EXTREMELY METAL-POOR STARS AND A HIERARCHICAL CHEMICAL EVOLUTION MODEL

YUTAKA KOMIYA
National Astronomical Observatory of Japan, Osawa, Mitaka, Tokyo, Japan
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ABSTRACT
Early phases of the chemical evolution of the Galaxy and formation history of extremely metal-poor (EMP) stars are investigated using hierarchical galaxy formation models. We build a merger tree of the Galaxy according to the extended Press–Schechter theory. We follow the chemical evolution along the tree and compare the model results to the metallicity distribution function and abundance ratio distribution of the Milky Way halo. We adopt three different initial mass functions (IMFs). In a previous study, we argued that the typical mass, \(M_{\text{typ}}\), of EMP stars should be high, \(M_{\text{typ}} \approx 10 M_\odot\), based on studies of binary origin carbon-rich EMP stars. In this study, we show that only the high-mass IMF can explain an observed small number of EMP stars. For relative element abundances, the high-mass IMF and the Salpeter IMF predict similar distributions. We also investigate dependence on nucleosynthetic yields of supernovae (SNe). The theoretical SN yields by Kobayashi et al. and Chieffi & Limongi show reasonable agreement with observations for \(\alpha\)-elements. Our model predicts a significant scatter of element abundances at \([\text{Fe}/\text{H}] < -3\). We adopted the stellar yields derived in the work of François et al., which produce the best agreement between the observational data and the one-zone chemical evolution model. Their yields well reproduce a trend of the averaged abundances of EMP stars but predict much larger scatter than do the observations. The model with hypernovae predicts Zn abundance, in agreement with the observations, but other models predict lower [Zn/Fe]. Ejecta from the hypernovae with large explosion energy is mixed in large mass and decreases the scatter of the element abundances.

Key words: Galaxy: evolution – Galaxy: formation – stars: abundances – stars: Population II

Online-only material: color figures

1. INTRODUCTION
Extremely metal-poor (EMP: \([\text{Fe}/\text{H}] < -2.5\) in this paper) stars are stars formed in the early universe in terms of chemical evolution. They are thought to have been formed at high redshift but are still shining with the glow of nuclear burning in the Local Group. Recent large-scale surveys have identified hundreds of EMP stars in the Milky Way halo (HK survey, Beers et al. 1992; Hamburg/ESO (HES) survey, Christlieb 2003, Christlieb et al. 2008; Sloan Extension for Galactic Understanding and Exploration (SEGUE), Yanny et al. 2009). Element abundances of these stars are revealed by follow-up spectroscopic observations. They provide a means of probing the earliest phases of the evolution of the Milky Way and supernovae (SNe) in the early universe.

In this paper, we refer to stars with \([\text{Fe}/\text{H}] \leq -2.5\) as EMP stars, although the term “EMP star” is usually used for \([\text{Fe}/\text{H}] < -3\) (Beers et al. 2005). As shown in our previous study (Komiya et al. 2010, hereafter Paper I), stars with \([\text{Fe}/\text{H}] \lesssim -2.5\) show some observational and theoretical peculiarities distinguishing them from more metal-rich Population II stars (see Section 2.1 of Paper I). In previous studies (Komiya et al. 2007, 2009b), we showed that the initial mass function (IMF) of stars with \([\text{Fe}/\text{H}] \lesssim -2.5\) should differ from that of metal-rich stars. The typical mass of the EMP stars is \(\sim 10 M_\odot\) and the present EMP stars in the Milky Way halo are the low-mass minorities. We refer to the mother stellar population with \([\text{Fe}/\text{H}] \lesssim -2.5\) as the EMP population and low-mass survivors with nuclear burning now as EMP survivors. Stars with \([\text{Fe}/\text{H}] < -5\) are referred to as hyper-metal-poor (HMP) stars. Two HMP stars detected in the Milky Way halo are the most metal-deficient objects observed yet (HE1327-2326, Frebel et al. 2005; HE0107-5240, Christlieb et al. 2002). The formation environment of the EMP population stars is thought to differ from present galaxies. EMP stars are formed in the process of galaxy formation in the early universe. In the cold dark matter universe, large galaxies like the Milky Way are formed through a merger of smaller galaxies as building blocks. According to the hierarchical structure formation scenario, a stellar halo is an aggregation of stars formed in the many small galaxies (Searle & Zinn 1978; Helmi 2008). Earlier theoretical studies show that the first stars are formed in very low-mass halos with \(\sim 10^8 M_\odot\) (Tegmark et al. 1997; Nishi & Susa 1999), and host galaxies of the second generation of stars are also small (Ricotti et al. 2002; Wise & Abel 2008). Chemical abundances of these building blocks can differ from one another. Unlike metal-rich stars, metals in EMP stars are synthesized by only one or a few precursory SN(e). Element abundances of the EMP stars can reflect individual characteristics of the precursory SN(e) and their host galaxies. A semi-analytic hierarchical approach can provide a framework within which to study the earliest phases of the chemical evolution and the formation history of the EMP stars.

One important point at issue for the earliest phases of chemical evolution is a possible difference in the IMF of EMP stars (e.g., Abia et al. 2001; Komiya et al. 2007). Theoretically, the typical mass of stars is large in the EMP environment and/or in the early universe. Numerical simulations show that Population III stars without metal are very massive (e.g., Bromm et al. 1999; Abel et al. 2002). For EMP stars with a little metal, the IMF can also be different from nearby stars (Omukai et al. 2005). The existence of the low-mass EMP survivors in the Galactic halo proves that some low-mass EMP stars can be formed, but the typical mass of the EMP population stars can be more massive than Population I stars. Komiya et al. (2007, 2009b) place constraints on the IMF of EMP stars from statistics.
of observed EMP survivors. It is known that a large fraction (~20%) of the EMP survivors is comprised of carbon-enhanced metal-poor (CEMP) stars. More than half of them show large $s$-process element enhancement. Abundance anomalies of the $s$-process element-enhanced CEMP stars (CEMP-s stars) are due to binary mass transfer. Intermediate massive EMP stars with 0.8–3 $M_\odot$ synthesize carbon and $s$-process elements in the asymptotic giant branch (AGB) phase and pollute their companions to make them CEMP-s stars. We propose that CEMP stars without $s$-process enhancement (CEMP-nos stars) are also formed through binary mass transfer but from more massive primaries with 4–6 $M_\odot$. From observational statistics of the CEMP-s and CEMP-nos stars, we put constraints on the mass distribution of primary stars of EMP binaries and conclude that the typical mass of EMP stars is large (Komiya et al. 2007). Komiya et al. (2009b) discuss the constraints of the IMF from CEMP stars again in detail and determine an additional constraint from the total number of EMP survivors. The number of EMP survivors in the Galactic halo is very small, and it indicates that the fraction of low-mass survivors among the EMP population is small. As a result, a lognormal IMF with medium mass, $M_{\text{med}} \sim 10 M_\odot$, and dispersion, $\Delta_{\text{med}} \sim 0.4$, can satisfy all the constraints. Lucatello et al. (2005) also put a constraint on the IMF of EMP stars from statistics of CEMP-s stars and argue that the typical mass of EMP stars is slightly higher than that of more metal-rich stars. However, because they do not take into account CEMP-nos stars and assume a stellar evolution model different from ours, they conclude a lower typical mass, $M_{\text{med}} = 0.79 M_\odot$.

In Paper I and Komiya et al. (2009a), we built a merger tree of the Galaxy and compute the enrichment history of iron abundance along the tree. The high-mass IMF with $M_{\text{med}} = 10 M_\odot$ (Komiya et al. 2007) was adopted in the computations. We also discussed the origin of HMP stars considering the effect of surface pollution by accretion of the metal-enriched interstellar matter. In this paper, we investigate chemical evolution of several elements with detailed theoretical nucleosynthetic yields of metal-deficient massive stars. Model results with high- and low-mass IMFs are compared with compiled observational data. To deal with individual characteristics of the EMP stars, all the individual EMP population stars are registered in our computations. We discuss not only averaged abundances but also their dispersion.

Tumlinson (2006) presents a semi-analytic hierarchical model for the Galactic halo. Salvadori et al. (2006) also calculate a hierarchical model with gas blowout from halos by bursty star formation taken into account, but they do not deal with individual stars and do not investigate diversity of the element abundances. These previous studies assume the Salpeter IMF for EMP stars. Additionally, these previous studies with hierarchical models investigate only iron abundance. We calculate the formation and evolution of a stellar halo with different IMFs and compare the predicted metallicity distribution functions (MDFs) and abundance ratio distributions. We use four different sets of core-collapse SN yields calculated for metal-poor stars. Argast et al. (2000) and Karlsson & Gustafsson (2005) investigate element abundances of EMP stars using inhomogeneous chemical evolution models. However, they do not take into account the merging history of the Galaxy, and stars are assumed to be formed randomly in space. They also do not investigate the IMF dependence.

This paper is organized as follows: The computation method and assumptions appear in the next section. Assumptions about IMFs and SN yields are described in Sections 2.2 and 2.3, respectively. In Section 3, we describe the observational sample for comparison. We give results in Section 4 and conclude the paper in Section 5.

2. COMPUTATION METHOD

2.1. A Hierarchical Chemical Evolution Model for EMP Stars

A hierarchical chemical evolution model for EMP stars was developed in Paper I. We built a merger tree semi-analytically, using the method of Somerville & Kolatt (1999) based on the extended Press–Schechter formalism (Lacey & Cole 1993). Along the merger tree, chemical enrichment and formation history of EMP stars are calculated. In this paper, abundances of O, Na, Mg, Si, Cr, Fe, and Zn are computed and compared to observations of metal-poor stars.

Stars are assumed to be formed in halos with virial temperature, $T_{\text{vir}}$, higher than $10^4$ K. Star formation efficiency is assumed to be constant and determined to give [Fe/H] = 0 at $z = 0$ ($2.1 \times 10^{-11} - 1.1 \times 10^{-10}$ yr$^{-1}$ for the following computations). To investigate diversity of element abundances, all the individual EMP population stars are registered in our computations. The mass of each EMP star is specified randomly according to the statistical weight with the IMF. Half of all the stellar systems are taken to be binaries, and a flat mass ratio distribution is assumed. Adopted IMFs are described in detail in Section 2.2. We set nucleosynthesis yields of each massive star as a function of its initial mass and metallicity. Assumptions about yields are described in Section 2.3. Each mini-halo is assumed to be chemically homogeneous.

We use the same assumptions about radiative and dynamical feedback from massive stars as those in Model P in Paper I. Massive stars ionize the ambient matter. At $z < 20$, Lyman–Werner background radiation inhibits star formation in mini-halos that are not pre-ionized. Energetic SN explosions blow out gas in their host mini-halos when their effective kinetic energy, $\epsilon E_k$, is larger than the binding energy, $E_{\text{bin}}$, of the gas of their host halos. Gas and metal ejected from mini-halos are mixed immediately and homogeneously throughout the intergalactic medium (IGM). Assumed explosion energies, $E_k$, of SNe are described in Section 2.3. From larger halos, a little fraction, $\eta E_k / E_{\text{bin}}$, of metal ejected by SNe is assumed to go to IGM, where $\epsilon$ is the fraction of SNe explosion energy converted into kinetic energy and $\eta$ is the fraction of the input kinetic energy that is retained by gas that escapes the host halo by wind. We assume $\epsilon = 0.1$ and $\eta = 0.1$, but results in this paper are almost independent from these parameters. Because of reionization, mini-halos with $T_{\text{vir}} < 10^4$ K cannot accumulate gas at $z < 10$.

Computations using different IMFs and different nucleosynthetic yields are presented. Adopted IMFs and SN yields are described in the following subsections and summarized in Table 1.

2.2. IMF

As stated in Section 1, in our earlier studies, we put constraints on the IMF of the EMP population stars from statistics of EMP survivors. We assume the lognormal form,

$$
\xi(m) \propto \frac{1}{m_{\text{exp}}^{\Delta}} \exp \left[ -\frac{(\log(m/M_{\text{med}}))^2}{2 \times \Delta_{\text{med}}^2} \right],
$$

and conclude that the high-mass IMF with $M_{\text{med}} = 10 M_\odot$, $\Delta_{\text{med}} = 0.4$ is in agreement with all the observational features. We use this high-mass IMF as the fiducial one.
Based on recent observations, Chabrier (2003) presents an IMF of the Galactic spheroid; a lognormal IMF with \( M_{\text{md}} = 0.22 \, M_{\odot}, \Delta M = 0.33 \) for stars with \( m < 0.7 \, M_{\odot} \), and \( \xi(m) \propto m^{-2.35} \) for higher mass stars. For comparison, computation with this standard low-mass IMF is also presented (Model CK). Since this IMF is the same as the Salpeter IMF for high-mass and intermediate massive stars, chemical evolution under this IMF is almost the same as the Salpeter IMF.

The IMF derived by Lucatello et al. (2005) is also tested (Model LK). They argue a lognormal IMF peaked with slightly higher mass, \( M_{\text{md}} = 0.79 \, M_{\odot}, \Delta M = 0.51 \), based on the statistics of the CEMP-s stars.

For simplicity, we use the same IMF for all the stellar populations in each computation. However, we note that the high-mass IMF is derived from statistics of EMP survivors. In the Galaxy today, more metal-rich stars are formed under a low-mass IMF.

The IMF of the first stars can be different from that of EMP stars. In Paper I, we discussed the typical mass of the first stars from the viewpoint of the number of surviving Population III stars. Observational scarcity of stars with [Fe/H] < −4 suggests that the typical mass of the first stars in each mini-halo is higher than that of the subsequent generations of stars. In this paper, \( M_{\text{md}} = 40 \, M_{\odot} \) is assumed for local first stars without an SN progenitor in their host mini-halos. The number of the predicted HMP stars becomes comparable with observations under this assumption. These three IMFs are shown in Figure 1.

Many numerical studies for the Population III star formation argue that one very massive single star (or binary; Turk et al. 2009) with \( m > 100 \, M_{\odot} \) is formed at the center of the primordial mini-halo (e.g., O’Shea & Norman 2007; Yoshida et al. 2008). On the other hand, some studies show that zero-metallicity gas can fragment into multiple pieces and that some low-mass stars are also formed without metal (Nakamura & Umemura 2001; Clark et al. 2008). In the latter studies, however, the typical mass of Population III stars is higher than nearby stars. Yoshida et al. (2007) show that stars with \( \sim 40 \, M_{\odot} \) are formed in a photoionized halo without metal. When a Population III star with \( \sim 200 \, M_{\odot} \) is formed, it explodes as a pair instability SN (PISN). We discuss the effect of the very massive first stars and PISNe in the Appendix.

### 2.3. Supernova Yields

In this study, stars with \( 10–50 \, M_{\odot} \) are assumed to explode as Type II SNe (SNe II). In Paper I, we simply assume that any SNe II eject 0.07 \( M_{\odot} \) of iron, but in this study, we consider dependence of yields on stellar initial mass and initial metallicity. For SNe II, we adopt four sets of yields. Figure 2 summarizes yields of SNe II with \( Z = 0 \) against initial mass, by theoretical models adopted in this study.

#### Table 1

| Name | IMF | SN Yield |
|------|-----|----------|
| KK   | Komiya et al. (2007, \( M_{\text{md}} = 10 \, M_{\odot} \)) | Kobayashi et al. (2006) |
| LK   | Lucatello et al. (2005, \( M_{\text{md}} = 0.79 \, M_{\odot} \)) | Kobayashi et al. (2006) |
| CK   | Chabrier (2003, \( M_{\text{md}} = 0.22 \, M_{\odot} \)) | Kobayashi et al. (2006) |
| KW   | Komiya et al. (2007) | Woosley & Weaver (1995) |
| KF   | Komiya et al. (2007) | François et al. (2004) |
| KC   | Komiya et al. (2007) | Chieffi & Limongi (2004) |
| KKn  | Komiya et al. (2007) | Kobayashi et al. (2006, no hypernova) |

Figure 1. Initial mass functions (IMFs) adopted in our computations. The solid red, dashed green, and dotted blue lines denote IMFs of Komiya et al. (2007), Chabrier (2003), and Lucatello et al. (2005), respectively.

(A color version of this figure is available in the online journal.)

Theoretical yields by Kobayashi et al. (2006) are used as the fiducial one (Model KK). They give yields of massive stars with various initial masses and initial metallicities by numerical calculations of stellar evolution and explosive nucleosynthesis at SNe II. They also present yields of hypernovae with larger explosion energy. Following Kobayashi et al. (2006), in this paper, 50% of the stars with \( m > 20 \, M_{\odot} \) are assumed to explode as hypernovae. Explosion energy of the SNe II is assumed to be \( E_k = 10^{51} \) erg for normal SNe and \( E_k = 10^{51} \times (m/ M_{\odot} - 10) \) erg for hypernovae. The most prominent nucleosynthetic feature of the hypernova is a large Zn yield. We note that, in the computation by Kobayashi et al. (2006), iron yields for normal SNe are tuned to 0.07 \( M_{\odot} \) by choosing the “mass cut” parameter. In such computations for SN nucleosynthesis, the location of the boundary between the part of the star that eventually collapses to a compact object and that which is expelled outward is a free parameter and referred to as mass cut. An amount of the ejected iron strongly depends on this parameter. For hypernovae, parameters involved in the mixing and fallback are determined to give \( [\text{O}/\text{Fe}] = 0.5 \). We also present a chemical evolution model without a hypernova (Model KKn) to show the contribution from hypernovae.

The theoretical yields by Woosley & Weaver (1995) are also adopted (Model KW). We use the explosion models labeled as 12A-22A, 25B, 30C, 35C, and 40C in Woosley & Weaver (1995). For explosion energy, resultant kinematic energy of their computations is used (\( 1.1–3.0 \times 10^{51} \) erg).

François et al. (2004) modify the yields by Woosley & Weaver (1995) and suggest the best-fit SN yields for α-elements and iron group elements, based on the comparison between one-zone...
et al. (1999) for metal yields of SNe Ia. In this study, we assume the fraction of stars that become SNe Ia depend on the IMFs. We use the W7 model in Iwamoto et al. (1995) since they do not derive the best-fit one. It is worth noting that some studies argue that the mass of the secondary star, without assuming a delay time distribution function, the delay time of each SN Ia is calculated from the mass of the secondary companion. Because individual stars are registered in our chemical evolution calculation and observational data. For oxygen, they adopt the yield by Woosley & Weaver (1995) without modification. Their best-fit yields are, as a matter of course, consistent with observations as far as the one-zone model with the Salpeter IMF goes. We adopt their yields to the hierarchical evolution model with the high-mass IMF (Model KF). Since they do not discuss metallicity dependence of the SN yields, the same yields are assumed for any metallicity in Model KF. For Na, we assume the same yield as Woosley & Weaver (1995) since they do not derive the best-fit one.

Chiefi & Limongi (2004) also give explosive yields of massive stars from $Z = 0$ to $Z = Z_{\odot}$. Chemical evolution computation using their results is also presented (Model KC). We note that they chose a mass cut parameter to eject $0.1 M_{\odot}$ of iron for all SNe II. Explosion energy is assumed to be $10^{55}$ erg.

For Type Ia SNe (SNe Ia), a single degenerate scenario is assumed. Following Greggio (2005), we assume that $9\%$ of the binary systems in which the initial mass of primaries is $2M_{\odot}$–$4M_{\odot}$ become SNe Ia. Delay time from star formation to SN explosion is equal to a lifetime of the secondary companion of a binary. Because individual stars are registered in our computation, the delay time of each SN Ia is calculated from the mass of the secondary star, without assuming a delay time distribution function. The event rate and delay time distribution of SN Ia depend on the IMFs. We use the W7 model in Iwamoto et al. (1999) for metal yields of SNe Ia. In this study, we assume for simplicity that frequency and yields of SNe Ia are metallicity independent. It is worth noting that some studies argue that the fraction of stars that become SNe Ia depends on the metallicity. Kobayashi et al. (1998) argue that only stars with metallicity larger than $[\text{Fe/H}] > -1$ become SNe Ia. However, dependence on the metallicity is not yet well understood.

Some stars with mass around $10 M_{\odot}$ are thought to become electron capture SNe of progenitor AGB stars with an O–Ne–Mg core. Wanajo et al. (2009) give nucleosynthesis yields in this type of explosion. Amounts of the ejected iron and $\alpha$-elements are much smaller than SNe II. One prominent feature of the predicted yields by Wanajo et al. (2009) is a large yield of Zn. They argue that O–Ne–Mg SNe can be a main source of Zn in the universe. The mass range and the fraction of the stars that become O–Ne–Mg SNe are not well revealed. We assume that stars with 9–10 $M_{\odot}$ become O–Ne–Mg SNe.

In this study, we omit the metal ejected by mass loss from intermediate massive stars. Because EMP stars are formed in the very early stages of chemical evolution, metal ejected from the intermediate massive stars that have longer lifetimes than massive stars should be negligible. Additionally, the amount of $\alpha$-elements, iron group elements, and Zn provided by the intermediate massive stars is thought to be less than by SNe (but see also Vangioni et al. 2010).

### 3. OBSERVATIONAL DATA

We adopt a bias-corrected halo MDF constructed from subsamples of the HES survey with moderate-resolution spectroscopy by Schörck et al. (2009). At $[\text{Fe/H}] < -3$, they have replaced the moderate resolution values with those derived from high-resolution spectroscopy, where available. Since the HES survey is biased toward low metallicity, they evaluate biases and give the selected fraction, $f_{s}$, as a function of metallicity and color. Instead of the raw MDF, $N_{\text{obs}}([\text{Fe/H}])$, of the HDS sample, a bias-collected MDF, $N_{\text{obs}}([\text{Fe/H}])/f_{s}([\text{Fe/H}])$, is plotted for comparison with the model results.

We also show an MDF compiled by the Stellar Abundance for Galactic Archaeology (SAGA) database (Suda et al. 2008) since we are interested in the low-metallicity tail of the MDF. SAGA compiles elemental abundances of EMP halo stars that received high-resolution spectroscopic observations. At $[\text{Fe/H}] < -3$, metallicity derived by moderate-resolution spectroscopy can be significantly different from that derived...
by high-resolution spectroscopy. High-resolution data tell us the accurate metallicity of EMP stars, and SAGA contains a large sample of EMP stars. We plot raw data compiled by the SAGA database; this is strongly biased toward low metallicity. However, we may well regard the selection of target stars for the follow-up observations as being hardly biased below the metallicity of $[\text{Fe}/\text{H}] \simeq -3$. The MDF of Schörck et al. (2009) contains only two stars at $[\text{Fe}/\text{H}] < -3.6$, and none at $[\text{Fe}/\text{H}] < -4.3$. Currently, 19 stars with $[\text{Fe}/\text{H}] < -3.6$ have been identified in the SAGA sample, and 2 stars have $[\text{Fe}/\text{H}] < -5$.

We consider not only the form of the MDF but also the total number of EMP survivors. In Paper I, we estimated efficiency of the identification of EMP survivors by the HES survey from its coverage area. The effective survey area is $S = 6726$ deg$^2$, and roughly 40% of the candidates, selected by the objective-prism survey, have been examined by the spectroscopic follow-up observations with medium resolution (Christlieb et al. 2008). We assume that almost all giant EMP survivors present in the survey fields are detected because of the large limiting magnitude of the HES survey ($B < 17.5$). When uniform distribution of the stellar halo is assumed, $\sim 5\%$ of the giant EMP survivors in the Milky Way halo are expected to be detected. In the following figures, we plot the predicted number of stars that are expected to be in the HES sample, assuming a uniform stellar halo. When de Vaucouleurs density distribution is assumed, detection frequency decreases by a factor of five, since many undetectable stars should be distributed in the inner part of the Galactic halo from the solar orbit.

For the elemental abundance ratio, we adopt data compiled by the SAGA database (Suda et al. 2011). Figure 3 shows distributions of O, Na, Mg, Si, Cr, and Zn abundances relative to iron against $[\text{Fe}/\text{H}]$. We select a high-resolution sample of $R \gtrsim 20,000$. We note that, since SAGA compiles data from many sources, the scatter of the abundances by the SAGA data set can be larger than the intrinsic scatter of the stellar abundances. To see the systematic difference between literatures, three subsamples analyzed by different authors are plotted by different symbols with error bars. Blue triangles ($\triangle$) in Figure 3 denote data analyzed by the First Stars project (Hill et al. 2002 and the other 13 papers in the series). Green squares (□) denote data of which the first author of the source paper is W. Aoki (Aoki et al. 2002 and the other 15 papers in the entry list of SAGA). The magenta inverted triangle (▽) shows the sample from Honda et al. (2004, 2007). These three subsamples are analyzed assuming a plane-parallel stellar atmosphere (one dimensional) and local thermal equilibrium (LTE), but there is a systematic difference in the abundance ratio owing to the difference in model atmospheres, parameters used during the analysis, and lines used in analysis. Other stars are plotted with red plus signs (+) and yellow crosses (×) for giants ($T_{\text{eff}} \lesssim 6000$ and $\log g \lesssim 3.5$) and dwarfs, respectively.

We plot only giant stars in the following figures since there is a systematic shift in stellar abundances between giants and dwarfs for some elements (Bonifacio et al. 2009). Carbon-enhanced stars with $[\text{C}/\text{Fe}] > 0.5$ are not plotted because their surface is thought to be polluted by binary mass transfer. Komiyai et al. (2007) show that carbon on these stars originates in the intermediate massive companion stars and that their surface abundances of O, Na, and Mg are also affected by binary mass transfer (Nishimura et al. 2009). Recently, abundance determinations with a non-LTE scheme (e.g., Mashonkina et al. 2008; Andrievsky et al. 2010) or with three-dimensional model atmospheres (e.g., Asplund & García Perez 2001; González Hernández et al. 2008) have been carried out. The difference in abundances determined with these models from one-dimensional

Figure 3. Abundance ratio distributions of metal-poor stars compiled by the SAGA database. Stars analyzed by the First Stars project (blue triangles, △), stars analyzed by Aoki et al. (green squares, □), and stars in Honda et al. (2004, 2007, magenta inverted triangles,▽) are plotted with error bars, where available. Other giants (red plus signs, +) and main-sequence stars (yellow crosses, ×) in the SAGA sample are plotted without error bars. Stars in common between two or three subsamples are connected with lines. See the text for details. (A color version of this figure is available in the online journal.)
is sensitive to individual SN yields. The MDF of Model KK model results are similar in the total number of EMP survivors. Results of Models KK, KW, KF, and KC, respectively. All long-dashed green, short-dashed blue, and dotted magenta lines in our earlier studies. significantly higher than nearby Population I stars, as shown indicates that the typical mass of EMP population stars is stars formed with metal ejected by only one or a few SN extremely metal-deficient stars are very early generations of of the stellar halo and large discrepancy cannot be explained by spatial inhomogeneity or insufficiency of the survey. This needs to distinguish which theoretical yield is the best one only from comparison with the observed MDF. Additionally, at such a low metallicity, the observational sample is very small and the pattern of the MDF has not yet been well revealed. The predicted number of stars with [Fe/H] < -2.5 is very small, and MDFs are bumpy because of numerical fluctuation. The number of observed HMP stars is comparable to the model results. For more metal-rich stars, an MDF depends on an averaged yield but is almost independent of characteristics of individual massive stars. At [Fe/H] > -2, the observed MDF overwhelms the number of stars predicted by the high-mass IMF models. One possible explanation of this excess is a changeover of the IMF. The IMF of metal-rich stars peaks at low mass. Yamada et al. (2011) indicate that an IMF can be a changeover from high mass to low mass at [Fe/H] > -3 based on statistics of stellar abundance of Zn and Co. If the typical mass becomes lower, the number of stars surviving increases. At this metallicity, some thick disk stars are thought to contaminate the sample. This also increases the number of stars. Formation of the thick disk and the IMF of these more metal-rich stars will be investigated in our future works.

**4. RESULTS AND DISCUSSION**

**4.1. Metallicity Distribution Functions**

Figure 4 shows resultant MDFs for three models using different IMFs. Solid red, dashed green, and dotted blue lines denote Models KK, LK, and CK, respectively. All three models predict similar patterns of the MDFs but quite different total numbers of EMP survivors. This is because fractions of low-mass stars are different. As seen in Figure 4, Model KK with the high-mass IMF is consistent with observations, but other models with lower mass IMFs predict many more EMP survivors. We may overestimate the efficiency of the identification of EMP survivors by the HES survey, because we assume homogeneity of the Galactic stellar halo and the HES survey reaches the outer end of the Galactic halo. However, as seen in Figure 4, the predicted number of EMP survivors for Models LK and CK is ~100–1000 times larger than those in observations, and this large discrepancy cannot be explained by spatial inhomogeneity of the stellar halo and/or insufficiency of the survey. This indicates that the typical mass of EMP population stars is significantly higher than nearby Population I stars, as shown in our earlier studies.

Figure 5 shows dependence on the SN yields. Solid red, long-dashed green, short-dashed blue, and dotted magenta lines denote results of Models KK, KW, KF, and KC, respectively. All model results are similar in the total number of EMP survivors.

At [Fe/H] < -3, the patterns of the MDF differ. These extremely metal-deficient stars are very early generations of stars formed with metal ejected by only one or a few SN progenitor(s) in their host halos. An MDF at [Fe/H] < -3 is sensitive to individual SN yields. The MDF of Model KK has a hump at [Fe/H] ~ -3.6. This is because iron yields of normal SNe II are tuned to 0.07 M⊙ in Kobayashi et al. (2006) and metallicity of a primordial mini-halo with typical mass becomes [Fe/H] ~ -3.6 by a single SN. We also see a smaller hump at [Fe/H] = -4 to -3 in other models. In Model KK, since energetic hypernovae blow out gas from mini-halos, the predicted number of stars with [Fe/H] ~ -3 to -2 is smaller than other models.

Model KC shows better consistency with observations than the other models. The MDF of Schöck et al. (2009) shows a steep drop around [Fe/H] = -3.6. In Model KC, since iron yield and explosion energy are assumed to be the same for all the SNe II, all the second and later generations of stars are distributed above [Fe/H] ~ -3.6. However, the theoretical iron yield strongly depends on the SN model parameters, and it is difficult to distinguish which theoretical yield is the best one only from comparison with the observed MDF. Additionally, at such a low metallicity, the observational sample is very small and the pattern of the MDF has not yet been well revealed.

The predicted number of stars with [Fe/H] < -4.5 is very small, and MDFs are bumpy because of numerical fluctuation. The number of observed HMP stars is comparable to the model results.

**4.2. Abundance Ratio Distribution**

In Figure 6, we show predicted and observed abundance ratio distributions for six elements for Model KK. The predicted
typical abundance ratio and their trend against metallicity are similar to the result of the chemical evolution model by Kobayashi et al. (2006). Since the abundance ratio differs from mini-halo to mini-halo in our model, abundance distributions show significant dispersion. The predicted scatters of abundances are prominent at [Fe/H] < −3. At larger metallicity, element abundances are averaged by mixing of ejecta from many SNe and the scatters decrease. As shown in Paper I, metals of stars with [Fe/H] = −2.5 originate in ~10 precursory SNe in their host mini-halos.

Most stars with [Fe/H] < −4 are local first stars without any precursory SN exploded in their host mini-halos. Metals in these stars originate in mixtures of matter ejected to IGM by SNe that had exploded in other mini-halos prior to the formation of the host mini-halos of these stars. Scatter of the abundances of these stars is smaller than the stars with −3 > [Fe/H] ≥ −4. Observed HMP stars show abundance anomalies of C, N, O, and Na, but these are thought to be due to the surface pollution by binary mass transfer (Suda et al. 2004; Nishimura et al. 2009).

4.2.1. α-Elements

For Mg and Si, the typical abundance ratio is consistent with observations. Observed distribution of [α/Fe] is almost flat against [Fe/H] at [Fe/H] < −1 and the dispersion is small. The predicted dispersion of the α-element abundances is comparable to or smaller than the dispersion of the observational sample.

Observationally, [O/Fe] of EMP stars shows a slight increasing trend as metallicity decreases but predicted abundances do not. Typical O abundance of the First Stars sample is ~0.2 dex higher than the predicted value. As seen in Figure 2, a larger amount of O is yielded in a more massive progenitor. If this increasing trend is real, stars more massive than 20 M⊙ are thought to be the dominant source of metal in EMP stars. Mg and Si abundances show no such trend, although a larger amount of these elements is yielded in a more massive progenitor. Another possible additional source of oxygen for EMP stars is intermediate massive AGB stars. However, because AGB stars eject both O and C, O abundances of stars other than CEMP stars should not be strongly affected by AGB stars. We note that observational determination of the oxygen abundance is difficult and that there is large uncertainty of the observational data.

Nissen et al. (2002) argue that, when three-dimensional effects are taken into account, [O/Fe] decreases in the metal-poor stars and the increasing trend diminishes. For some EMP stars with low [O/Fe], oxygen is undetectable.

The sample from the First Stars project shows very small scatter for Mg and Si. This is consistent with the result of Model KK. As seen in the following, Model KK with hypernovae predicts the smallest scatters among the computations in this paper. This is because [O/Fe] in the hypernovae ejecta is tuned to be constant, and large energy of the hypernovae efficiently mixes the interstellar medium. The observed small scatter of the First Stars sample indicates that gas in the early universe is mixed with large mass. However, the subsamples by other authors show larger scatter (~0.5 dex). Further observations are required to understand the gas dynamics in the early universe. For Mg, the First Stars sample is distributed at a slightly lower [Mg/Fe] than the model results, but other samples are consistent. Andrievsky et al. (2010) argue that, when non-LTE effects are taken into account, the mean value of [Mg/Fe] increases and becomes similar to the mean value of [O/Fe]. This will improve the consistency between the model and observed data.

Observationally, it is known that [α/Fe] decreases as [Fe/H] increases at [Fe/H] > −1 for stars in the Milky Way. In many chemical evolution studies, this decreasing trend has been explained by the contribution of SNe Ia (Matteucci 2008, and references therein). SNe Ia eject large amounts of iron after a
long delay time and decrease [\(\alpha/Fe\)] at large metallicity. Under the high-mass IMF, the contribution from SNe Ia is relatively weak, because the number of intermediate massive stars relative to high-mass stars is small. In Model KK, [\(\alpha/Fe\)] decreases at [\(Fe/H\)] > −1 but the rate of the decline is smaller than that in the observations. Although the IMF is assumed to be the same for the whole metallicity range, for simplicity in this study our high-mass IMF is derived from the statistics of the EMP survivors, and the IMF should be different at higher metallicity.

4.2.2. Na

For Na, the observational sample of EMP stars shows quite large scatter. All the subsamples show large scatter; this is thought to be intrinsic. Observed stars with lower [Na/Fe] have abundance similar to the model result, but some other stars show larger [Na/Fe]. This indicates that there are additional sources of Na. Internal mixing may modify the surface Na abundance of some evolved EMP survivors (Spite et al. 2006). As discussed in Nishimura et al. (2009), in intermediate massive EMP stars at the AGB stage, Na can be synthesized and dredged up by the He-flash-driven deep-mixing, which is a mixing mechanism peculiar to the EMP stars. Stars with high [Na/Fe] can be influenced by matter ejected from these AGB stars. At [\(Fe/H\)] > −2, predicted typical abundance and their increasing trend are consistent with observations. We note that, when the non-LTE effect is taken into account, Na abundance of some stars for which a high [Na/Fe] value is reported decreases to [Na/Fe] ∼ −0.2 (Andrievsky et al. 2007).

4.2.3. Cr

[Cr/Fe] shows a decreasing trend as metallicity decreases. The predicted relative abundance is not consistent with the observations of EMP stars, as noted by Kobayashi et al. (2006). We note that the sample of Honda et al. (2004) is distributed around [Cr/Fe] = 0 and is consistent with model results. However, the First Stars sample and Aoki’s sample show a clear decreasing trend with small scatter.

4.2.4. Zn

In the models in this paper, Zn is mainly produced by O–Ne–Mg SNe, Wanajo et al. (2009) predict a large Zn yield for O–Ne–Mg SNe. Hypernovae are also important sources of Zn, especially at very low metallicity. For EMP stars, all observational subsamples show a similar abundance distribution, and they are consistent with the model result.

Observations show an increasing trend of [Zn/Fe] as metallicity decreases. Both subsamples by the First Stars group, and Aoki et al. also show a clear increasing trend with small scatter. The model result shows flat distribution and predicts lower [Zn/Fe] at [\(Fe/H\)] ≥ −2. Recently, Yamada et al. (2011) have shown that a decrease in [Zn/Fe] above [\(Fe/H\)] > −2.2 may be due to a changeover of the IMF from high mass to low mass. The IMF changeover lowers the frequency of the hypernova and lowers the [Zn/Fe]. The contribution from hypernovae is discussed again with results of the model without hypernovae in Section 4.3.

At [\(Fe/H\)] = −2 to −1, the model predict higher [Zn/Fe] than that in the observations. Zn is thought to be overproduced by O–Be–Mg SNe. Criterion for O–Ne–Mg SNe is not yet revealed (Herwig 2005), and the number of O–Ne–Mg SNe may be smaller.

The predicted scatter of Zn is larger than that of other elements. This is because hypernovae and O–Ne–Mg SNe eject matter with high [Zn/Fe], but normal SNe with mass \(m > 20 M_\odot\) eject a small amount of Zn.

4.2.5. IMF Dependence

Figures 7 and 8 show predicted abundance ratio distributions by models using different IMFs. Model CK predicts a similar typical abundance ratio to Model KK. O, Mg, and Si are mainly
provided by stars with mass heavier than $20 \, M_\odot$ and iron is ejected by all SNe II and SNe Ia. For EMP stars, [$\alpha$/Fe] depends on a fraction of stars with $>20 \, M_\odot$ among SNe II and it depends on the IMF. For Models KK and CK, the typical mass of stars is quite different but the slope of the IMFs at mass range to be SNe II ($10$–$50 \, M_\odot$) is similar, as seen in Figure 1. The relative frequency of heavier ($>20 \, M_\odot$) and lighter ($<20 \, M_\odot$) SNe II is similar for both IMFs, and typical [$\alpha$/Fe] are also similar. However, Model CK predicts that some stars with low oxygen abundance ([O/Fe] $\sim$ 0.2–0.3) are distributed at a very low metallicity range ([Fe/H] $\lesssim$ −3.5). These stars are born in mini-halos formed at low redshift. In this model, many SNe Ia yield iron at lower redshift, and iron ejected from mini-halos lowers the [O/Fe] of IGM. Metallicity of the IGM is still low because the ejected matter is diluted in large mass. Mini-halos formed with the IGM polluted by SNe Ia have low [O/Fe] but
low metallicity. Observationally, these stars are not detected. If the ejected matter is mixed in smaller mass, iron and oxygen abundances of polluted IGM become larger and these O-poor stars dissipate. We note that oxygen abundance of these stars can be lower than the detection limit of O. Some stars without detection of O possibly have such an abundance feature.

For Model LK, $[O/Fe]$ is obviously lower than that in Models KK and CK in the whole metallicity range, as seen in Figure 8. This is because a slope of the IMF is steeper at the mass range of stars to become SNe II. The relative frequency of heavier SNe II ($\gtrsim 20 M_\odot$) is smaller and a smaller amount of $\alpha$-elements is ejected. The predicted distribution of $[O/Fe]$ is much lower than that in the observations for EMP stars. At $[Fe/H] \sim -2$, the abundances of Mg, Si, and Na relative to iron are also lower than those in the observations.
At [Fe/H] ≥ −1, we can for Models CK and LK see clear decreasing trends for the α-element abundances as metallicity increases. Relative numbers of SNe Ia are larger for these models, and they lower the [α/Fe] at higher metallicity.

4.2.6. Supernova Models

Figures 9, 10, and 11 show abundance ratio distributions for Models KW, KF, and KC using SN yields by Woosley & Weaver (1995), François et al. (2004), and Chieffi & Limongi (2004), respectively.

For Model KW, as François et al. (2004) pointed out, predicted α-element abundances do not agree with the observations. Predicted abundances of the O, Mg, and Na relative to iron are 0.5 dex or more lower than the observational sample.

For Model KF, since François et al. (2004) modify the nucleosynthetic yields to match observational data, predicted typical abundances of EMP stars show good agreement with observations for elements other than Na. The decreasing trend of [Cr/Fe] at low metallicity is also reproduced. They assume that an SN with larger initial mass ejects a smaller amount of Cr (see Figure 2). Since a star with larger mass has a shorter lifetime, [Cr/Fe] increases as metallicity increases with time. However, all other studies with nucleosynthesis computations predict that a more massive star yields a larger amount of Cr.

While Model KF well reproduces the typical abundances, it predicts larger dispersion of the element abundances than do the observations. Specifically, [O/Fe] distributes from −1.5 to +1.5 at [Fe/H] < −3. This model also predicts some stars with [Si/Fe] > +1. The predicted scatter is much larger than that in the observations, and it indicates that a one-zone model is inadequate to understand the earliest phases of the chemical evolution and metal yields of very metal-poor SNe.

Model KC predicts typical abundances in agreement with the observational sample, for Mg and Si. Lower O abundance than that in the observations is predicted, but observed O abundances can be lower when the non-LTE and three-dimensional effect is taken into account, as mentioned above.

This model predicts some stars with very low [O/Fe] and [Mg/Fe] at [Fe/H] < −3. Such abundance patterns are produced from SNe at the low-mass end of the mass range to become SNe II. As seen in Figure 2, stars with 10–12 M⊙ yield a small amount of O and Mg. The lower mass limit to become SNe II is assumed to be 10 M⊙ in this paper, but the fate of the stars with ∼10 M⊙ is not well revealed. Some stars with ∼8–12 M⊙ are thought to become “super-AGB” stars (Garcia-Berro & Iben 1994) and evolve to O–Ne–Mg white dwarfs or electron capture SNe (Herwig 2005) with a very low iron yield.
The absence of the very $\alpha$-poor stars possibly indicates that the lower mass limit to become SNe II is larger than $10 \, M_\odot$ at very low metallicity. Kawabata et al. (2010) argue that stars with $8-12 \, M_\odot$ become “faint SNe” with a low iron yield. Although Chieffi & Limongi (2004) have assumed the iron yield is $0.1 \, M_\odot$ for all SNe, observations indicate that some SNe yield lower amounts of iron.

Na is overproduced at higher metallicity ([Fe/H] $> -2$). Cr abundance at solar metallicity is consistent with the observations, but the increasing trend is not reproduced.

Very large scatter of Zn is predicted because Chieffi & Limongi (2004) argue that a large amount of Zn is yielded in an SN II with $m < 13 \, M_\odot$, but a very low amount of Zn is yielded in an SN with $m = 13 \, M_\odot$. When the low-mass limit to become SNe II is larger as discussed above, stars with very high [Zn/Fe] are not formed. A yield of Zn is sensitive to entropy during explosive Si-burning at SN explosion. As discussed later, energetic hypernovae are thought to be required to explain Zn abundance of EMP stars and their trend.

4.3. Hypernova versus Normal SN

Figures 12 and 13 show a result of Model KKn without hypernova contribution. The MDF of Model KKn is similar to that in Model KK. For the abundance ratio distributions, the most plausible difference from Model KK is lower [Zn/Fe]. Since hypernovae synthesize a much larger amount of Zn than normal SNe, Zn abundance of Model KKn is lower than that in Model KK and lower than that in observations for EMP stars. $\alpha$-element abundances predicted by Model KKn are slightly higher than those in Model KK, and [O/Fe] shows better agreement with observations than Model KK. But for Mg and Cr, Model KKn predicts slightly higher relative abundances than do the observations. This is because a normal SN yields a smaller amount of iron than a hypernova.

Large explosion energy of hypernovae affects also gas dynamics. Many mini-halos are blown up by their large explosion energy, and ejected metal is mixed in a large mass. Since it averages element abundances, the scatter of the predicted abundance of Model KK is smaller than that in other models. The observed small scatter of [$\alpha$/Fe] suggests that there were many hypernovae in the early phases of the chemical evolution. We note that, however, Kobayashi et al. (2006) have tuned parameters in their computations to get [O/Fe] = 0.5 for all hypernovae, and the scatter of the $\alpha$-element abundances is decreased artificially.

5. CONCLUSIONS

We compute formation history of EMP stars with a hierarchical chemical evolution model and present MDFs and abundance ratio distributions. We adopt various IMFs and SN yields and compare the results. As for IMFs, we adopt the high-mass IMF given in our earlier studies (Komiyâ et al. 2007, 2009b), the IMF by Lucatello et al. (2005), and the standard low-mass IMF by Chabrier (2003). The pattern of the MDFs is similar for these three models but the predicted numbers of EMP survivors are quite different. The high-mass IMF model predicts a number of EMP survivors comparable to that in the observations, but the other two IMFs predict many more EMP stars in our scenario. Our hierarchical model reproduces a steep decline of the MDF below [Fe/H] = −3.6 and a tail below [Fe/H] < −4.

Abundance ratio distributions predicted by the high-mass IMF are similar to the Salpeter IMF and the predicted $\alpha$-element abundances are consistent with observations. The typical value of [$\alpha$/Fe] depends on the slope of the IMF at a mass range in which stars explode as SNe II, and the high-mass IMF with $M_{\text{min}} = 10 \, M_\odot$ and $\Delta M = 0.4$ has a slope similar to the Salpeter IMF. The IMF by Lucatello et al. (2005), which has a steeper slope at 10–50 $M_\odot$ predicts lower [$\alpha$/Fe].

Using our hierarchical models we investigate not only the averaged abundance and their trend against metallicity but also the scatter of the abundances. Abundance distributions strongly depend on the adopted SNe nucleosynthesis models. For typical abundances of $\alpha$-elements, yields by Kobayashi et al. (2006), François et al. (2004), and Chieffi & Limongi (2004) show reasonable agreement with the observational sample. The sample from the First Stars project shows very small scatter for [Mg/Fe] and [Si/Fe]. This indicates that the abundance ratio ejected by various SNe is homogeneous or that the inter stellar matter is well mixed in large mass. The result with yields by Kobayashi et al. (2006) is consistent with this very small scatter. However, stars analyzed by other authors show larger scatter. Although the SN yields by François et al. (2004) are the best-fit yields as far as averaged abundances, their yields predict much larger scatter than all the observational samples for O and Si. The absence of stars with low [O/Fe] and low [Mg/Fe] possibly indicates that iron yields of stars with mass around 10 $M_\odot$ are lower than normal SNe II.

The observed decreasing trend of [Cr/Fe] as metallicity decreases cannot be explained by the adopted yields by the theoretical SN nucleosynthesis computations. For Na, intermediate massive AGB stars or internal mixing affects surface abundances of some EMP stars with Na enhancement. For O, Mg, and Na, correction of three-dimensional and/or non-LTE effect is thought to decrease the scatter of observed abundances and improve the consistency of the model result. Hypernovae are the plausible dominant source of Zn for EMP stars. Models without hypernovae predict lower [Zn/Fe] than do the observations. The observed increasing trend of [Zn/Fe] as metallicity decreases is not reproduced in our hierarchical models.

Results in this paper depend on the models of SN nucleosynthesis and accuracy of the abundance determination from spectroscopic observational data. The theoretical SN yields are still largely uncertain. Observational subsamples by different authors show different abundance distributions for some
elements. Recent studies with three-dimensional/non-LTE effects taken into account show that averaged abundances shift significantly by these effects, and dispersion of abundances becomes smaller for some elements. Further theoretical and observational studies are required to reveal the origin of metals in the EMP stars and nature of the metal-poor SNe.

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APPENDIX
PAIR INSTABILITY SUPERNOVA

First stars formed without metal are thought to be very massive stars with mass larger than $100 \, M_\odot$. Many numerical simulations for first star-forming clouds argue that only one very massive density peak is formed without fragmentation (e.g., Abel et al. 2002; O’Shea & Norman 2007; Yoshida et al. 2008, but see also Clark et al. 2008). Stars with mass $140–270 \, M_\odot$ become PISNe with huge explosion energy. Theoretical studies of SN nucleosynthesis show that metal yields by PISNe are quite different from SNe II (Umeda & Nomoto 2002; Heger & Woosley 2002). The amount of metal ejected by the energetic PISNe is much larger than that from SNe II. They show a strong "odd–even effect"; i.e., ratio between the yields of elements with even atomic number and odd atomic number is quite large. Zn production is very inefficient relative to other elements such as iron. However, observational studies of the element abundances of the EMP stars show that there is no nucleosynthetic signature of the PISNe.

Metal provided by massive stars is thought to change the IMF and enable low-mass star formation. The critical metallicity to the low-mass star formation is investigated through studies of cooling processes in a molecular cloud by dust and/or metal. Studies with dust argue that cooling by the $H_2$ molecule formed on the surface of the dust sufficiently cool the gas cloud and lower their Jeans mass at metallicity $[Fe/H] \gtrsim -6$ (Omukai et al. 2005; Schneider 2006), and low-mass stars are formed.

In this appendix, we present a computation with PISNe taken into account. We assume that typical mass is very massive, $M_{\text{md}} = 200 \, M_\odot$, for stars with $[Z/H] < -6$ and stars with mass $140–270 \, M_\odot$ become PISNe. Other assumptions are the same as for Model KK. PISN yields by Umeda & Nomoto (2002) are adopted.

Figures 14 and 15 show MDFs and relative abundance distributions, respectively. The results are quite similar to the results of Model KK without PISNe, and we cannot distinguish the observable signature of the PISNe. PISNe eject a large amount of metal at energetic explosions, and the ejected metal is mixed into IGM. Metallicity of the IGM is enriched over $[Z/H] = -6$ by a few dozen PISNe occurring at very high redshift. After that, the IMF is changed to the high-mass one for EMP stars ($M_{\text{md}} = 10 \, M_\odot$). Matter ejected by SNe II is mixed into the IGM, and SNe II become the dominant source of the metal for stars with $[Fe/H] \gtrsim -5$. Additionally, as we have shown in Paper I, surface pollution by accretion of interstellar matter changes surface abundances of HMP stars with $[Fe/H] < -5$ after their formation, and the signature of the PISNe should be covered. In conclusion, the abundance pattern peculiar to the PISNe ejecta is obscured.

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