METAL ENRICHMENT HISTORY OF THE PROTO-GALACTIC INTERSTELLAR MEDIUM

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Abstract. To investigate the metal enrichment history of the primordial interstellar medium (ISM), we have studied the long-term evolution of supernova remnants (SNRs) and how SNRs distribute the heavy metals into the ISM when they explode. With the assumed IMF for massive stars, we have computed the multiple supernova explosions and evolution in an inhomogeneous ISM. We compare the predicted metallicity distribution of metal deficient halo stars with the observed one.

Keywords: chemical evolution, SNR, ISM

1. Introduction

The observed diversity in the abundance patterns of metal-deficient stars in the Galactic halo (McWilliam et al., 1995; Ryan, Norris and Beers, 1996) is naturally explained by an inhomogeneous chemical evolution scenario (Audouze and Silk, 1995; Shigeyama and Tsujimoto, 1998). Shigeyama and Tsujimoto (1998) have suggested that star formation occurs in the thin shell produced by a supernova (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. Accordingly, star formation induced by quite few or a single SN event produces the observed diversity in the abundance patterns of metal-deficient stars. Based on this scenario, several authors have attempted to construct inhomogeneous chemical evolution models (Suzuki, Yoshii and Kajino, 1999).

In this paper, we present the results of our inhomogeneous chemical evolution model of the ISM and compare the preliminary results with the abundance patterns of metal-deficient stars. In contrast to the model like Suzuki, Yoshii and Kajino (1999), we use a 3-D hydrodynamical model for a supernova remnant (SNR) evolution. For the first time, our models represent one-generation of inhomogeneous chemical enrichment history of the ISM with a realistic 3-D hydrodynamical model. To model the 3-D evolution of SNRs, we have constructed a parallel 3-D hydrodynamics code incorporating self-gravity and radiative cooling of the ISM (Nakasato and Shigeyama, 2000). Here, we only note the highlights of our numerical code: (1) we use the efficient Godonuv type scheme for hydrodynamics, (2) we implement the consistent multi-fluid advection method (Plewa

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and Müller, 1999) to follow the mixing of heavy element ejected by SN explosions, and (3) our code is fully parallelized using MPI.

2. Multiple Super Novae Model

In Nakasato and Shigeyama (2000), we have calculated the evolution of a SNR in the primordial ISM to investigate the metal enrichment of the primordial gas. We have paid special attention to how the inhomogeneity of ISM affects the metal enrichment of the primordial gas in that paper. We have followed the evolution of a SNR with a progenitor mass of 20 $M_\odot$ using our code and compared the resulting metal abundance with results with analytical work of Shigeyama and Tsujimoto (1998). Although the results depend on where the SN explodes, our results were in accordance with the analytical work with accuracy of ~ 0.3 dex (Nakasato and Shigeyama, 2000). As expected, the evolution of the SNR is very affected by the inhomogeneity of the ISM, e.g., the iso-surface of metal enriched region was very deformed by the Rayleigh-Taylor instability.

In this paper, we present the preliminary results of how the mixing of heavy elements ejected by multiple SN explosions proceeds using the same numerical code. Here, we describe the initial model setup. As a simulation volume, we setup a square periodic box of 200 pc. We set the cell size to 1 pc so that our simulation box consists of 200^3 zones. We produce the inhomogeneous ISM density field as the initial model of ISM with the following procedure. Firstly, an initial density field is generated by the COSMICS package (Bertschinger, 1995) with a power spectrum of the density expressed as $P(k) \propto k^{-1}$. The initial mean number density of the box is set to $n = 100\,\mathrm{cm}^{-3}$. We assume that the initial temperature is uniform with $T = 100$ K. Then we have followed the hydrodynamical evolution of the box for $5t_{\mathrm{dyn}}$, where $t_{\mathrm{dyn}} \sim 2.7$ Myr in the present case. Due to the self-gravity, filamentary and knotty structures gradually form like in calculations of the cosmological structure formation. We use this inhomogeneous ISM structure as the initial model for the following SNR calculation.

In the simulation box, we assume that 100 massive stars between 20 $M_\odot$ and 80 $M_\odot$ form at a same time with the Salpter initial mass function. These stars are randomly located within the simulation box. After this setup, we start the simulation by exploding stars depending on their lifetime. To mimic the explosions, we deposit the SN explosion energy ($E_{\mathrm{sn}} = 10^{51}$ erg) in a cell where the progenitor star is. For the lifetime of stars, we use the fitting formula of David, Forman and Jones (1990). With this formula, the lifetime for 20 $M_\odot$ and 80 $M_\odot$ stars are 11.0 and 4.8 Myr, respectively. We arrange that the most massive star (hence the shortest lifetime star) explodes at t = 0.0. And we continue the evolution for 7 Myr from the first explosion. Namely, we stop the calculation in ~ 1 Myr after the last explosion (the least massive star). We treat some fraction of progenitor mass as heavy elements and in this model we consider the mixing of only two heavy elements, Mg and Ca.

For the fraction of Mg and Ca in each progenitor star, we use a value interpolated from the table in Tsujimoto et al. (1995).

3. Results

As shown in Nakasato and Shigeyama (2000), the heavy elements ejected by a SN explosion are mixed and diluted with the ISM during the evolution of the present model. Moreover, the heavy elements ejected by each SN explosion are mixed and diluted as the results of the interaction between SNRs. Since each progenitor star has a different [Ca/Mg] ratio depending on the mass, the [Ca/Mg] of the ISM at final stage of the model eventually shows a certain distribution. We have computed several models. Each model differs by its initial inhomogeneous ISM structure and the choice of the stellar mass and the location of the stars. However, there is little difference in the overall evolution between different initial models.

In the early stage of the model, each SNR expands into the ISM almost freely. After the middle stage of the model, the tip of some SNRs begin to interact with each other. Since we assume all progenitor stars form at the same time, SN explosions are more frequent in the later stage and the volume of the low density region is then wider. After 7 Myr of evolution, the ISM structure becomes very filamentary and knotty since the ISM is sweeped up by the multiple SNRs. Namely, most of the mass resides in several knots. Because the thermal energy of 100 SN explosions is by far large enough to un-bind the total mass of $\sim 2 \times 10^7$ $M_\odot$ box, most mass will be lost if we do not use the periodic boundary condition.

As the result of these models, we obtain the distribution of Mg and Ca in the simulation box. Figure 1 shows the mass including heavy metal at $t = 7$ Myr as a function of [Ca/Mg] and [Mg/H] (we note that we combine the results of 5 models to plot this figure). Our model successfully produce the diversity of heavy elements. There are a number of peaks around ranges $-3.5 <$ [Mg/H] < -2.5. Most of the mass resides in the region where $-3.5 <$ [Mg/H] < -2.5 and $-0.6 <$ [Ca/Mg] < -0.3. If we compare our results with the abundance patterns of halo stars (McWilliam et al., 1995; Ryan, Norris and Beers, 1996), we see that although the large diversity in [Mg/H] obtained by our model is in accordance with the observation, the distribution of [Ca/Mg] dose not match very well. This is mainly due to the assumed range of progenitor mass. The highest value of [Ca/Mg] in the nucleosynthesis model (Tsujimoto et al., 1995) for the mass range between 20 $M_\odot$and 80 $M_\odot$is -0.1 at $M_{progenitor} \sim 60$ $M_\odot$. On the other hand, the observed [Ca/Mg] for most halo stars is larger than 0.0. To obtain a result compatible with the observations, we need to assume a wider mass range for progenitor stars. Finally, we note that this result is preliminary. Model with different numerical/physical parameters and a detailed comparison with observations will be presented elsewhere.

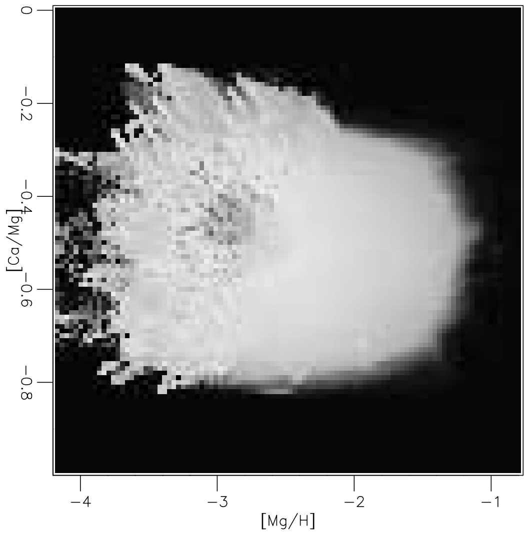

Figure 1. The mass as a function of [Ca/Mg] and [Mg/H].

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