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The neutrino-process and light element production

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Stars with mass more than about 10 $M_\odot$ are known to culminate their evolution as supernova explosion and a huge number of neutrinos should be emitted from the collapsing core. Previous studies for Type II supernovae have revealed that a fraction of the neutrinos can interact with stellar material and induce some characteristic nucleosynthesis of light elements (^{7}Li, ^{11}B, ^{19}F) and heavy elements (^{138}La, ^{180}Ta). We studied the neutrino-processed nucleosynthesis in Type Ib(c) supernovae whose progenitors have lost their H-rich (and He) envelopes before explosions. We found that Type Ib/c supernovae can produce ^{11}B as much as Type II supernovae.

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1. Introdunction

As a massive star collapses and explodes as a supernova, most of the gravitational energy released from the formation of a proto-neutron star is carried away by neutrinos. Although cross sections of neutrino-nucleus reactions are very small, a fraction of neutrinos can scatter off nuclei to the excited states, induce ejection of a neutron, proton, or α-particle, and leave the observational signature of the ν-process nucleosynthesis in the yields of some species including light elements such as Li and B. For example, ^{7}Li can be produced in He-rich envelopes via ^{4}He($\nu,\nu'p$)^{3}H(α,γ)^{7}Li reaction and ^{11}B in inner C-rich shells via ^{12}C($\nu,\nu'p$)^{11}B reaction. The stellar materials including newly-synthesized light elements are accelerated by strong shock wave, a part of which is destroyed by shock heating, and finally ejected into the interstellar matter to make a partial contribution to the next generations of star formation. Light element isotopes are also known to be produced from some other processes; ^{7}Li from big bang nucleosynthesis, ^{7}Li and ^{11}B from AGB stars and novae [1], and all stable isotopes of Li, Be, and B (LiBeB) from Galactic cosmic-ray (CR) nucleosynthesis [2].

Despite a great deal of efforts dedicated to investigate these processes, the origins of LiBeB are not fully understood and there remain some observational features which conflict with theoretical predictions. For instance, theoretical predictions for LiBeB production from Galactic CRs alone indicate quadratic relation between BeB abundances and metallicity, while observations clearly show linear relation. CNO CRs from superbubbles [3], supernovae or Wolf-Rayet stars [4], and Type Ic supernovae [5, 6] have been suggested to account for the observed linearity. However, the CR spallations cannot be the only source of boron isotopes because the CR spallations do not reproduce the high ^{11}B-to-^{10}B abundance ratio as observed in meteorites, and another source of ^{11}B such as supernova ν-process is necessary.

In order to solve these problems, it is required to accurately and quantitatively evaluate each contribution of the LiBeB production process. We report that energetic core-collapse Type Ib and Ic SNe (SNe Ib/c) could be a viable astrophysical site where light elements including boron isotopes are produced. Our nucleosynthesis model takes account of the ν-process in SNe Ib/c and also spallation reactions of accelerated SN ejecta interacting with interstellar/circumstellar matter, which do not conflict with the observed linear relation between BeB abundances and the metallicity in metal-deficient halo stars. The progenitor of an SN Ib(c) is a He(C/O) star and its H (and He) envelopes have been stripped during the stellar evolution. Although the explosion mechanism of SNe Ib/c has not been clarified, neutrinos should be one of the main carriers of the gravitational energy release from the collapsing core. The robustness of neutrino emission from a collapsing proto-neutron star which was evolved from a $\sim 40 M_\odot$ progenitor star was studied in numerical simulation [7]. Even in the case that the central core of such a star eventually turns into a black hole, a temporally formed proto-neutron star is shown to emit a huge amount of neutrinos before collapsing to the black hole. Even after the black hole formation, neutrinos are being emitted from accretion disk [8]. Therefore, a huge amount of neutrinos are emitted from the central region of an SN Ib/c so that the ν-process can operate in the exploding supernova material.

2. Calculations

2.1 Supernova models

Several explosion models including Type Ib, Ic, and II supernovae are considered. Their supernova types, masses at main sequence phase ($M_{\rm ms}$) and just before explosion ($M_{\rm sn}$), explosion energies ($E_{\rm ex}$), and corresponding supernovae are listed in Table 1. The explosion energy is released at the center of the progenitor star as thermal energy. Resulting shock wave accelerates the stellar materials and explodes the progenitor as a supernova. Time evolutions of physical quantities in the progenitor are calculated with 1D hydrodynamic code which takes account of the effects of special relativity. We solve the special relativistic hydrodynamic equations in Lagrangian coordinates with an ideal equation of state involving gas and radiation pressure. Adiabatic indices are treated as functions of pressure and gas density. Details on the numerical method are described in [6].

Type	$M_{\rm ms}$ [$M_\odot$]	$M_{\rm sn}$ [$M_\odot$]	$E_{\rm ex}$ [10^{51}ergs]	SN	Reference
Ib	15	4	1	1993J	[9]
Ic	15	3	1	1994I	[10]
Ic	25	5	4	2002ap	[11]
Ic	40	15	30	1998bw	[12]
II	16	16	1	1987A	[13]

Table 1: Parameters of stellar models.

2.2 The neutrino process

Explosive nucleosynthesis in these supernovae is calculated as a post process. We use a nuclear reaction network consisting of 291 species of nuclei and taking account of the ν-process [14]. Neutrinos are emitted from a collapsing proto-neutron star [7] and/or the innermost region just above a black hole [8]. Neutrino properties, particularly in SNe Ib/c, are still uncertain. We therefore use a supernova-neutrino model [14] that the neutrino luminosity decreases exponentially with a time scale of 3 s and that the neutrino temperature of each species does not change with time. The total energy carried out by neutrinos is assumed to be 3×10^{53} ergs.

Two different models for neutrino temperatures are supposed here. In the first model, the temperature of the other flavors, $\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$, takes an identical value of $T_{\nu_{\mu,\tau}}$ = 6 MeV. This temperature model is referred to as the "standard" $T_{\nu_{\mu,\tau}}$ model. The light element synthesis in an $\sim 20 M_\odot$ Type II supernova with the standard temperature model well reproduces the supernova contribution of the ^{11}B production during Galactic chemical evolution [14]. The third peak of r-process elements is also reproduced well in neutrino-driven wind models using these temperatures. In the second model, the temperature of $\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$ is set to be $T_{\nu_{\mu,\tau}}$ = 8 MeV. This temperature model is referred to as the "high" $T_{\nu_{\mu,\tau}}$ model. A newly forming proto-neutron star in an SN Ib/c should be more compact than that of an SN II. Therefore, the neutrino temperature of the collapsing proto-neutron star is reasonably assumed to be larger than that of SN II [7]. For both models the temperatures of ν_e and $\bar{\nu}_e$ are set to be T_{ν_e} = 3.2 MeV and $T_{\bar{\nu}_e}$ = 5 MeV.

Our calculations show that the light elements such as ^{11}B, ^{11}C, ^{10}B, ^{7}Li, and ^{7}Be are mainly produced in the O/Ne layer. The mass fractions of some light elements are also large in the innermost regions where α-rich freeze out is achieved and complete Si-burning occurs. There is no qualitative difference in the light element distributions between the standard and high $T_{\nu_{\mu,\tau}}$ models except that the mass fraction of each species in the high $T_{\nu_{\mu,\tau}}$ model at a given mass coordinate is roughly twice as large as the one in the standard $T_{\nu_{\mu,\tau}}$ model.

In SN 1998bw model, several light elements produced from ^{12}C-neutrino reactions are exposed to explosive nucleosynthesis when the shock arrives. ^{11}B, ^{11}C, and ^{10}B are destroyed subsequently by collisions with protons and α-particles. ^{7}Li and ^{7}Be are photodisintegrated to ^{3}H and ^{3}He, respectively. After the shock passage, the exploding materials are still being irradiated by neutrinos so that light elements are produced through the ν-process again. This is the reason why larger mass fractions of ^{11}B, ^{7}Li, and ^{7}Be in the outermost region ($M_r \gtrsim 13.5 M_\odot$) survive, being avoided from explosive nucleosynthesis (see Figure 1 in [15]).

In the innermost region, light elements are produced after the termination of the nuclear statistical equilibrium. The main product in α-rich freeze out is ^{4}He. About 20 % of ^{4}He by mass fraction is also produced in complete Si-burning. The ν-process of ^{4}He produces ^{3}H and ^{3}He in cooling materials, followed by α-capture reactions to produce ^{7}Li and ^{7}Be. Furthermore, ^{11}B and ^{11}C are produced by α-captures, and ^{10}B by ^{7}Be$(\alpha, p)^{10}$B reaction.

Both cases of $T_{\nu_{\mu,\tau}}$ synthesize significant amount of ^{11}B of order $10^{-7} M_\odot$ in SN 1998 model. The yield of ^{7}Li is of the order of $10^{-9} - 10^{-8} M_\odot$. This yield is much smaller than that produced in SNe II. Most of ^{7}Li in SNe II is produced in the He-rich layer. In contrast, almost all H and He layers of SN Ic progenitors have been stripped via stellar wind and/or binary effect before explosion. The yields of ^{6}Li, ^{9}Be, and ^{10}B are of the order of or below $10^{-9} M_\odot$ due to smaller branching ratios of neutrino-^{12}C reactions [14].

2.3 Spallation reactions around SNe Ic

As discussed in [5, 6, 16], the progenitors of SNe Ic are so compact that a small fraction of ejecta can be accelerated nearly to the speed of light. Thus accelerated surface layers of SNe Ic, which are composed of C and O, interact with interstellar matter or circumstellar matter, and produce the light element isotopes via spallation reactions of CNO with protons or α-particles.

Calculated results show that the mass of ^{11}B produced in SN 1998bw model via spallation reactions is $1.3 \times 10^{-6} M_\odot$, which is larger than that synthesized via the ν-process even in the high $T_{\nu_{\mu,\tau}}$ model. The resultant isotopic ratio of ^{11}B/^{10}B (~ 3) from spallation reactions in this model is predominantly determined by the ratio of cross sections of the reaction p,α + O $\rightarrow ^{10}$B to that of p,α + O $\rightarrow ^{11}$B. The yields of the other light elements are listed in [15].

3. Summary

We have estimated the production of light elements including boron isotopes via the ν-process in SNe Ib, Ic, and II and found that SNe Ib/c can be viable ^{11}B producers as well as SNe II. It is reasonable to assume that the radii of neutrino spheres in SNe Ib/c are smaller than those in SNe II because of the compactness of SN Ib/c progenitors, leading to the higher temperatures of emitted neutrinos and anti-neutrinos. Higher $T_{\nu_{\mu\tau}}$ results in higher LiBeB yields through neutral current reactions in the ν-process, which raises the significance of potential roles of SNe Ib/c in the light element production. For SN 1998bw model, the resulting number abundance ratio of B isotopes from both the ν-process and spallations turns out to be $^{11}\mathrm{B}/^{10}\mathrm{B} = 3.7$ (for standard $T_{\nu_{\mu,\tau}}$) -4.3 (for high $T_{\nu_{\mu,\tau}}$). These $^{11}\mathrm{B}/^{10}\mathrm{B}$ ratios seem to agree well with solar values. However, the frequency of SNe Ic, in particular with high explosion energy as assumed here, is quite low and borons in meteorites should be dominated by those originated from SNe II and Galactic CRs. In fact, according to [17] the estimated frequency ratio of SNe Ib/c to SNe II in local spiral galaxies falls in the range of 0.41 to 0.058 and the neutrino-processed $^{11}\mathrm{B}$ yield from each SN Ib/c is at most comparable to the contribution from SN II (averaged value per supernova $\sim 8.3 \times 10^{-7}\ M_{\odot}$ from [18]; see also the case of SN 1987A model with similar parameter set in [14]). These facts lead to a conclusion that SNe Ib/c do not dominate the bulk of present $^{11}\mathrm{B}$ in the Galaxy. Contribution from SNe Ib/c to the light element production in metal-deficient stars might be outstanding because an SN Ib/c progenitor is surrounded by its wind material and the light elements produced in the explosion are likely to be inherited directly by next generations of stars, which would show high BeB abundances overlying small amounts of BeB from the other processes. An extraordinary Be-rich halo star HD106038 [19] could be a candidate star exhibiting such a process.

References

[1] Cameron, A. G. W. 1955, ApJ, 121, 144

[2] Rollinde, E., Maurin, D., Vangioni, E., Olive, K. A., & Inoue, S. 2008, ApJ, 673, 676

[3] Higdon, J. C., Lingenfelter, R. E., & Ramaty, R. 1998, ApJL, 509, L33

[4] Yoshii, Y., Kajino, T., & Ryan, S. G. 1997, ApJ, 485, 605

[5] Fields, B. D., Daigne, F., Cassé, M., & Vangioni-Flam, E. 2002, ApJ, 581, 389

[6] Nakamura, K., & Shigeyama, T. 2004, ApJ, 610, 888

[7] Sumiyoshi, K., Yamada, S., & Suzuki, H. 2007, ApJ, 667, 382

[8] Surman, R., & McLaughlin, G. C. 2005, ApJ, 618, 397

[9] Shigeyama, T., Suzuki, T., Kumagai, S., Nomoto, K., Saio, H., & Yamaoka, H. 1994, ApJ, 420, 341

[10] Iwamoto, K., Nomoto, K., Höflich, P., Yamaoka, H., Kumagai, S., & Shigeyama, T. 1994, ApJL, 437, L115

[11] Mazzali, P. A. et al. 2002, ApJL, 572, L61

[12] Nakamura, T., Mazzali, P. A., Nomoto, K., & Iwamoto, K. 2001, ApJ, 550, 991

[13] Thielemann, F.-K., Hashimoto, M.-A., & Nomoto, K. 1990, ApJ, 349, 222

[14] Yoshida, T., Suzuki, T., Chiba, S.,Kajino, T., Yokomakura, H., Kimura, K., Takamura, A., & Hartmann, D. H. 2008, ApJ, 686, 448

[15] Nakamura, K., Yoshida, T., Shigeyama, T., & Kajino, T. 2010, ApJL, 718, L137

[16] Nakamura, K., Inoue, S., Wanajo, S., & Shigeyama, T. 2006, ApJL, 643, L115

[17] Cappellaro, E., Evans, R., & Turatto, M. 1999, A&A, 351, 459

[18] Rauscher, T., Heger, A., Hoffman, R. D., & Woosley, S. E. 2002, ApJ, 576, 323

[19] Smiljanic, R., Pasquini, L., Primas, F., Mazzali, P. A., Galli, D., & Valle, G. 2008, MNRAS, 385, L93