NUCLEOSYNTHESIS IN HIGH-ENTROPY HOT BUBBLES OF SUPERNOVAE AND ABUNDANCE PATTERNS OF EXTREMELY METAL-POOR STARS

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ABSTRACT

There have been suggestions that the abundance of extremely metal-poor (EMP) stars can be reproduced by hypernovae (HNe), not by normal supernovae (SNe). However, recently it was also suggested that if the innermost neutron-rich or proton-rich matter is ejected, the abundance patterns of ejected matter are changed, and normal SNe may also reproduce the observations of EMP stars. In this Letter, we calculate explosive nucleosynthesis with various $Y_e$ and entropy, and investigate whether normal SNe with this innermost matter, which we call the “hot-bubble” component, can reproduce the observations of EMP stars. We find that neutron-rich ($Y_e = 0.45–0.49$) and proton-rich ($Y_e = 0.51–0.55$) matter can increase Zn/Fe and Co/Fe ratios as observed, but tend to overproduce other Fe-peak elements. In addition, we find that if slightly proton-rich matter with $0.50 < Y_e < 0.501$ with $s/k_b \sim 15–40$ is ejected as much as $\sim 0.06 M_\odot$, even normal SNe can reproduce the abundance of EMP stars, though it requires fine-tuning of $Y_e$. On the other hand, HNe can more easily reproduce the observations of EMP stars without fine-tuning. Our results imply that HNe are the most likely origin of the abundance pattern of EMP stars.

Key words: nuclear reactions, nucleosynthesis, abundances – supernovae: general

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1. INTRODUCTION

The observational trends of extremely metal-poor (EMP) stars reflect supernova (SN) nucleosynthesis of Population (Pop) III or almost metal-free stars. Their observed abundances show quite interesting patterns. There are significant differences between the abundance patterns in the iron-peak elements below and above $[\text{Fe/H}] \sim -2.5$. For $[\text{Fe/H}] \lesssim -2.5$, the mean value of $[\text{Cr/Fe}]$ and $[\text{Mn/Fe}]$ decrease toward lower metallicity, while $[\text{Co/Fe}]$ and $[\text{Zn/Fe}]$ increase (McWilliam et al. 1995; Cayrel et al. 2004).

Umeda & Nomoto (2002, 2005) and Tominaga et al. (2007) show that these trends can be related to the variations of explosion energy of core-collapse SNe, i.e., high $[\text{Zn, Co/Fe}]$ and low $[\text{Cr, Mn/Fe}]$ can be explained by a high-energy SN (“hypernova,” HN), while low $[\text{Zn, Co/Fe}]$ and high $[\text{Cr, Mn/Fe}]$ by a normal SN. On the other hand, Heger & Woosley (2008) studied the evolution and parameterized explosions of Pop III stars with masses ranging from 10 to 100 $M_\odot$. They have concluded that the EMP stars do not show the need for an HN component and that explosion energies less than 1.2 $B$ seem to be preferred, though their models tend to underproduce Co and Zn.

These previous works do not include any contribution from hot bubbles in the innermost region of SNe. However, recent multi-dimensional simulations have shown that both the neutron-rich and proton-rich matter in hot bubbles are ejected from the hot-bubble regions (e.g., Janka et al. 2003). This innermost matter with various $Y_e$ and entropy is considered to be the origin of the heavier elements than Zn, but also can be the important site for the lighter elements (e.g., Hoffman et al. 1996). Heger & Woosley (2008) suggest that Co and Zn in their models can be enhanced by this innermost matter.

Our previous work, Izutani et al. (2009), has studied nucleosynthesis of lighter neutron-capture elements (weak $r$-process elements), Sr, Y, and Zr, by considering small amount of mass ejection from below the conventional mass cut, or from the hot-bubble regions. In that paper, we assumed that the “hot-bubble” matter has the same entropy as the supernova shock, though in reality it may have higher entropy (e.g., in Janka et al. 2003 the hot-bubble matter has the entropy in the range $s/k_b \sim 30–50$). We have found that HN models with neutron-rich matter can reproduce these elements, but normal SN models cannot when we assume the same entropy as the supernova shock for the matter below the mass cut. However, from the observational trends of $[\text{Zn/Fe}]$ and $[\text{Sr/Fe}]$ (see Figure 15 and the discussion in Izutani et al. 2009), it is highly possible that the main origin of the weak $r$-process is normal SNe. In addition, some weak $r$-process stars have also Mo, Ru, and Rh, though the HN model cannot reproduce those elements. Therefore, we need to consider higher-entropy calculations to clarify the origin of these elements.

In this Letter, we perform similar calculations as Izutani et al. (2009) with a wider range of $Y_e$ and entropy. We discuss whether normal SNe with the high-entropy hot-bubble component can reproduce the observations of EMP stars especially paying attention to Fe-peak elements. We also discuss some implications for the origin of the weak $r$-process elements, Sr–Rh.

2. MODEL AND METHOD

The calculation method and other assumptions are the same as described in Umeda & Nomoto (2002, 2005) and Izutani et al. (2009) except for the size of the nuclear reaction networks. In this Letter, we adopt the Pop III progenitors as in Umeda & Nomoto (2002, 2005) and apply the model with $M = 15 M_\odot$ and $E_{51} = 1$ (normal SN model), and $M = 25 M_\odot$ and $E_{51} = 20$ (HN model). Detailed nucleosynthesis is calculated as a postprocessing after the hydrodynamical calculation with a simple $\alpha$-network. The isotopes included in the postprocess calculations for $Y_e < 0.51$ are 809 species up to $^{121}$Pd, and the ones for $Y_e \geq 0.51$ are 652 species up to $^{115}$Pd (for details see N. Izutani et al. 2010, in preparation). As for the HN model, we consider a model for which the density in the complete
normal SN models with the abundance patterns of the EMP stars (blue circles with error bars). The observations from Si to Zn are the average of four EMP stars with $-4.2 < [\text{Fe/H}] < -3.5$ from Cayrel et al. (2004). The observations from Sr to Zr and from Mo to Rh are the ones of CS 22897-008 (François et al. 2007) and HD 122563 (Honda et al. 2007), respectively. Among them, only the HN3 model reproduces both Co and Zn. In addition, the HN3 model may reproduce Sr, Y, and Zr if the hot-bubble component is added as in Izutani et al. (2009). The normal SN model with $s/k_b \sim 15$ neutron-rich matter has a high ratio of Zn, but does not reproduce Co. The normal SN model with $s/k_b \sim 150$ neutron-rich matter reproduces not only [Sr, Y, Zr/Fe] \sim 0 but also [Mo, Ru, Rh/Fe] \sim 0. The models with proton-rich matter reproduce neither Co nor weak $\gamma$-process elements, which we do not show in this figure. (A color version of this figure is available in the online journal.)

Si-burning region is artificially reduced to 1/3 (or entropy is enhanced by a factor of 3) of the original as well as the original model. The HN model with the entropy enhanced by a factor of 3 fits the observation from Ca to Zn except Cr as shown in Figure 1. We call this model “HN3 model” ($s/k_b \sim 50$) and we refer to the HN model with the original entropy as the “HN model” ($s/k_b \sim 15$). As for the normal SN model, the density for the postprocessing is multiplied by factors of $1/k_b$ ($s/k_b \sim 5$), $1/3$ ($s/k_b \sim 15$), $1/10$ ($s/k_b \sim 40$), and $1/35$ ($s/k_b \sim 150$). This modification of density mimics hot bubbles in multi-dimensional simulations.

We obtain the final yields by adding matter above and below $M_{\text{cut}}$. We set $M_{\text{cut}} = 1.50 M_\odot$ for the normal SN model and $1.88 M_\odot$ for the HN3 model. As a result, the normal SN model ejects 0.07 $M_\odot$ of $^{56}$Ni, which is similar to SN1987A, and the HN3 model ejects 0.51 $M_\odot$ of $^{56}$Ni.\(^1\)

3. ABUNDANCE PATTERNS OF WHOLE EJECTA WITH MASS EJECTION BELOW $M_{\text{cut}}$

In Figure 1, the abundance patterns from Si to Ru are compared with those of EMP stars. As for Co and Zn, the HN3 model well reproduces the observations, while the normal SN model does not, as described in the figure caption. As for Sr, Y, and Zr, both the HN3 model with the neutron-rich hot-bubble matter ($s/k_b \sim 15$) and the normal SN model with the neutron-rich hot-bubble matter well reproduce the observations. However, as for the heavier elements, Mo, Ru, and Rh, only the normal SN models with the $s/k_b \sim 150$ neutron-rich hot-bubble matter reach the observations.

4. PARAMETER DEPENDENCE OF NUCLEOSYNTHESIS

In this section, we show parameter dependences of the products in hot bubbles. In Figure 2, we show [Co, Zn/Fe] versus $Y_e$. We show only the cases with $0.50 \leq Y_e \leq 0.501$ in Figure 2 because matter with $Y_e$ in this range shows better fitting to the abundance of EMP stars than neutron-rich ($0.45 \leq Y_e \leq 0.49$) and proton-rich ($0.51 \leq Y_e \leq 0.55$) matter as mentioned in the next paragraph. [Co/Fe] first increases as $Y_e$ increases, but decreases for larger $Y_e$ in all the SN models. $Y_e$ at [Co/Fe] peak becomes larger with higher entropy. [Co/Fe] has the peak at $Y_e = 0.5003$, 0.5004, and 0.5005 for $s/k_b \sim 5, 15,$ and 40, respectively. [Co/Fe] becomes higher with higher entropy. The highest [Co/Fe] is ~0.5, 0.7, and 0.9 for $s/k_b \sim 5, 15,$ and 40, respectively. [Zn/Fe] is nearly 0 regardless of $Y_e$ when $s/k_b \sim 5$, but decreases as $Y_e$ increases in the higher-entropy ($s/k_b \sim 15$ and 40) cases. [Zn/Fe] becomes higher with higher entropy. For example, [Zn/Fe] is ~0.1, 0.4, and 0.9 with $Y_e = 0.50$ for $s/k_b \sim 5, 15,$ and 40, respectively. For comparison, we also show [Zn, Co/Fe] in the complete Si-burning region of the HN3 model by the horizontal lines.

Neutron-rich matter ($0.45 \leq Y_e \leq 0.49$) also produces Co and Zn to some extent, but at the same time tends to overproduce Ni (Figure 3). EMP stars show [Co/Ni] > 0, while neutron-rich matter shows [Co/Ni] < 0. Proton-rich low-entropy matter also produces Co and Zn, but the abundance of Co is smaller than the case with $0.50 \leq Y_e \leq 0.501$. Proton-rich high-entropy matter produces less Co and Zn than proton-rich low-entropy matter. In addition, both neutron- and proton-rich matter tend to overproduce Cu.

5. TRENDS OF Fe-PEAK ELEMENTS OF THE WHOLE EJECTA

Here, we describe in detail the abundance patterns of Fe-peak elements in the whole ejecta with mass ejection below $M_{\text{cut}}$ or with a hot-bubble component. For the matter below $M_{\text{cut}}$, the yields are averaged for $Y_e$ values ranging from 0.45 to 0.50 for neutron-rich matter and from 0.51 to 0.55 for proton-rich matter. The entropy below $M_{\text{cut}}$ is fixed. The other parameter of our model is the mass of ejected matter from the regions below $M_{\text{cut}}$. $\Delta M$. $\Delta M$ is added to the matter above $M_{\text{cut}}$, and they are assumed to be ejected to the outer space all together.
Figure 2. [Co,Zn/Fe] in “hot bubbles” of SNe. [Co/Fe] and [Zn/Fe] are represented by magenta and blue figures, respectively. The ratios for $s/k_b$ = 5 (original), 15, and 40 flows in the normal SN model are represented by solid, dashed, and dash-dotted lines, respectively. The horizontal lines indicate the ratios in the HN3 model with the original $Y_e$, 0.50.

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

Figure 3 shows comparison between observed [Co/Fe], [Ni/Fe] versus [Zn/Fe] and those in our models. Therefore, the trends of their values are similar with the ones seen in Figure 2, but on the other hand their exact values are different between Figures 2 and 3 because the total ejecta includes the incomplete Si-burning region where Fe is produced, but Co and Zn are not. For example, [Zn/Fe] is $\sim 0.6$ and [Co/Fe] is $\sim 0.2$ in the total ejecta of HN3 (open cyan triangle in Figure 3), while [Zn/Fe] is $\sim 0.9$ and [Co/Fe] is $\sim 0.4$ in the complete Si-burning region (blue and magenta horizontal lines in Figure 2).

The gradient of [Co/Fe] versus [Zn/Fe] in EMP stars is larger than that of the normal SN models with a hot-bubble component. The normal SN models with neutron-rich (0.45 $\leq Y_e \leq 0.50$) matter (indicated by blue circles) show the best Co/Zn among all the normal SN models. However, Figure 3 (right panel) shows that the normal SN models with neutron-rich matter tend to overproduce Ni (see also the caption of Figure 3) as also mentioned in Section 4, though [Ni/Fe] in EMP stars with [Zn/Fe] = 0.2–0.3 is well reproduced if some small amount of neutron-rich matter is added ($\lesssim$ 0.006 $M_\odot$). On the other hand, the HN3 model is marginally consistent with the observed [Co/Fe] and well reproduces the observed [Ni/Fe]. In Figure 3, we also plot the ratios for the SN models with $Y_e$ = 0.50, 0.5004, and 0.501 with $s/k_b$ = 15 (red filled circles), and $Y_e$ = 0.50, 0.5005, and 0.502 with $s/k_b$ = 40 (magenta filled circles). We show $Y_e$ = 0.5004 for $s/k_b$ = 15 matter and $Y_e$ = 0.5005 for $s/k_b$ = 40 matter because [Co/Fe] has its peak at this $Y_e$ value in each case. When $s/k_b$ = 15, [Co/Fe] has its peak value ($\sim 0.4$) at $Y_e$ = 0.5004, and [Co/Fe] decreases with higher $Y_e$. [Co/Fe] is $\sim 0.1$ at $Y_e$ = 0.501. The similar trend of [Co/Fe] and $Y_e$ can be seen when $s/k_b$ = 40. These trends are consistent with the ones shown in Figure 2.

As for the HN model and the HN3 model, we also show a version where the complete Si-burning region is set to be $Y_e = 0.5001$ (see Umeda & Nomoto 2005). In this version, [Co/Fe] becomes higher and the HN models well reproduce

Figure 3. Comparison between observed abundance ratios and those in our models. Left panel: [Co/Zn] vs. [Zn/Fe]. Right panel: [Ni/Fe] vs. [Zn/Fe]. The observations are represented by black crosses. The observations with high [Sr/Ba] and [Y/Eu] (weak-$r$ process star: see Izutani et al. 2009 for details) are enclosed by black circles. The ratios for the normal SN model with neutron-rich and proton-rich matter are represented by blue and green circles, respectively. Small and big circles indicate the models with $\Delta M = 0.006 M_\odot$ and 0.06 $M_\odot$, respectively. For the SN models, we show only the original entropy models because they have better [Co/Fe] than higher entropy models. All the SN models with a hot-bubble component do not reach the observations of [Co/Fe]. Among them, the SN model with neutron-rich matter ($Y_e = 0.45–0.50$) of $s/k_b = 5$ shows the best Co/Zn ([Co/Fe] $\sim 0.3$ at [Zn/Fe] $\sim 0.7$) but tends to overproduce Ni ([Ni/Fe] $\sim 0.5$ at [Zn/Fe] $\sim 0.7$). The ratios for the HN models and HN3 models are represented by cyan filled circles and open triangles, respectively. We also show the ratios for the SN models with $Y_e = 0.50$, 0.5005, and 0.502 with $s/k_b = 40$ (magenta filled circles), and the ratios for the SN models with $Y_e = 0.50$, 0.5004, and 0.501 with $s/k_b = 15$ (red filled circles). $\Delta M$ is 0.06 $M_\odot$ in these six models. The ratio for the normal SN model without hot bubbles is located at the coordinate origin.

(A color version of this figure is available in the online journal.)
the observations. For example, [Zn/Fe] is $\sim 0.6$ and [Co/Fe] is $\sim 0.2$ in the HN3 model with $Y_e = 0.50$ (cyan open triangle with letters “HN3 0.50” in Figure 3), while [Zn/Fe] is $\sim 0.6$ and [Co/Fe] is $\sim 0.3$ in the HN3 model with $Y_e = 0.5001$ (cyan open triangle with letters “HN3 0.5001” in Figure 3).

6. DISCUSSION

In this Letter, we have confirmed that only HN-type mass ejection can reproduce the abundance of Fe-peak elements in EMP stars, and neither neutron- nor proton-rich high-entropy matter ejection can help. This also means that if normal SNe eject HN-like matter below $M_{\text{cut}}$, then even normal SNe can reproduce [Co,Zn/Fe] in EMP stars. More quantitatively, we find that the observations require ejection of as much as $0.06 M_\odot$ matter with $Y_e = 0.500-0.501$ with $s/k_b \sim 15-40$. This condition may be difficult to realize for a normal SN. For example, according to Janka et al. (2003), in their models the amount of $Y_e < 0.47, \leq 0.50,$ and $>0.50$ matter is $<10^{-4} M_\odot, 6 \times 10^{-3} M_\odot,$ and $0.03 M_\odot$, respectively, and only a small fraction of matter is in the range of $Y_e = 0.500-0.501$. Therefore, this solution seems too contrived, though the SN explosion mechanism is still uncertain and thus we cannot conclusively deny such a possibility.

Here, we discuss the additional cases with different timescales, the time the flow takes to cool from some temperature to a lower temperature. As a result, [Co/Fe] is changed by the timescale below $T = 4 \times 10^9$ K (Pruet et al. 2005). The timescale below $T = 4 \times 10^9$ K multiplied by a factor of $1/2$ and $2$ gives [Co/Fe] $\sim 0.5$ and $0.2$, respectively, while [Co/Fe] $\sim 0.4$ in the case with the original timescale as mentioned in Section 5. However, the $Y_e$ range and ejected mass needed do not greatly differ; the upper limit of $Y_e$ becomes a little larger, $Y_e \sim 0.502$, and the ejected mass a little smaller, $\sim 0.03 M_\odot$.

There is another reason why SN models are not favored to explain large [Co,Zn/Fe] stars. As mentioned in the introduction, [Co/Fe] decreases with higher metallicity, and many stars show [Co/Fe] $\sim 0$ when [Fe/H] $\gtrsim -2.5$. At this age, only core-collapse SNe are considered to contribute to interstellar matter from the observation of [$\alpha$-elements/Fe]. If the typical value of [Co/Fe] in normal SN is $\sim 0.3$, [Co/Fe] does not decrease to $\sim 0$ at [Fe/H] $\sim -2.5$. On the other hand, the initial mass function average of the supernova ejecta can be [Co,Zn/Fe] $\sim 0$ even though HN models have large [Co,Zn/Fe] (Tominaga et al. 2007).

Therefore, we suggest that Co and Zn in EMP stars originated from HNe, not from normal SNe. As for the weak $r$-process elements, it is not clear that Sr–Zr-rich weak $r$-process stars are always Mo–Rh rich. Observational data of both Sr–Zr and Mo–Rh are obtained in only two weak $r$-process stars HD122563 and HD88609 (Honda et al. 2007). Sr–Zr are produced in a neutron-rich hot bubble of $s/k_b \sim 15$, while both Sr–Zr and Mo–Rh are produced in a neutron-rich hot bubble of $s/k_b \sim 150$, which may be the part of neutrino-driven wind rather than the hot-bubble component (Roberts et al. 2010). Of course, this work is only a parametric search, and some other possibilities may exist in reality. Further investigation is needed to disclose the origin of the abundances in EMP stars.

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