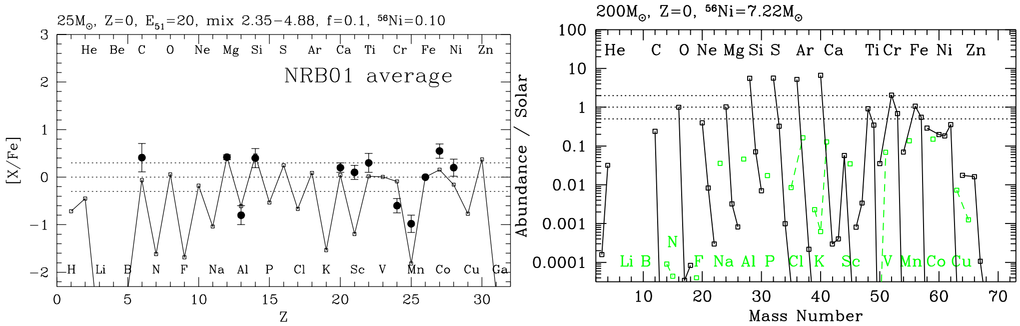

Fig. 7. (left) Averaged elemental abundances of stars with [Fe/H] = −3.7 (Norris et al. 2001) compared with a theoretical supernova yield (Umeda & Nomoto 2003b). (right) Yields of a pair-instability supernova from the 200 $M_\odot$ star (Umeda & Nomoto 2002).

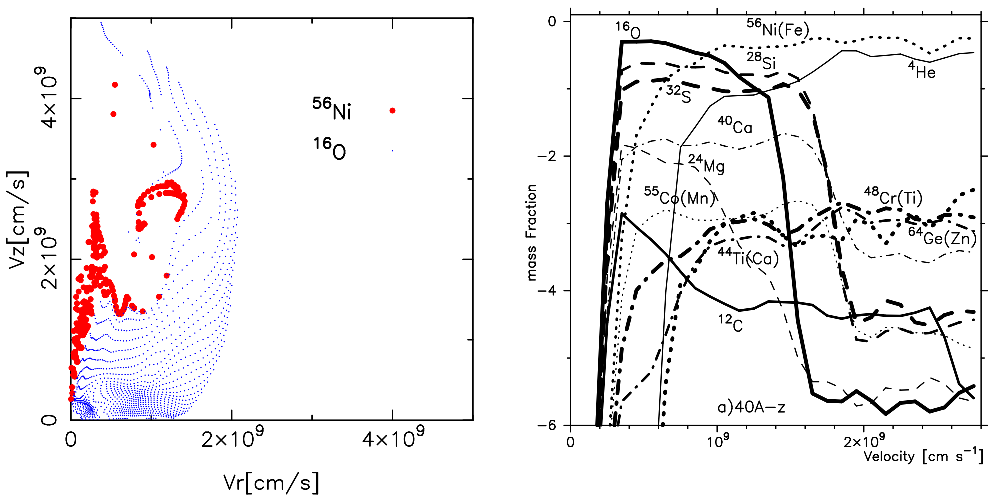

Fig. 8. Left: Distributions of ^{56}Ni (which decays into ^{56}Fe: filled circles) and ^{16}O (dots). The mass elements in which the mass fraction of each isotope exceeds 0.1 are plotted. Right: Mass fractions of selected isotopes in the velocity space along the z-axis (Maeda & Nomoto 2003ab).

elongated in the jet direction, while that of ^{16}O is concentrated in the central region.

Zn and Co are ejected at higher velocities than Mn and Cr, so that the latter accrete onto the central remnant more easily. As a consequence, [Zn/Fe] and [Co/Fe] are enhanced, while [Mn/Fe] and [Cr/Fe] are suppressed.

5. The First Stars

It is of vital importance in current astronomy to identify the first generation stars in the Universe, i.e., totally metal-free, Pop III stars. The impact of the formation of Pop III stars on the evolution of the Universe depends on their typical masses. Recent numerical models have shown that, the first stars are as massive as ~ 100 $M_\odot$ (Abel, Bryan, & Norman 2002). The formation of long-lived low mass Pop III stars may be inefficient because of slow cooling of metal free gas cloud, which is consistent with the failure of attempts to find Pop III stars.

If the most Fe deficient star, HE0107-5240, is a Pop III low mass star that has gained its metal from a companion star or interstellar matter (Yoshii 1981), would it mean that the above theoretical arguments are incorrect and that such low mass Pop III stars have not been discovered only because of the difficulty in the observations?

Based on the results in the earlier section, we propose that the first generation supernovae were the explosion of $\sim$ 20-130 $M_{\odot}$ stars and some of them produced C-rich, Fe-poor ejecta. Then the low mass star with even [Fe/H] < -5 can form from the gases of mixture of such a supernova ejecta and the (almost) metal-free interstellar matter, because the gases can be efficiently cooled by enhanced C and O ([C/H] ~ -1).

We have shown that the ejecta of core-collapse supernova explosions of 20-130 $M_{\odot}$ stars can well account for the abundance pattern of EMP stars. In contrast, the observed abundance patterns cannot be explained by the explosions of more massive, 130 - 300 $M_{\odot}$ stars. These stars undergo pair-instability supernovae (PISNe) and are disrupted completely (e.g., Umeda & Nomoto 2002; Heger & Woosley 2002), which cannot be consistent with the large C/Fe observed in HE0107-5240 and other C-rich EMP stars. The abundance ratios of iron-peak elements ([Zn/Fe] < -0.8 and [Co/Fe] < -0.2) in the PISN ejecta (Fig. 7; Umeda & Nomoto 2002; Heger & Woosley 2002) cannot explain the large Zn/Fe and Co/Fe in the typical EMP stars (McWilliam et al. 1995; Primas et al. 2000; Norris et al. 2001) and CS22949-037 either. Therefore the supernova progenitors that are responsible for the formation of EMP stars are most likely in the range of $M \sim 20 - 130$ $M_{\odot}$, but not more massive than 130 $M_{\odot}$.

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