Chemical Evolution of Heavy Elements in the Early Galaxy: Implications for Stellar Sources

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Abstract: An overview of the sources for heavy elements in the early Galaxy is given. It is shown that observations of abundances in metal-poor stars can be used along with a basic understanding of stellar models to guide the search for the source of the heavy r-process nuclei (r-nuclei). Observations show that this source produces very little of the elements from C through Zn, including Fe. This strongly suggests that O–Ne–Mg core-collapse supernovae (SNe) from progenitors of \( \sim 8–11 M_\odot \) are the source for the heavy r-nuclei. It is shown that a two-component model based on the abundances of Fe (from Fe core-collapse SNe) and Eu (from O–Ne–Mg core-collapse SNe) gives very good quantitative predictions for the abundances of all the other elements in metal-poor stars.

Keywords: Galaxy: evolution — nuclear reactions, nucleosynthesis, abundances — stars: Population II — supernovae: general

1 Introduction

There are two approaches to studying chemical evolution. The straightforward approach relies on the knowledge of all nucleosynthetic sources, their elemental yields, their occurrences in the interstellar medium (ISM) and their exchange of material with the ISM. Based on this knowledge, both the average and the scatter for the abundance of any element in the ISM can be calculated as functions of time. Unfortunately, our knowledge of nucleosynthetic sources is rather incomplete. So this forward approach cannot be applied to all elements. On the other hand, the elemental abundances in stars generally reflect the composition of the ISM from which they formed. Given a large collection of data on stellar abundances, it is possible to infer the characteristics of some nucleosynthetic sources from these data with the help of some basic understanding of stellar models. This reverse approach works best at early times when only a small number of potential sources could have contributed to the ISM. This paper presents a combination of forward and reverse approaches to studying chemical evolution of heavy elements in the early Galaxy. The goal is to illustrate what can be learned about stellar sources from such studies.

Here ‘early’ means the first Gyr or so of Galactic history. During this epoch, only short-lived massive stars could have had time to evolve and contribute their nucleosynthetic products to the ISM. As \( \sim 1/3 \) of the solar Fe inventory was contributed by core-collapse supernovae (SNe, mostly Type II) associated with massive stars over a period of \( \sim 10 \) Gyr, ‘early times’ also correspond to \( <1/30 \) of the solar Fe abundance in the ISM. In the notation \([\text{Fe/H}] = \log(\text{Fe}/H) - \log(\text{Fe}/H)_\odot\), such times correspond to metal-poor ISM with \([\text{Fe/H}] < -1.5\). Three groups of heavy elements will be discussed: (1) the elements from C through Zn with mass numbers \( A < 70 \), (2) the elements from Sr through Ag with \( A \approx 88-110 \) and (3) the elements with \( A \approx 130 \) through the actinides attributed to the rapid neutron capture process (the r-process). The solar abundances of the elements with \( A \approx 88-209 \) received important contributions from the slow neutron capture process (the s-process). However, as the major s-processing occurs in long-lived (with lifetimes of \( >1 \) Gyr) stars of a few \( M_\odot \), the s-process contributions to the ISM at \([\text{Fe/H}] < -1.5\) can be ignored to good approximation. Likewise, contributions to the Fe group elements from Type Ia SNe associated with white dwarfs evolved from long-lived low-mass stars in binaries can also be ignored at \([\text{Fe/H}] < -1.5\).

2 Elements from C through Zn

The relevant sources for the elements from C through Zn are massive stars of \( >11 M_\odot \), which give rise to Fe core-collapse SNe at the end of their evolution. The elements from C through Al are mainly produced by hydrostatic burning during the pre-SN evolution and the elements from Si through Zn are mainly produced by explosive burning associated with the propagation of the SN shock through the shells above the Fe core. While the production of all these elements has some important dependence on the initial metallicity of the SN progenitor through, for example mass loss, pre-SN density structure and details of the explosion, theoretical yields of individual elements are broadly similar over a wide range of
The typical luminosity of the initial neutrino emission is the protoneutron star is modified by the reactions fluxes, the neutron-to-proton ratio of the material close to \( \approx 3 \) (e.g. Fröhlich et al. 2006a, Tomimaga et al. 2007). However, there are also important deficiencies of the SN models. For example, the calculated abundance ratios of N, K, Sc, Ti, Mn and Co relative to Fe are too low compared with observations (e.g. Tomimaga et al. 2007). Nitrogen is produced by the CN cycle when the C from He burning is mixed into the H burning shell. This production can be greatly enhanced by rotationally induced mixing when rotation is explicitly included in evolutionary models of metal-poor massive stars (e.g. Meynet, Ekström & Maeder 2006). On the other hand, the underproduction of K, Sc, Ti, Mn and Co can be remedied by modifying, for example the electron fraction of the material undergoing explosive nucleosynthesis.

The electron fraction \( Y_e \) specifies the neutron-to-proton ratio of the material and plays a crucial role in nucleosynthesis. The conversion between neutrons and protons can only proceed through the weak interaction involving neutrinos. The death of massive stars can be considered as a neutrino phenomenon. When the Fe core of such a star collapses into a protoneutron star, a great amount of gravitational binding energy is released in \( v_\nu, \bar{v}_\nu, L_\nu, v_\bar{\nu} \) and \( v_\nu \) with average energies of \( (E_\nu) \approx 10-20\text{MeV} \). Typical luminosity of the initial neutrino emission is \( L_\nu \sim 10^{52} \text{erg s}^{-1} \) per species. In the case of stable protoneutron stars, neutrino emission with \( L_\nu \sim 10^{51} \text{erg s}^{-1} \) per species lasts for \( \approx 20\text{s} \). With such intense neutrino fluxes, the neutron-to-proton ratio of the material close to the protoneutron star is modified by the reactions

\[
\begin{align*}
v_\nu + p & \rightarrow n + e^+, \\
v_\bar{\nu} + n & \rightarrow p + e^-.
\end{align*}
\]

The \( Y_e \) relevant for explosive nucleosynthesis in this material then depends on the competition between the above two reactions (e.g. Qian et al. 1993; Fuller & Meyer 1995; Qian & Woosley 1996). The rates of these reactions are proportional to the neutrino flux \( L_\nu/(E_\nu) \) and the cross section, which in turn is proportional to \( \langle |(E_\nu + \Delta^2) \rangle \approx (E_\nu^2) \pm 2\Delta (E_\nu) \) with the minus sign being for reaction (1), the plus sign for reaction (2) and \( \Delta = 1.293\text{MeV} \) being the neutron-proton mass difference. When the reaction rates are sufficiently high, \( Y_e \) is determined by their ratio as (Qian & Woosley 1996)

\[
Y_e \approx \left[ 1 + \frac{E_\nu}{E_{\bar{\nu}}} \left( \frac{\epsilon_{v_\nu} - 2\Delta}{\epsilon_{v_\bar{\nu}} + 2\Delta} \right) \right]^{-1},
\]

where \( \epsilon_{v_\nu} \approx (E_\nu^2)/(E_\nu) \).

As an example, the pairs of \( \epsilon_{v_\nu} \) and \( \epsilon_{v_\bar{\nu}} \) for \( v_\nu \) and \( v_\bar{\nu} \) emitted by the protoneutron star in the SN model of Woosley et al. (1994) during the first \( \approx 20\text{s} \) of its life are shown as the solid curve in Figure 1. The lower left end of the curve corresponds to the onset of the Fe core collapse at time \( t=0 \). Time increases along the curve in intervals of \( \approx 1/3\text{s} \) for \( t = 0 - 4\text{s} \) and \( \approx 1\text{s} \) for \( t > 4\text{s} \). The ratio \( L_\nu/L_{\bar{\nu}} \) stays close to 1 throughout the evolution. Values of \( \epsilon_{v_\nu} \) and \( \epsilon_{v_\bar{\nu}} \) lying above the upper dashed line in Figure 1 would give \( Y_\nu < 0.5 \) for \( L_\nu/L_{\bar{\nu}} = 1 \) according to equation (3), those below the lower dashed line would give \( Y_\nu > 0.5 \) for \( L_\nu/L_{\bar{\nu}} = 1.1 \) and those between the two dashed lines would give \( Y_\nu \approx 0.5 \), with the exact \( Y_\nu \) being sensitive to the value of \( L_\nu/L_{\bar{\nu}} \). Figure 1

![Figure 1](https://www.cambridge.org/core/terms)

Example evolution of \( \epsilon_{v_\nu} \) and \( \epsilon_{v_\bar{\nu}} \) for \( v_\nu \) and \( v_\bar{\nu} \) emitted by a protoneutron star (solid curve). Time increases along the solid curve starting from the lower left end. The ratio \( L_\nu/L_{\bar{\nu}} \) stays close to 1 throughout the evolution. Values of \( \epsilon_{v_\nu} \) and \( \epsilon_{v_\bar{\nu}} \) lying above the upper dashed line would give \( Y_\nu < 0.5 \) for \( L_\nu/L_{\bar{\nu}} = 1 \), those below the lower dashed line would give \( Y_\nu > 0.5 \) for \( L_\nu/L_{\bar{\nu}} = 1.1 \) and those between the two dashed lines would give \( Y_\nu \approx 0.5 \), with the exact \( Y_\nu \) being sensitive to the value of \( L_\nu/L_{\bar{\nu}} \). See Qian & Woosley (1996) for details.

Chemical Evolution of Heavy Elements in the Early Galaxy
3 Production of Heavy Elements in the Neutrino-Driven Wind

Reactions (1) and (2) not only are important for determining the $Y_e$ of the material close to the protoneutron star, but also heat this material, enabling it to expand away from the protoneutron star as a neutrino-driven wind (e.g. Qian & Woosley 1996). In fact, as long as a stable protoneutron star is formed by some core collapse, its neutrino emission drives such a wind for $\sim 20$ s. As the wind expands away from the protoneutron star, neutrinos can continue to affect nucleosynthesis. For example, the nuclear flow in proton-rich conditions encounters bottlenecks at nuclei with extremely slow proton-capture and $\beta^-$-decay rates. In the presence of an intense $\nu_e$ flux, the neutrons produced by reaction (1) can be captured by such nuclei to break through the bottleneck, giving rise to the so-called $\nu$-process (Frohlich et al. 2006b), which can produce many nuclei beyond $^{64}$Zn. It is important to find out whether the process (Fröhlich et al. 2006b), which can produce many nuclei beyond $^{64}$Zn. It is important to find out whether the process (Fröhlich et al. 2006b), Pruet et al. (2006) and Wanajo (2006).

As shown in Figure 1, the difference between $\epsilon_{\nu_e}$ and $\epsilon_{\alpha}$ increases with time and the neutrino-driven wind eventually becomes neutron-rich (i.e. $Y_e < 0.5$). What can be produced in a neutron-rich wind? In general, nucleosynthesis during expansion of material from an initial state of high temperature depends on $T_e$, the entropy $S$ and the dynamic expansion timescale $\tau_{\text{dyn}}$ of this material. In the neutrino-driven wind, these three parameters are determined by the mass, radius and neutrino emission characteristics of the protoneutron star (e.g. Qian & Woosley 1996). As the neutrino emission characteristics evolve, the conditions in the wind change accordingly. For illustration, we consider two sets of conditions corresponding to winds taking off at two different times from a protoneutron star of 1.4 Msun, with a radius of 10 km. At an earlier time, the wind has $Y_e \approx 0.47$, $S \approx 70$ (in units of Boltzmann constant per nucleon) and $\tau_{\text{dyn}} \approx 0.024$ s. As the neutron-rich material in this wind expands, the free nucleons first combine into $\alpha$-particles. This consumes essentially all the protons. Then an $\alpha$-process occurs to burn $\alpha$-particles and the remaining neutrons into heavier nuclei (Woosley & Hoffman 1992). By the time all charged-particle reactions (CPRs) cease at sufficiently low temperature due to the Coulomb barrier, the dominant products are Sr, Y and Zr with $A \sim 90$ and no neutrons are left to further process these nuclei by neutron capture (Hoffman, Woosley & Qian 1997). By the time all charged-particle reactions (CPRs) cease at sufficiently low temperature due to the Coulomb barrier, the dominant products are Sr, Y and Zr with $A \sim 90$ and no neutrons are left to further process these nuclei by neutron capture (Hoffman, Woosley & Qian 1997). For a late wind with $Y_e \approx 0.37$, $S \approx 90$ and $\tau_{\text{dyn}} \approx 0.066$ s, the dominant products are Zr, Mo, Ru, Rh, Pd and Ag with $A \sim 96-110$ (Hoffman et al. 1997). These nuclei are also produced by CPRs during the $\alpha$-process and no neutrons are left at the end. As another example, we consider a late wind from a heavier protoneutron star of 2 Msun but with the same radius of 10 km. The conditions of $Y_e \sim 0.35$, $S \sim 140$ and $\tau_{\text{dyn}} \sim 0.11$ s in this wind result in major production of Sn, Sb and Te, with $A \sim 124$ in addition to the nuclei with $A \sim 96-110$. Once again, all these nuclei are produced by CPRs during the $\alpha$-process and few neutrons are left at the end (Hoffman et al. 1997).

The above discussion shows that for the typical conditions in a neutron-rich wind, elements from Sr through Ag with $A \sim 88-110$ and in some cases nuclei with $A \sim 124$, are produced by CPRs during the $\alpha$-process. As no or very few neutrons are left at the end of the $\alpha$-process, these nuclei are the main products in such winds. In contrast, if the abundance ratio of neutrons to heavy nuclei greatly exceeds $\sim 10$ when CPRs cease to occur at a temperature of several $10^8$ K due to the Coulomb barrier, then the $\alpha$-process smoothly merges with the $\nu$-process as the heavy nuclei produced by the former rapidly capture neutrons at lower temperatures. This is the neutrino-driven wind model for the $r$-process (e.g. Woosley & Baron 1992; Meyer et al. 1992; Takahashi, Witti & Janka 1994; Woosley et al. 1994; Watanabe & Ishimaru 2006). In this model, the final abundance pattern produced by the $r$-process depends on how many neutrons are left for each seed nucleus at the end of the $\alpha$-process. For example, a neutron-to-seed ratio of $n/s = 40$ would dominantly produce an abundance peak at $A \sim 130$ while another value of $n/s = 90$ would dominantly produce nuclei of $A > 130$ with an abundance peak at $A \sim 195$.

In general, a specific value of $n/s$ can be achieved by various combinations of $Y_e$, $S$ and $\tau_{\text{dyn}}$. A lower $Y_e$ corresponds to a higher initial neutron abundance and usually also means that more neutrons are left at the end of the $\alpha$-process. A value of $S > 10$ indicates that the energy density of the material is dominated by radiation (and electron–positron pairs for sufficiently high temperature). The production of seed nuclei is severely suppressed for $S > 100$. This is because in producing the seed nuclei the nuclear flow must rely on the three-body reaction $\alpha + \alpha + n \rightarrow ^{9}\text{Be} + y$ to bridge the gap at $A = 5$ and 8. It only requires a photon of 1.573 MeV to dissociate a $^4\text{Be}$ nucleus back into two $\alpha$-particles and a neutron. For a high $S$, there are a significant number of such photons in the high-energy tail of the Bose–Einstein distribution over the temperature range of $3-9 \times 10^8$ K for the $\alpha$-process. The dynamic timescale $\tau_{\text{dyn}}$ controls how fast the temperature drops, thereby specifying the duration of the $\alpha$-process. Clearly, the shorter $\tau_{\text{dyn}}$ is, the fewer seed nuclei are produced. In summary, a lower $Y_e$, or a higher $S$, or a shorter $\tau_{\text{dyn}}$ tends to give a larger $n/s$.

Combinations of $Y_e$ and $S$ that would result in major production of an $r$-process abundance peak at $A \sim 195$ for three different values of $\tau_{\text{dyn}}$ (Hoffman et al. 1997; see also Meyer & Brown 1997; Freiburghaus et al. 1999) are shown in Figure 2. It can be seen that for $Y_e \sim 0.4$ and $S \sim 100$ typical of the neutrino-driven wind, an extremely short dynamic timescale of $\tau_{\text{dyn}} \sim 0.004$ s is required to produce an $r$-process abundance peak at $A \sim 195$. 

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Figure 2: Combinations of $\dot{T}_N$ and $\dot{S}$ that would result in major production of an $r$-process abundance peak at $A \sim 195$ during expansion of material from an initial state of high temperature for three values of $\dot{T}_{\nu_{\mu}}$. See Hoffman et al. (1997) for details.

However, the actual dynamic timescale typical of the wind is $\dot{T}_{\nu_{\mu}} \sim 0.01-0.1$ s. Studies by several groups (Qian & Woosley 1996; Witt et al. 1994; Thompson, Burrows & Meyer 2001) found that it is generally very difficult to obtain the conditions required for producing an $r$-process abundance peak at $A \sim 195$ in the neutrino-driven wind, although it is quite plausible that the conditions in the wind from at least some protoneutron stars (e.g. those with masses of $\sim 2 M_\odot$) are sufficient for producing $r$-process nuclei up to $A \sim 130$.

4 Source for $r$-Process Nuclei with $A > 130$

In search of the source for the heavy $r$-process nuclei ($r$-nuclei) with $A > 130$, especially those in the peak at $A \sim 195$ of the solar $r$-process abundance pattern ($r$-pattern; e.g. Arlandini et al. 1999), there were attempts to modify the conditions in the neutrino-driven wind by, for example, including the effects of a magnetic field above the protoneutron star (Thompson 2003) as well as proposals of alternative sites such as neutron star mergers (e.g. Freiburghaus, Rosswog & Thielmann 1999) and the wind from the accretion disk around a black hole (Pruet et al. 2003; McLaughlin & Surman 2005). Yet another approach is to seek guidance from observations. For example, the detection of the $r$-process element ($r$-element) Ba with $A \sim 135$ in a number of stars with [Fe/H] $\sim -3$, especially the high Ba enrichments in several stars with [Fe/H] $\sim -3$, is crucial in evaluating neutron star mergers as the major source for the heavy $r$-nuclei. These events are much rarer (by at least a factor of $10^3$) than Fe core-collapse SNe. If neutron star mergers were the major source for the heavy $r$-nuclei, then enrichment in these nuclei would not occur until the ISM had already been substantially enriched in Fe by Fe core-collapse SNe (Qian 2000; Argast et al. 2004). This is in contradiction to the observations of stars with significant to high Ba abundances but very low Fe abundances. Therefore, it appears very unlikely that neutron star mergers are the major source for the heavy $r$-nuclei. In contrast, if some events with a Galactic rate of occurrences similar to that of Fe core-collapse SNe are the source for such nuclei, then the expected relationship between Ba and Fe abundances is in good agreement with stellar observations (e.g. Argast et al. 2004).

Extensive observations of the abundances of a wide range of elements in metal-poor stars provide further guidance to the search of the source for the heavy $r$-nuclei. Figure 3b shows the data for the three stars on the right of the vertical dotted line, the data on the heavy $r$-elements are compared with the solid, dot-dashed and dashed curves, which are the solar $r$-pattern (Arlandini et al. 1999) translated to pass through the Ba data for CS 31082–001 in the region to the left of the vertical dotted line are again connected by solid line segments as a guide. The downward arrow at the asterisk for N indicates an upper limit. Note that the available abundances for the elements from O through Ge are almost indistinguishable for the three stars. The log $\epsilon$ values for the elements from Sr through Pt are connected by solid line segments as a guide. There is a range of $\sim 2$ dex in the abundances of the heavy $r$-elements for the three stars shown.

Figure 3: Data on the elements from C through Pt in CS 31082–001 (asterisks; Hilt et al. 2002), HD 115444 (filled circles) and HD 122563 (squares; Westin et al. 2000) with [Fe/H] = $-2.9$ and $-2.74$, respectively. (a) The values of $\log \epsilon(E)$ vs log $E$ is $-1.9 \pm 0.99$ and $-2.74$, respectively. (a) The values of $\log \epsilon(E)$ vs log $E$ for the solar $r$-pattern are indicated by solid line segments as a guide. There is a range of $\sim 2$ dex in the abundances of the heavy $r$-elements for the three stars shown.
The decoupling between these elements and the heavy nuclei appears to be complete: the major source for the former produces very little of the heavy elements, which again closely follow the solar r-pattern. However, as shown by the data on these stars (Hill et al. 2002; Cowan et al. 2002; Sneden et al. 2003; Ivans et al. 2006) and reflected by their [Fe/H] values, the abundances of the elements between O and Ge differ by a factor of ~8 and 6 for the former and latter pair, respectively. Therefore, the decoupling between the heavy r-nuclei and the elements from C through Ge appears to be complete: the major source for the former group of nuclei produces very little of the latter while the major source for the latter produces very little of the former.

The elements from C through Zn are produced between the core and the H envelope by explosive burning during a core-collapse SN or by hydrostatic burning during the pre-SN evolution. Stars of >11 M☉ develop Fe cores surrounded by extensive shells of Si, O, C and He. Consequently, Fe core-collapse SNe from these stars are the major source for the elements from C through Zn in the early Galaxy. The decoupling between these elements and the heavy r-nuclei discussed above then strongly suggests that such SNe are not the source for the heavy r-nuclei. In contrast, stars of ~8–11 M☉ develop degenerate O–Ne–Mg cores, at least some of which eventually collapse to produce SNe (e.g. Nomoto 1984, 1987; Ritossa, García-Berro & Iben 1999). Models of O–Ne–Mg core-collapse SNe show that the total amount of material ejected from between the core and the H envelope is only ~0.01–0.04 M☉ (Mayle & Wilson 1988; Kitaura, Janka & Hillebrandt 2006), much smaller than the ~1 M☉ for Fe core-collapse SNe. Thus, O–Ne–Mg core-collapse SNe contribute very little to the elements from C through Zn. The decoupling between these elements and the heavy r-nuclei can then be explained by attributing the heavy r-nuclei to such SNe as argued in Qian and Wasserburg (2002, 2003, 2007).

O–Ne–Mg core-collapse SNe were also proposed as the source for the heavy r-nuclei based on considerations of Galactic chemical evolution by other studies (e.g. Mathews, Bazan & Cowan 1992; Ishimaru & Wanajo 1999). This proposal is supported by the model for r-process nucleosynthesis presented in Ning, Qian & Meyer (2007). Unlike previous models based on assumed extremely neutron-rich ejecta (e.g. Wheeler, Cowan & Hillebrandt 1998; Wanajo et al. 2003), this new model relies on the SN shock that rapidly accelerates through the surface C-O layers of the O–Ne–Mg core due to the steep density fall-off in these layers. This gives rise to fast expansion of the shocked ejecta on dynamic timescales of τdyn~10^-4 s. Together with an entropy of S~100 and
As summarized in Table 1, considerations of chemical evolution of heavy elements can be seen that the data on the heavy elements from Sr through Ag is shown as the curves labelled in Figure 5a. These data are linked by line segments to guide the eye. The solar r-pattern is translated to pass through the Eu data (curves labelled as such). Squares with downward arrows indicate upper limits. The abundance pattern of the heavy r-elements (\(Z > 56\)) and above) in HD 122563 shown in (a) exhibits substantial differences from the solar r-pattern, especially for Ce and Pr. In addition, HD 122563 has much larger proportions of the elements from Sr through Ag relative to the solar r-pattern. (b) Comparison of the data on HD 122563 (squares with error bars linked by line segments, Honda et al. 2006) with those on CS 22892–052 (curves labelled as such, Sneden et al. 2003) normalized to the same log e(\(Y/Z\)) as for HD 122563.

Table 1. Stellar sources for heavy elements

<table>
<thead>
<tr>
<th>(A &gt; 130)</th>
<th>(8–11, M_\odot)</th>
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<tbody>
<tr>
<td>C to Zn ((A &lt; 70))</td>
<td>Yes</td>
</tr>
<tr>
<td>Sr to Ag ((A = 88–110))</td>
<td>Yes</td>
</tr>
<tr>
<td>r-nuclei ((A = 130))</td>
<td>Maybe</td>
</tr>
<tr>
<td>r-nuclei ((A &gt; 130))</td>
<td>No</td>
</tr>
</tbody>
</table>

* Progenitors of Fe core-collapse SNe.

† Progenitors of O–Ne–Mg core-collapse SNe.

an initial electron fraction of \(Y_e \sim 0.495\) (e.g. for a composition of \(^{13}\)C, \(^{12}\)C; \(^{16}\)O \(\approx 1 : 3 : 3\) by mass), this fast expansion enables an r-process to occur in the shocked ejecta, producing the heavier nuclei with \(A > 130\) through the actinides. To further test this model requires two lines of important studies: (1) calculating the evolution of \(8–11\, M_\odot\) stars to determine the pre-SN conditions of O–Ne–Mg cores, especially the neutron excess and density structure of the surface layers; and (2) simulating the collapse of such cores and the subsequent shock propagation to determine the conditions of the shocked surface layers. As these layers contain very little mass, simulations with extremely fine mass resolutions are required to demonstrate the fast expansion of shocked ejecta that is the key to the production of the heavy r-nuclei in the above model.

5 Conclusions

As summarized in Table 1, considerations of chemical evolution of heavy elements in the early Galaxy based on stellar observations and current understanding of stellar models show that (1) Fe core-collapse SNe from progenitors of \(8–11\, M_\odot\) are the major source for the elements from C through Zn in the early Galaxy; (2) O–Ne–Mg core-collapse SNe from progenitors of \(8–11\, M_\odot\); and (3) as both Fe and O–Ne–Mg core-collapse SNe can produce proton-neutron stars that emit neutrinos to drive winds, both kinds of SNe can produce the elements from Sr through Ag by CPRs during the \(\omega\) process. The neutrino-driven winds in some Fe core-collapse SNe (e.g. those producing heavier proton-neutron stars) may even produce r-nuclei with \(A \sim 130\) (corresponding to the elements Te, I and Xe), but stellar observations cannot help us to identify the sources for these nuclei as they are inaccessible to spectroscopic studies.

Based on the above attribution, one may try to identify two templates for the overall production of heavy elements by Fe and O–Ne–Mg core-collapse SNe, respectively. The squares with error bars in Figure 5a show the data on the elements from Sr through Ag compared with the solar r-pattern translated to pass through the Eu data (curves labelled as such). Squares with downward arrows indicate upper limits. The abundance pattern of the heavy r-elements (\(8–11\, M_\odot\)) and above) in HD 122563 shown in (a) exhibits substantial differences from the solar r-pattern, especially for Ce and Pr. In addition, HD 122563 has much larger proportions of the elements from Sr through Ag relative to the solar r-pattern as compared to the solar r-pattern. (b) Comparison of the data on HD 122563 (squares with error bars linked by line segments, Honda et al. 2006) with those on CS 22892–052 (curves labelled as such, Sneden et al. 2003) normalized to the same log e(\(Y/Z\)) as for HD 122563.

Ag lie far above it. This suggests that the source responsible for the abundances in HD 122563 is not a major contributor to the heavy r-elements but mainly produces the elements from Sr through Ag. Consequently, the overall abundance pattern in this star including the elements from C through Zn may be taken as representative of the yields of Fe core-collapse SNe. For convenience, this pattern will be referred to as the L-pattern (-dominated by lighter nuclei). As Fe core-collapse SNe are the major source for Fe in the early Galaxy, the Fe abundance in a metal-poor star can be used along with the L-pattern to identify the absolute contributions from such SNe to all the elements in this star.

As shown in Figures 3 and 4, a number of metal-poor stars exhibit a highly regular abundance pattern of the heavy r-elements that is essentially identical to the solar r-pattern. The data on one such star, CS 22892–052, which are shifted to pass through the Y data for
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for the abundances of these elements in CS 22892–052
CS 22892–052 indicates that Fe core-collapse SNe con-
HD 122563 for comparison with the latter star, are shown
as the curves labelled so in Figure 5b. The Fe abundance
HD 122563 (Honda et al. 2006) and CS 22892–052
remains to be seen whether self-consistent ab initio mod-
the L-pattern and the H-pattern are indeed characteris-
tics of the yields of Fe and O–Ne–Mg core-collapse SNe,
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\[
\frac{\Delta \log \epsilon(Sr)}{[Fe/H]} - \frac{\Delta \log \epsilon(Eu)}{[Fe/H]} = \frac{\Delta \log \epsilon(Fc)}{[Fe/H]} + \frac{\Delta \log \epsilon(Eu)}{[Fe/H]}. \tag{4} 
\]

where (E/Fe)$_{\text{cal}}$ and (E/Eu)$_{\text{cal}}$ are the yield ratios representing
the L-pattern and the H-pattern taken from the
data on HD 122563 (Honda et al. 2006) and CS 22892–052
(Sneden et al. 2003), respectively. As an example, the
abundances of Sr for a large number of metal-poor stars
are calculated from equation (4) using the observed Fe
and Eu abundances and compared with the data in terms
of $\Delta \log \epsilon(Sr) \equiv \log \epsilon(Sr)_{\text{cal}} - \log \epsilon(Sr)_{\text{obs}}$ in Figure 6a.
It can be seen that the calculated Sr abundances are within
0.3 dex of the data for the majority of the stars. With the
limited data available for the elements Nb, Mo, Ru, Rh,
Pd and Ag, even better agreement between the calculated
and observed abundances is obtained for these elements
as shown in Figure 6b. In conclusion, the two-component
model based on equation (4) appears to provide a very
good description of the abundances in metal-poor stars.
It remains to be seen whether self-consistent ab initio mod-
els of stellar evolution and nucleosynthesis can show that
the L-pattern and the H-pattern are indeed characteris-
tics of the yields of Fe and O–Ne–Mg core-collapse SNe,
respectively.
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