METAL ENRICHMENT OF THE PRIMORDIAL INTERSTELLAR MEDIUM THROUGH THREE-DIMENSIONAL HYDRODYNAMICAL EVOLUTION OF THE FIRST SUPERNOVA REMNANT

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ABSTRACT

The long-term evolution of supernova (SN) remnants in the primordial interstellar medium (ISM) with an inhomogeneous structure is calculated to investigate metal enrichment of the primordial gas. For this purpose, we have constructed a parallel three-dimensional hydrodynamics code incorporating the radiative cooling and self-gravity. The self-gravity and radiative cooling develop the inhomogeneous structure of the ISM from a small perturbation with a power-law spectrum. The resultant density ranges from 0.5 to \(10^6\) cm\(^{-3}\). Calculations for an SN with the progenitor mass of \(20 M_\odot\) are performed as the first step of a series of our study. It is found from the results that a single SN distributes some of the newly synthesized heavy elements into a dense filament of the ISM with densities ranging from 100 to \(10^6\) cm\(^{-3}\) depending on where the SN explodes. Thus, the metallicity [Mg/H] of the dense filaments polluted by the SN ejecta becomes \(-2.7 \pm 0.5\). From these filaments, the first Population II stars will form. This value is in accordance with previous analytical work by Shigeyama & Tsujimoto with an accuracy of \(\sim 0.3\) dex.

Subject headings: galaxies: ISM — hydrodynamics — ISM: abundances — ISM: structure — methods: numerical — supernova remnants

1. INTRODUCTION

Recently, the diversity in the abundance patterns of metal-deficient stars in the Galactic halo has been observed by several authors (McWilliam et al. 1995; Ryan, Norris, & Beers 1996). In addition, theoretical attempts (Audouze & Silk 1995; Shigeyama & Tsujimoto 1998) have led to the conclusion that star formation induced by quite few or a single supernova (SN) event results in the observed diversity in abundance patterns. In particular, Shigeyama & Tsujimoto (1998) have suggested that star formation occurs in the thin shell produced by an SN explosion and that stars of the next generation inherit the abundance pattern thereof. This shell was assumed to contain all the heavy elements newly synthesized and ejected by the SN. As a result, the abundance pattern of new stars is determined by combinations of the SN ejecta and the interstellar medium (ISM) swept up by the explosion. In this scenario, the Rayleigh-Taylor instability is supposed to destroy the dense heavy-element layer into numbers of blobs that penetrate into the supernova remnant (SNR) shell. It is clear that a spherically symmetric SNR in a uniform ISM cannot bring its heavy-element layer into the thin shell formed immediately behind the shock front. To check whether the abundance in the thin shell produced by an SNR reaches the average abundance inside the SNR as predicted by Shigeyama & Tsujimoto (1998), it is necessary to calculate the hydrodynamical evolution of the SNR in three dimensions.

The evolution of an SNR is characterized by several phases (Chevalier 1977): the ejecta-dominated phase, Sedov-Taylor (ST) phase, pressure-driven snowplow (PDS) phase, and momentum-conserving snowplow phase. Each phase has been investigated by a number of authors; e.g., for the first two phases see Truelove & McKee (1999), and for the last two phases see Ciofi, McKee, & Bertchinger (1988). Most of these previous studies have been restricted to spherically symmetric SNRs in the uniform ISM. However, the inhomogeneity of an ISM affects the evolution of an SNR. A model of SNR evolution in an ISM with a density gradient (Hnatyk & Petruk 1999) has shown that the shape of the SNR was easily deformed to be nonspherical in \(\sim 10,000\) yr after the explosion. However, our objective is to see how a single SN event distributes newly synthesized heavy elements in the ISM when the SNR stops expanding at \(t > 1\) Myr after the explosion. The ISM must also evolve on this timescale because of gravity and radiative cooling. Hence, we need to follow the evolution of an SNR in the inhomogeneous and evolving ISM for more than 1 Myr.

In this Letter, we investigate the evolution of an SNR originated from a Population III star in the inhomogeneous ISM with the primordial abundances by using a three-dimensional hydrodynamics code. Especially, we will focus our attention on the correlation of the abundance of heavy elements with the gas density in each cell to identify the abundance of heavy elements that would be inherited by stars of the next generation. Consequently, we can test the hypothesis proposed by Shigeyama & Tsujimoto (1998).

2. THE METHOD AND INITIAL MODEL

To model the three-dimensional evolution of an SNR, we have constructed a parallel three-dimensional hydrodynamics code incorporating self-gravity and radiative cooling of the ISM with no heavy elements. We adopt the Godunov-type (Godunov 1959) scheme to solve the hydrodynamical equations (the Harten–Lax–Van Leer Contact method in Toro 1997). The usage of the first-order scheme reduces not only the computational costs of the three-dimensional calculation by a factor of 2 compared with higher order schemes like the piecewise parabolic method (Colella & Woodward 1984) but also the number of boundary values to be transferred in parallel version. To obtain a second-order scheme in time, the Strang-type dimensional splitting (Strang 1968) is used. In addition, we have made two modifications to the usual Godunov-type scheme. First, to properly follow the adiabatic change of thermal energy in a preshock region, we adopt the method used in a usual cosmological hydrodynamics code (Ryu et al. 1993). Second, the consistent multifluid advection method (Plewa & Müller 1999) is imple-
mented since we are interested in how heavy elements ejected by an SN explosion mix with the ISM. The three-dimensional Poisson equation is solved by the fast Fourier transform method to calculate the self-gravity of the ISM. To solve the energy equation including the radiative cooling term, we use an implicit method, i.e., the Newton-Raphson method.

In the early stage of the universe, the gas contains no heavy elements and the main coolant at temperatures below 10⁴ K is hydrogen molecules. However, to solve rate equations for the formation and destruction of hydrogen molecules is not feasible for a simulation such as that presented here. We note that there are some attempts to this approach (e.g., Abel et al. 1998). Accordingly, throughout this Letter, we use the radiative cooling rates for the gas with [Fe/H] = −2 to mimic the cooling function of the very early stage of the universe. The cooling rate is computed by MAPPINGS III software by R. S. Sutherland (MAPPINGS III is the successor of MAPPINGS II, described in Sutherland & Dopita 1993). The radiative cooling due to hydrogen molecules is not included in MAPPINGS III. In the low-temperature range as low as 1000 K, the adopted cooling rate is slightly lower than the cooling rate by hydrogen molecules (see Fig. 2 of Nakasato, Mori, & Nomoto 2000).

We use the equation of state incorporating hydrogen and helium in ionization equilibrium. We have assumed that ions and electrons are in thermal equilibrium, since the temperature in the SNR is almost always below 10⁵ K during the evolution.

The ISM is modeled by a periodic square box composed of 150² zones. The size of the simulation box is set to 80 pc to cover the maximum size of an SNR. The simulation procedure is divided into the following two stages.

The first stage of the simulation is devoted to archiving an inhomogeneous ISM structure. First, an initial density field \( \rho(r) \) for the first stage of the simulation is generated by the COSMICS package (E. Bertschinger 1995) with a power spectrum of the density expressed as \( P(k) \propto k^{-1} \). The initial mean number density of hydrogen atoms is set to \( n = 100 \text{ cm}^{-3} \). We assume that the initial temperature is uniform with T = 100 K. Then we obtain the initial velocity field \( \mathbf{v}(r) \) by integrating the equation of motion for one dynamical time \( t_{\text{dyn}} \sim [1/(4\pi G \rho^n)]^{1/2} \sim 2.7 \text{ Myr} \) in the present case, where \( G \) is the gravitational constant. We use the Zeldovich approximation (Zeldovich 1970) in this integration: \( v_i(r) = a_i(r)t_{\text{dyn}} \), where \( a_i(r) \) is the acceleration field generated by \( \rho(r) \) through the Poisson equation. Then we have followed the hydrodynamical evolution of the box for further \( 5t_{\text{dyn}} \). As a result of the self-gravity, filamentary and knotty structures gradually form as in calculations of the cosmological structure formation. In \( 5t_{\text{dyn}} \) of the evolution, the inhomogeneity develops in the box with the density ranging from 0.5 to \( 10^6 \text{ cm}^{-3} \). The volume filling factor of the low-density region with \( n < 10^2 \text{ cm}^{-3} \) (this equals the initial mean density) is \( \sim 84\% \). The velocity dispersion is about 3 \( \text{ km s}^{-1} \). This value will be used to test the hypothesis of Shigeyama & Tsujimoto (1998). In the subsequent paper, we will present a detailed analysis of the three-dimensional inhomogeneous structure of the ISM obtained in the first stage of our simulation.

In the second stage of our simulation, we model the ST and PDS phases of the evolution of an SNR with the same code. For the initial condition of the SNR model, we deposit the SN explosion energy \( E_{\text{sn}} = 10^{51} \text{ ergs} \) into a cell as thermal energy. At the same time, we add the progenitor mass \( 20 M_\odot \) as a fiducial value to the same cell and treat 1.7% (0.34 \( M_\odot \)) of the progenitor mass as Mg (Tsujimoto et al. 1995).

In this Letter, we do not intend to simulate the star formation processes. Instead, we show the results for two cases: when the first SNR event occurs in a low-density region (case 1) and a high-density region (case 2). We consider the region where \( n \) is lower than \( 10^2 \text{ cm}^{-3} \) as the low-density region and the rest of the box as the high-density region. In case 1, we select an arbitrary cell in the low-density region as an SN site. After the star formation, the star leaves the star-forming site and moves around under the gravitational field of the ISM. Thus, most SNR events are expected to occur in the low-density regions as a result of the large volume filling factor. Also, in case 2, we select an arbitrary cell in the high-density region as an SN site. In case 2, we treat 20 \( M_\odot \) of the gas in the cell as the progenitor mass.

3. RESULTS

3.1. Case 1: Low-Density Regions

The first SN occurs in a smooth region where the density gradient of the ISM is small. This region corresponds to a "hole" (or a tenuous region) of the inhomogeneous ISM. The

\footnote{The abundance ratios of the other heavy elements with respect to Fe have the "primordial" values in Sutherland & Dopita (1993).}

\footnote{Available at http://arcturus.mit.edu/cosmics.}

![Fig. 1.—Top: Evolution of the volume filling factor (V) of the metal-enriched region. Bottom: Evolution of the deformation factor (D) of the metal-enriched region. In both panels, the solid and dotted lines correspond to cases 1 and 2, respectively.}
number density \((n)\) of the chosen SN site at the end of the first stage is \(\sim 13 \text{ cm}^{-3}\). After adding 20 \(M_\odot\) ejecta to the cell, \(n\) becomes \(\sim 5350 \text{ cm}^{-3}\). The temperature \((T)\) of the SN site becomes \(\sim 1.2 \times 10^4 \text{ K}\) at the beginning of the second stage. Then a strongly shocked region is produced and the density of the cell decreases very quickly. Although the ejecta soon become nearly spherical in less than 0.1 Myr, they are deformed after the collision with the dense structure of the ISM.

To see the evolution of the shape of the ejecta quantitatively, let \(V\) be the volume of the metal-enriched regions and \(S\) be the surface area of the metal-enriched regions. We define the volume filling factor \((V_f)\) as \(V/L^3\) and the deformation factor \((D_f)\) as \(S/(4\pi[(3V)/(4\pi)])^{2/3}\), where \(L\) is the size of the simulation box. Figure 1 shows the evolutions of \(V_f\) (top) and \(D_f\) (bottom), with the solid line representing case 1. In the PDS phase of a spherical SNR in a uniform ISM, the shocked volume evolves proportional to \(t^{2/3}\) (Cioffi et al. 1988). If we assume that \(V_f\) evolves proportional to \(t^{\alpha}\), the exponent \(\alpha\) during the first 1 Myr is smaller than unity and then increases to almost unity at \(t \sim 3\) Myr. It is likely that the ejecta expand faster than the shock front in later phases. The fact that \(D_f\) shown in the lower panel is significantly greater than unity indicates that the shape of the surface of the ejecta becomes very deformed from a sphere as a result of the Rayleigh-Taylor instability.

Figure 2 shows the mass of the heavy elements at \(t = 3\) Myr as a function of number density \((\log n)\) and metallicity \(([\text{Mg/H}]\)\). We note that this mass distribution function does not change its shape for the last 1 Myr. There are two peaks in this diagram. One is located at \((\log n, [\text{Mg/H}]) \sim (0, -2)\) and is not so pronounced as the other. The total amount of the heavy elements involved in this peak is not so large. The low density indicates that these heavy elements have been staying near the SN site. The other peak is located at \((\log n, [\text{Mg/H}]) \sim (2.1, -2.7)\). A majority of the heavy element comes from the density and the second from the sound speed (or the velocity dispersion). Thus, the \([\text{Mg/H}]\) estimated from this equation would be \(\sim -2.9\). The analytical work and three-dimensional calculation have shown a fairly good agreement in this respect. What Shigeyama & Tsujimoto (1998) did not mention is that this peak has a finite width. This metallicity distribution can be considered to be a consequence of the inhomogeneity of the ISM: a part of the ejecta that penetrates into a dense part of the primordial ISM mixes with it and tends to get a small metallicity. On the other hand, a part of the ejecta that contacts with a tenuous part of the ISM mixes with a small amount of ISM thereof and thus gets a larger metallicity. A part of the ejecta that never mixes with the ISM will keep its initial metallicity.

The resultant \([\text{Mg/H}]\) ranges \(-3.2 < [\text{Mg/H}] < -2.2\) with a peak at \([\text{Mg/H}] \sim -2.7\). With the resolution of our calculations, i.e., \(dx \sim 0.53\) pc, a cell with \(\log n > 2.43\) includes more than \(1 M_\odot\) of gas. Thus, the metallicity inherited by the next generation of stars may be overestimated unless the mass of these stars is much smaller than \(1 M_\odot\).

### 3.2. Case 2: High-Density Regions

In this case, \(n\) and \(T\) of the SN site at the beginning of the second stage are \(\sim 11,500 \text{ cm}^{-3}\) and \(5.6 \times 10^7 \text{ K}\), respectively. The evolution of \(V_f\) and \(D_f\) is presented in Figure 1 with the dotted lines. We can see that \(V_f\) is always smaller than in case 1 and \(D_f\) is always higher than in case 1. This is because the SN occurs in a dense filament that produces a large density gradient. Namely, the SNR easily expands perpendicular to the direction of the filament but is much slowed down along the direction of the filament.

The surface of the metal-enriched region at \(t = 3\) Myr is shown in Figure 3 together with the filamentary structure of the ISM. The SN site is located at the center of the simulation box. The yellow surface represents the \([\text{Mg/H}] = -2.6\) iso-surface, and the orange filamentary shape shows the three-dimensional density structure. The ejecta expand into tenuous regions of the ISM and are deformed by the filamentary ISM structure.
our code, we first evolve a random density field and obtain the inhomogeneous ISM model. Then we follow the long-term evolution of an SNR to see how a single SN distributes the newly synthesized heavy elements into the ISM.

For the site of the first SN event in the simulation, we consider low-density and high-density environments. In both cases, a strong shock is produced and then the shock front is slowed down by collisions with the filamentary structure of the ISM. Our calculations indicate that a majority of the newly synthesized heavy elements is distributed into the gas in filamentary structures to get the metallicity of $-3.2 \leq [\text{Mg}/\text{H}] \leq -2.2$ depending on the SN site. Thus, Population II stars born from a high-density filament polluted with the ejecta of an SN will have $[\text{Mg}/\text{H}] \sim -2.7$ on their surfaces. We have compared the values of $[\text{Mg}/\text{H}]$ in dense regions of the simulation box with those estimated from the analytical work by Shigeyama & Tsujimoto (1998) and found that they are in agreement with each other with an accuracy to $\leq 0.3$ dex, although the assumed density structure of the ISM in Shigeyama & Tsujimoto (1998) is quite different from that in the present work.

To understand the metal enrichment process at the early stages of galaxy evolution, we will need to eliminate (or identify, at least) the influences from numerical artifacts that may be caused by the limited resolution of our model. First, we need to deposit thermal energy into one cell to initiate an SN. A significant fraction of the explosion energy of a real SN with the size of $\sim 0.5$ pc must be in the form of kinetic energy. Thus, the ejecta of a real SN are expected to penetrate deeper into the filamentary structure to get lower metallicity than shown in this Letter. Second, the inhomogeneous ISM model obtained in the first stage of our simulation procedure may be changed depending on a number of model assumptions, which include the initial power spectrum of the model, the cooling rates due to molecular hydrogen, the neglect of the dark matter potential, the effect of radiative transfer, etc.

We will report results of a detailed study of the inhomogeneous ISM and longer evolution of the metallicity distribution in a separate paper (N. Nakasato & T. Shigeyama 2000, in preparation). Calculations for SNe with different progenitor masses will also be performed to see the abundance patterns of Population II stars.

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REFERENCES

Abel, T., Anninos, P., Norman, M. L., & Zhang, Y. 1998, ApJ, 508, 518
Audouze, J., & Silk, J. 1995, ApJ, 451, L49
Chevalier, R. A. 1977, ARA&A, 15, 175
Cioffi, D. F., McKee, C. F., & Bertschinger, E. 1988, ApJ, 334, 252
Colella, P., & Woodward, P. R. 1984, J. Comput. Phys., 54, 174
Godunov, S. K. 1959, Mat. Sb., 47, 271
Hnaryk, B., & Petruk, O. 1999, A&A, 344, 295
McWilliam, A., Preston, G. W., Sneden, C., & Searle, L. 1995, AJ, 109, 2757
Nakasato, N., Mori, M., & Nomoto, K. 2000, ApJ, 535, 776
Plewa, T., & Müller, E. 1999, A&A, 342, 179
Ryan, S. G., Norris, J. E., & Beers, T. C. 1996, ApJ, 471, 254
Ryu, D., Ostriker, J. P., Kang, H., & Cen, R. 1993, ApJ, 414, 1
Shigeyama, T., & Tsujimoto, T. 1998, ApJ, 507, L135
Strang, G. 1968, SIAM J. Numer. Anal., 5, 506
Sutherland, R. S., & Dopita, M. A. 1993, ApJS, 88, 253
Toro, E. F. 1997, Riemann Solvers and Numerical Methods for Fluid Dynamics (Berlin: Springer)
Truelove, J. K., & McKee, C. F. 1999, ApJS, 120, 299
Tsujimoto, T., Nomoto, K., Yoshii, Y., Hashimoto, M., Yanagida, S., & Thielemann, F.-K. 1995, MNRAS, 277, 945
Zeldovich, Ya. B. 1970, A&A, 12, 2