FOSSIL IMPRINTS OF THE FIRST-GENERATION SUPERNOVA EJECTA IN EXTREMELY METAL-DEFICIENT STARS

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ABSTRACT

Using the results of nucleosynthesis calculations for theoretical core-collapse supernova models with various progenitor masses, it is shown that the abundance patterns of C, Mg, Si, Ca, and H that are seen in extremely metal-deficient stars with \([\text{Fe/H}] \leq -2.5\) follow those seen in the individual first-generation supernova remnants (SNRs). This suggests that most of the stars with \([\text{Fe/H}] \leq -2.5\) were made from individual supernova (SN) events. To obtain the ratio of heavy elements to hydrogen, a formula is derived to estimate the mass of hydrogen swept up by an SNR when it occurs in the interstellar matter with the primordial abundances. We use \([\text{Mg/H}]\) to indicate the metallicities instead of \([\text{Fe/H}]\). The metallicities \([\text{Mg/H}]\) predicted from these SNRs range from \(-\sim 4\) to \(-\sim 1.5\), and the mass of Mg in an SN is well correlated with its progenitor mass. Thus, the observed \([\text{Mg/H}]\) in an extremely metal-deficient star has a correspondence to the progenitor mass. A larger \([\text{Mg/H}]\) corresponds to a larger progenitor mass. Therefore, the so-called “age-metallicity relation” does not hold for stars with \([\text{Fe/H}] \leq -2.5\). In contrast, the \([\text{Mg/Fe}]\) ratios in the theoretical SNRs have a different trend from those in extremely metal-deficient stars. It is also shown that from the observed trend of \([\text{Mg/Fe}]\), one can predict the Fe yield of each SN given the correspondence of \([\text{Mg/H}]\) to the progenitor mass. The Fe yields thus obtained are consistent with those derived from SN light-curve analyses. This indicates that there is still a problem in modeling a core-collapse supernova at the beginning of its explosion or mass cut. The abundance determination of O in extremely metal-deficient stars, which has not been done from observational analyses, is strongly desired in order to test the hypothesis that the elements in an extremely metal-deficient star come from a single SN event and to obtain reliable yields for SNe.

Subject headings: nuclear reactions, nucleosynthesis, abundances — stars: abundances — stars: Population II — supernovae: general — supernova remnants

1. INTRODUCTION

Recent observations and analyses imply that the abundance pattern of an extremely metal-deficient star with \([\text{Fe/H}] \leq -2.5\) may retain information of a preceding single supernova (SN) event or, at most, a few SNe (McWilliam et al. 1995; Ryan, Norris, & Beers 1996). A theoretical attempt from this point of view has already been made by Audouze & Silk (1995) to explain the observed abundance patterns. They argued that a combination of yields from two SNe with different progenitor masses at the main sequence (\(M_a\)) is consistent with the abundance patterns of stars with the lowest metallicity (\([\text{Fe/H}] \sim -4\)).

Assuming that the formation of extremely metal-deficient stars is triggered by a single supernova remnant (SNR) and that the formed stars retain the abundance pattern of this SN, one could predict the abundance patterns (including hydrogen) of these stars from the theoretical SN models available at present (see, e.g., Woosley & Weaver 1995; Tsujimoto et al. 1995; Nomoto et al. 1997). In this Letter, we will compare the abundance pattern obtained in this way with observations, in order to test whether the chemical enrichment by individual SNRs could explain the observed abundances on the surfaces of extremely metal-deficient stars. We will use the models in Woosley & Weaver (1995, hereafter WW95) and those in Tsujimoto et al. (1995, hereafter T95) and Nomoto et al. (1997).

The metallicity of a star has usually been indicated by \([\text{Fe/H}]\). On the other hand, the yields of Fe from SN models to date have not converged (WW95; T95) because of uncertainties in the explosion mechanism and fallback dynamics or because of the mass cut between the forming neutron star (or black hole) and the ejected envelope (see, e.g., Thielemann, Hashimoto, & Nomoto 1990). Thus, the yields of lighter \(\alpha\)-elements are more reliably calculated. We will use \([\text{Mg/H}]\) instead of \([\text{Fe/H}]\) to specify the metallicity because (1) Mg is less affected by the mass cut in SN models than Fe is, (2) Mg is not synthesized or broken by the SN shock, (3) the mass of ejected Mg increases with increasing progenitor mass, and (4) the abundance of Mg is observationally derived for many stars with \([\text{Fe/H}] \leq -2.5\). There is a disadvantage in this element; i.e., two SN models (WW95 and T95) give somewhat different masses of Mg as a function of the progenitor mass (Fig. 1, squares). The best element to be used in this respect would be O (Fig. 1, pentagons) if O abundances were available for many stars with \([\text{Fe/H}] \leq -2.5\).

There is a clear trend in the observed \([\text{C/Mg}]-[\text{Mg/H}]\) plot (Fig. 2, crosses) for \([\text{Mg/H}] < -2\) that cannot be reconciled with the conventional one-zone models of the Galactic chemical evolution that assume a complete mixing of elements inside the Galaxy. The difference of the observed \([\text{C/Mg}]\) in the range of \(-3.5 \leq [\text{Mg/H}] \leq -2\) gives a mean gradient of \(\Delta[\text{C/Mg}]/\Delta[\text{Mg/H}] \approx -0.7\). On the other hand, the one-zone Galactic chemical evolution model (T95) would predict the evolutionary change in \([\text{C/Mg}]\) starting with the value of \(-1.2\) given by the most massive star (\(M_m \approx 50 \, M_\odot\)) and converging
cores that retain the abundance pattern of the SN. These cloud behind the shock front is fragmented into a number of cloud cores that become dynamically unstable (Vishniac 1983). Thus, the dense shell is expected that the ejecta already approach the dense shell at the beginning of the PDS phase and merge with it during this phase. Second, an isothermal shock front is considered to be dynamically unstable (Vishniac 1983). Thus, the dense shell behind the shock front is fragmented into a number of cloud cores that retain the abundance pattern of the SN. These cloud cores embedded in a high ambient pressure become seeds of stars of the next generation (Nakano 1998). Some of the stars thus formed are currently observed as extremely metal-deficient stars. Accordingly, the average abundance pattern inside the SNR is assumed to represent the abundance pattern in all these stars.

Cioffi et al. (1988) obtained the time $t_{\text{PDS}}$ when an SNR loses its identity. This time is a function of the ratio of the shock velocity to the sound speed $c_s$ (or the velocity dispersion) of the ISM at the beginning of the PDS phase ($t = t_{\text{PDS}}$) and $t_{\text{PDS}}$ itself. For an SNR in a homogeneous ISM with the density of $n_1$, $t_{\text{PDS}}$ is determined by

$$\frac{1}{n_1} \frac{\partial e}{\partial t} = -\alpha \Delta(T),$$

where $e$ and $\Delta(T)$ are the internal energy and the cooling function at the temperature $T$, respectively. All the variables are evaluated at the shock front using Sedov-Taylor solutions for the point explosion with the energy $E_0$ and the number density $n_1$. The constant $\alpha$ should be equal to 1.85 in order to reproduce $t_{\text{PDS}}$ for the numerical simulation in Cioffi et al. (1988) when
\(\Delta(T)\) for the solar abundances is used. Then \(\Delta_{\text{primordial}}(T)\) is constructed for the gas composed of only hydrogen and helium, with their mass ratio \(X_h/X_\text{He} = 0.75:0.25\) under the collisional ionization equilibrium. For \(n_1 \geq 10^{-5}\) cm\(^{-3}\), equation (1) gives \(T > 10^4\) K. Thus, the ionization of hydrogen does not affect the dynamics.

The mass of hydrogen \(M_{\text{sw}}\) thus obtained with \(\Delta(T) = \Delta_{\text{primordial}}(T)\) in equation (1) is approximated by the formula

\[
M_{\text{sw}} = 5.1 \times 10^4 M_\odot \left(\frac{E_0}{10^{51} \text{ ergs}}\right)^{0.97} \times n_1^{-0.62} \left(\frac{c_s}{10 \text{ km s}^{-1}}\right)^{-0.97}.
\]

The \(M_{\text{sw}}\) is insensitive to \(n_1\). The sound speed \(c_s\) was assumed to be 10 km s\(^{-1}\) (or \(T \sim 10^3\) K). This mass depends on \(E_0\) and \(n_1\) in a different way than that of Ciolfi et al. (1988) because of the different cooling function used here. The cooling function with the primordial abundances is approximately proportional to \(T^{-2}\) instead of \(T^{-1/2}\) in Ciolfi et al. (1988).

3. ABUNDANCE PATTERNS IN EXTREMELY METAL-POOR STARS

Here we assume that all the stars with \([\text{Mg/H}] < -2\) are made from individual SNRs. Abundance patterns in individual SNRs will be calculated based on yields from theoretical SN models and will be compared with those on the surface of metal-deficient stars obtained by McWilliam et al. (1995). For SN models in a metal-free environment, we use the models Z12A, Z13A, Z15A, Z22A, Z30B, Z35C, and Z40C in WW95 to retain the monotonicity of the mass of Mg as a function of the progenitor mass (Fig. 1, filled squares). Another group of SN models is taken from T95, in which the initial metallicity is solar. The parameters of both models are listed in Table 1.

We divide elements into two categories. One category is composed of the elements not (or at least less) affected by the mass cut in SN models. The examples are C, Mg, Si, and Ca. The other is composed of those affected by the mass cut and includes Cr, Mn, Fe, Co, Ni, for example. This division is necessary because the mass cut in SN models to date is totally artificial and uncertain.

Elements not influenced by the mass cut.—The yields of elements not influenced by the mass cut are expected to be more reliably calculated in SN models than those influenced by the mass cut. Therefore, observed abundance ratios of [C/Mg], [Ca/Mg], and [Si/Mg] with respect to [Mg/H] (Fig. 2) can tell whether extremely metal-deficient stars were formed from individual SNe. These abundance ratios that were derived from SN models (open circles: WW95; filled circles: T95) are also plotted in the same figure, in which [Mg/H] is calculated from the ratio of the mass of Mg in an SNR to that of hydrogen swept up by the same SNR (see eq. [2]). The relations between [Mg/H] and \(M_{\text{sw}}\) are shown in Table 1 for both SN models. The values of [Mg/H] for \(M_{\text{sw}} \sim 10 M_\odot\) (the lower mass limit of the core-collapse SN progenitor) from both models are not so far from the observed lowest value of [Mg/H] \(\sim -3.7\), and the metallicity [Mg/H] increases with increasing progenitor mass \(M_{\text{sw}}\). From this, we infer that there are more stars at lower metallicties according to an IMF that decreases toward high masses if stars with lower masses, say 10 \(M_\odot\), explode in the regions that have not been polluted by other SNRs before. This condition is represented as \(n_1 V_{\text{SNR}} \int_{0}^{M_{\odot}} \phi(m)dm < 1\) star. Here

\[
n_1, \phi, \text{ and } V_{\text{SNR}} \text{ denote the number density of the first-generation stars, the IMF normalized to unity between the lower and upper mass limits, and the maximum volume occupied by a single SN, respectively. This condition results in a star formation efficiency for the first-generation stars smaller than 2\%, if the Salpeter IMF is used.}

A trend seen in the observed [C/Mg] (the crosses in the top panel of Fig. 2) is well reproduced by both models. This means that stars with [Mg/H] \(\sim -3.5\) were made from individual low-mass \((M_{\text{sw}} \sim 10 M_\odot)\) SNe and that stars with [Mg/H] \(\sim -2\) were made from individual high-mass SNe \((M_{\text{sw}} \sim 50 M_\odot)\). For [Si/Mg], both models are also consistent with the observations, although the observed [Si/Mg] has no clear trend. The [Ca/Mg] ratios derived from T95 with \(M_{\text{sw}} \geq 20 M_\odot\) deviate from the observations and give lower values in the region [Mg/H] \(\sim -2.5\). This indicates that the yields of Ca from T95 with \(M_{\text{sw}} \geq 20 M_\odot\) are too small. These abundance patterns, together with the predicted [Mg/H] ratios in Table 1, suggest that stars with \(-3.5 < [\text{Mg/H}] < -2\) are made from individual SN events.

Elements influenced by the mass cut.—The top panel of Figure 3 shows that the [Mg/Fe] ratios derived from both models do not follow the observations. This reconfirms that none of the two models correctly describe the dynamics and/or nucleosynthesis near the surface of the Fe core in progenitor stars during the explosion. In both models, less massive stars have Fe yields that are too large, again from less massive stars in T95 have Fe yields that are too small, but the opposite is the case for WW95. The bottom panel of Figure 3 shows that the [Ca/Fe] ratios from both models are smaller than the observations. This can be ascribed to Fe yields that are too large, again from less massive stars of theoretical models. An apparent fit of the observational data to the model for [Mg/H] \(> -2.5\) is a consequence of two errors in the yields of both Ca (see § 3) and Fe for more massive stars (see the next section).

Abundances of some heavy elements in the ejecta of the 20 \(M_\odot\) supernova were deduced from the SN 1987A observations (Thielemann et al. 1990 and references therein). Since the mass of Mg that was ejected from SN 1987A was not estimated from the observations, we derive the mass of Mg by reducing the value of T95 to match the observed [Mg/Fe] ratio in extremely metal-deficient stars. The corresponding change of [Mg/Fe] is shown by the arrow in the top panel of Figure 3. If we use the mass of Mg derived in this way and the observed masses of C, Si, Fe, and Ca (the upper limit), the abundance ratios of the model with \(M_{\text{sw}} = 20 M_\odot\) would move, following the arrows in Figure 2 and the arrows in the bottom panel of Figure 3. Thus, the abundance pattern of the best observed SN coincides

| Name | \(M_{\text{sw}}\) (\(M_\odot\)) | \(E_0\) (\(10^{51}\) ergs) | [Mg/H] | \(M_{\text{sw}}\) (\(M_\odot\)) | \(E_0\) (\(10^{51}\) ergs) | [Mg/H] |
|------|-----------------|-----------------|-------|-----------------|-----------------|-------|
| Z12A | 12 | 1.28 | -4.1 | 13 | 1 | -3.6 |
| Z13A | 13 | 1.29 | -3.6 | 15 | 1 | -3.1 |
| Z15A | 15 | 1.27 | -3.2 | 18 | 1 | -2.9 |
| Z22A | 22 | 1.26 | -2.8 | 20 | 1 | -2.4 |
| Z25B | 25 | 1.83 | -2.9 | 29 | 1 | -2.3 |
| Z30B | 30 | 2.06 | -2.5 | 40 | 1 | -1.9 |
| Z35C | 35 | 2.49 | -2.6 | 70 | 1 | -1.6 |
| Z40C | 40 | 3.01 | -2.6 | ... | ... | ... |

**TABLE 1**

Input Parameters in SN Models and Calculated [Mg/H] Ratios in Corresponding SNRs
Fig. 3.—Top panel: the crosses are the observed \([\text{Mg/Fe}]\) for stars plotted against \([\text{Mg/H}]\) (McWilliam et al. 1995). The solid curve shows the \(\chi^2\) fit of the observed points, with the errors given in McWilliam et al. (1995), to a cubic polynomial formula. The open and filled circles show the same quantities in the first-generation SNRs calculated from theoretical SN models (WW95 [open circles]; T95 [filled circles]). Bottom panel: same as the top panel, but for \([\text{Ca/Fe}]\). See text for arrows.

with that in extremely metal-deficient stars with \([\text{Mg/H}] \sim -2.6\), and the mass of Mg in the 20 \(M_\odot\) from T95 might be overestimated.

4. IRON YIELDS DEDUCED FROM EXTREMELY METAL-DEFICIENT STARS

We will reverse the argument in the preceding sections. Let us suppose that the trends in the observed abundance ratios, say \([\text{Mg/Fe}]\), show yields of SNe as a function of \([\text{Mg/H}]\). The \(\chi^2\) fit of the observational data to a cubic polynomial formula gives the solid curve in the top panel of Figure 3. This curve and the \([\text{Mg/H}]\) ratio of each model help us predict the mass of Fe (\(M_{\text{Fe}}\)) from an SN as a function of \(M_{\odot}\). The filled circles in Figure 4 show the predicted Fe masses using T95. These Fe masses are completely different from those given in the original models (triangles), but they hardly change the average Fe yield integrated over the Salpeter IMF. The open circles are those from WW95 and give a similar amount of Fe for each progenitor mass. The points with error bars, which are also shown in the same figure, are the Fe masses obtained from SN light-curve analyses. Good fits of the Fe masses from the light-curve analyses to those inferred from the abundance patterns demonstrate that this procedure for obtaining the Fe yields works, if the Fe yields are not affected by the initial metallicities.

5. CONCLUSIONS

We have shown that the abundance patterns of C, Mg, Si, Ca, and H theoretically predicted in the first-generation SNRs are in good agreement with those observed in extremely metal-deficient stars with \(-4 < [\text{Fe/H}] < -2.5\). All these elements are thought to be less affected by the mass cut in SN modeling than heavier elements like Fe are. This agreement implies that each extremely metal-deficient star was formed from a single SN event. In contrast, both theoretical SN models predict different trends in the \([\text{Mg/Fe}]-[\text{Mg/H}]\) plot from the observed one. Conversely, the mass of Fe that is ejected by each SN as a function of \(M_{\text{Fe}}\) can be derived from the observed \([\text{Mg/Fe}]-[\text{Mg/H}]\) trend combined with the \([\text{Mg/H}]-M_{\odot}\) relation in theoretical SN models. This \(M_{\text{Fe}}\) as a function of \(M_{\odot}\) is consistent with that derived from SN light-curve analyses. Following the same procedure presented in this Letter for obtaining the Fe yields, we can derive the yields for other elements such as Ti, Cr, Mn, Co, and Ni and \(r\)-process elements (Tsujimoto & Shigeyama 1998), all of which are very uncertain in SN models. If O abundances are deduced in extremely metal-deficient stars, we will be able to obtain more reliable yields for SNe.

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