# 論文の内容の要旨

## 論文題目 Supernova Nucleosynthesis with Neutrino Processes and Origin of Extremely Metal-Poor Stars (超新星ニュートリノ元素合成と超金属欠乏星の起源)

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This thesis aims to discuss the origin of extremely metal-poor (EMP) stars, especially whether it is normal supernovae (SNe) with $E_{\rm exp} \sim 1 \times 10^{51}$ ergs or hypernovae (HNe) with $E_{\rm exp} \gtrsim 10 \times 10^{51}$ ergs from comparison of their observations and theoretical supernova (SN) yields.

EMP stars with [Fe/H] $\lesssim -$ 3 may have been formed just a few generations after the first-generation Population (Pop) III stars, or they may even represent the second generation. Their abundance patterns may be the result of nucleosynthesis in even one single core-collapse SN. In other words, SNe of Pop III or almost metal-free stars should reproduce the abundance patterns of EMP stars.

The observed abundances of metal-poor halo stars show quite interesting patterns. There are significant differences between the abundance patterns in the iron-peak elements below and above [Fe/H] $\sim -$ 2.5. For [Fe/H] $\lesssim -$ 2.5, the mean values of [Cr/Fe] and [Mn/Fe] decrease toward lower metallicity, while [Co/Fe] and [Zn/Fe] increase (McWilliam et al. 1995; Cayrel et al. 2004).

Umeda & Nomoto (2002) shows that the trends of [Zn,Co/Fe] and [Cr,Mn/Fe] can be related to the variations of explosion energy of core-collapse SNe, i.e., high [Zn,Co/Fe] and low [Cr,Mn/Fe] can be explained by HNe while low [Zn,Co/Fe] and high [Cr,Mn/Fe] by normal SNe. This is because of the larger mass ratio between the complete Si-burning region and the incomplete Si-burning region in the HN model than in the normal SN model.

Although HNe are considered to be the possible origin of EMP stars from their result, there remain some problems to be solved in order to conclude that the origin of EMP stars is HNe.

First, we should modify $Y_{\rm e}$ and entropy to some extent in order to reproduce Co, Mn and Sc. As for K, we cannot reproduce EMP stars even

with these modifications. Second, we do not consider the contribution from the innermost matter to SN yields. Third, SN yields in our group do not include neutrino processes. Fourth, there is a possibility of uncertainty in SN yields from a different set of nuclear reaction rates.

In this thesis, I approach the remaining problems with a different approach in each chapter. From all the results in this thesis, I make a conclusion about which is the more possible origin of EMP stars, normal SNe or HNe.

(Chapter 3)

As for Pop III and almost metal-free SNe, Umeda & Nomoto (2002) and Heger & Woosley (2010) reach the contrary conclusion even though their method and approach are similar. Umeda & Nomoto (2002) suggests HNe, while Heger & Woosley (2010) suggests normal SNe as Pop III and almost metal-free SNe.

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 matters are ejected from the hot-bubble regions (e.g., Janka et al. 2003). This innermost matter with various $Y_{\rm e}$ 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).

In Chapter 3, I perform hot-bubble calculations using one-dimensional trajectory mimicking multi-dimensional simulations, and discuss whether normal SNe with hot-bubbles can reproduce EMP stars especially paying attention to Fe-peak elements.

As a result, I find that neutron-rich ($Y_{\rm e}$ = 0.45-0.49) and proton-rich ($Y_{\rm e}$ = 0.51-0.55) matter can increase Zn/Fe and Co/Fe ratios as observed, but tend to overproduce the other Fe-peak elements such as Ni. Among hot-bubble matter with various parameters, neutron-rich and low-entropy of $s/k_{\rm b} \sim 5$ matter is the best to reproduce Co, but at the same time, overproduces Ni.

There has been no work that cuts to the heart of the matter, and it has remained to be mystery whether Zn and Co in EMP stars reflect HNe or normal SNe with hot-bubbles. From my work, it becomes clear for the first time that HNe are the only origin of Zn and Co in EMP stars, and that there is no problem to use these elements as a barometer of explosion energy. This is an important result for unclosing the SN mechanism.

(Chapter 4)

I also discuss weak r-process elements (Sr, Y and Zr) in Chapter 4. I investigate normal SN and HN models with neutron-rich matter ejection from the inner region of the conventional mass-cut. I find that explosive nucleosynthesis in a HN can reproduce the high abundances of Sr, Y, and Zr, but that the enhancements of Sr, Y, and Zr are not archived by nucleosynthesis in a normal SN. I also find that it is dependent on entropy whether elements from Ga to Rb are produced with those from Sr to Zr . It will be possible to determine of what entropy matter contributes to weak r-process stars from the observational abundances from Ga to Rb.

(Chapter 5)

In Chapter 5, I calculate normal SN and HN yields applying the latest progenitor models and neutrino reaction rates, and compare these yields with EMP stars. I also investigate production process of each nuclide in detail.

I find that $\nu$-processes can enhance the Mn abundance with $E_\nu = 3 \times 10^{53}$ ergs to fit the EMP stars in the normal SN model, while cannot enhance in the HN model. Even $E_\nu = 9 \times 10^{53}$ ergs is not enough to reproduce [Mn/Fe] in the HN models. In the HN models, neutrino flux becomes smaller because the radius becomes larger by the shockwave than in the normal SN models. Therefore, the effects of neutrino reactions becomes smaller in the HN models than in the normal SN models. The $\nu$-processes also enhance [Sc/Fe] in the normal SN model to some extent. However, the enhancement is not enough to fit EMP stars. As for Co, there is no enhancement with $\nu$-processes both in the SN and HN models.

(Chapter 6)

The quantity of K is generally underestimated by the models of supernovae. These days, various SN explosion models are being suggested. It is no wonder that new hydrodynamics never before seen in explosion simulations actually occurs. In this situation, it is not enough to calculate post-process nucleosynthesis using the hydrodynamic trajectories of SN simulations. In Chapter 6, I investigate favorable conditions for producing K by performing a wide parametric search using analytical hydrodynamic models.

I find that the case with proton-rich and high initial density of $\sim 10^9$ [g/cm$^3$] is the only one where [K/Fe] becomes high enough to reproduce EMP stars. My result means that proton-rich and high density of $10^9$ [g/cm$^3$] actually exists in SNe, or that the origin of K is other than SNe, i.e., stellar evolution.

(Chapter 7)

In my calculation, I adopt Thielemann's REACLIB, BASEL (Thielemann et al. 1987), and complement reaction rates which is not included in BASEL set with a new set of REACLIB (JINA REACLIB). The reason for my using BASEL is that our group's previous works has been using BASEL, and that I would like to maintain consistency with the previous results. However, it is true that we should make sure to what extent those results are changed with a different set of reaction rates.

In Chapter 7, I recalculate SN and HN yields applying a different set of nuclear reaction rates, and investigate whether uncertainty from reaction rates can change the abundances largely or not. I find that the reaction rates of $^{63}$Ga(p,$\gamma$)$^{64}$Ge by NON-SMOKER code (Rauscher and Thielemann 2000) is at least not good for reproducing the observations because it increases [Cu/Fe] and decreases [Zn/Fe]. I also find that [Co/Fe] increases with the rate of $^{59}$Cu(p,$\gamma$)$^{60}$Zn by NON-SMOKER, but the enhancement is not enough to reproduce the observation. Although some uncertainty from different sets of reaction rates does exist, HN models are still better to reproduce [Zn,Co/Fe] in EMP stars.

(Chapter 8)

In Chapter 8, discussion and conclusion are given. From all the results in this thesis, I conclude that HNe are still the most possible origin of EMP stars.