The yields of r-process elements and chemical evolution of the Galaxy

1 Introduction

Elemental abundances in metal-poor Galactic halo stars are providing evidence of the earliest Galactic nucleosynthesis history and clues about the identities of the first stellar generations, the progenitors (or predecessors) of the halo stars. The sample of identified field stars with [Fe/H]\textlesss\textless-2.5 has increased by more than an order of magnitude in the last decade. Because the elements in the atmospheres of these stars have been produced in a small number of nucleosynthetic events, abundance determinations can provide direct tests of model yields from different nuclear processes.

The elements heavier than the iron peak are made through neutron capture via two principal processes: the r-process and the s-process (Burbidge et al., 1957). The r-process (for rapid process) occurs when neutrons are added much more rapidly than the $\beta$ decay times of the relevant nuclei. The site or sites of the r-process are not known, although suggestions include the $\nu$-driven wind of Type II SNe (e.g., Woosly and Hoffman, 1992; Woosly et al., 1994) and the mergers of neutron stars (e.g., Lattimer and Schramm, 1974; Rosswog et al., 2000).

Particular attention to the Galactic evolution of elements produced by neutron-capture nucleosynthesis was given by Mathews et al., (1992), Pagel and Tautvaisiene (1997), and more recently by Travaglio et al. (1999). These authors adopted the standard approach to Galactic chemical evolution, assuming that stars form from a chemically homogeneous medium at a continuous rate. A more realistic model for the chemistry and dynamics of the gas is needed in order to investigate the earliest phases of halo evolution.

Recently, several chemical evolution models statistics on the build-up of chemical elements in the early Galaxy (e.g., Tsujimoto et al., 1999; Argast et al., 2000; Oey, 2000; Travaglio et al., 2001; Fields et al., 2002); Tsujimoto et al., (1999) provided an explanation for the spread of Eu observed in the oldest halo stars in the context of a model of supernova-induced star formation. Assuming that r-process nucleosynthesis sites would most likely be identified with Type II supernovae (SNe II), Mathews et al. (1992) suggested a mass range of $M_{\text{ms}}=7-8M_\odot$ for the site, while Travaglio et al. (1999) supported a somewhat higher mass range, $M_{\text{ms}}=8-10M_\odot$. Cescutti et al. (2005) concluded that the Eu should originate as
an r-process element in stars with masses in the range 10–30\(M_\odot\).

Recent observations and the analyses imply that the abundance pattern of an extremely metal-deficient star with [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 et al., 1996). Tsujimoto and Shigeyama (1998) have also shown that the mass of r-process elements ejected by each SN II as a function of progenitor mass at the main sequence (\(M_{ms}\)) can be derived from the observed [Ba/Mg]-[Mg/H] trend combined with the [Mg/H]-\(M_{ms}\) relation in theoretical SN models. But some of extremely metal-deficient stars with [Fe/H] \(\leq\) -2.5 could be formed out of gas enriched by several SNe (Fields et al., 2002).

In this paper, we assume that the stars on the left-side [Ba/Mg]-[Mg/H] boundary are made from individual supernova events. In Section 2 we discuss the r-process elements yields based on the model proposed by Tsujimoto and Shigeyama (1998). In Section 3 the r-process elements yields are used to explore the early stages of inhomogeneous chemical evolution in the Galaxy. Conclusions are given in Section 4.

2 Production site and yield for r-process elements

Assuming that the stars on the left-side [Ba/Mg]-[Mg/H] boundary retain the abundance pattern of a single supernova and using the similar procedure presented by Tsujimoto and Shigeyama (1998), we can calculate the r-process elements yields as a function of the initial stellar mass from theoretical SN models (e.g., Woosley and Weaver, 1995; Tsujimoto et al., 1995; Nomoto et al., 1997).

In Fig. 1a, which uses the data of Mcwilliam et al. (1995), Mcwilliam (1998), Lai et al. (2004), Honda et al. (2004) and Barklem et al. (2005), the [Ba/Mg] values for a sample of metal-poor stars are plotted against [Mg/H]. We infer yields for Ba element from the left-side boundary of observed abundances in stars with -4 \(\leq\) [Fe/H] \(\leq\) -2.5 by calculating the chi-squared fit to the data. The fitted line is shown in Fig. 1a, which represents the mass range of the r-process site. This gives a relation between the metallicity [Mg/H] of stars and the mass Mms of SN II progenitor as shown in Fig. 1b. Since the observed abundances in CS22892-052 and other stars strongly enriched r-elements ([Eu/Fe] \(\geq\) 1.0) may not reflect the composition of the ISM from which it formed (Qian and Wasserburg, 2003, Barbey et al. 2005), we exclude these stars in our calculation.

Using the theoretical nucleosynthesis mass of Mg for each Mms (Tsujimoto et al., 1995), the ejected mass of element as a function of Mms is derived. The yield of Ba obtained is shown in Fig. 2. In addition, Eu is a tracer of the r-process, so we investigate the enrichment of Eu as a representative of r-process elements. Because the abundance pattern of heavy neutron capture elements (Z \(\geq\) 56) for each star is quite similar to that of the r-process component in solar-system material (Senden et al., 1994, Cowan et al., 1995), the Eu yield can be derived from \(M_{ej, Eu} = M_{ej, Ba} (\frac{Eu}{M_{ms}})\), and also shown in Fig. 2. According to our present models, SNe II with Mms = 12–20\(M_\odot\) do not produce significant amounts of r-process elements. It is indicated that SNe with Mms \(\geq\) 18\(M_\odot\) are r-process main sites. The derived mass of Ba synthesized in SNe II is \(3 \times 10^{-6}M_\odot\) for Mms = 20\(M_\odot\), which is in good agreement with the values of Tsujimoto and Shigeyama (2001) and Pastorello (2005). We remind the reader that our model is based on the observed abundances of the metal-poor stars, so the uncertainties of those observations will be involved in the model calculations. We note from Fig. 1a and 1b.
that for the massive stars \((M > 25M_\odot)\) the boundary is not explicit, so the uncertainties of the \(r\)-process yields for these stars are larger than those of lower mass stars.

### 3 The \(r\)-process scatter and the Galactic halo evolution

The very metal-poor stars, presently found in the halo of the Galaxy, are believed to have formed at the earliest times, shortly after it became possible for the Universe to make stars with sufficiently long main-sequence lifetimes to survive for \(\sim 14\) Gyr (Senden et al., 2003). The chemical compositions of these stars are thus expected to reflect a quite small number of nucleosynthesis processes, possibly as small as one (e.g., the stars on the left-side boundary in Fig. 1a), while the compositions of metal-rich stars reflect the cumulative results of the various processes that have been in operation during the entire history of Galactic chemical evolution. Models for \(r\)-process nucleosynthesis and for the Galactic chemical evolution must account for the scatter of \(r/Fe\) between halo stars, as well as for the smaller scatter between disk stars. We assume, as Fields et al. (2002) did, that the observed Pop II \(r/Fe\) abundance in each star reflect \(r\)-process contributions of a few SNe II. The basic idea is that the \(r/Fe\) scatters arise from mixing among different mass SNe II, which can produce different yields of \(r\)-process elements.

To model the scatter of \(r/Fe\), we create a set of halo stars and deduce the history-the nucleosynthetic ancestry -of each. We assume that a single supernova event mixes its metals and \(r\)-elements over a region of mass \(M\) and analyze the mixing history of the interstellar medium (ISM). For the first generation of SN, the \(r\)-elements and iron yield of in the \(i\)th region is \(m_{r1}(i)\) and \(m_{Fe1}(i)\) respectively. Since a given parcel of ISM gas can be enriched to different degrees by the ancestors it had, the new region (with mass \(M\) also) polluted by the successive generation of SN comprises material originating from J old regions. The accumulated \(r\)-elements and iron yields of \(i\)th new region after the \(N\)th generation of SN are

\[
m_{rN}(i) = m_{r1}(N-1,i) + m_{rN} \tag{1}
\]

\[
m_{FeN}(i) = m_{Fe1}(N-1,i) + m_{FeN} \tag{2}
\]

where the reduced yields of the former (\(N-1\)) generations SNe contributed to the new region are

\[
m'_{r(N-1),i} = \sum_j P_{j,i} m_{r(N-1)}(k_j) \quad \text{and} \quad m'_{Fe(N-1),i} = \sum_j P_{j,i} m_{Fe(N-1)}(k_j). \tag{3}
\]

To simplify notation, we will define the scale \(r/Fe\) ratio to be

\[
R = \frac{r/Fe}{(r/Fe)_\odot}
\]

which implies that \([r/Fe] = \log R\) When taking the yield of SN II with \(M_{ms} = 20M_\odot\) and \(m_{Fe} = 0.07M_\odot\), we can obtain a value of \(R\approx 50\), which is consistent with the value of Fields et al. (2002). We assume that each of the halo stars we create incorporates gas cloud which has been enriched by some number \(N\) of supernova: this is the number of supernova ancestors for the star. Let the total number of supernova events be \(N\), we have that

\[
R_{N,i} = \frac{m_{rN}(i)/A_{r}}{m_{FeN}(i)/A_{Fe} / (r/Fe)_{\odot}} \tag{4}
\]

At the very earliest time, when single supernova events really contaminate a given star, the \([r/Fe]\) scatter only populates the extremes; at later time, mixing becomes efficient gradually, and then the scatter decreases. So the \([r/Fe]\) becomes a tracer of the inhomogeneity of the halo. Several groups (Argast et al., 2000; Tsujimoto et al., 1999; Oey, 2000) have used similar arguments to motivate detailed models that explain the observed \([r/Fe]\) scatter in terms of \(r\)-process nucleosynthesis and an inhomogeneous chemical evolution of the Galactic halo. In our model, the \(Fe\) yield is given in Fig. 2 and iron yield is adopted as follows:

**Case A:** \(M_{Fe} = 0.07M_\odot\)

**Case B:** \(M_{Fe}\) is a function of progenitor mass (Tsujimoto et al., 1995).

The metallicity determines the total number of supernova ancestors via

\[
[Fe/H]_{N,i} = \log X_{Fe^+} - \log X_{Fe^0} = \log \frac{m_{FeN}(i)}{M \times X_{Fe^0}} \tag{5}
\]
where $X_{\text{Fe}}$ and $X_{\text{Fe}}$ are the mass fraction of Fe in solar system and the polluted region respectively. In the early Galaxy, the gas composed of only hydrogen and helium with their ratio $X_H:X_{He}=0.75:0.25$, so

$$M = M_{SW}/0.75$$

where $M_{SW}$ is the mass of hydrogen swept up by an supernova remnant (Shigeyama and Tsujimoto 1998). On one hand, when $J$ is large enough, equations (4) and (5) will give the form of well-mixed chemical evolution of the Galactic halo which could not explain the scatter of [Eu/Fe] observed for metal-poor stars, on the other hand, when $J=1$, these equations will give the result that all the Fe and r-elements ejected from N supernovae may pollute only one supernova remnant and this is not what actually occurs. In fact, the $J$ must be very small, so we take $J=2$ in this work.

It is of interest to consider making the mass of ancestor a random variable. The initial mass distribution of supernova progenitor is generated according to the formula of Eggleton et al. (1989),

$$M = \frac{0.19 X}{(1 - X)^{0.75} + 0.032(1 - X)^{0.25}}$$

where $X$ is a random number uniformly distributed between 0 and 1, which leads to a mass function similar to that of Miller and Scalo (1979). Results for a Monte Carlo simulation of a stellar population appear in Fig. 3 and Fig. 4 for Case A and Case B respectively. The degree of scatter increases with decreasing metallicity because of counting statistics, so that the lowest metallicity events record the nuclesynthesis of a few events. Using the abundance pattern of heavy neutron-capture elements ($Z \geq 56$) is quite similar to that of the r-process component in solar-system material (Sneden et al., 1994; Cowan et al., 1995), Figs. 5 and 6 show the scatters of [Ba/Fe], [Ce/Fe], [La/Fe], [Nd/Fe], [Pr/Fe], [Sm/Fe] for Case A and B respectively. A comparison with the observed data in Figs. 3-6 shows that the model gives a good fit to the available data. We thus conclude that the observed scatter in [r/Fe] can be understood by our model.

4 Conclusions

Assuming that the stars on the left-side [Ba/Mg]-[Mg/H] boundary retain the abundance pattern of a single supernova, we have calculated the r-process elements yields as a function of the initial stellar mass from theoretical SN models. The scatter of [r/Fe] in halo strongly suggests that SNe II associated with stars of progenitor mass $M_{ms} \leq 18M_{\odot}$ are infertile sources for the production of r-process elements, which is in agreement with the result of Tsujimoto et al. (2000). We conclude that SNe
Fig. 5 Correlation of [X/Fe] with [Fe/H]. The symbols represent the data taken from the same refs of Fig. 3. The dots represent the Case A result of our model, where X represents successively Ba, Ce, La, Nd, Pr, Sm.

II with $20M_\odot \leq M_{ms} \leq 40M_\odot$ are the dominant source of r-process nucleosynthesis in the Galaxy. The effect on the SNe II which produces the high r-process yield could be significant. Assuming a Salpeter IMF with $\alpha=-2.35$, the ratio of these stars compared to the all massive stars is about $\sim 18\%$, which is higher than the value of case A in Fields, Truran, and Cowan (2002). In fact, the mean value of [r/Fe] obtained in our work is also higher than the value of R in Fields et al. (2002).

We have presented an approach to understand the scatter in heavy r-process-to-iron ratio in metal-poor halo stars and used a stochastic description of progenitor mass SNe II that contribution to the heavy r-process and iron abundances in each halo star. The random star-to-star variations in nucleosynthetic ancestry lead to scatter in [r/Fe]. The models we present are all successful in reproducing the scatter in the available data, which go down to about [Fe/H] $\approx 3$. In conclusion, the ratios of [r/Fe] with the metallicity are twofold. One is the abundance ratios for $[\text{Fe/H}] \leq -2.5$ imprinted by the nucleosynthesis in a few supernovae on the timescale $\sim 10^7$ yr and the other for $[\text{Fe/H}] \geq -2$ results from the mixing of the products from a whole site of the nucleosynthesis, taking place on the timescale longer than $10^9$ yr.

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Fig. 6 Correlation of [X/Fe] with [Fe/H]. The symbols represent the data taken from the same refs of Fig. 3. The dots represent the Case B result of our model. Where X represents successively Ba, Ce, La, Nd, Pr, Sm.

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