Supernova Neutrino Process and its Impact on the Galactic Chemical Evolution of the Light Elements

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In order to resolve the overproduction problem of $^{11}\text{B}$ in supernova explosions during Galactic chemical evolution, the dependence of the ejected masses of the light elements produced through the $\nu$-process in supernova explosions on supernova neutrino parameters is investigated and constraints on the supernova neutrinos are evaluated. Detailed nucleosynthesis in a supernova explosion model corresponding to SN 1987A is calculated by postprocessing. The ejected masses of $^{11}\text{B}$ and $^7\text{Li}$ depend strongly on the temperature of $\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$ and are roughly proportional to the total neutrino energy. The range of temperature of $\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$ appropriate for the amount of $^{11}\text{B}$ necessary for Galactic chemical evolution and the total neutrino energy deduced from the gravitational energy of a typical neutron star is between 4.8 MeV and 6.6 MeV. In the case of neutrino energy spectra with non-zero chemical potential, this range decreases by about 10%.

1. INTRODUCTION

Supernova explosions are one of the sites promoted for the production of light elements, Li, Be, and B, in Galactic chemical evolution (GCE), in addition to the Galactic Cosmic Rays (GCRs), AGB stars, and novae \cite{1}. They continuously provide $^7\text{Li}$ and $^{11}\text{B}$ through the interactions of nuclei such as $^4\text{He}$ and $^{12}\text{C}$ with neutrinos emitted from a proto-neutron star. This synthesis process is called the $\nu$-process \cite{2}.

Overproduction of $^{11}\text{B}$ in supernovae is one of the standing problems in supernova nucleosynthesis and the GCE (e.g., \cite{1}). Previous works have indicated that the supernova contribution of $^{11}\text{B}$ production evaluated from supernova nucleosynthesis models \cite{3} is too large by a factor of $2.5 \sim 5.6$ to reproduce the GCE of the light elements; the factor depends on models of the GCE \cite{1,4,5}. Most supernova nucleosynthesis calculations were carried out with a total neutrino energy of $3 \times 10^{53}$ ergs and temperature of 8 MeV for $\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$ and 4 MeV for $\nu_{\text{e}}$ and $\bar{\nu}_{\text{e}}$ \cite{2,3}. The supernova explosion mechanism has not been resolved, so the characteristics of the supernova neutrinos, especially their energy spectra, have not been fully determined \cite{6}. Therefore, the light element amounts
have not been obtained from a specific neutrino model precisely determined by supernova explosion models. Therefore, we systematically investigate the dependence of the light element synthesis in supernova explosions on the supernova neutrinos. Furthermore, on the basis of the evaluated dependence and the results of the GCE of the light elements, we restrict the characteristics of the supernova neutrinos, such as their energy spectra.

2. SUPERNOVA EXPLOSION AND SUPERNOVA NEUTRINO MODELS

The neutrino luminosity is assumed to decrease exponentially with a decay time of $\tau_\nu = 3$ s as in [2,3,7]. The luminosity is equally divided into each favor of neutrinos. The neutrino energy spectra are assumed to obey Fermi distribution with zero chemical potential. We set the temperature of $\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$, $T_\nu$, and the total neutrino energy $E_\nu$ as parameters. The ranges of $T_\nu$ and $E_\nu$ are $4.0 \text{ MeV} \leq T_\nu \leq 9.0 \text{ MeV}$ and $1.0 \times 10^{53} \text{ ergs} \leq E_\nu \leq 6.0 \times 10^{53} \text{ ergs}$. These ranges include the neutrino temperatures adopted in previous studies [3,7] and the total neutrino energy range ($2.4 \times 10^{53} \text{ ergs} \leq E_\nu \leq 3.5 \times 10^{53} \text{ ergs}$) deduced from the gravitational energy of a $\sim 1.4 \text{ M}_\odot$ neutron star [8]. For the temperatures of $\nu_e$ and $\bar{\nu}_e$, we choose 3.2 MeV and 5.0 MeV [7]. With these neutrino temperatures, a successful $r$-process abundance pattern, an appropriate third-to-second peak ratio, has been obtained using a neutrino-driven wind model [7].

The supernova explosion is pursued using a spherically symmetrical Lagrangian PPM code with 13 element $\alpha$-particle nuclear reaction network for energy generation [9]. The presupernova structure is adopted from a 16.2 $\text{M}_\odot$ star corresponding to SN 1987A [10]. The explosion energy is set to be $1 \times 10^{51} \text{ ergs}$ and the mass cut is set to be $1.6 \text{ M}_\odot$. Detailed nucleosynthesis of the supernova explosion is calculated by postprocessing. The nuclear reaction network consists of 291 species of nuclei [7]. We interpolate the logarithmic values of the cross sections listed in [11].

3. RESULTS AND DISCUSSION

Figure 1 shows mass fraction distribution of light elements in the supernova ejecta. The light elements are mainly produced in the He/C layer and smaller amounts are in the inner O rich layer. We have shown that $^7\text{Li}$ and $^{11}\text{B}$ are produced through the $\nu$-process reactions: $^4\text{He}(\nu, \nu'p)^3\text{H}$, $^4\text{He}(\nu, \nu'n)^3\text{He}$ and $\alpha$-captures in the He layer and $^{12}\text{C}(\nu, \nu'p)^{11}\text{B}$ in the inner O rich layer [7]. They are partly destroyed by the capture of $\alpha$-particles.

The ejected mass of $^{11}\text{B}$ as a function of the temperature of $\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$, $T_\nu$, is shown in Fig. 2. The dependence of $T_\nu$ on the ejected mass is stronger than linear. Since the ejected mass is roughly proportional to $E_\nu$ [7], the dependence of $T_\nu$ is stronger than the $E_\nu$ dependence. This is because the dependence on the cross sections of the $\nu$-process is larger than a linear dependence. The $^{11}\text{B}$ ejected mass in the case of $E_\nu = 3 \times 10^{53} \text{ ergs}$ and $T_\nu = 8 \text{ MeV}$ is consistent with that in [3] in spite of different values of $T_{\nu_e}$ and $T_{\bar{\nu}_e}$. Since $T_{\nu_e}$ and $T_{\bar{\nu}_e}$ are smaller than $T_\nu$ and neutral current interactions are important for the $\nu$-process of the light elements, the difference of $T_{\nu_e}$ and $T_{\bar{\nu}_e}$ from [3] scarcely affects the ejected masses of the light elements [7].

We will apply the above results to GCE of the light elements. Recent studies of the GCE have indicated that both GCRs and supernovae contribute to the B production: $^{10}\text{B}$ is produced through the GCRs and $^{11}\text{B}$ is produced through the GCRs and SNe. In
order to reproduce meteoritic $^{11}\text{B}/^{10}\text{B}$ ratio (=4.05) at solar metallicty, the supernova contribution of $^{11}\text{B}$ is important since the $^{11}\text{B}/^{10}\text{B}$ ratio of the GCRs is 2.5 \cite{1,12}. However, $^{11}\text{B}$ is overproduced in SN nucleosynthesis models \cite{3} compared to the evaluation of the GCE. Prior evaluations of the GCE of the light elements give the overproduction factor $f_\nu$ to be 0.18 \cite{4}, 0.28 \cite{5}, and 0.40 \cite{1}. Thus, we set the range of the factor appropriate for the $^{11}\text{B}$ amount in GCE to be $0.18 \leq f_\nu \leq 0.40$ as in \cite{7}. The corresponding range of the $^{11}\text{B}$ ejected mass is $3.3 \times 10^{-7} M_\odot \leq M(^{11}\text{B}) \leq 7.4 \times 10^{-7} M_\odot$ (two horizontal lines of Fig. 2). We also restrict $E_\nu$ to be the gravitational energy of a typical neutron star (see §2) \cite{8}. Finally, we obtain a shaded region satisfying both of the conditions of the $^{11}\text{B}$ mass and $E_\nu$ (see Fig. 2). The obtained range of $T_\nu$ is $4.8 \text{ MeV} \leq T_\nu \leq 6.6 \text{ MeV}$, which is smaller than 8 MeV in \cite{8}.

Our evaluation is carried out only in the case of SN 1987A, which corresponds to about 20 $M_\odot$ star in ZAMS stage. For $^{11}\text{B}$ production, the $\nu$-process reactions of $^4\text{He}$ in the He layer and $^{12}\text{C}$ in the O layer are important. It depends on the progenitor mass models which layer is more important. Fortunately, however, the neutrino temperature dependence does not change strongly in either $\nu$-process reactions. Thus, the appropriate range of the neutrino temperature would be a good approximation for supernovae with different progenitor masses. The investigation of the dependence of the $^{11}\text{B}$ production on the neutrinos spectra for different progenitor mass is a future subject.
We briefly discuss the effect of non-zero chemical potential of the supernova neutrinos. Detailed discussion is written in [13]. Recent studies on the neutrino transfer during supernova explosions have indicated that the energy spectra of the supernova neutrinos approximately obey “pinched” Fermi-Dirac distribution rather than that with zero chemical potential [6]. In such a case, it is expected that the ejected masses of the light elements change since reaction rates of the $\nu$-process change. Hartmann et al. [14] discussed the effect of non-zero chemical potential assuming that cross sections of the $\nu$-process are proportional to the square of the neutrino energy. We generalize their discussion: we approximate the cross sections of the $\nu$-process to the $\alpha$th power low of the neutrino energy. Then, we evaluate the effect on the reaction rates of the $\nu$-process. The reaction rates of the $\nu$-process can be written as a function of the degeneration factor $\eta_\nu = \mu_\nu/kT_\nu$ for given $\alpha$ and the neutrino temperature $T_\nu$, and increase by a factor of 1.4 $\sim$ 1.5 in the case of $\eta_\nu = 3$ and of the $\alpha$ range $4 \leq \alpha \leq 7$ compared to that with $\eta_\nu = 0$. Since the ejected masses of $^{11}$B and $^7$Li are roughly proportional to the $\nu$-process reaction rates, they increase with the same factor. In this effect, the neutrino temperature range appropriate for the $^{11}$B amount in GCE should decrease in the case of non-zero chemical potential. In the case of $\eta_\nu = 3$, this range decreases by 10% at most.

REFERENCES

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