EXPLOSIVE NUCLEOSYNTHESIS IN AXISYMMETRICALLY DEFORMED TYPE II supernovae

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ABSTRACT

Explosive nucleosynthesis under the axisymmetric explosion in Type II supernovae has been examined by means of two-dimensional hydrodynamic calculations. We have compared the results with the observations of SN 1987A. Our chief findings are as follows: (1) \(^{44}\)Ti is synthesized in a sufficient amount to explain the tail of the bolometric light curve of SN 1987A. We think this is because the alpha-rich freezeout takes place more actively under the axisymmetric explosion. (2) \(^{57}\)Ni and \(^{56}\)Ni tend to be overproduced compared with the observations. However, this tendency relies strongly on the model of the progenitor.

We have also compared the abundance of each element in the mass number range \(A = 16-73\) with the solar values. We have found three outstanding features. (1) For the nuclei in the range \(A = 16-40\), their abundances are insensitive to the initial form of the shock wave. This insensitivity is favored since the spherical calculations thus far can explain the solar system abundances in this mass range. (2) There is an enhancement around \(A = 45\) in the axisymmetric explosion that compares fairly well with that of the spherical explosion. In particular, \(^{44}\)Ca, which is underproduced in the present spherical calculations, is enhanced significantly. (3) In addition, there is an enhancement around \(A = 65\). This feature relies on the form not of the mass cut but of the initial shock wave. This enhancement may cause the problem of overproduction in this mass range, although this effect would be relatively small since Type I supernovae are chiefly responsible for this mass number range.

Subject headings: nuclear reactions, nucleosynthesis, abundances — supernovae: general — supernovae: individual (SN 1987A)

1. INTRODUCTION

Supernovae play an important role in ejecting heavy elements produced in massive stars (e.g., Woosley & Weaver 1995 and references therein). It is important to determine the composition of ejected gas as a function of stellar mass since it is a basic factor in the chemical evolution of galaxies. In this paper, we discuss Type II supernovae, which are considered to be the death of a massive star whose mass exceeds 8 times the solar mass (\(M_\odot\)) (e.g., Hashimoto 1995).

The mechanism of Type II supernovae has been understood as follows (e.g., Bethe 1990): When the mass of the iron core of the progenitor exceeds the Chandrasekhar mass, the star begins to collapse. The collapse continues until the central density of the collapsing core reaches about 1.5–2 times the nuclear matter density (\(\rho = 2.7 \times 10^{14} \text{ g cm}^{-3}\)), beyond which matter becomes too stiff to be compressed further. A shock wave then forms and propagates outward. At first, the shock wave is not so strong and stalls in the Fe core. However, by the neutrino heating, the shock wave is revived, begins to propagate outward again, and finally produces the supernova explosion. This phenomenon is known as delayed explosion, which is the most promising theory for the mechanism of Type II supernova explosions.

When the shock wave passes Si-rich and O-rich layers, the temperature becomes high enough to cause many nuclear reactions. This phenomenon is known as explosive nucleosynthesis in Type II supernovae. Many calculations have so far been performed on explosive nucleosynthesis in supernovae (e.g., Woosley & Weaver 1986; Hashimoto, Nomoto, & Shigeyama 1989; Thielemann, Hashimoto, & Nomoto 1990; Hashimoto 1995; Woosley & Weaver 1995).

SN 1987A in the Large Magellanic Cloud has provided the most precise data to test the validity of such calculations. For example, the bolometric luminosity began to increase a few weeks after the explosion (Catchpole et al. 1987; Hamuy et al. 1987), which is attributed to the decay of the radioactive nucleus \(^{56}\)Ni. \(^{56}\)Ni is synthesized during the explosion, and the mass is estimated to be 0.07–0.076 \(M_\odot\) on the basis of the luminosity study (Shigeyama, Nomoto, & Hashimoto 1988; Woosley & Weaver 1988). \(^{57}\)Ni and \(^{44}\)Ti are also thought to be important nuclei in explaining the bolometric light curve. Since the half-lives of these nuclei are longer than that of \(^{56}\)Co, their decays are thought to be responsible for the tail of the light curve. In fact, the observed bolometric light curve's decline rate is slowed down since \(\sim 900\) days after explosion (Suntzeff et al. 1991). The ratio of \(^{57}\)Ni to \(^{56}\)Ni is estimated from the X-ray light curve to be \(1.5 \pm 0.5\) times the solar \(^{56}\)Fe/\(^{56}\)Fe ratio (Kurfess et al. 1992). The \(^{44}\)Ti/\(^{56}\)Ni ratio is also estimated and must be larger than 1.8 times the solar \(^{44}\)Ca/\(^{56}\)Fe ratio if the contribution from the pulsar is negligible (Kumagai et al. 1993). There is another important nucleus whose amount is estimated by the observation of SN 1987A. That nucleus is \(^{58}\)Ni, which is produced at the innermost region of the ejecta and gives very important information about the mass cut. From the spectroscopic observation of SN 1987A, the ratio \(\left(\frac{^{58}\text{Ni}}{^{56}\text{Ni}}\right) = \frac{\left[X(^{58}\text{Ni})/X(^{56}\text{Ni})\right]}{\left[X(^{58}\text{Ni})/X(^{56}\text{Fe})\right]_\odot} = 0.7-1.0\) (Rank et al. 1988).
Numerical calculations can reproduce the amount of $^{56}\text{Ni}$, the ratio of $^{57}\text{Ni}$ to $^{56}\text{Ni}$, and the ratio of $^{58}\text{Ni}$ to $^{56}\text{Ni}$ (Hashimoto et al. 1989). However, the ratio of $^{44}\text{Ti}$ to $^{56}\text{Ni}$ has never been reproduced. It is reported that $^{44}\text{Ti}$ cannot be produced in a sufficient amount to explain the tail of the light curve in a wide parameter range (Woosley & Hoffman 1991). Another candidate that can explain the light curve is a pulsar. If the energy supply by the pulsar dominates, the light curve will be flat. However, such flatness has not been observed yet. The effect of long recombination and cooling timescales of the remnant is also considered for the explanation (Fransson & Kozma 1993). However, Fransson & Kozma admit that their results depend on the model of the progenitor and that more careful calculation must be needed for the quantitative estimates. In the present circumstances, the explanation of the bolometric light curve is still open to argument.

Another touchstone of the numerical simulations is the solar system abundances. The appropriate combination of the contribution from Type I and Type II supernovae can reproduce the solar system abundance ratios within a factor of 2 for typical species (Hashimoto 1995). However, there are some problems. For example, $^{35}\text{Cl}$, $^{38}\text{K}$, and $^{44}\text{Ca}$ are synthesized to about only one-tenth of the solar value. On the other hand, $^{56}\text{Ni}$ is produced to about 3 times the solar value.

Are there any effects that can solve the problems mentioned above, that is, the $^{44}\text{Ti}$ problem in SN 1987A and the reproduction of the solar system abundance? We suggest the effects of asymmetric (in particular, axisymmetric) explosion will change the present circumstances. All calculations regarding nucleosynthesis have been done on the assumption that the explosion is spherically symmetric. However, there are some reasons why we should take account of the asymmetry in supernova explosion. Among them is a well-known fact that most massive stars are rapid rotators (Tassoul 1978). Since stars are in reality rotating, the effect of rotation should be investigated in numerical simulations of a collapse-driven supernova. Thus far, several simulations have been done by a few groups in order to study rotating core collapse (Müller, Rybicka, & Hillebrandt 1980; Tohline, Schomberg, & Boss 1980; Müller & Hillebrandt 1981; Bodenheimer & Woosley 1983; Symbalisty 1984; Mönchmeyer & Müller 1989; Finn & Evans 1990; Yamada & Sato 1994). As a result, some numerical simulations of a collapse-driven supernova suggest the possibility of axisymmetric explosion if the effects of a stellar magnetic field and/or stellar rotation are taken into consideration. There is also the possibility that the axisymmetrically modified neutrino radiation from a rotating proto-neutron star causes asymmetric explosion (Shimizu, Yamada, & Sato 1994). We note these effects mentioned above tend to cause axisymmetric explosion. Furthermore, many observations of SN 1987A suggest the asymmetry of the explosion. The clearest are the speckle images of the expanding envelope with high angular resolution (Papaliolis et al. 1989), where an oblate shape with an axis ratio of $\sim 1.2-1.5$ was shown. Similar results were also obtained from the measurement of the linear polarization of the scattered light from the envelope (Cropper et al. 1988). If the envelope is spherically symmetric, there is no net linear polarization induced by scattering. Assuming again that the shape of the scattering surface is an oblate or prolate spheroid, one finds that the observed linear polarization corresponds to an axis ratio of $\sim 1.2$.

Because of the reason mentioned above, it is important to investigate the effect of axisymmetric explosion on explosive nucleosynthesis. In the present paper, we calculate the explosive nucleosynthesis for a 20 $\text{M}_{\odot}$ star under the axisymmetric explosion and investigate if the difficulties mentioned above are improved by its effect.

We show our method of calculation for the explosive nucleosynthesis in § 2. Results are presented in § 3. Summary and discussion are given in § 4.

2. MODEL AND CALCULATIONS

2.1. Hydrodynamics

We performed two-dimensional hydrodynamic calculations. The calculated region corresponds to a quarter part of the meridian plane under the assumption of axisymmetry and equatorial symmetry. The number of meshes is 300 x 10 (300 in the radial direction, and 10 in the angular direction). The innermost and outermost radii are set to be 10$^8$ cm and 2 x 10$^{10}$ cm, respectively. We use the Roe method for the calculation (Roe 1981; Yamada & Sato 1994). The basic equations are as follows:

$$\begin{align*}
\dot{\rho} &= -\frac{1}{r^2} \frac{\partial}{\partial r} (\rho u r^2) - \frac{1}{r \sin \theta} \frac{\partial}{\partial \theta} (\rho u \sin \theta), \\
\dot{\rho} \rho u &= -\frac{1}{r^2} \frac{\partial}{\partial r} (\rho u^2 r^2) - \frac{1}{r \sin \theta} \frac{\partial}{\partial \theta} (\rho u u \sin \theta) \\
&\quad - \frac{\partial}{\partial r} [\rho \rho u u] + \frac{\rho u^2}{r}, \\
\dot{\rho} \rho u &= -\frac{1}{r^2} \frac{\partial}{\partial r} [(E + P) u r^2] - \frac{1}{r \sin \theta} \frac{\partial}{\partial \theta} [(E + P) u \sin \theta],
\end{align*}$$

where $\rho$, $P$, and $E$ are the mass density, pressure, total energy density per unit volume and $u$, and $u$ are velocities of a fluid in $r$ and $\theta$-directions, respectively. The first equation is the continuity equation, the second and third are the Euler equations, and the fourth is the equation of the energy conservation. We use the equation of state,

$$P = \frac{1}{3} a T^4 + \frac{b}{A_m} T,$$

where $a$, $A_m$, and $m_a$ are the radiation constant, Boltzmann constant, mean atomic weight, and atomic mass unit, respectively.

In this paper, we assume the system is adiabatic after the passage of the shock wave because the entropy produced during the explosive nucleosynthesis is much smaller than that generated by the shock wave. As a result, the entropy per nucleon is conserved.

2.2. Postprocessing

In order to calculate the change of the chemical composition of the star, we use a test particle approximation. Particles numbering 10($r \times 10(\theta)$ and 40($r \times 10(\theta)$) are
scattered in the Si-rich and O-rich layers, respectively, with the increasing interval in the radial directions and the same interval in the angular ones in each layer. This is because explosive nucleosynthesis can occur mainly in the inner region where the temperature is sufficiently high to cause nuclear reactions. On the other hand, little change occurs in the outer region, and we do not need to scatter many particles there.

We preserve the time evolution of density and temperature along each trajectory of test particles. It is assumed that test particles are at rest at first and move with the local velocity at their positions after the passage of a shock wave. Thus, we can calculate each particle's path by integrating $\frac{dx}{dt} = v(t, x)$, where the local velocity $v(t, x)$ is given from the hydrodynamic calculations mentioned above. The density and the temperature of a test particle at each time are determined by interpolation of the Eulerian mesh the particle is in at the moment. Nucleosynthesis calculations are done separately for each trajectory of test particles using a nuclear reaction network explained below (after the hydrodynamic simulations). In calculating the total yields of elements, we assume that each test particle has its own mass, which is determined from the initial distribution of the test particles so that their sum becomes the mass of the Si-rich and O-rich layers, and we also assume that nucleosynthesis occurs uniformly in each mass element. In this way, the total chemical composition can be calculated by summing the final chemical composition of each mass element weighted by its mass.

It is noted that the above assumption is valid when the typical size of a test particle calculated from its mass and density is smaller than the temperature scale height at its position. It is also necessary that the shear of the flow is not very large in the mass element. In this calculation we assumed that the initial velocity of the matter is radial behind the shock wave (see § 2.4) and the timescale of the explosive nucleosynthesis is small (~1 s); we think this assumption is reasonable. Regardless, this is only the first step in the estimation of chemical abundances in an axisymmetric supernova explosion, and improvement in resolution of mesh and test particles is now underway.

**2.3. Nuclear Reaction Network**

We have calculated the explosive nucleosynthesis using the time evolution of $(\rho, T)$ discussed in § 2.2. Since the system is not in chemical equilibrium, we must calculate the change of the chemical composition with the use of the nuclear reaction network. It contains 242 species (see Fig. 1; Hashimoto et al. 1989). The basic equations for the abundance changes are

$$\dot{y}_i = \alpha_{ijkl} y_j y_k y_l + \beta_{ijkl} y_j y_k + \gamma_{ij} y_j ,$$

where $n_i$ is the number density of ith nucleus $i$ and $N_A$ is Avogadro's number. Reaction rates are defined by $\alpha_{ijkl}, \beta_{ijkl}$, and $\gamma_{ij}$, which have dimensions of $s^{-1}$. The first term of the right-hand side represents three-body reactions such as the triple-alpha process, the second is for two-body reactions, and the third is for one-body reactions such as the photodisintegration or $\beta$-decay. We integrate this system of coupled differential equations by an implicit method (Hashimoto, Hanawa, & Sugimoto 1983). To construct a large network relevant for the calculation of the explosive nucleosynthesis, data of reaction rates were used from various sources (e.g., Hashimoto & Arai 1985).

![Table of nuclei included in our nuclear reaction network: 242 species are included. The gray-colored nuclei denote stable nuclei.](image)
2.4. Initial Conditions

The progenitor of SN 1987A, Sk _69°202, is thought to have had a mass of _20 M_☉ in the main-sequence stage (Shigeyama et al. 1988; Woosley & Weaver 1988) and had a _6 M_☉ helium core (Woosley 1988). In the present paper, the presupernova model that is obtained from the evolution of a helium core of 6 M_☉ (Nomoto & Hashimoto 1988) is used for the initial density and composition. Table 1 shows the radii of the Fe/Si, Si/O, and O/He interfaces in this model.

We will explain the form of the initial shock wave. Since there is still uncertainty as to the mechanism of Type II supernovae, precise explosive nucleosynthesis calculations have not been performed from the beginning of core collapse. Instead, explosion energy is deposited artificially at the innermost boundary (e.g., Hashimoto 1995). Instead, explosion energy is deposited artificially at the innermost boundary (e.g., Hashimoto 1995). There is another method used by Woosley: “the method of the piston” (see Woosley & Weaver 1995). However, both methods are only approximations, and determining the initial condition has been a problem in the explanation of explosive nucleosynthesis. In this paper, the method of energy deposition is taken and the explosion energy of 1.0 _ 10^51 ergs is injected to the region from 1.0 _ 10^8 to 1.5 _ 10^8 cm (that is, at the Fe/Si interface).

As for the axisymmetric explosion, the initial velocity of matter behind the shock wave is assumed to be radial and proportional to r _ [(1 + x cos 2θ)/(1 + x)], where r, θ, and x are radius, the zenith angle, and the free parameter that determines the degree of the axisymmetric explosion, respectively. Since the ratio of the velocity in the polar region to that in the equatorial region is 1: [(1 _ x)/(1 + x)], more extreme jetlike shock waves are obtained as x gets larger. In the present study, we take x = 0 for the spherical explosion and x = _2, _3, and _3 (these values mean that the ratios of the velocity are 2:1, 4:1, and 8:1, respectively) for the axisymmetric ones (see Table 2). We assumed that the distribution of thermal energy is same as the velocity distribution and that total thermal energy is equal to total kinetic energy.

We note that the form of the initial shock wave cannot be known directly from either observation or theory. As a result, the value of x cannot be known a priori. However, it is reported that there is a possibility for a shock wave to be jetlike if the proper angular momentum of the progenitor is assumed (Yamada & Sato 1994). Because of this, we think our formulation of the initial shock wave is not so unreasonable. At least, there is a possibility for the shock wave to be axisymmetric as we have assumed. Moreover, the desired value of x in SN 1987A would be in this range, as shown in § 3.

3. RESULTS

3.1. Reproduction of Observational Data of SN 1987A

3.1.1. Mass Cut

In Type II supernovae, there is boundary that separates ejecta and the central compact object. This boundary is known as the mass cut. Strictly speaking, the position of the mass cut should be determined by hydrodynamic calculation including gravity; that is, the matter that has positive total energy (sum of the kinetic, thermal, and gravitational energy) can escape, and the matter that has negative energy falls back into central compact object. However, it is very difficult to determine the position of the mass cut hydrodynamically since it is sensitive not only to the explosion mechanism but also to the presupernova structure, stellar mass, and metallicity. In fact, it is reported that total amount of isotopically 56Ni cannot be reproduced by the piston method, which determines the mass cut hydrodynamically (Woosley & Weaver 1995).

There is another way to determine the position of the mass cut. Among the many observational data of SN 1987A, the total amount of 56Ni in the ejecta is one of the most reliable. For that reason, the position of the mass cut can be determined so as to contain _0.07 M_☉ 56Ni in the ejecta (Hashimoto 1995). We took the same approach in this paper. However, this method is simple only for spherical calculations. We must extend this method for multidimensional calculations as follows: we assume that the larger total energy (internal energy plus kinetic energy) a test particle has, the more favorably it is ejected (Yamada, Shimizu, & Sato 1993). We first calculate the total energy of each test particle at the final stage of our calculations (~ 10 s) and then add up the mass of isotopically 56Ni in descending order of the total energy until the summed mass reaches 0.07 M_☉. The rest of isotopically 56Ni is assumed to fall back into the central compact object even if it has a positive energy at that time. We show the position of the mass cut for each model in Figures 2 and 3. We note that the filled circles, which show test particles that will be ejected, are plotted for their initial positions. In this way, the position of the mass cut is easily determined. The tendency for more matter around the polar axis to be ejected is consistent with the initial form of the shock wave. We refer to this mass cut as A7. To see the dependence of our analysis on the position of the mass cut, we take another mass cut for comparison. This mass cut is set to be spherical and determined so as to contain 0.07 M_☉ 56Ni in the ejecta. We refer to this mass cut as S7.

3.1.2. Comparison with SN 1987A

We show the ratios _44Ti/56Ni_, _57Ni/56Ni_, and _58Ni/56Ni_. These quanta are defined as below:

_44Ti/56Ni_ ≡ [X(44Ti)/X(56Ni)]/[X(44Ca)/X(56Fe)]_☉ ,
_57Ni/56Ni_ ≡ [X(57Ni)/X(56Ni)]/[X(55Fe)/X(56Fe)]_☉ ,
_58Ni/56Ni_ ≡ [X(58Ni)/X(56Ni)]/[X(58Ni)/X(56Fe)]_☉ ,

TABLE 1

| Interface | Radius (cm) | Radius (M_☉) |
|-----------|-------------|--------------|
| Fe/Si ..... | 1.5 _ 10^8 | 1.4          |
| Si/O .....  | 3.0 _ 10^8 | 1.7          |
| O/He .....  | 6.3 _ 10^9 | 3.8          |

TABLE 2

| PARAMETER | S1 | A1 | A2 | A3 |
|-----------|----|----|----|----|
| x .......... | 0  | 1/3| 3/5| 7/9|
| V_θ/V_φ* .... | 1:1 | 2:1| 4:1| 8:1|

* The ratio of the velocity in the polar region (θ = 0°) to that in the equatorial region (θ = 90°).
where $X$ denotes mass fraction. We must first note the following. It is reported that this 6 $M_\odot$ model is neutron-rich and that the value of $Y_e$ for $M > 1.607$ $M_\odot$ (=0.494) is artificially changed to that of $M > 1.637$ $M_\odot$ (=0.499) to suppress the overproduction of neutron-rich nuclei (Hashimoto 1995). This means that the range of convective mixing in the presupernova model is artificially changed. Anyway, at first, we also modify the 6 $M_\odot$ model in the same way. The result is summarized in Table 3 (case A). We can see clearly that more $^{44}$Ti is produced as the degree of the axisymmetric explosion gets larger. It is also noted that a sufficient amount of $^{44}$Ti is produced in the axisymmetric explosion to explain the tail of the bolometric light curve of SN 1987A. Since $^{44}$Ti is synthesized through the alpha-rich freezeout, high entropy is needed for the synthesis of this nucleus. Since the matter becomes radiation dominated after the passage of the shock wave, the entropy per baryon can be written approximately as below:

$$S_\gamma = \frac{16\sigma}{3k_Bc} \frac{m_w}{\rho N_A} T^3,$$

where $\sigma$, $k_B$, $c$, $m_w$, $T$, $\rho$, and $N_A$ are Stefan-Boltzmann constant, Boltzmann constant, speed of light, atomic mass unit, temperature, density, and Avogadro constant, respectively. The entropy is normalized in units of $k_B$. We show distribu-
TABLE 3

| Model | Form of the Mass Cut | $M_\odot$ | $^{44}\text{Ti}/^{56}\text{Ni}^*$ | $^{57}\text{Ni}/^{56}\text{Ni}^b$ | $^{58}\text{Ni}/^{56}\text{Ni}^c$ |
|-------|----------------------|----------|-----------------|----------------|-----------------|
| S1    | S7                   | 1.59     | 0.74            | 1.5           | 7.1             |
| A1    | S7                   | 1.57     | 1.4             | 2.5           | 7.5             |
| A2    | S7                   | 1.56     | 2.2             | 2.8           | 6.6             |
| A3    | S7                   | 1.55     | 4.3             | 2.8           | 6.6             |
| S1    | A7                   | 1.59     | 0.74            | 1.5           | 2.0             |
| A1    | A7                   | 1.57     | 2.4             | 3.2           | 9.8             |
| A2    | A7                   | 1.61     | 3.7             | 3.3           | 8.8             |
| A3    | A7                   | 1.68     | 6.0             | 3.2           | 7.1             |

Case B:

| Model | Form of the Mass Cut | $M_\odot$ | $^{44}\text{Ti}/^{56}\text{Ni}^*$ | $^{57}\text{Ni}/^{56}\text{Ni}^b$ | $^{58}\text{Ni}/^{56}\text{Ni}^c$ |
|-------|----------------------|----------|-----------------|----------------|-----------------|
| S1    | S7                   | 1.59     | 0.76            | 1.5           | 1.5             |
| A1    | S7                   | 1.59     | 1.4             | 1.7           | 1.9             |
| A2    | S7                   | 1.58     | 1.9             | 1.7           | 1.8             |
| A3    | S7                   | 1.57     | 4.0             | 1.8           | 1.6             |
| S1    | A7                   | 1.59     | 0.76            | 1.5           | 1.5             |
| A1    | A7                   | 1.63     | 2.2             | 1.8           | 1.5             |
| A2    | A7                   | 1.75     | 3.5             | 1.8           | 1.3             |
| A3    | A7                   | 1.80     | 6.0             | 1.8           | 0.97            |

Note.—"Mass of NS" means the baryon mass of the central compact object (neutron star).

$^a$ $^{44}\text{Ti}/^{56}\text{Ni} = [X(44\text{Ti})/X(56\text{Ni})]/[X(44\text{Ca})/X(56\text{Fe})]_\odot$.

$^b$ $^{57}\text{Ni}/^{56}\text{Ni} = [X(57\text{Ni})/X(56\text{Ni})]/[X(57\text{Fe})/X(56\text{Fe})]_\odot$.

$^c$ $^{58}\text{Ni}/^{56}\text{Ni} = [X(58\text{Ni})/X(56\text{Ni})]/[X(58\text{Ni})/X(56\text{Fe})]_\odot$.

...tions of the entropy per nucleon for S1 and A3 models in Figure 4. We note that the contours are drawn for the initial positions of the test particles. It is clear from Figure 4 that higher entropy is achieved in the polar region for the axisymmetric explosion. We will explain this tendency. The relation between energy density and temperature behind the shock wave can be written approximately as below:

$$E = aT^4,$$

where $a$ is radiation constant and $E$ is in units of ergs cm$^{-3}$. As more energy is deposited initially in the polar region, a higher temperature is achieved. As a result, higher entropy is achieved in the polar region than the equatorial region. We show in Figure 5 the contours of $^{44}\text{Ti}$ and $^4\text{He}$ in model A3. $^{44}\text{Ti}$ is highly produced in the polar region together with $^4\text{He}$, as expected.

On the other hand, $^{57}\text{Ni}$ and $^{58}\text{Ni}$ are overproduced and inconsistent with the observations in the axisymmetric explosion. This is because the ejecta contains the neutron-rich matter in the polar region for the axisymmetric explosion cases (see Figs. 2 and 3). We note that even if the mass cut is set to be spherical, the ejecta contains more neutron-rich matter in the axisymmetric case. This is because the mass cut tends to be smaller in axisymmetric explosion...
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Fig. 5a

Fig. 5b

(a) Contour of the mass fraction of $^{44}$Ti in the A3 model. The maximum value of the mass fraction of $^{44}$Ti is $1.3 \times 10^{-2}$. (b) Same as (a) but for $^4$He. The maximum value is $4.0 \times 10^{-1}$. Contours are drawn for the initial position of test particles.

Since a smaller amount of $^{56}$Ni is produced (see the mass cut of S7 in Table 3), we perform the same calculations for the modified $6 M_\odot$ model, in which the value of $\gamma_e$ for $M > 1.5 M_\odot$ is artificially changed to that of $M > 1.637 M_\odot$. The results are summarized in Table 3 (case B). We can see the amount of $^{44}$Ti is still enough to explain the light curve, and the amount of $^{57}$Ni and $^{58}$Ni is consistent with the observations. This means that the uncertainty of the presupernova model has a great influence on the chemical composition of the ejecta.

We have an additional comment on the mass cut and the mass of the central compact object. There is a tendency that as the degree of the axisymmetric explosion gets larger, the mass of the central compact object also becomes larger if the mass cut is set to be A7 (see In particular, there is a possibility that the mass of the central object is large enough to cause gravitational collapse and forms black hole instead of neutron star. If a pulsar is not found in SN 1987A, it may be worth considering seriously this effect.

3.2. Comparison with Solar System Abundances

Next, we calculate the total amount of heavy elements in the range $A = 16$–$73$ and compare them with solar system abundances. We note that information about initial mass function (IMF), chemical composition of ejecta for each mass range of the progenitor, and the ratio of Type I and Type II supernovae is necessary when the reproduction of solar system abundances is attained. In this paper, we can make only a suggestion for the degree of impact of axisymmetric explosion on the reproduction of solar system abundances because our calculations used only the $6 M_\odot$ model. The calculations of explosive nucleosynthesis for a wide range of progenitors' mass are now underway.

We will comment on this analysis. At first, all unstable nuclei produced in the calculation are assumed to decay to the corresponding stable nuclei when compared with the solar values. Secondary, two forms of the mass cut, which are mentioned above, are used in this analysis to see its influence on the result.

Figures 6 and 7 show the results for three models, that is, the S1, A1, and A3 models for the mass cut of A7. Figure 6 shows the comparison of the composition for $A = 16$–$73$ normalized by the S1 model. Open circles denote the A1/S1 comparison, and filled circles denote the A3/S1 comparison. Figure 7 illustrates the comparison of the abundances of ejected nuclei with the solar values (normalized at $^{16}$O). It is evident from the Figure 6 that the amount of nuclei in the range $A = 16$–$40$ is almost same among three models, and there are two peaks around $A = 45$ and $A = 65$. We will comment on these three outstanding features. First, the result that the amount of nuclei is hardly changed in the
range \( A = 16-40 \) is important, since spherical calculations can reproduce well the solar system abundances in this range (Hashimoto 1995). Second, the enhanced nuclei near \( A = 45 \) are \(^{44}\text{Ca},^{47}\text{Ti},^{48}\text{Ti},\) and \(^{52}\text{Cr}\), which are synthesized by the alpha-rich freezout like \(^{44}\text{Ti}\) in § 3.1.2. We can say that this enhancement is additional evidence for the more active alpha-rich freezout under the axisymmetric explosion. Third, the peak around \( A = 65 \) is thought to be made by the strong shock in the polar region in the axisymmetric explosion, which can cause a nuclear reaction against the Coulomb repulsion. Figure 8 is the same as Figure 6 but for the mass cut of S7. The peak around \( A = 65 \) still exists, and this suggests that the feature of overproduction of heavy elements around \( A = 65 \) is fatal one for the axisymmetric explosion.

We will pay attention to each nucleus individually. As mentioned in § 1, it is reported that \(^{35}\text{Cl},^{39}\text{K},^{44}\text{Ca}\) are underproduced and \(^{58}\text{Ni}\) is overproduced in spherical calculations to date. The amounts of \(^{35}\text{Cl}\) and \(^{39}\text{K}\) produced by the asymmetric explosion are almost the same as those produced by the spherical explosion. However, more \(^{44}\text{Ca}\) is produced in the axisymmetric explosions compared with the spherical explosion. The problem of the less production of this nucleus may be saved by this effect. \(^{58}\text{Ni}\) is very sensitive to the \( Y_e \) of the progenitor and the position of the mass cut. However, we can say that neutronization should also be suppressed in the axisymmetric explosion as seen in § 3.1 to be consistent with the observation.

4. SUMMARY AND DISCUSSION

We have calculated the explosive nucleosynthesis in a supernova of a 6 \( M_\odot \) helium core on the assumption that the explosion is axisymmetric. We inspected the effect of axisymmetric explosion by comparing the results with the observation of SN 1987A and solar system abundances.

As for SN 1987A, we show that a sufficient amount of \(^{44}\text{Ti}\) is produced in the axisymmetric explosion to explain the tail of the light curve. To put it differently, the degree of the axisymmetric explosion to explain that observation must be at least that given in our models. Although our forms of the initial shock wave are only assumptions, our results suggest a lower constraint on the degree of the axisymmetric explosion dependent on the amount of \(^{44}\text{Ti}\). We note that some of our results strain the limits set on the \(^{44}\text{Ti}/^{56}\text{Ni}\) ratio in a spherical explosion (Woosley & Hoffman 1991). We think this is because the localized energy in the polar region introduces high entropy and produces a large amount of \(^{44}\text{Ti}\) there. It is difficult to use the bolometric light curve to estimate precisely its amount because of the presence of the bright optical surroundings and the freezeout effect (Fransson & Kozma 1993). However, this amount may be identified from observations by X-ray and gamma-ray satellites in future, which may reveal the effects of an axisymmetric explosion.

Moreover, it is reported that the estimated mass of \(^{44}\text{Ti}\) by the observation of Cas A is \((1.4 \pm 0.4)-3.2 \pm 0.8) \times 10^{-4} M_\odot\) (Iyudin et al. 1994). Although its abundance is still controversial, this value is more than that predicted by spherical calculation (Timmes et al. 1996). Since the form of the Cas A remnant is far from spherical, it may support our results.

No complaints will be made if the amounts of other nuclei such as \(^{57}\text{Ni}\) and \(^{58}\text{Ni}\) are consistent with observations. However, in the present study, they tend to be overproduced in the axisymmetric explosion. It is noted that the 6 \( M_\odot \) helium core is in itself too neutron-rich in the Si layer, and the value of \( Y_e \) needs to be modified to explain the observed \(^{58}\text{Ni}\) even in the spherical explosion (Hashimoto 1995). We also showed in this paper that if the value of \( Y_e \) in the Si layer is modified, the amounts of \(^{57}\text{Ni}\) and \(^{58}\text{Ni}\) can be in the range of the observation with the amount of \(^{44}\text{Ti}\) hardly changed. It will be necessary to perform our calculation with various presupernova models to see the dependence of our results on the model of the progenitor, in particular, on \( Y_e \) distribution.

We also compared the results with solar system abundances. There are three outstanding features in the axisymmetric explosion. One is that the amount of nuclei in the
range $A = 16 - 40$ is hardly changed by the form of the initial shock wave. The others are that there are two peaks around $A = 45$ and $A = 65$. The insensitivity of these nuclei is good for axisymmetric explosions because of the fact that the spherical calculations thus far can explain the solar system abundances well in this range (for the spherical case, see Hashimoto 1995). However, we cannot also solve the problem of the underproduction of $^{44}\text{Cl}$ and $^{44}\text{K}$. We note that $^{44}\text{Ca}$, which is mainly synthesized through the decay of $^{44}\text{Ti}$, is produced more in the axisymmetric explosion. This means that the axisymmetry of explosion has a positive effect on explaining the solar values of this nucleus. On the other hand, the effect of the peak around $A = 65$ may be relatively small since Type I supernovae are chiefly responsible for this mass number range (e.g., Hashimoto 1995). This means, fortunately, the problem of overproduction of heavy elements in this range may not occur. We are now calculating explosive nucleosynthesis for wide range of progenitors' mass and will report on this influence in the near future. We will give an additional comment. The greater amount of $^{44}\text{Ca}$ means a more active alpha-rich freezeout; that is, more helium remains because of high entropy per baryon. We should note that $^4\text{He}$ produced in this region may have an effect on the production of $^7\text{Li}$ through the neutrino process. In addition, the production of $^7\text{Li}$ becomes more efficient if axisymmetric radiation of neutrinos (Shimizu et al. 1994) causes the explosion axisymmetric.

We will consider the reliability of our calculations. As for the mesh resolution, 10 angular zones may seem coarse. However, in the calculation of explosive nucleosynthesis, convection will not play an important role, and we think high mesh resolution is not needed. We are doing more precise calculations using a supercomputer now. We will estimate the dependence of results on mesh resolution in future. In addition, we should explore the sensitivity of results to the initial conditions, such as total explosion energy, the ratio of initial thermal energy to kinetic energy, and initial radius of the shock wave. This is because with either method for the initial shock condition, that is, the method of energy deposition or of the piston, the peak temperatures are incorrect in the early history of the shock (Aufderheide, Baron, & Thielemann 1991). In the present circumstances, there is no self-consistent way to produce an initial shock wave, and the only thing we can do is to calculate with various initial conditions. Finally, we comment on the dimensionality of the simulations. All the simulations presented here are performed in two dimensions since three-dimensional computations require much more computer time and memory. Two-dimensional calculation may limit some flow modes that are allowed in three-dimensional simulations. As a result, the entropy per baryon may be kept higher in the polar region after the passage of the shock wave, which generates a greater amount of $^{44}\text{Ti}$ in two-dimensional calculations. However, we think its influence will be small since equatorial symmetry will be kept approximately in the jet-like explosion and convection will not play an important role in this study. Anyway, we should examine this two-dimensional effect in future. We will estimate the influence of these effects mentioned above and confirm the credibility of each calculation.

We have done the calculation of the explosive nucleosynthesis under the axisymmetric explosion for the first time. The feature of axisymmetric explosion may have many attractions in addition to explosive nucleosynthesis. For example, it is shown that a part of $^{56}\text{Ni}$ can be mixed into the outer layer by Rayleigh-Taylor instabilities in the jetlike explosion with smaller perturbations compared with spherical explosion (Yamada & Sato 1991). In addition, the axisymmetric mass cut and jetlike explosion may be advantageous for ejecting $r$-process material. The amount of $r$-process material that is ejected should be very little and, simultaneously, must be ejected. We think the jetlike explosion will be one of the mechanisms that can explain such characteristic. Moreover, some effects such as a rotation of the progenitor may show the possibility of axisymmetric explosion, and it may be an essential feature for presupernova to explode (e.g., Yamada & Sato 1994; Mönchmeyer, Schäfer, Müller, & Bates 1991).

This work is the first step for an examination of explosive nucleosynthesis under axisymmetric explosion. However, axisymmetric explosion has the possibility to solve many mysteries of supernova explosion. In the future, we will calculate axisymmetric explosive nucleosynthesis systematically for various progenitor models with different masses to reveal the influence of axisymmetric explosions more clearly.

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