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Supernova nucleosynthesis and stellar population in the early Universe

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Abstract. Supernovae (SNe) play a major role in producing heavy elements in the Universe. We discuss the role(s) of SNe resulting from the core-collapse of a massive star (whose main-sequence mass is $\sim 10 - 100 M_{\odot}$) and those from a very massive star ($\sim 300 - 1000 M_{\odot}$). The abundance patterns of extremely metal-poor halo stars, which are relics of the stellar population in the early-phase of the Galaxy, can be explained as a consequence of SN explosions from the massive stars ($10 - 100 M_{\odot}$). Variations in properties of nearby SNe, from the aspherical hyper-energetic SNe to the highly jet-powered faint SNe, can explain variations in the abundance patterns of the metal-poor halo stars. The theoretical nucleosynthesis yields of the very massive stars ($300 - 1000 M_{\odot}$), assuming they were the predominant first generation stars and exploded as supernovae, are consistent with the abundance patterns of intracluster medium. Such stars might also be major contributors to the cosmic reionization.

Key words. Stars: Population II – Galaxy: abundances – Supernovae: general

1. Introduction

Supernovae (SNe) play major roles in producing heavy elements in the Universe. The nucleosynthesis yields are dependent on the progenitor main-sequence mass (hereafter $M_{\rm ms}$), through different evolution and final fate for different $M_{\rm ms}$ (e.g., Nomoto & Hashimoto 1988). There are probably other functions, e.g., metallicity, rotation, binarity, that also control the properties of the SN explosions (e.g., Heger et al. 2003).

Stars with $M_{\rm ms} \sim 10 - 100 M_{\odot}$ end up with the collapse of iron-core. Although the final fate, either the explosion or entire collapse, has not been clarified theoretically (e.g., Bruenn et al. 2006; Burrows et al. 2007; Janka et al. 2007), at least a fraction of such stars should, observationally, explode as a supernova.

Very massive stars (VMSs) with $M_{\rm ms} > 100 M_{\odot}$ are at most a negligible fraction of the stellar population in the present Universe. However, the first generation stars (i.e., Pop III stars) in the early Universe might be very different from the present population, since the complete lack of heavy elements drastically changes cooling processes within protostellar

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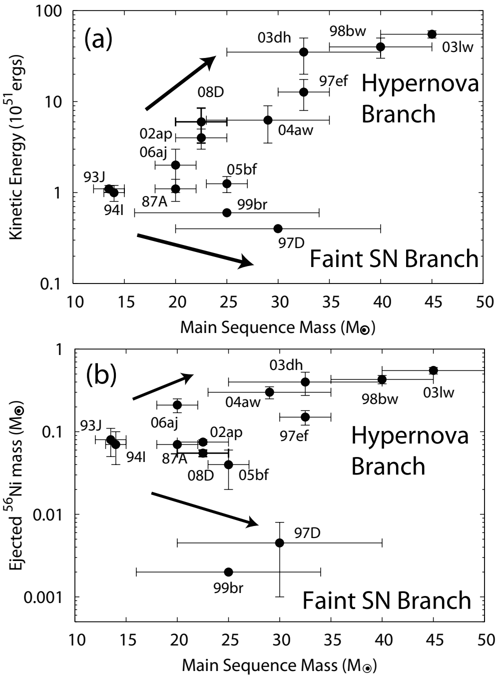

Fig. 1. Properties of core-collapse SNe as a function of the main-sequence mass of the progenitor star (Nomoto et al. 2008). (a) Kinetic energy of the explosion, and (b) the mass of ^{56}Ni ejected at the explosion. For the source of individual observations and references, see Kawabata et al. (2009), Mazzali et al. (2009), and Tanaka et al. (2009)

clouds (see Yoshida et al. 2008 and references therein). A proto-star core of $\sim 10^{-2} M_\odot$ can accrete the materials from the surrounding cloud of $10^3 - 10^5 M_\odot$ at the rate of $10^{-3} M_\odot$ / year or higher in the metal-free environment. Then, the mass of such stars can reach $\sim 30 - 100 M_\odot$ at the zero-age main-sequence phase, and $\sim 300 - 1000 M_\odot$ at the end of the main-sequence phase (Omukai & Palla 2003; Ohkubo et al. 2009). They might avoid the strong mass loss due to the pulsational instability at the zero-metallicity, and survive as the VMSs through their lives (Nomoto et al. 2003).

2. Observational Constraints on Nearby SNe

Properties of SNe from progenitor stars with $M_{\rm ms} \sim 10-100 M_\odot$ can be constrained from observations of nearby SNe. Figure 1 shows the kinetic energy of the explosion ($E_{\rm K} = 10^{51} E_{51}$ erg) and the mass of ^{56}Ni ejected at the explosion [$M(^{56}{\rm Ni})$], as a function of $M_{\rm ms}$ (Nomoto et al. 2008).

Canonical core-collapse SNe have $E_{51} \sim 1$ and $M(^{56}{\rm Ni}) \sim 0.07 M_\odot$. They are results of an explosion of a progenitor star with $M_{\rm ms} \lesssim 20 M_\odot$. On the other hand, SNe with $M_{\rm ms} \gtrsim 20 M_\odot$ show diverse properties: There are a class of energetic and bright SNe with $E_{51} \gtrsim 10$ and $M(^{56}{\rm Ni}) \gtrsim 0.2 M_\odot$ ("Hypernovae"; Iwamoto et al. 1998; Woosley, Eastmas, & Schimidt 1999; Mazzali et al. 2002), as well as a class of weak and faint SNe with $E_{51} \ll 1$ and $M(^{56}{\rm Ni}) \lesssim 0.01 M_\odot$ (faint SNe; Turatto et al. 1998).

Hypernovae are sometimes observed in association with energetic high-energy transient, Gamma-Ray Bursts (GRBs) (Galama et al. 1998; Hjorth et al. 2003; Stanek et al. 2003). The hypernova progenitor masses, $M_{\rm ms} > 30 M_\odot$, are consistent from the expectation that GRBs are end-products of a massive star, perhaps a result of the formation a black hole (e.g., Woosley 1993). One possible function which discriminates the canonical SNe and GRB-SNe could be whether the collapse results in the formation of a black hole or a neutron star (Mazzali et al. 2006; Maeda et al. 2007). It has also been shown that at least a few GRBs did not apparently have an associated SN, indicating that a fraction of GRBs are associated with a quite faint SN or even no successful SNe took place with them (Della Valle et al. 2006; Fynbo et al. 2006; Gal-Yam et al. 2006).

Another important feature which affects the nucleosynthesis is an asphericity of the explosion. It has been observationally indicated that core-collapse SNe are aspherical in general, likely having a specific axis of the explosion (Maeda et al. 2008; Modjaz et al. 2008; Taubenberger et al. 2009). It has further been suggested, by modeling the optical observations, that the degree of asphericity is dependent on the progenitor mass, with the GRB-SNe ($M_{\rm ms} \gtrsim 30 M_\odot$) having the largest asphericity (Maeda et al. 2006ab).

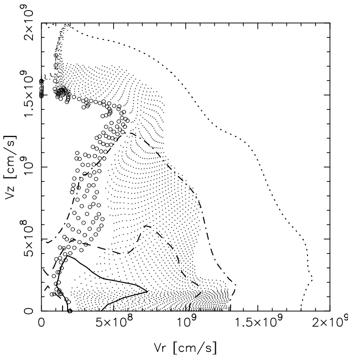

Fig. 2. Distribution of Fe (circles) and O (dots) in the aspherical supernova explosion model (Maeda et al. 2002). Materials produced with strong α-rich freezeout (e.g., Zn, Co) are confined in the "jet" direction, and thus preferentially ejected.

3. Aspherical Supernovae, Gamma-Ray Bursts, and Metal-Poor Halo Stars

Extremely metal-poor halo stars (EMPSs) are believed to have been formed from a gas cloud which had suffered from metal pollution by only one or a few SNe. As such, their abundance patterns should reflect nucleosynthesis yields of an individual SN – they provide clues to the nature of the stellar population and supernovae in the early phase of the Galaxy (Audouze & Silk 1995). The EMPSs by definition lack the iron content, i.e., [Fe/H] $\equiv \log[(X_{\rm Fe}/X_{\rm H})/(X_{\rm Fe}/X_{\rm H})_\odot] \lesssim -3$. EMPSs with the smallest [Fe/H] ($\lesssim -5$) are called hyper metal-poor stars (HMPSs: Christlieb et al. 2002; Frebel et al. 2005). The EMPSs are further divided into sub classes by carbon content (Beers & Christlieb 2005), i.e., Carbon-rich EMPSs (CEMPSs) if [C/Fe] $\gtrsim 1$. Note that the HMPSs discovered to date are all carbon-rich, reaching to [C/Fe] ~ 4.

A question is whether and how the nucleosynthesis yields of supernovae are compatible to these EMPSs. Briefly, the explosion properties affect the nucleosynthesis yields in the following ways. (1) The explosion energy: For larger $E_{\rm K}$, the explosive nucleosynthesis proceeds more actively. It results in a larger amount of Fe-peak elements and intermediate elements like Si, S, as well as a smaller amount of C and O (Nakamura et al. 2001; Umeda & Nomoto 2005). (2) The explosion asphericity: For larger asphericity, the elements produced by strong α-rich freezeout (e.g., Zn, Co) become more abundant, while the elements produced by incomplete Si burning (e.g., Mn, Cr) generally become less abundant (Nagataki 2000; Maeda et al. 2002; Maeda & Nomoto 2003; Tominaga et al. 2007a; Tominaga 2009).

The typical abundance patterns of EMSs are well reproduced by hypernova models (Umeda & Nomoto 2002; Iwamoto et al. 2005; Tominaga et al. 2007b). To explain the oversolar [Zn/Fe] typically seen in the EMPSs, Umeda & Nomoto (2003) introduced the "mixing-fallback-process" in which they assume a fraction of the innermost materials experiencing the strong α-rich freezeout are mixed upward and ejected. They argued that it could be possible by a jet-like aspherical explosion. Maeda et al. (2002) and Maeda & Nomoto (2003) showed that such an effect is indeed realized in a jet-like aspherical explosion without fine-tuning of the initial conditions (Fig. 2).

Maeda & Nomoto (2003) suggested that the observed trends of some Fe-peak elements seen in EMPSs can be explained as a sequence of different degree of asphericity. Observationally, [(Zn, Co)/Fe] is larger for smaller [Fe/H], while [(Cr, Mn)/Fe] is smaller (McWilliam et al. 1995; Ryan et al. 1996; Primas et al. 2000; Blake et al. 2001). As such, if SNe with the larger degree of asphericity are responsible to the abundance patterns of EMPSs with smaller [Fe/H], the trends can be reproduced (Fig. 3). In view of the relation of $M_{\rm ms}$ and the degree of asphericity, and further with $E_{\rm K}$ (§2), such a relation between $M_{\rm ms}$ and [Fe/H] is not surprising. Tominaga et al. (2007) showed that detailed abundance patterns of typical EMPSs can be nicely fit by the aspherical hypernova explosion (Fig. 4).

One can also think about even more highly-collimated jet-powered SNe (Maeda & Nomoto 2003; Tominaga et al. 2007a), although there has been no direct observational counterpart so far. The highly-collimated explosion can be realized only when the time

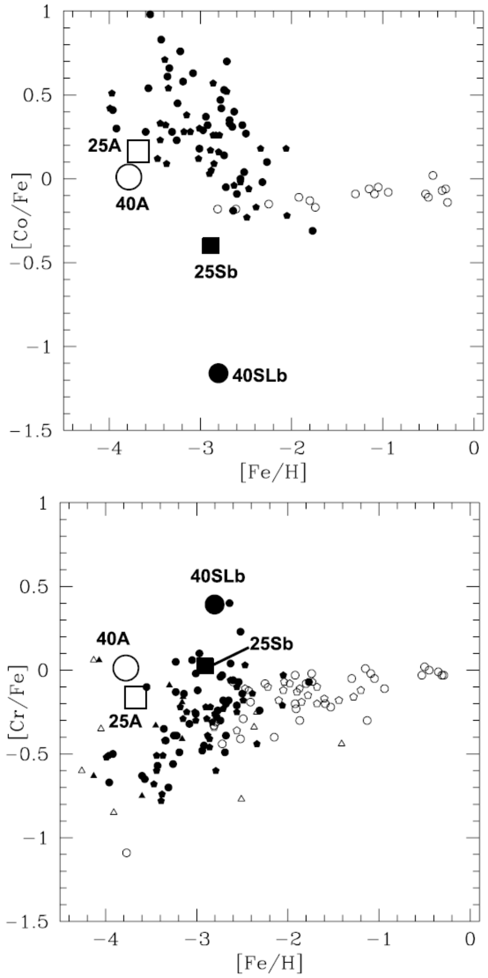

Fig. 3. [(Co, Cr)/Fe] of EMPSs as a function of [Fe/H]. Models are shown by open circle (aspherical SN with $M_{ms} = 40M_{\odot}$), filled circle (spherical SN with $M_{ms} = 40M_{\odot}$), open square (aspherical SN with $M_{ms} = 25M_{\odot}$), filled square (spherical SN with $M_{ms} = 25M_{\odot}$). From Maeda & Nomoto (2003). Note that [Cr/Fe] shown here is for the measurement from Cr I lines, which is inconsistent with that from a Cr II line (Honda et al. 2004; Bonifacio et al. 2009).

scale of the energy injection from the central compact remnant is larger than the time scale of the jet penetrating the progenitor envelope. Thus, such an explosion is characterized by the small energy injection rate. The pressure within the jet is thus small, and the jet would not penetrate outward until the most part of the progenitor star collapse to the central remnant. As a result, such an explosion is characterized by a small amount of the ejected materials and $M(^{56}\mathrm{Ni})$ (Tominaga et al. 2007a; Maeda & Tominaga 2009; see also Maeda & Nomoto 2003; Nagataki et al. 2003). Because of the small $M(^{56}\mathrm{Ni})$, the nucleosynthesis yield is characterized by large [C/Fe]. Maeda & Nomoto (2003) and Tominaga et al. (2007a) suggested that such an explosion could be responsible for the CEMPSs and HMPSs. Such an SN should be very faint, and thus it does not conflict with the no direct detection so far.

Tominaga et al. (2007a) suggested that a few GRBs without apparent SN association can be understood in this jet-powered SN context. They showed that detailed abundance patterns of CEMPSs and HMPSs can be nicely fit by such a highly jet-powered SN nucleosynthesis (Fig. 4). They thus proposed that SNe responsible for formation the EMPSs, CEMPSs, and HMPSs belong to continuous series of a black-hole-forming SNe with different energy injection rate (which translates to different asphericity), being closely related to GRBs.

4. Very Massive Stars, Intra-Cluster Medium, and Cosmic Reionization

It is possible that the first-generation stars were more massive than $300M_{\odot}$ (§1). Although they pass through the pair instability region in the density - temperature diagram through the evolution, the oxygen burning there is not strong enough to disrupt the whole star, unlike $\sim 100 - 300M_{\odot}$ star which end up with the pair-instability SNe (Barkat et al. 1967; Umeda & Nomoto 2002; Heger & Woosley 2002). Such very massive stars (VMSs) undergo iron core-collapse at the end of their lives.

The outcome of the core-collapse of VMSs has not been clarified. Following the hypothesis that such stars formed rapidly rotating black holes and exploded as a jet-like aspherical SN, we investigated the nucleosynthesis signatures of such SNe (Ohkubo et al. 2006). Figure 5 shows that a moderately aspherical explosion predicts the nucleosynthesis yields

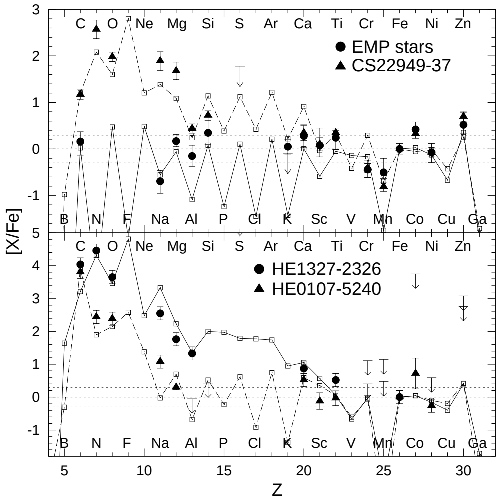

Fig. 4. Comparison between the aspherical and jet-powered models and abundances of EMPSs. Typical EMPSs can be fit by the (moderate) aspherical model similar to that shown in Figure 2, although the CEMPSs and HMPSs are nicely fit by the narrowly-collimated, jet-powered SNe. From Tominaga et al. (2007a).

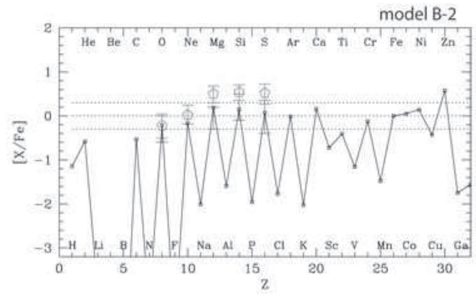

Fig. 5. Supernova yields from a moderately aspherical explosion (like Figure 2) of VMSs, as compared to the abundances of ICM (Ohkubo et al. 2006).

consistent with the abundance patterns of intracluster medium (ICM). Within the reasonable range of the explosion parameters, such VMS explosions never explain the abundance patterns of EMPSs.

The VMSs might also be the major sources of the cosmic reionization. Ohkubo et al. (2006) computed the efficiency of the reionization as compared to the metal production; $N_{\rm Lyc}/N_{\rm b}$, the number of ionizing photons per baryon produced by VMSs, and its relation to the metallicity contributed by the same VMSs. Taking $N_{\rm Lyc}/N_{\rm b} = 1 - 10$ as the measure of the reionization (see Venkatesan & Truran 2003), then our VMS models predict that the reionization was completed when $Z/Z_{\odot} = 10^{-3.4} - 10^{-4.4}$. Thus, the VMSs were capable to reionize the Universe at the redshift $z > 7$.

5. Conclusions

For the stars with $M_{\rm ms} \sim 10-100 M_{\odot}$, the properties of the SN explosions are constrained by observing nearby SNe. Such analyses revealed the existence of highly aspherical hypernovae, faint SNe, as well as moderate asphericity in core-collapse SNe in general. Taking into account those findings, we have shown that abundance patterns of EMPSs and the variation (e.g., CEMPSs, HMPSs) can be explained within the framework of supernova nucleosynthesis of stars with $M_{\rm ms} \sim 10 - 100 M_{\odot}$.

The abundance patterns of ICMs are different from EMPSs, and thus to explain them requires different sources. The supernova nucleosynthesis yields from the hypothesized VMSs with $M_{\rm ms} \sim 300 - 1000 M_{\odot}$ are consistent with the abundance patterns of ICMs. In addition, the model predicts the epoch of the reionization - metallicity relation appropriately.

Summarizing these results, the following is a possible scenario about the stellar population of the early Universe and their contribution to the production of heavy elements. (1) First generation stars were born from primordial, totally metal-free clouds. As such, the Initial Mass Function (IMF) was significantly different from the present, and the majority of them might be very massive stars with $M_{\rm ms} \sim 300 - 1000 M_{\odot}$. (2) These VMSs provided the reionizing photons, and then provided heavy elements into space. A fraction of the newly synthesized materials were escaped to ICMs. (3) From the ISM polluted by the VMSs, the second generation stars were formed. Although the metallicity is still low, the metal cooling is now important and the IMF for these second generation stars were close to the present one. (4) The $10-100M_{\odot}$ stars exploded as SNe, providing further metals into the space. The low-mass stars formed from the chemically polluted clouds thus have abundance patterns of SNe from these second generation stars. They survive until now, observed at EMPSs.

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