CHEMICAL EVOLUTION OF THE GALACTIC HALO THROUGH SUPERNOVA-INDUCED STAR FORMATION AND ITS IMPLICATION FOR POPULATION III STARS

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ABSTRACT

A model for Galactic chemical evolution, driven by supernova-induced star formation, is formulated and used to examine the nature of the Galactic halo at early epochs. In this model, new stars are formed following each supernova event; thus, their abundance pattern is determined by the combination of heavy elements ejected from the supernova itself and those elements that are already present in the interstellar gas swept up by the supernova remnant. The end result is a prediction of large scatter in the abundance ratios among low-metallicity stars, reflecting a different nucleosynthesis yield for each Type II supernova with a different progenitor mass. Formation of new stars is terminated when supernova remnants sweep up too little gas to form shells. We show from calculations based on the above scenario that (1) the observed [Fe/H] distribution for the Galactic halo field stars can be reproduced without effectively decreasing the heavy-element yields from Type II supernovae by some manipulation required by previous models (e.g., via mass loss from the early Galaxy or later mixing with “pristine” hydrogen clouds), (2) the large observed scatter in the abundance ratio [Eu/Fe] for the most metal-poor stars can also be reproduced, and (3) the frequency distribution of stars in the [Eu/Fe]-[Fe/H] plane can be predicted. Our model suggests that the probability of identifying essentially metal-free stars (Population III) in the local halo is around one in $10^3-10^4$, provided that star formation in the halo is confined to individual gas clouds with a mass of $10^{-3}-10^6 \, M_\odot$ and that the initial mass function of metal-free stars is not significantly different from the Salpeter mass function.

Subject headings: Galaxy: evolution — Galaxy: halo — stars: abundances — stars: formation — supernovae: general — supernova remnants

1. INTRODUCTION

In conventional chemical evolution models, stars are assumed to form from well-mixed gas clouds at a rate proportional to some power of the gas density (Schmidt 1959), thus inheriting the abundance pattern of the gas at that time (e.g., Tinsley 1980). This simplified treatment of the complex star formation process has been remarkably successful in accounting for the general features of the chemical compositions of nearby stars and H II regions in a consistent manner (e.g., Pagel & Patchett 1975; Matteucci & Greggio 1986; Yoshii, Tsujimoto, & Nomoto 1996). However, Shigeyama & Tsujimoto (1998, hereafter ST98) and Tsujimoto & Shigeyama (1998) argued that these conventional models cannot be applied to the early stage of the Galactic halo, because observed abundance patterns of extremely metal-deficient stars in the range of $-4 < [\text{Fe/H}] < -2.5$ (McWilliam et al. 1995; Ryan, Norris, & Beers 1996) are incompatible with those predicted by these simple formulations (see also Audouze & Silk 1995).

As an alternative, they proposed a scenario in which stars are born from each supernova remnant (SNR), following a sweeping up of the interstellar gas and the formation of a dense shell immediately behind the radiative shock front. The dense shell is dynamically overstable (Vishniac 1983; Ryu & Vishniac 1987) so that it is broken into a few thousand fragments, in each of which the self-gravity is unimportant. According to Nakano (1998), it is likely that, for at least some of these fragments, the ambient pressure outside the fragments exceeds the critical value above which no equilibrium state exists. Such fragments will dynamically contract and eventually form stars.

This hypothesis sheds light on the entire process of early-epoch star formation. Galactic chemical evolution is envisioned as a successive sequence of supernova (SN) explosions, shell formation, and resulting star formation. In this picture, the abundance pattern of each star is set not only by the heavy elements ejected from the SN explosion that directly precedes local star formation, but it also incorporates those elements already present in the interstellar gas that are swept up by the SNR. The predicted stellar abundance patterns are thus different from those of the gas at the time when stars form. This difference can be quite large in the early stage of Galactic evolution, when the metallicity in the gas is very low. The abundance ratios of low-metallicity stars are predicted to exhibit a large star-to-star scatter, depending in detail on the abundance patterns of SN ejecta with different progenitor masses.

By incorporation of a sequence of SN-induced star formation into the enrichment process of heavy elements, we describe the evolution of stellar abundances in the Galactic halo characterized by the inhomogeneous mixing of chemical compositions in dense shells and the ambient medium.

2. CHEMICAL EVOLUTION IN A CLOUD

We assume that the star-forming process is confined to separate clouds, of mass $M_c$, which make up the entire halo. In this section, we present a formulation to describe the chemical evolution in a cloud that is initially composed of metal-free Population III (Pop III) stars and gas that has yet to form stars. The mass fraction of such stars in our model is a parameter hereafter denoted by $x_{\text{III}}$, the massive ones of which eventually explode as Pop III SNe to initiate chemical evolution.
All stars of subsequent generations are assumed to form in SNR shells. The mass fraction of each shell that turns into stars is assumed to be constant and is denoted by $\epsilon$. Heavy elements ejected from an SN are assumed to be trapped and well-mixed within the SNR shell. Some of these elements go into stars of the next generation, and the rest are left in the gas that will be mixed with the ambient medium. The above process will repeat with increasing metallicity until SNRs can no longer sweep up enough gas to form shells. No stars will form from SNRs after this happens, and the process terminates.

When stars form as above, the star formation rate (SFR) $\dot{M}_s(t)$ induced by Pop III SNe at time $t$ measured from the birth of their progenitor stars is given by $\dot{M}_s(t) = \epsilon \Phi(m) \rho_s(t) R_{SN} E(m) \Phi(m)$, and the SFR for later generations can be expressed as

$$\dot{M}_s(t) = \int_{m_{min}}^{m_{max}} dm M_{\text{SN}}(m, t) \frac{\Phi(m)}{m} M_s[t - \tau(m)],$$

where $\tau(m)$ denotes the lifetime of a star of mass $m$, and $m_s$ is the stellar mass for which $\tau(m) = t$. The initial mass function (IMF) $\Phi(m)$ used here is a Salpeter one, with a slope index of $-1.35$. An upper mass limit of stars is assumed to be $m_s = 50 M_\odot$; a lower mass limit of $m_* = 0.05 M_\odot$ (Tsujimoto et al. 1997) is also assumed. The lower mass limit for stars that explode as SNe is taken to be $m_{SN, min} = 10 M_\odot$. The mass of the shell $M_{\text{SN}}(m, t)$ formed at time $t$ from an SN with progenitor mass $m$ is expressed as $M_{\text{SN}}(m, t) = M_{\text{SN}}(m) + M_{\text{SN}}(m, t)$, where $M_{\text{SN}}(m)$ is the mass of the SN ejecta, and the mass of the swept-up gas is given by $M_{\text{SN}}(m, t) = \rho_s(t) R_{SN} E(m) \Phi(m) \rho_s(t)$. Here $\rho_s(t)$ is the density of the interstellar gas, and $R_{SN}[E(m), \rho_s(t)]$ is the maximum radius of the SNR shell. $M_{\text{SN}}(m, t)$ is insensitive to time $t$ because $M_{\text{SN}}$ is proportional to $\rho_s(t)^{-0.06}$ (see ST98). The SN explosion energy is assumed to be $E(m) = 10^{51}$ ergs, irrespective of stellar mass $m$. Thus, a constant value of $M_{\text{SN}}(m, t) = 6.5 \times 10^4 M_\odot$ will be used below.

Utilizing the SFR introduced in equation (1), the mass $M_s(t)$ and the metallicity $Z_s(t)$ of the gas will change with time according to the following formulae:

$$\frac{dM_s}{dt} = -\dot{M}_s(t) + \int_{m_{min}}^{m_{max}} dm M_{\text{SN}}(m) \frac{\Phi(m)}{m} M_s[t - \tau(m)],$$

$$\frac{d(Z_s M_s)}{dt} = -\int_{m_{min}}^{m_{max}} dm Z_s(m, t) e M_{\text{SN}}(m, t) \frac{\Phi(m)}{m}$$

$$\times M_s[t - \tau(m)] + \int_{m_{min}}^{m_{max}} dm [M_{\text{SN}}(m)$$

$$- M_s(t)] \frac{\Phi(m)}{m} \int_{m_{min}}^{m_{max}} dm'$$

$$\times Z_s[m', t - \tau(m)] e M_{\text{SN}}(m', t - \tau(m)) \frac{\Phi(m')}{m'}$$

$$\times M_s[t - \tau(m) - \tau(m')] + \int_{m_{min}}^{m_{max}} dm$$

$$\times M_s(t - \tau(m) - \tau(m')) [M_{\text{SN}}(m')$$

$$- \tau(m)] \frac{\Phi(m')}{m'} M_s[t - \tau(m) - \tau(m')],$$

where $M_s(m)$ is the mass of all synthesized heavy elements ejected from a star with mass $m$, and $Z_s(m, t)$ is the metallicity of stars born at time $t$ from an SNR shell with progenitor mass $m$, which is defined as $Z_s(m, t) = [M_s(m) + Z_s(t) M_{\text{SN}}(m, t)]/[M_{\text{SN}}(m) + M_{\text{SN}}(m, t)]$.

Since $M_s(0) = x_{III} M_s$ and $M_s(t) = (1 - x_{III}) M_s$ at $t = 0$, after specifying $x_{III}$ and $M_s$ and setting $Z_s(0) = 0$, equations (2) and (3) are then integrated. Star formation stops when the total
The total number of stars in each case is normalized to 100. The dashed line denotes the age-metallicity relation of the gas.

The mass involved in SNR shells reaches the total mass of gas, i.e.,

\[
\int_{t - \Delta t}^{t} dt' \int_{m_{\text{max}}(m, \tau)}^{m_{\text{top}}(m, \tau)} dm \frac{M_{\odot}(m, t') \phi(m)}{m} \times \dot{M}_{\odot}[t' - \tau(m)] = M_{\odot}(t),
\]

where \(\Delta t\) is the time for the turbulent motion in the ambient medium to destroy completely the shape of an SNR shell. In the following calculation, \(\Delta t = 3 \times 10^{6}\) yr is adopted, which corresponds to the crossing time of the turbulent flow over an SNR.

The heavy-element yields from SNe are estimated directly from the observed abundances in metal-poor stars, as opposed to the presently uncertain predictions of theoretical supernovae models, using the procedure proposed by ST98 and Tsujimoto & Shigeyama (1998). We note that the europium yield is estimated from the data of Ryan et al. (1996).

3. Results

From the formulation in the preceding section, we calculate the chemical evolution for Galactic halo stars. The free parameters in our model are the mass fraction \(x_{\text{III}}\) of metal-free Pop III stars initially formed in each cloud and the mass fraction \(\epsilon\) of stars formed in a dense shell of each SNR. The values of these parameters are chosen to reproduce the observed [Fe/H] distribution function of halo field stars for [Fe/H] < -1. If \(x_{\text{III}}\) is larger than about \(1 \times 10^{-2}\), the total gas swept up by the first SNRs exceeds the entire amount of available gas, and thus star formation stops at the first or second generation. In order for the enrichment process to continue as a sequence of SN-induced star formation, \(x_{\text{III}}\) must be less than about \(1 \times 10^{-2}\). In addition, \(\epsilon\) must be strictly confined within a narrow range so that slightly more than one massive star is born from each SNR. This might imply that star formation is suppressed and self-regulated by the photoionization from an OB star. A value of \(\epsilon = 4.3 \times 10^{-3}\) is found to give the best fit to the observed [Fe/H] distribution function for various values of \(x_{\text{III}}(<1 \times 10^{-2})\). If \(\epsilon\) slightly exceeds this critical value, star formation will soon stop with little enrichment by heavy elements. On the other hand, if \(\epsilon\) is taken slightly below its critical value, star formation will proceed until most of the gas is used up. In such a scenario, the majority of halo stars become too metal-rich to be consistent with observations.

The duration \(\Delta T\) of star formation in a cloud is related to \(x_{\text{III}}\) in the sense that a smaller \(x_{\text{III}}\) gives a longer \(\Delta T\). Here we define a probability \(p_{\text{III}}\) of observing Pop III stars as a fraction of their number among all of the long-lived stars that have ever formed with \(m < M_{\odot}\). The probability \(p_{\text{III}}\) decreases with increasing \(\Delta T\)—this relation is shown by the thick line in Figure 1. Each value of \(p_{\text{III}}\) corresponds to about 10 times \(x_{\text{III}}\), because about 10% of \(M_{\odot}(0)\) has been converted to stars in the end. We note that the most metal-poor halo stars exhibit abundance patterns of genuine SN II origin, showing the over-abundance of \(\alpha\)-elements relative to iron Fe (e.g., Wheeler, Sneden, & Truran 1989), which means that they were born before SNe Ia start to contaminate the gas with their products. If the lower bound for the lifetime of SN Ia is set at 1 Gyr (Yoshii, Tsujimoto, & Kawara 1998), the duration \(\Delta T\) has an upper bound, and the probability \(p_{\text{III}}\) should be larger than \(10^{-4}\). However, such an argument does not hold if relatively few SNe Ia occur at [Fe/H] < -1 as argued by Kobayashi et al. (1998).

One absolute condition under which the SN-induced star formation proceeds in a cloud is that at least one massive star...
of Pop III must initially explode as an SN. Therefore, for each mass $M_*$ of a cloud, a lower bound of $p_{\text{HI}}$ exists, and this is indicated in Figure 1 by the vertical dashed line. If $M_*$ is in a range of several $10^5 - 10^7 M_{\odot}$, which is inferred from the mass scale of the Galactic globular clusters, one Pop III star might be observed in a complete sample of $10^3 - 10^4$ halo stars. This estimate depends critically on the assumed IMF for Pop III stars. For instance, if we adopt the theoretical IMF for metal-free stars proposed by Yoshii & Saio (1986), the expected $p_{\text{HI}}$ is reduced by a factor of 15-45.

Figure 2 shows the predicted stellar [Fe/H] distribution function for $x_{\text{HI}} = 10^{-6}$, as compared with the data obtained by Ryan & Norris (1991). The result has been convolved with a Gaussian of $\sigma = 0.15$ dex (dotted line) and $\sigma = 0.3$ dex (solid line) because measurement errors in [Fe/H] lie between these values (Ryan & Norris 1991). Rather good agreement with the data is obtained for [Fe/H] $< -1$ using the Salpeter IMF, without decreasing the heavy-element yield by some manipulation such as mass loss from the halo (Hartwick 1976; Searle & Zinn 1978; Bond 1981; Laird et al. 1988; Ryan & Norris 1991). The termination of star formation at the gas metallicity of [Fe/H] $\sim -1.5$, leaving about 90% of the initial gas, produces the peak of stellar frequency at [Fe/H] $\sim -1.6$, as observed.

Figure 3 shows the predicted [Fe/H] distribution function of stars formed at a given age in the age-[Fe/H] plane. Three distribution functions shown at different ages of $4 \times 10^8$, $8 \times 10^8$, and $1.2 \times 10^9$ yr normalized in such a way that the total number of stars is 100. The dashed line denotes the age-metallicity relation of the gas. It is important to note from this figure that the stellar metallicity does not correspond to a unique age but that the scatter in stellar [Fe/H] among stars formed at a given age progressively diminishes with time. As can be appreciated from inspection of the figure, some stars with abundance [Fe/H] $> -3.0$ will form at essentially the same time as stars with abundances much lower than this value.

Our primary concern is whether the observed stellar elemental abundance patterns in the most metal-deficient halo stars can be predicted by our model. The abundance ratio [Eu/Fe] is a suitable probe for this purpose, because this ratio in extremely metal-deficient stars (McWilliam et al. 1995; Ryan et al. 1996) spans over 2 dex, far exceeding the measurement errors. Figure 4 shows the color-coded frequency distribution of stars in the [Eu/Fe]-[Fe/H] plane, normalized to unity when integrated over the entire area (see the color bar for the scale). In order to compare with the data, the frequency distribution has been convolved with a Gaussian with $\sigma = 0.2$ dex for [Eu/Fe] and $\sigma = 0.15$ dex for [Fe/H]. For illustrative purposes, the frequency distribution without convolution is also shown in the inset. The predicted [Eu/Fe]-[Fe/H] relation for the gas is shown by the dashed line. The predicted scatter in [Eu/Fe] becomes smaller toward larger [Fe/H] and converges to a plateau at $-2 < [\text{Fe/H}] < -1$. This tendency, which is also seen in other elements, is understood by considering that the major contribution to stellar metallicity has switched from the ejecta of SNe to the metallicity in the interstellar gas swept up by SNRs.

4. CONCLUSION

We have presented a new model for Galactic chemical evolution based on the SN-induced star formation hypothesis. An overview of our model applied to the Galactic halo as follows: (1) The metal-free Pop III stars form by some (as yet unspecified) mechanism in primordial gas clouds of the Galactic halo. (2) The most massive stars among them explode as Type II SNe, which trigger a series of star formation events. (3) Star formation terminates when dense shells cannot be formed from SNe. (4) About 90% of the cloud mass remains unused in star formation and may fall onto the still-forming Galactic disk. Our model predicts that stellar abundance patterns are different from those of the interstellar gas at the time when stars form. Calculations presented here have shown that the observed features of a large scatter in the europium-to-iron abundance ratios and the metallicity distribution function with $[\text{Fe/H}] > -1.6$ for halo field stars are naturally reproduced. A particularly attractive feature of our model is that an agreement with this mean stellar metallicity is achieved without decreasing the value of heavy-element yields from SNe.

Our model strongly suggests the existence of metal-free Pop III stars, because it is the first SN explosions among them that trigger a series of SN-induced star formation. Provided that star formation is confined to separate clouds with a mass of $10^4 - 10^7 M_{\odot}$, and that metal-free stars have a Salpeter IMF, it is estimated from the model that one Pop III star would be found in a sample of $10^3 - 10^4$ halo stars. Ongoing surveys that seek to increase the numbers of stars known at the lowest metal abundances (e.g., Beers, Preston, & Shectman 1992) provide the best hope for the eventual detection of this very first generation of stars. However, the probability of detecting them would be smaller if the primordial IMF is enhanced on the massive part compared with the Salpeter IMF (Yoshii & Saio 1986) and/or if the accretion of interstellar gas contaminates the surface of metal-free stars (Yoshii 1981). Both of these possible complications are suitable for direct tests via high-resolution observations of a sufficiently large sample of dwarf and giant stars with [Fe/H] $< -2.0$, which already exists (see Beers 1999 for a review). For an insight into the star formation process, it may be interesting to consider that stars can be born from interstellar gas disturbed by shock waves, implying that the first-generation stars (Pop III stars) could have been born in a dense shell formed by shock waves triggered by a cloud-cloud collision in a protogalaxy.

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