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Nucleosynthesis in Population III Supernovae

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Abstract. 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). 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 as the First (Pop III) Supernovae.

1. Hypernova Branch and Faint Supernova Branch

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, e.g., Zampieri, et al. 2003). These two types of supernovae are likely to be "black-hole-forming" supernovae with rotating or non-rotating black holes. Figure 1 shows E and the mass of ^{56}Ni ejected, $M(^{56}\mathrm{Ni})$, as functions of the main-sequence mass M_{ms} of the progenitor star obtained from fitting the optical light curves and spectra (Nomoto et al. 2003ab; Zampieri et al. 2004).

2. Hypernovae and Zn, Co, Mn, Cr

In core-collapse supernovae/hypernovae, iron-peak elements are produced in two distinct regions, which are characterized by the peak temperature, T_{peak}, of the shocked material. For $T_{\mathrm{peak}} > 5 \times 10^9$K, material undergoes complete Si burning whose products include Co, Zn, V, and some Cr after radioactive decays. For $4 \times 10^9\mathrm{K} < T_{\mathrm{peak}} < 5 \times 10^9$K, incomplete Si burning takes place and its after decay products include Cr and Mn.

Nucleosynthesis with very large explosion energies has the following characteristics (Nakamura et al. 2001):

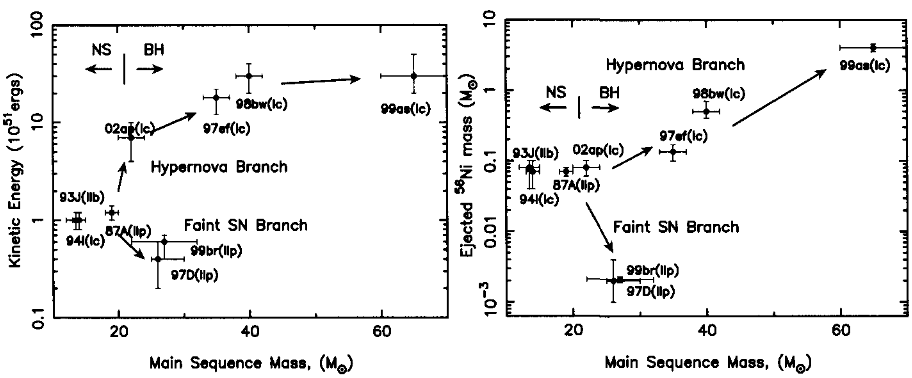

Figure 1. The explosion energy and the ejected ^{56}Ni mass as a function of the main sequence mass of the progenitors for several supernovae/hypernovae (Nomoto et al. 2003ab).

(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 2002, 2005).

(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.

At early epochs the Galaxy was not yet chemically well-mixed, so that [Fe/H] may well be determined by a single SN event (Audouze & Silk 1995). 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 to -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).

(2) [Zn/Fe]~ 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).

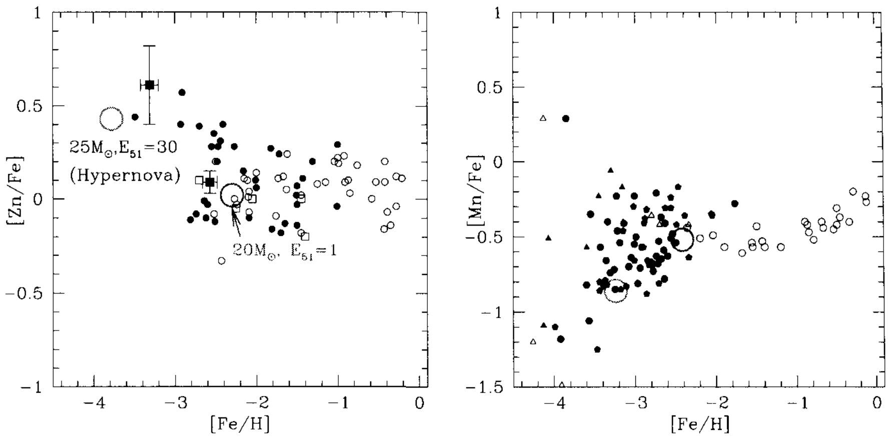

Figure 2. Observed abundance ratios of [Zn, Mn/Fe] vs [Fe/H] compared with the ($20M_\odot$, $E_{51} = 1$) and ($25M_\odot$, E_{51}=30) models (large open circles).

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) E is larger to move the outer edge of the complete Si burning region to larger M_r, or (2) asphericity in the explosion is larger.

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, 2005). Therefore, hypernovae could explain the large Zn and Co abundances and the small Mn and Cr abundances observed in very metal-poor stars (Fig. 2).

3. 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 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 that of Fe (Christlieb et al. 2002). Interestingly, this is not the only extremely metal poor star to exhibit large C/Fe and N/Fe ratios, but several other such stars have been discovered (Aoki et al. 2002).

3.1. The Most Fe-Poor Star HE0107-5240

We consider a model in which C-rich EMP stars are produced in the ejecta of (almost) metal-free supernova mixed with extremely metal-poor interstellar

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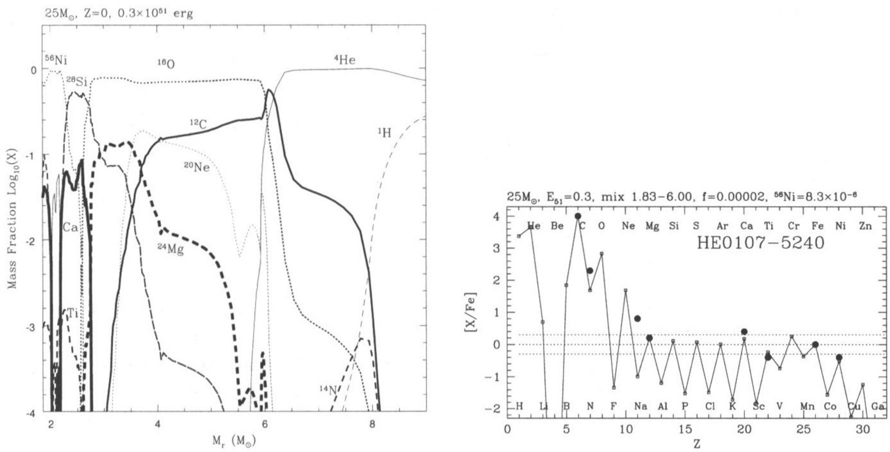

Figure 3. (left) The abundance distributions for the 25 $M_\odot$ model with the explosion energy $E_{51} = 0.3$. (right) Elemental abundances of the C-rich most Fe deficient star HE0107-5240 (filled circles), compared with a theoretical supernova yield (Umeda & Nomoto 2003).

matter (Umeda & Nomoto 2003). In Figure 3 (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 $E_{51} = 0.3$.

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 3 (left), where M_r denotes the Lagrangian mass coordinate measured from the center of the pre-supernova model (Umeda & Nomoto 2003). The processed material is assumed to mix uniformly in the region from $M_r = 1.8$ $M_\odot$ and 6.0 $M_\odot$. 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 8×10^{-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 $M_\odot$ of ^{12}C. Mixing of H into the He shell-burning region produces 4×10^{-4} $M_\odot$ of ^{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 2003). The "mixing and fall-back" effect may also be effectively realized in non-spherical explosions accompanying energetic jets (e.g., Maeda et al. 2002, 2003; Maeda & Nomoto 2003).

In this model, (N, Na)/Fe appear to be underproduced. However, N and Na 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; Iwamoto et al., in preparation).

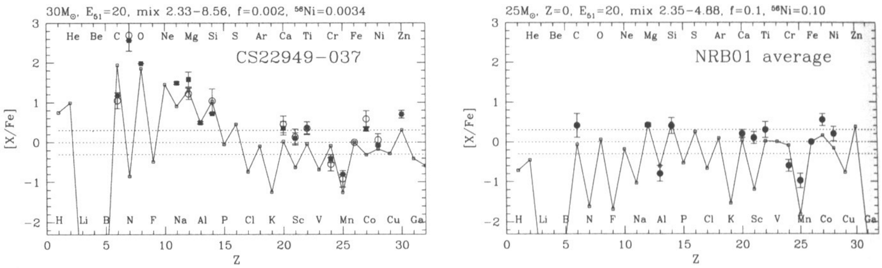

Figure 4. (left) Elemental abundances of CS 22949-037 (open circles for Norris et al. 2001, and solid squares for Depagne et al. 2002), compared with a theoretical supernova yield. (right) Averaged elemental abundances of stars with [Fe/H] = −3.7 (Norris et al. 2001) compared with a theoretical supernova yield (Umeda & Nomoto 2003, 2005).

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

The "mixing and fallback" scenario is commonly required to reproduce the abundance pattern of typical EMP stars. In Figure 4 (left) we show a model, which is in good agreement with CS22949-037 (Umeda & Nomoto 2003). This star has [Fe/H] = −4.0 and is also C, N-rich (Norris, Ryan, & Beers 2001; Depagne et al. 2002), though the C/Fe and N/Fe ratios are smaller than in 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 the relatively large Mg/Fe and Si/Fe ratios.

A similar degree of the mixing, but for a more massive progenitor, would also reproduce the abundances of CS29498-043 (Aoki et al. 2002).

We assume a larger fraction of ejection than in 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 to explain the large Zn/Fe, Co/Fe and Ti/Fe ratios (Umeda & Nomoto 2002).

3.3. 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 4 (right) 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 with a larger fraction (∼ 10%) of the processed materials in the ejecta. This yield (Umeda & Nomoto 2005) is recommended as the averaged core-collapse SN yield to be used in chemical evolution models.

4. The First Stars

We have shown that the ejecta of black-hole-forming supernovae from 20 − 130 $M_\odot$ stars can well account for the abundance pattern of EMP stars. In contrast, the observed abundance patterns, such as the large C/Fe observed in HE0107-5240 and other C-rich EMP stars, cannot be explained by pair-instability super-

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novae (PISNe) of $130-300$ $M_\odot$ stars (Umeda & Nomoto 2002; Heger & Woosley 2002). 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 observed in typical EMP stars nor in CS22949-037.

We thus propose that the first generation supernovae were the explosion of $\sim 20-130$ $M_\odot$ stars and that some of them produced C-rich, Fe-poor ejecta. Then small mass stars with even [Fe/H] < -5 can form from the mixture of such a supernova ejecta with the (almost) metal-free interstellar medium, since the gas can cool efficiently thanks to the enhanced C and O abundances ([C/H]~ -1).

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