Nucleosynthesis in Black-Hole-Forming Supernovae and Extremely Metal-Poor Stars

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Stars more massive than $\sim$ 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 are characterized by larger abundance ratios (Zn,Co,V,Ti)/Fe and smaller (Mn,Cr)/Fe, 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 deficient 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.

§1. Introduction

Among the important developments in recent studies of supernovae (SNe) are the discoveries of two distinct types of 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.

§2. Hypernova branch and faint supernova branch

Type Ic Hypernova SN 1998bw was probably linked to GRB 980425,[9] thus establishing for the first time a connection between gamma-ray bursts (GRBs) and the 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 at $E \sim 3 \times 10^{52}$ erg.[16,46]

Subsequently, other "hypernovae" have been recognized, such as SN 1997ef,[17,22] SN 1999as,[13,19] and SN 2002ap.[23] Figure 1 shows the near-maximum spectra and

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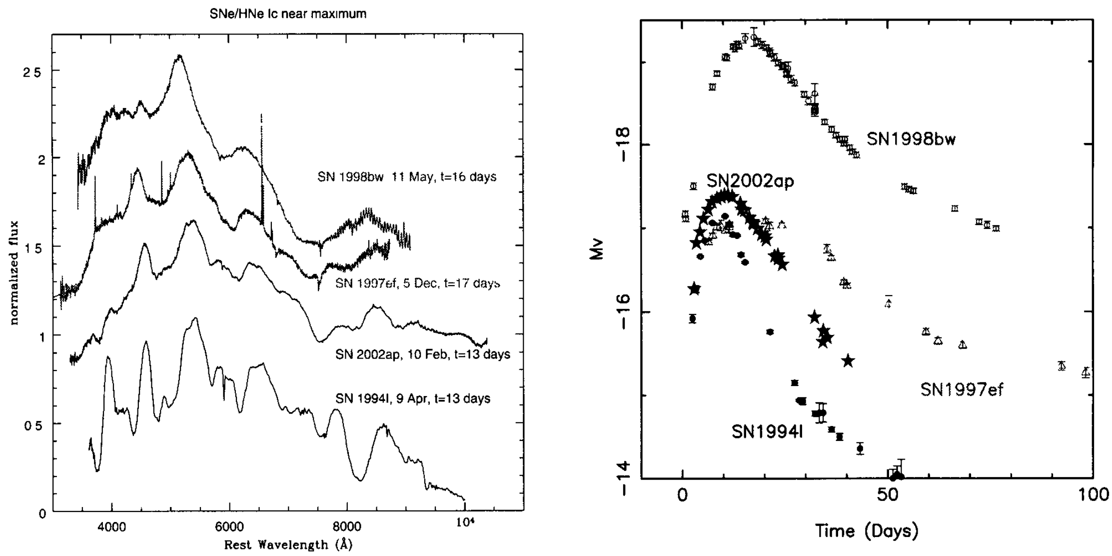

Fig. 1. Left: The near-maximum spectra of Type Ic SNe and hypernovae: SNe 1998bw, 1997ef, 2002ap, and 1994I. Right: The observed V-band light curves of SNe 1998bw (*open circles*), 1997ef (*open triangles*), 2002ap (*stars*), and 1994I (*filled circles*).[23]

the absolute V-light curves 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_{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.[11),41),48)] In Fig. 2, therefore, we propose that SNe from stars with $M_{\mathrm{ms}} \gtrsim$ 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. 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_{ms}. Between the two branches, there may be a variety of SNe.[11)]

This trend might be interpreted as follows. Stars with $M_{\mathrm{ms}} \lesssim$ 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 (SN 1987A may be a borderline case between the neutron star and black hole formation). Stars with $M_{\mathrm{ms}} \gtrsim$ 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 hypernova explosions

In core-collapse supernovae/hypernovae, stellar material undergoes shock heating and subsequent explosive nucleosynthesis. Iron-peak elements are produced in

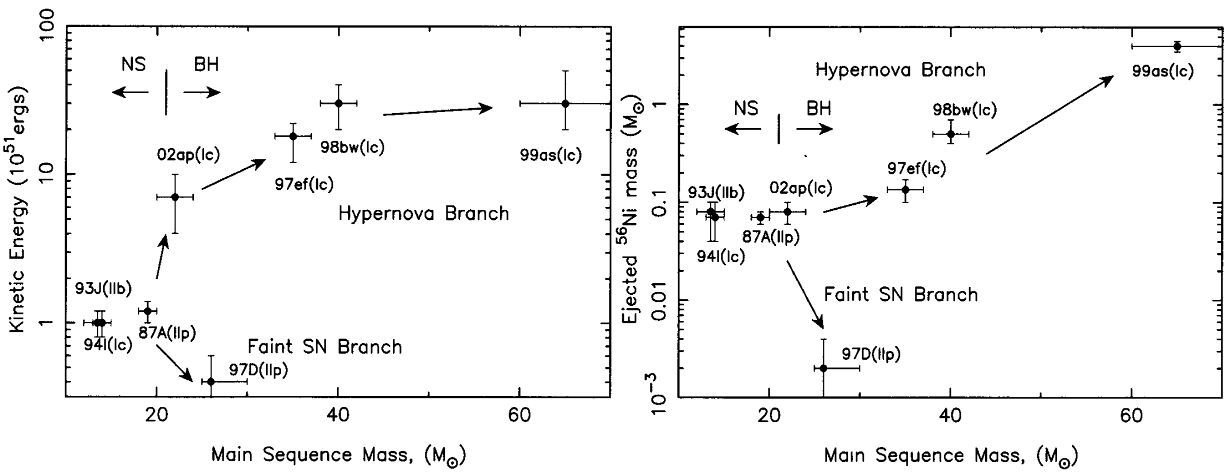

Fig. 2. The explosion energy and the ejected ^{56}Ni mass as a function of the main sequence mass of the progenitors for several supernovae/hypernovae.[31]

two distinct regions, which are characterized by the peak temperature, $T_{\rm peak}$, of the shocked material. For $T_{\rm peak} > 5 \times 10^9$ K, material undergoes complete Si burning whose products include Co, Zn, V, and some Cr after radioactive decays. For 4×10^9 K $< T_{\rm peak} < 5 \times 10^9$ K, incomplete Si burning takes place and its after decay products include Cr and Mn.[12),40)]

3.1. *Supernovae vs hypernovae*

The right panel of Fig. 3 shows the composition in the ejecta of a 25 $M_\odot$ hypernova model ($E_{51} = 10$). The nucleosynthesis in a normal 25 $M_\odot$ SN model ($E_{51} = 1$) is also shown for comparison in the left panel of Fig. 3.

We note the following characteristics of nucleosynthesis with very large explosion energies:[27)–29),33)]

(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.[33)]

(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.[44)]

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.[3)]

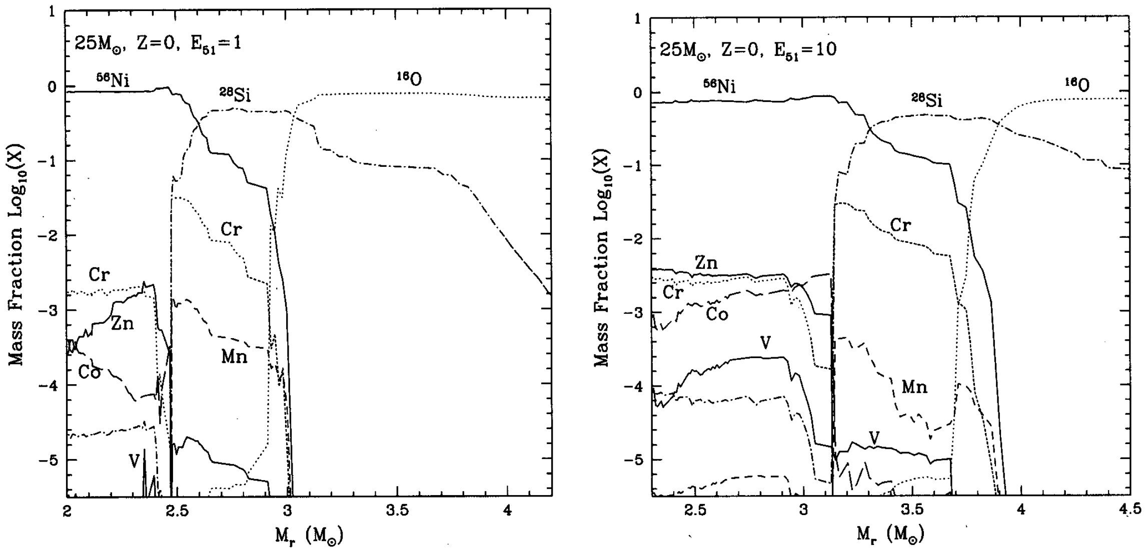

Fig. 3. Abundance distribution plotted against the enclosed mass M_r after the explosion of Pop III 25 $M_\odot$ stars with $E_{51} = 1$ (left) and $E_{51} = 10$ (right).[42]

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.[35] 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[35],[38] 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 (Fig. 4; Refs. 24) and 35)).

(2) [Zn/Fe]~ 0 for [Fe/H] $\simeq -3$ to 0,[39] while at [Fe/H] < -3.3, [Zn/Fe] increases toward smaller metallicity (Fig. 4; Refs. 5) and 34)).

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,[25] (2) E is larger to move the outer edge of the complete Si burning region to larger M_r,[26] 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.[33],[42],[43] Models with $E_{51} = 1$ do not produce sufficiently large [Zn/Fe]. To be compatible with the observations of [Zn/Fe] ~ 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"

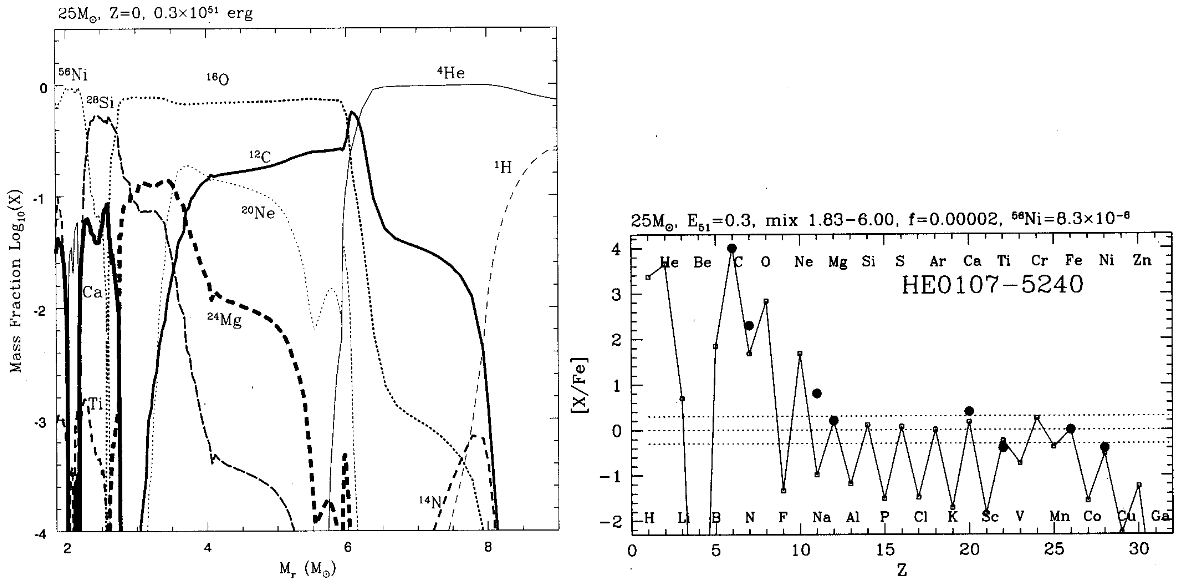

Fig. 4. (left) The post-explosion abundance distributions for the 25 $M_\odot$ model with the explosion energy $E_{51} = 0.3$.[45] (right) Elemental abundances of the C-rich most Fe deficient star HE0107-5240 (filled circles), compared with a theoretical supernova yield.[45]

mass-cut model, can be avoided.[33] 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.[33),43]

§4. Extremely metal-poor (EMP) stars and faint supernovae

Recently the most Fe deficient and C-rich low mass star, HE0107-5240, was discovered.[7] 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.[37]

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.[7] Interestingly, this is not the only extremely metal poor (EMP) stars that have the large C/Fe and N/Fe ratios, but several other such stars have been discovered.[36] 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 metal-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.[45]

In Fig. 4 (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 $E_{51} = 0.3$.[45]

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 Fig. 4 (left), where M_r denotes the Lagrangian mass coordinate measured from the center of the pre-supernova model.[45] 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.[10),18] 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 $4\ \times\ 10^{-4}\ M_\odot$ ^{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.[45]

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.[6]

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 Fig. 5 (left) we show a model, which is in good agreement with CS22949-037.[45] This star has [Fe/H] $= -4.0$ and also C, N-rich,[8),32] 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 would also reproduce the abundances of CS29498-043,[2] which shows similar abundance pattern.

We assume a larger fraction of ejection, 2%, from the mixed region for CS22949-037 than HE0107-5240, 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.[42]

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 under-produced. However, these elements may be enhanced efficiently in the aspherical explosions.[20),21] Almost the same effects as the "mixing and fallback mechanism" are realized if the explosion is jet-like, although the total energy can be smaller if the beaming angle of the jet is small.[21]

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 5 (right) shows that the averaged abundances of [Fe/H] $= -3.7$ stars in Norris et al.[32] can be fitted well with the model of 25 $M_\odot$ and $E_{51} = 20$ but larger fraction ($\sim 10\%$) of the processed materials in the ejecta.

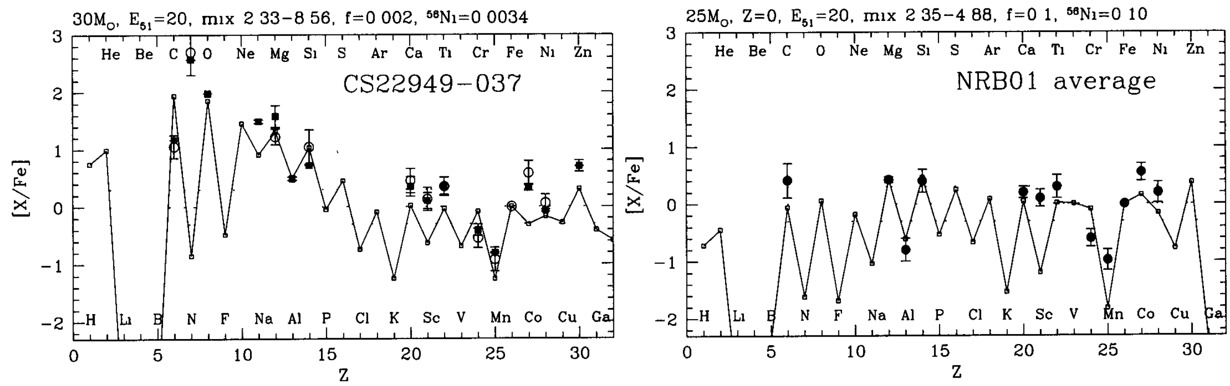

Fig. 5. (left) Elemental abundances of CS 22949-037 (open circles for Ref. 32), and solid squares for Ref. 8)), compared with a theoretical supernova yield.[45] (right) Averaged elemental abundances of stars with [Fe/H] $= -3.7$.[32]

§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 $M_\odot$.[1] 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,[47] 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).

5.1. *Pair-instability supernovae*

We have shown that the ejecta of core-collapse supernova explosions of massive stars can well account for the abundances of EMP stars. We can put further constraint on the typical mass of Pop III. The abundances of all observed EMP stars including the most metal-poor one are inconsistent with the abundance pattern of pair-instability supernovae (PISNe). For typical EMP stars and CS22948-037, enrichment by PISNe cannot be consistent with the observed abundant Zn/Fe and Co/Fe ratios.[14),42)] For HE0107-5240 and other C-rich EMP stars, PISNe enrichment is difficult to account for the large C/Mg ratios. Therefore the supernova progenitors that are responsible for the formation of EMP stars are in the range of $M \sim 20$ - $130\ M_\odot$, but not more massive than $130\ M_\odot$. This upper limit depends on the stability of massive stars as will be discussed below.

5.2. *Stability and mass loss of massive Pop III stars*

To determine the upper limit mass of the Zero Age Main Sequence (ZAMS), we analyze a linear non-adiabatic stability of massive ($80 M_\odot$ - $300 M_\odot$) Pop III stars using a radial pulsation code.[30)] Because CNO elements are absent during the early stage of their evolution, the CNO cycle does not operate and the star contracts until temperature rises sufficiently high for the 3α reaction to produce ^{12}C. We calculate that these stars have $X_{\rm cno} \sim 1.6 - 4.0 \times 10^{-10}$, and the central temperature $T_c \sim 1.4 \times 10^8 K$ on their ZAMS. We also examine the models of Pop I stars for comparison.

Table I shows the results for our analysis. The critical mass of ZAMS Pop III star is $128 M_\odot$ while that of Pop I star is $94 M_\odot$. This difference comes from very compact structures (with high T_c) of Pop III stars.

Stars more massive than the critical mass will undergo pulsation and mass loss. We note that the e-folding time of instability is much longer for Pop III stars than Pop I stars with the same mass, and thus the mass loss rate is much lower. These results are consistent with Refs. 15) and 4). However, the absence of the indication of PISNe may imply that these massive stars above $130\ M_\odot$ undergo significant mass loss, thus evolving into Fe core-collapse rather than PISNe.

Table I. The results of the stability analysis for Pop III and Pop I stars. ○ and × represent that the star is stable and unstable, respectively. The e-folding time for the fundamental mode is shown after × in units of 10^4yr.[30)]

mass ($M_\odot$)	80	100	120	150	180	300
Pop III	○	○	○	× (9.03)	× (4.83)	× (2.15)
Pop I	○	× (7.02)	× (2.35)	× (1.43)	× (1.21)	× (1.71)

§6. Discussion

We have first shown that signatures of hypernova nucleosynthesis are seen in the abundance patterns in extremely metal-poor (EMP) stars. We suggest that hypernovae of massive stars may make important contributions to the Galactic (and cosmic) chemical evolution, especially in the early low metallicity phase. The IMF of Pop III stars might be different from that of Pop I and II stars, and that more massive stars are abundant for Pop III.

We have also shown that the most iron-poor star as well as other C-rich EMP stars is likely to be enriched by massive supernovae that are characterized by relatively small Fe ejection. Such supernovae are not just hypothetical but have been actually observed, forming a distinct class of type II supernovae ("faint supernovae": Ref. 31)). The proto-type is SN1997D, which is very under luminous and shows quite narrow spectral lines[41] (also SN1999br[48]): These features are well modeled as an explosion of the 25 $M_\odot$ star with small explosion energy $E_{51} = 0.4$. On the other hand, typical EMP stars without enhancement of C and N correspond to the abundance pattern of energetic supernovae ("hypernovae": Ref. 31)).

For both cases black holes more massive than $\sim$ 3 - 10 $M_\odot$ must be left as a result of fallback, suggesting that the copious formation of the first black holes from the first stars. These black holes may consist of some of the dark mass in the Galactic halo. In our scenario, HE0107-5240 with [Fe/H] $= -5.3$ was formed from C, O-enhanced gases with [C,O/H] ~ -1. With such enhanced C and O, the cooling efficiency is large enough to form small mass stars. As far as the low mass EMP stars are C-rich, therefore, their small masses are consistent with the massive Pop III star formation. Rather their C-richness implies that Pop III stars that are responsible for their formation are massive enough to form (the first) black holes.

Acknowledgements

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