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Chemical Evolution of the Juvenile Universe

G. J. Wasserburg[A,C] *and Y.-Z. Qian*[B]

[A] Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, USA
[B] School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA
[C] Corresponding author. Email: gjw@gps.caltech.edu

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Abstract: Models of average Galactic chemical abundances are in good general agreement with observations for [Fe/H] > -1.5, but there are gross discrepancies at lower metallicities. Only massive stars contribute to the chemical evolution of the 'juvenile universe' corresponding to [Fe/H] $\lesssim -1.5$. If Type II supernovae (SNe II) are the only relevant sources, then the abundances in the interstellar medium of the juvenile epoch are simply the sum of different SN II contributions. Both low-mass ($\sim$8–11 $M_\odot$) and normal ($\sim$12–25 $M_\odot$) SNe II produce neutron stars, which have intense neutrino-driven winds in their nascent stages. These winds produce elements such as Sr, Y and Zr through charged-particle reactions (CPR). Such elements are often called the 'light *r*-process elements', but are considered here as products of CPR and not the *r* process. The observed absence of production of the low-*A* elements (Na through Zn including Fe) when the true *r*-process elements (Ba and above) are produced requires that only low-mass SNe II be the site if the *r* process occurs in SNe II. Normal SNe II produce the CPR elements in addition to the low-*A* elements. This results in a two-component model that is quantitatively successful in explaining the abundances of all elements relative to hydrogen for $-3 \lesssim$ [Fe/H] $\lesssim -1.5$. This model explicitly predicts that [Sr/Fe] ≥ -0.32. Recent observations show that there are stars with [Sr/Fe] $\lesssim -2$ and [Fe/H] < -3. This proves that the two-component model is not correct and that a third component is necessary to explain the observations. The production of CPR elements associated with the formation of neutron stars requires that the third component must be massive stars ending as black holes. It is concluded that stars of $\sim$25–50 $M_\odot$ (possibly up to $\sim$100 $M_\odot$) are the appropriate candidates. These produce hypernovae (HNe) that have very high Fe yields and are observed today. Stars of $\sim$140–260 $M_\odot$ are completely disrupted upon explosion. However, they produce an abundance pattern greatly deficient in elements of odd atomic numbers, which is not observed, and therefore they are not considered as a source here. Using a Salpeter initial mass function, it is shown that HNe are a source of Fe that far outweighs normal SNe II, with the former and the latter contributing $\sim$24% and $\sim$9% of the solar Fe abundance, respectively. It follows that the usual assignment of $\sim\frac{1}{3}$ of the solar Fe abundance to normal SNe II is not correct. This leads to a simple three-component model including low-mass and normal SNe II and HNe, which gives a good description of essentially all the data for stars with [Fe/H] $\lesssim -1.5$. We conclude that HNe are more important than normal SNe II in the chemical evolution of the low-*A* elements from Na through Zn (including Fe), in sharp distinction to earlier models.

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

1 Introduction

The problem of the 'chemical evolution of the Galaxy' has attracted many workers over the last several decades. The models that seek to address this evolution are, for the most part, focused on contributions from Type II supernovae (SNe II), SNe Ia and asymptotic giant branch (AGB) stars. The problem is complex as it depends on the elemental yields of all the diverse sources. For example, both the 'weak' and 'main' *s*-process aspects as well as the *r*-process contributions must be included in such calculations in order to treat the neutron-capture elements (e.g. Travaglio et al. 2004). The complication also comes from the large uncertainties in the frequencies of occurrence for the sources and the problem of mixing, which may be local or between different regions of the Galaxy (e.g. disk and halo). The results from these chemical evolution studies, while very model dependent, give a good description of the general average abundance patterns as a function of [Fe/H] $= \log(\text{Fe/H}) - \log(\text{Fe/H})_\odot$ for disk stars. The results from one such study are shown in Figure 1 (taken from Figure 5 in Travaglio et al. 2004). As can be seen, the solid and dashed curves give a good description of the evolution of [Ba/Fe], [Eu/Fe] and [Ba/Eu] for stars with [Fe/H] > -1.5 in the thin and thick disk, respectively. The thick solid curves in the top two panels showing only the *s*-process contributions to Ba and Eu indicate that the onset

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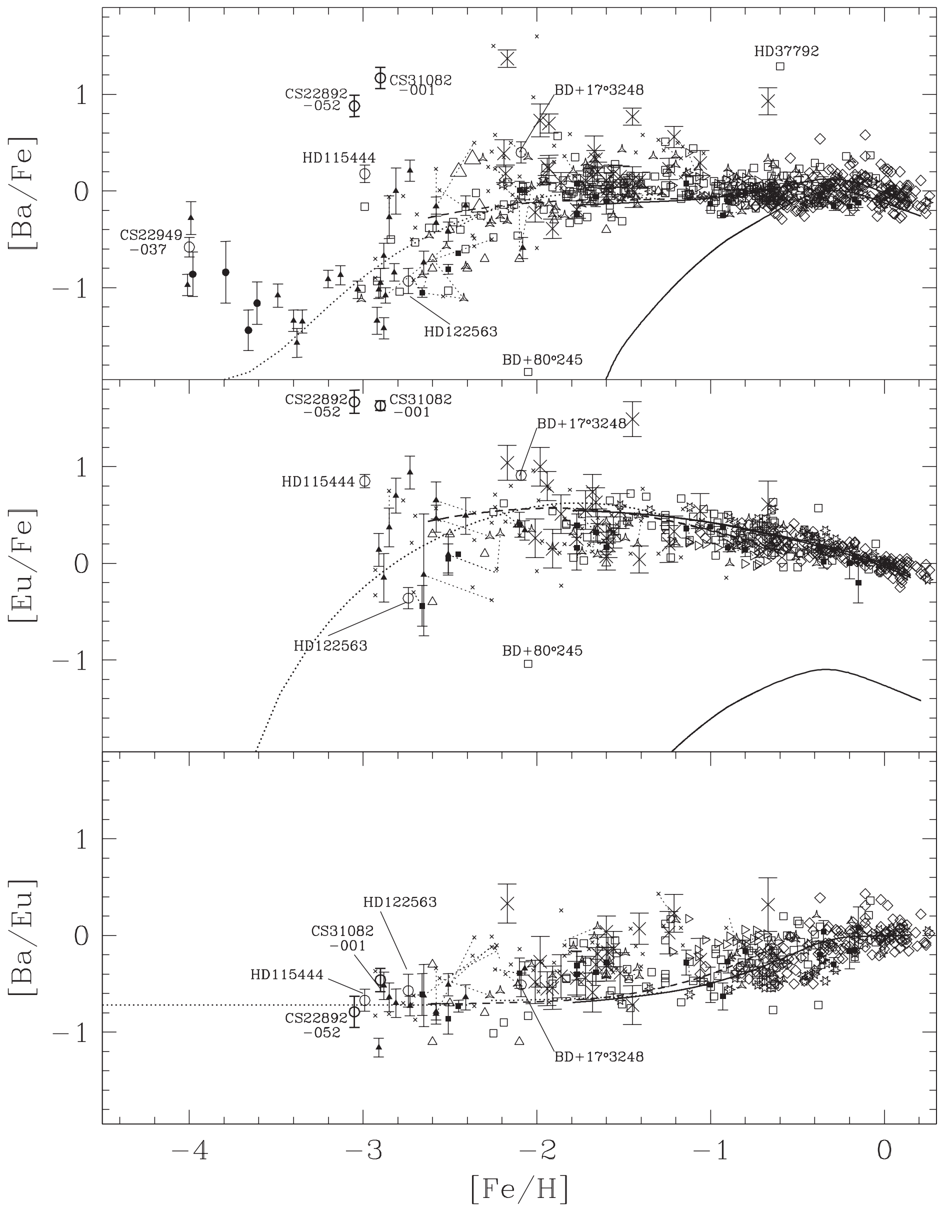

Figure 1 Comparison of the results from a Galactic chemical evolution model with the data on [Ba/Fe], [Eu/Fe] and [Ba/Eu] versus [Fe/H] (taken from Figure 5 in Travaglio et al. 2004, see that reference for the data sources. Reproduced by permission of the AAS). The solid, dashed and dotted curves show the evolution of [Ba/Fe], [Eu/Fe] and [Ba/Eu] with [Fe/H] for stars in the thin disk, thick disk and halo, respectively. The *s*-process contributions to Ba and Eu are shown by the thick solid curves in the top two panels. The regime of [Fe/H] $\lesssim -1.5$ is taken to represent the 'juvenile' universe.

of major *s*-process contributions is at [Fe/H] ~ -1 and that the *s* process contributes very little Eu.

The analyses illustrated in Figure 1 are for 'average abundances' and do not predict the abundance (E/H) of element E relative to hydrogen in an individual star. Inspection of Figure 1 shows that this description of abundances fails for [Fe/H] $\lesssim -1.5$, the regime of which represents the 'halo' phase in the interconnected evolution of the disk and the halo (see the dotted curves in Figure 1). It is this regime that is the focus of our interest. We consider that [Fe/H] $\lesssim -1.5$ corresponds to a 'juvenile' universe. It will be shown that data in this juvenile regime with far fewer contributing stellar sources lead to a clearer understanding of the nature and types of these sources in spite of the very large discrepancies between the model of average abundances and the data shown in Figure 1.

In all of the Galactic chemical evolution (GCE) studies, success in reproducing the solar abundances is taken as a measure of validity of the approach. When an element receives contributions from multiple sources, to correctly account for its solar abundance requires the identification of all the important sources and the calculation of the relative contributions of these sources. In this case, failure to include all the relevant sources results in erroneous attribution to the sources that are included in the GCE model to reproduce the solar abundances. When the contributing stellar sources evolve on very different timescales, observations covering a wide range of [Fe/H] can help

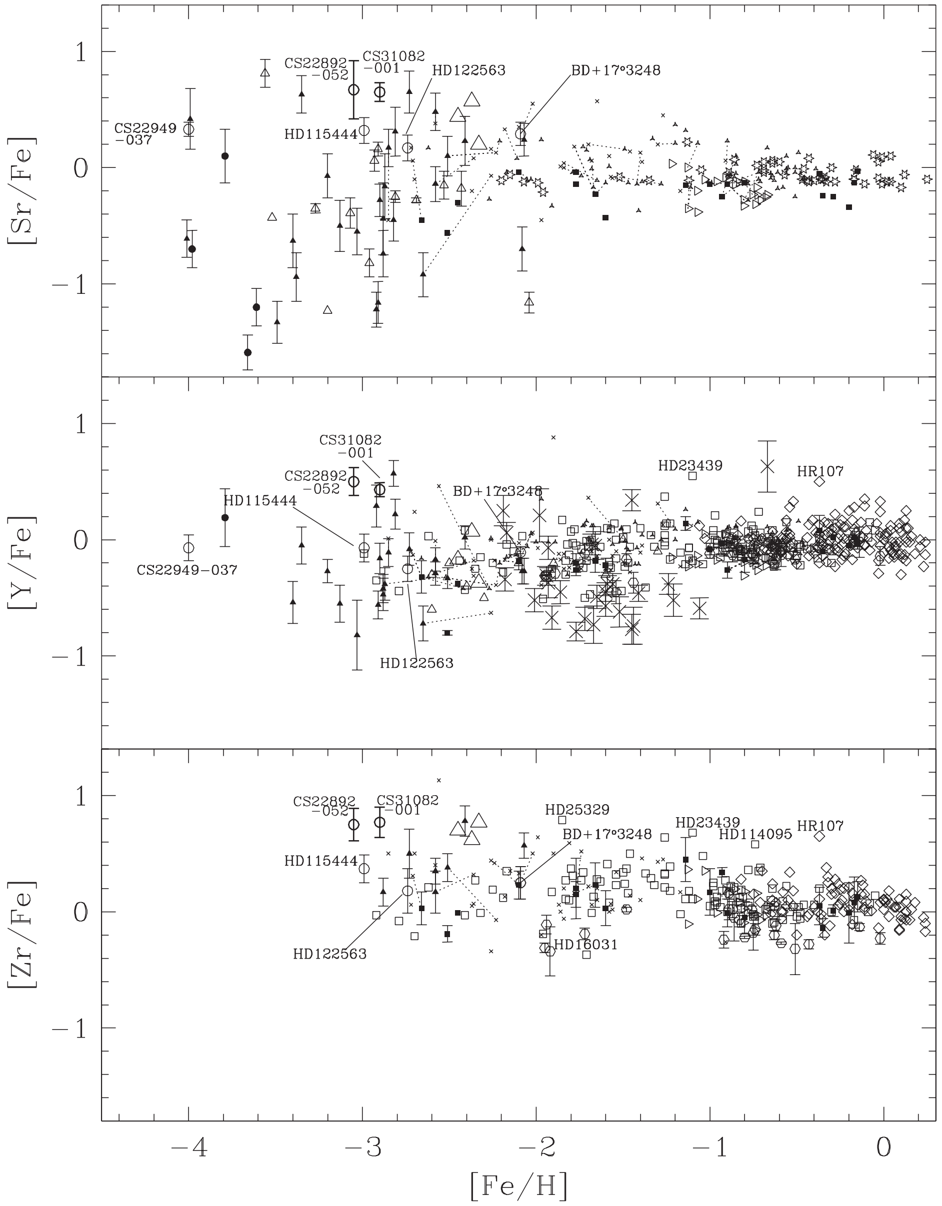

Figure 2 Data on [Sr/Fe], [Y/Fe] and [Zr/Fe] versus [Fe/H] (taken from Figure 4 in Travaglio et al. 2004; see that reference for the data sources. Reproduced by permission of the AAS). Note the wide scatter of data for [Fe/H] $\lesssim -1.5$, especially for [Fe/H] $\lesssim -3$.

in estimating the relative importance of these sources. For example, Fe production in SNe II associated with rapidly-evolving massive stars and in SNe Ia associated with slowly-evolving low-mass stars is well established by both observation and theory. In contrast, O is produced in SNe II but not in SNe Ia. As a result, there is a general trend for [O/Fe] to decrease as [Fe/H] increases. Using the data on [O/Fe] versus [Fe/H], Timmes, Woosley & Weaver (1995) estimated that $\sim\frac{1}{3}$ to $\frac{1}{2}$ of the solar Fe abundance is produced by SNe II. However, it will be shown that this attribution to SNe II is far too large and that another massive stellar source for Fe and other elements of ‘low’ mass numbers (low-A elements from Na through Zn including Fe with mass numbers $A \sim 23$–70) is in play. It will be shown that the effects of this additional source cannot be discerned based on timescales for stellar evolution alone, but are exhibited by the data on three groups of elements represented by Fe, Sr and Ba, respectively, for metal-poor stars with [Fe/H] $\lesssim -1.5$ formed in the juvenile universe.

The increase of [Fe/H] is usually taken as a measure of the passage of time. However, very low [Fe/H] values cannot give precise timing for the chemical enrichment but only indicate an early epoch during which few enrichment events occurred in a local region. It is widely recognized that metal-poor stars, especially those with [Fe/H] $\lesssim -3$, sample grossly inhomogeneous mixtures of the products from various massive stellar sources. This inhomogeneity is clearly demonstrated by the large scatter of $\gtrsim 2$ dex in [Ba/Fe] and [Eu/Fe] at [Fe/H] ~ -3 in contrast to the reasonably well-defined trends at [Fe/H] > -1.5 shown in Figure 1. The same conclusion is also reached from the data on [Sr/Fe], [Y/Fe] and [Zr/Fe] versus [Fe/H] shown in Figure 2 (taken from Figure 4 in Travaglio et al. 2004). In particular, there is wide scatter in [Sr/Fe] at any specific [Fe/H] for $-4 \lesssim$ [Fe/H] $\lesssim -3$. Clearly, to account for the scatter shown in Figures 1 and 2 requires multiple massive stellar sources with greatly-varying yields of Sr, Y, Zr, Ba and Eu relative to Fe. It will be shown that some elements such as Ba and Eu are never co-produced with Fe and others such as Sr, Y and Zr are produced sometimes with and sometimes without Fe.

Professor Roberto Gallino has persistently emphasized that understanding the production of Sr, Y and Zr is a key to understanding the evolution of the elements. Their possible origin in the *r* process and *s* process is problematic. We have followed Roberto's guidance in this important problem, but not in a direction that he would approve and report our findings here. The purpose is to make certain that his blood pressure is kept sufficiently elevated to support his 'vital signs' over the next two decades. Rather than using estimates of elemental yields from stellar models, we focus on the observed abundances at low metallicities where contributions to the interstellar medium (ISM) from SNe Ia and AGB stars should be small and the dominant contributions come from massive stars with short lifetimes. Our approach is to use the elemental abundances observed in metal-poor stars as a guide to the stellar sources of nuclei, in particular Sr, Y and Zr, as well as Fe, Ba and Eu. The abundances of these elements observed in selected stars are used as the templates of nucleosynthesis for the identified sources. Before we present our latest results, we give a brief review of some earlier works in connection with or parallel to this approach.

2 Review of Earlier Works

Since the seminal works of Burbidge et al. (1957) and Cameron (1957), elements heavier than the Fe group have been considered as produced predominantly by the *r* process and *s* process. The solar abundances, which are largely based on measurements of isotopic and chemical abundances in meteorites, are the observational basis for de-convoluting the *r*-process and *s*-process components in the 'bulk solar' abundance data. The net solar abundance of an element E is

$$N_\odot(\mathrm{E}) = N_{\odot,\mathrm{r}}(\mathrm{E}) + N_{\odot,\mathrm{s}}(\mathrm{E}), \qquad (1)$$

where $N_{\odot,\mathrm{r}}(\mathrm{E})$ and $N_{\odot,\mathrm{r}}(\mathrm{E})$ are the contributions from the *r* process and *s* process, respectively. The *s*-process contributions (*s* contributions) have been studied by many workers. This allows the *r* contributions to be inferred by subtracting the *s* contributions from the net solar abundances (e.g. Käppeler, Beer & Wisshak 1989; Arlandini et al. 1999). In cases where the *s* contributions are large or dominate, there is considerable uncertainty in inferring the *r* contributions. This is true for Sr, Y, Zr and Ba. Recent advances in the study of the *s* process have been largely due to the exquisite experimental work on neutron-capture cross sections at stellar energies by F. Käppeler and his colleagues at Karlsruhe and to the thorough and deep analyses of the *s* process in AGB stars (with assumptions about the '^{13}C pocket' as the neutron source) by R. Gallino and his colleagues at Torino [see e.g. Busso, Gallino & Wasserburg (1999) for a review].

The matter of *r* contributions is particularly ill-defined as the '*r*-process' site is assigned to SNe II but models have not succeeded in finding a suitable stellar environment with adequate neutron flux. It was anticipated that the right conditions for the *r* process would be found in the neutrino-driven winds from a nascent neutron star (e.g. Woosley et al. 1994), but at present, this approach is without success (see e.g. Qian 2003 for a review). Parametrized models assuming an adequate neutron source are capable of fitting the inferred solar *r*-process abundance pattern (solar *r* pattern, see e.g. Kratz et al. 1993; Meyer & Brown 1997; Freiburghaus et al. 1999). These approaches calculate, in some detail, the relative *r*-process yields and loosely associate them with SNe II resulting from core collapse. However, such models are without a direct consequential relationship to stellar evolution and explosion. In particular, there is no basis in such calculations for the decoupling of the 'heavy' *r*-process elements (*r* elements) such as Ba and Eu from the low-*A* elements such as Fe (see below). Similar parametrized calculations were also performed to fit the abundances of the *r* elements in metal-poor stars (e.g. Montes et al. 2007; Farouqi et al. 2009).

New insights into the *r* process were gotten from investigation of short-lived nuclei in the early solar system. Both ^{129}I and ^{182}Hf are produced predominantly by the *r* process and their lifetimes are similar. The discrepancy found between their abundances in meteorites led to the proposal by Wasserburg, Busso & Gallino (1996) that there was not 'an *r* process' but that there had to be two (or more) *r* processes to explain the meteoritic data. These workers proposed that the sites for producing the 'heavy' and 'light' *r* elements with $A > 130$ and $A \lesssim 130$, respectively, were different, with the source (H) for heavy *r* elements occurring at a high frequency and that (L) for the light ones at a low frequency. Further, they predicted that, at low metallicities where fewer sources might contribute to the ISM from which stars formed, the relative abundances of heavy and light *r* elements should show a scatter. This model of diverse *r*-process sources was extensively developed by Qian & Wasserburg (2000) with the H source predicted to have a very low yield ratio of light *r* elements relative to the heavy ones. It was found by Sneden et al. (2000) that the abundance of the light *r*-element Ag relative to the heavy *r*-element Eu in the ultra-metal-poor star CS 22892–052 was significantly lower compared with the solar *r* pattern, but not nearly as low as initially predicted for the H source by Qian & Wasserburg (2000, see also Qian, Vogel & Wasserburg 1998).

The timescales for stellar evolution have been well established. It is clear that during the first $\sim 10^9$ yr after the big bang, the stellar sources contributing to the ISM (and the intergalactic medium, IGM) must have masses of $M \gtrsim 3\,\mathrm{M}_\odot$, and the dominant sources must be massive stars of $M \gtrsim 8\,\mathrm{M}_\odot$ with rapid evolutionary timescales of $\ll 10^9$ yr. We define this domain as the 'juvenile' universe and consider SNe II and other massive stars as the major sources. Note that SNe Ia are associated with the evolution of low-mass stars in binaries and thus cannot have been major early polluters. Taking $\sim\frac{2}{3}$ of the solar Fe abundance to be contributed by SNe Ia and the rest by all massive stellar sources over a period of $\sim 10^{10}$ yr prior to the formation of the solar system, we estimate that a metallicity of [Fe/H] $\sim \log(1/30) \sim -1.5$ is reached by the end of the first $\sim 10^9$ yr. Thus the juvenile universe corresponds to [Fe/H] $\lesssim -1.5$ (where the s contributions from AGB stars to the ISM are also negligible; see Figure 1). This is precisely the region where the broad-brush GCE models have failed (see Figure 1).

The main facts that are actually known about the juvenile universe are the observed abundances in metal-poor stars residing in the Galactic halo. The observational studies of these stars have blossomed to produce a considerable database of high-quality elemental abundances, which has been the guide to all advances in the field. In particular, the observational data show that the production of the heavy r elements (Ba and above) are independent of the production of the low-A elements from Na through Zn including Fe (see Figure 3). This means that associating the r process with SNe II requires that such SNe II cannot produce much Fe. This recognition led us to conclude that if the r process occurs in SNe II, the site must be low-mass ($\sim$8–11 $\mathrm{M}_\odot$) SNe II (Qian & Wasserburg 2002, 2003). Further, the data showed that the abundances of all heavy r elements closely follow the solar r pattern in general. Thus this pattern appears to be relatively robust, although there are deviations in some cases. The above two observational facts are the basis of all our discussions.

Using the available data and considering that the diversity of stellar sources must be quite restricted, efforts were made to identify the yield templates of potential significant sources (e.g. Qian & Wasserburg 2001, 2002). The paper titled 'A Model for Abundances in Metal-Poor Stars' (Qian & Wesserburg 2001) argued that the elemental abundances relative to hydrogen in metal-poor stars can be explained by two kinds of SNe II (H and L) and the 'Population III' (Pop III) very massive stars (VMS), which were supposed to occur only in the earliest epochs and provided a 'prompt inventory' (P-inventory) of metals. The yield templates of all three sources were obtained from the solar r contributions and the abundances in two selected stars with [Fe/H] ≈ -3 but with very different abundances of heavy r elements. It was found that a good match to the abundances of Sr, Y, Zr and Ba (relative to hydrogen) could be obtained for many stars if the standard solar r contributions of these elements were substantially increased. This suggested that it was necessary to revise the solar r contributions, and hence the solar s contributions, of Sr, Y, Zr and Ba reported by käppeler et al. (1989) and Ariandini et al. (1999).

A study on GCE of Sr, Y and Zr by Travaglio et al. (2004) found that if data on metal-poor stars were included in the evolution calculation, then this required increases in the solar r contributions of Sr, Y and Zr in quantitative accord with the results of Qian & Wasserburg (2001). These revised solar r contributions are essentially what we use at present. Travaglio et al. (2004) further proposed that some lighter element primary process (LEPP), possibly a variant of the r process, had to exist as an additional source for Sr, Y and Zr.

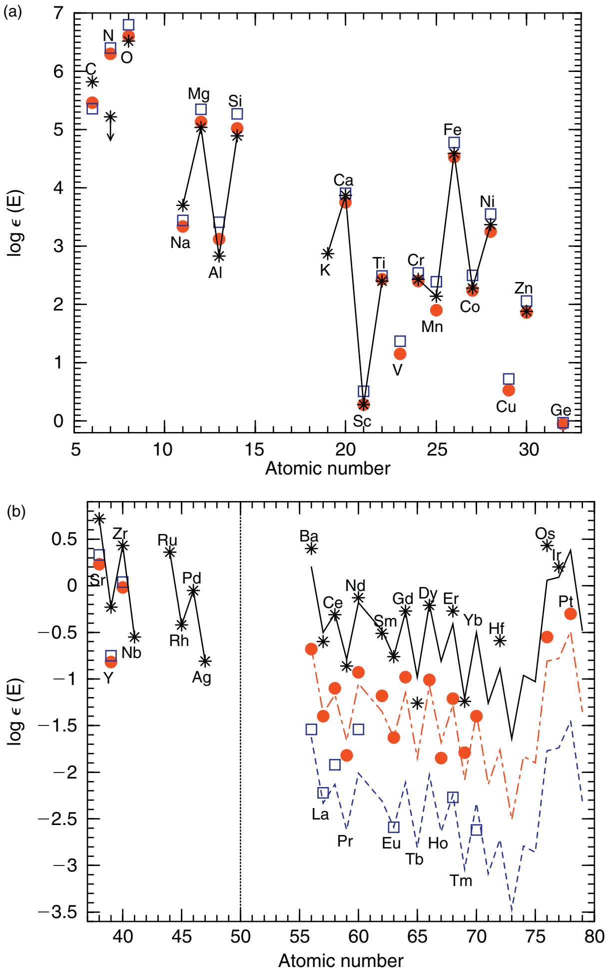

Figure 3 Data on CS 31082–001 (asterisks, Hill et al. 2002), HD 115444 (filled circles) and HD 122563 (squares, Westin et al. 2000) with [Fe/H] = −2.9, −2.99 and −2.74, respectively. (a) The values of $\log \epsilon(\mathrm{E}) \equiv \log(\mathrm{E/H}) + 12$ for the elements from C through Ge. The data on CS 31082–001 are connected by solid line segments as a guide. Note that the available abundances for the low-A elements from Na through Zn are almost indistinguishable for the three stars. (b) The $\log \epsilon$ values for the elements from Sr through Pt. The data for CS 31082–001 in the region to the left of the vertical line are again connected by solid line segments as a guide. In the region to the right of the vertical 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 Eu data for CS 31082–001, HD 115444 and HD 122563, respectively. Note the general agreement between the data and the solid and dot–dashed curves. There is a range of $\sim$2 dex in the abundances of the heavy r elements for the three stars shown. Combined with their nearly identical abundances of the low-A elements, this shows that the production of the heavy r elements is independent of the production of the low-A elements.

The general approach taken by us is that stars are reliable adding machines operated by the diverse sources contributing to the ISM from which they formed. Certain 'rules' for the stellar adding machines found by Qian & Wasserburg (2001) turned out to be misleading. There was an apparent sharp increase in abundances of heavy *r* elements at [Fe/H] ~ -3. It was assumed that this metallicity represented a 'baseline' enrichment (the *P*-inventory) due to production by VMS (Qian & Wasserburg 2002). It was shown later that this baseline enrichment could be reached rapidly through production by SNe II inside halos of sufficient mass that could gravitationally bind the SN II debris (Qian & Wasserburg 2004). Thus there is no need for the *P*-inventory proposed earlier.

As the field developed, we found that essentially all of the observed abundances for a large number of elements (relative to hydrogen) in stars with $-3 \lesssim [\mathrm{Fe/H}] \lesssim -1.5$ could be explained by a mixture of two components, *H* and *L*, with yield patterns taken from two template stars (Qian & Wasserburg 2007). The *H* contributions are measured by the abundance of a heavy *r*-element such as Eu (or Ba) and the *L* contributions by that of Fe. The study of *r*-process models in conjunction with the observational data on metal-poor stars also led Montes et al. (2007) to the conclusion that a two-component model can explain the available data. These workers explored the possibility that a variant of the *r* process could be the LEPP source for Sr, Y and Zr proposed by Travaglio et al. (2004).

The results of the two-component model led to some surprising conclusions: (1) the abundances of a large number of elements relative to hydrogen can be calculated with considerable reliability for essentially all stars with $-3 \lesssim [\mathrm{Fe/H}] \lesssim -1.5$ using the assumed *H* and *L* yield templates, (2) the production of heavy *r* elements was decoupled from that of the low-*A* elements from Na through Zn including Fe and (3) the abundance patterns of the low-*A* elements were essentially the same for all stars with $-3 \lesssim [\mathrm{Fe/H}] \lesssim -1.5$ with only few exceptions. These conclusions let to the result that normal SNe II of $\sim$12–25 $\mathrm{M}_\odot$, which produce Fe, cannot be the source for the heavy *r* elements. This then restricted the possible source for these elements to low-mass SNe II of $\sim$8–11 $\mathrm{M}_\odot$ with very little Fe production (see e.g. Woosley, Heger & Weaver 2002 for such an *r*-process model). Rule (3) was particularly surprising as the yields of SNe II of different masses are known to be quite variable (e.g. Wooseley, Heger & Weaver 2002). Hence, with few stellar sources contributing to a local ISM at very low [Fe/H], there should be substantial scatter in the abundance patterns of the low-*A* elements in metal-poor stars. This is not the case in general.

The matter was brought to sharp focus by the following: (1) the assignment of the heavy *r* elements to low-mass SNe II, (2) both low-mass and normal SNe II produce neutron stars as shown by theoretical models (e.g. Nomoto 1987; Woosley et al. 2002), (3) many of the so-called light *r* elements such as Sr, Y and Zr are readily produced in the neutrino-driven winds from nascent neutron stars (e.g. Woosley & Hoffman 1992) and not in a true *r* process and (4) there was no sound basis for relating the high neutron fluxes required for production of the heavy *r* elements to a neutrino-driven wind directly. This then provided qualitative justification for taking the relative yields of the light to heavy *r* elements for the *H* source (low-mass SNe II) and those of the light *r* elements to Fe for the *L* source (normal SNe II) from the abundances in two template stars. The so-called light *r* elements such as Sr, Y and Zr are now specifically attributed to charged-particle reactions (CPR) in the neutrino-driven winds and thus are not considered to be true *r*-process elements. The sources proposed for the two-component model are summarized in Table 1.

Table 1. Two-component model

	Low-*A* elements	CPR elements	Heavy *r* elements
Low-mass SNe II (*H*)	No	Yes	Yes
Normal SNe II (*L*)	Yes	Yes	No

The two-component model had clear predictions about the possible values of [Sr/Fe], [Y/Fe] and [Zr/Fe] that could be observed (Qian & Wasserburg 2007). In particular, as normal SNe II (*L*) produce both Sr and Fe while low-mass SNe II (*H*) produce Sr but no Fe (see Table 1), the lowest value of Sr/Fe predicted by this model is fixed by the yield ratio $(\mathrm{Sr/Fe})_\mathrm{L}$ for normal SNe II. This lower limit is $[\mathrm{Sr/Fe}] \geq -0.32$. Using the *H* and *L* yield templates, the abundances of all elements in any star with $[\mathrm{Fe/H}] \lesssim -1.5$ can be calculated from the observed abundances of an heavy *r*-element such as Eu (or Ba) and a low-*A* element such as Fe. This model led to excellent predictions for many stars with $-3 \lesssim [\mathrm{Fe/H}] \lesssim -1.5$. However, more extensive data at $[\mathrm{Fe/H}] < -3$ showed that there was a clear violation of the lower limit on [Sr/Fe]. It is the failure of this prediction by the two-component model that has led to a clearer view of the contributors to the chemical evolution of both the juvenile universe and the subsequent epoch. It will be shown that massive stars of $\sim$25–50 $\mathrm{M}_\odot$ (possibly up to $\sim$ 100 $\mathrm{M}_\odot$) are very important players throughout the history of the universe. This is the focus of the present work.

3 Three-Component Model

The high-resolution (e.g. Johnson & Bolte 2002; Honda et al. 2004; Aoki et al. 2005; François et al. 2007; Cohen et al. 2008) and medium-resolution (Barklem et al. 2005) observations of elemental abundances in a large number of low-metallicity stars in the Galactic halo — and a single star in a dwarf galaxy (Fulbright, Rich & Castro 2004) — now provide a data base for determining the nature of the stellar sources contributing to the ISM/IGM at metallicities of $-5.5 < [\mathrm{Fe/H}] \lesssim -1.5$. These data taken in conjunction with stellar models appear to define the massive stars active in the juvenile universe. This changes our views of what may be Population-III stars and what stellar

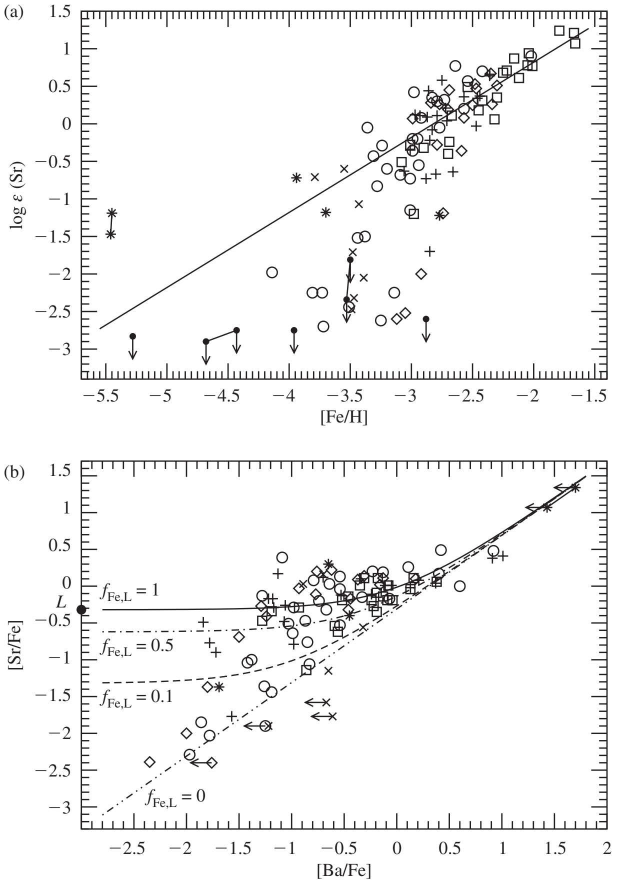

Figure 4 (a) High-resolution data on log ϵ(Sr) versus [Fe/H]. The solid line is calculated from the two-component model for a well-mixed ISM/IGM. Note that there is a great deficiency of Sr for many sample stars with $[Fe/H] \lesssim -3$. It is evident that a source producing Fe and no Sr is required. (b) Evolution of [Sr/Fe] with [Ba/Fe] for the data shown in (a). The curves correspond to different fractions $f_{Fe,L}$ of Fe due to the L source (normal SNe II). Note the data points lying on the $f_{Fe,L} = 0$ curve and those above the $f_{Fe,L} = 1$ curve. Details for these and the subsequent figures as well as the data sources can be found in Qian & Wasserburg (2008).

types are continuing contributors through the present epoch.

As mentioned in Section 2, the two-component model predicts $[Sr/Fe] \geq -0.32$ for all stars with $[Fe/H] \lesssim -1.5$ (Qian & Wasserburg 2007). This rule appears to be well followed for $[Fe/H] > -3$. However, a serious problem with this model arises below $[Fe/H] \sim -3$. In this domain the extended database shows that there is a gross deficiency of Sr (and other CPR elements) relative to Fe (see Figure 4a). It follows that a third component in addition to low-mass and normal SNe II is required to account for all the abundance data. Further, if Sr, Y and Zr are CPR nuclei, then this third component must be a massive stellar source of Fe leaving behind a black hole instead of a neutron star that can produce the CPR nuclei in the neutrino-driven winds.

The effects of all three stellar sources are most clearly seen if we consider the relationship of Sr (a CPR element in our model) in conjunction with Ba (a true r-element at low metallicities) and Fe. Using the yield ratios $(Sr/Ba)_H$ of the H source (low-mass SNe II) and $(Sr/Fe)_L$ of the L source (normal SNe II) we obtain:

$$\left(\frac{Sr}{H}\right) = \left(\frac{Sr}{Ba}\right)_H \left(\frac{Ba}{H}\right) + \left(\frac{Sr}{Fe}\right)_L \left(\frac{Fe}{H}\right) f_{Fe,L}, \qquad (2)$$

where $f_{Fe,L}$ is the fraction of Fe from the L source (the two-component model corresponds to $f_{Fe,L} = 1$). The above equation can be rewritten as:

$$[Sr/Fe] = \log(10^{[Sr/Ba]_H + [Ba/Fe]} + f_{Fe,L} \times 10^{[Sr/Fe]_L}). \quad (3)$$

The evolution of [Sr/Fe] with [Ba/Fe] for the high-resolution data shown in Figure 4a is exhibited in Figure 4b along with the curves representing Equation (3) for $f_{Fe,L} = 0$, 0.1, 0.5 and 1 (using $[Sr/Ba]_H = -0.31$ and $[Sr/Fe]_L = -0.32$). Similar results are found for the medium-resolution data. While there appears to be a clustering of data in the neighborhood of $f_{Fe,L} = 1$ corresponding to Fe contributions exclusively from the L source in Figure 4b, there is a substantial fraction of the data lying down to $f_{Fe,L} = 0$. This requires an Fe source not related to normal SNe II and clearly shows that the preponderance of the Fe in many sample stars is from this third source that produces no Sr. Essentially the same results shown for [Sr/Fe] versus [Ba/Fe] are found for [Y/Fe] versus [La/Fe] and [Zr/Fe] versus [Ba/Fe], where La and Ba are measures of the true r contributions. These results clearly show that there are major contributions from the third source producing Fe with no CPR elements and no r-nuclei. Thus, according to the neutrino-driven wind model for production of the CPR elements, this third source cannot be massive stars ending as neutron stars but those producing black holes.

The matter at hand is: What is the nature of this third source? Consideration of the yields of VMS (∼140–260 $M_\odot$) associated with pair-instability SNe (PI-SNe) shows that these sources are characterized by strong deficiencies in the elements of odd atomic numbers (e.g. Na, Al, K, Sc, V, Mn, Co). Neither the data from earlier studies by McWilliam et al. (1995) nor the more precisely-determined data from recent studies by Cayrel et al. (2004) on low-metallicity halo stars exhibit these deficiencies. It follows that PI-SNe cannot be the third source. A plausible candidate is hypernovae (HNe) from progenitors of ∼25–50 $M_\odot$. These stars are known to be active in the current epoch, although little attention has been paid to them in consideration of GCE. They have explosion energies far above those of low-mass and normal SNe II and are presumed to be associated with gamma-ray bursts. The yields of HNe are generally not well known, but the typical Fe yield inferred from observations is ∼0.5 $M_\odot$, much higher than the yield of ∼0.07 $M_\odot$ for normal SNe II (Tominaga, Umeda & Nomoto 2007).

If we assume a Salpeter initial mass function (IMF) for massive stars of ∼8–50 $M_\odot$, the relative rates are $R_{HN} : R_H : R_L \sim 0.36 : 0.96 : 1$ for HNe, low-mass SNe II (H) and normal SNe II (L), respectively. Of the Fe contributed by massive stars to the ISM/IGM, the fraction

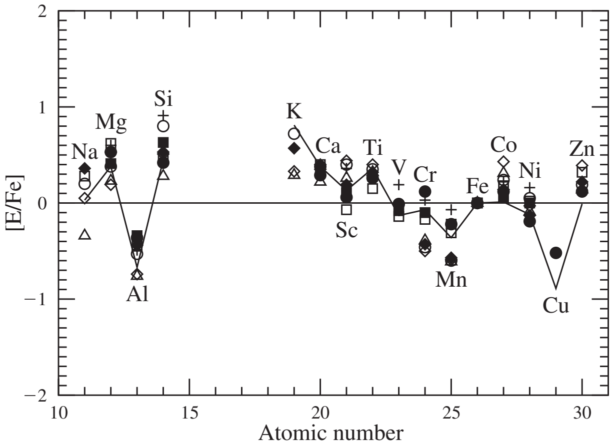

Figure 5 Data on the low-A elements from Na through Zn for stars with 'pure' HN contributions ($f_{\mathrm{Fe,L}} = 0$ in Figure 4b). For reference, the solid curve represents the abundance pattern measured for a star with $[\mathrm{Fe/H}] = -2$, which was previously identified with the yield pattern of the low-A elements for normal SNe II (L). There is no apparent difference between this pattern and the data points for stars with no normal SN II contributions.

Table 2. Three-component model

	Low-A elements	CPR elements	Heavy r elements
Low-mass SNe II (H)[a]	No	Yes	Yes
Normal SNe II (L^*)[a]	Yes	Yes	No
HNe	Yes	No	No

[a] $[\mathrm{Sr/Ba}]_{\mathrm{H}} = -0.31$, $[\mathrm{Sr/Fe}]_{\mathrm{L^*}} = 0.3$.

from HNe is ~0.72. Thus HNe are the dominant Fe source at early epochs with contributions far exceeding those of normal SNe II. This seems to explain the earlier conundrum (Qian & Wasserburg 2002) that the yield patterns for the low-A elements from Na through Zn in stars at very low metallicities ($[\mathrm{Fe/H}] < -3$) appear to be indistinguishable from what was attributed to normal SNe II at higher metallicities (see Figure 5). This general regularity of abundance patterns was found by McWilliam et al. (1995) and shown more extensively and precisely by Cayrel et al. (2004). Figure 5 clearly shows that even for stars deficient in Sr, Y or Zr, the abundance patterns for all the low-A elements are approximately constant. Thus the diverse normal SN II contributions cannot govern these abundance patterns. The corresponding abundances of the low-A elements must then reflect the dominant input to the ISM/IGM from HNe and not normal SNe II.

It is now evident that the inventory of the low-A elements including Fe that we had attributed to normal SNe II is in fact the mixture of HN and normal SN II ejecta where the preponderant contributions are from HNe. The stars that formed in the juvenile universe appear to have inherited the bulk of their low-A elements from the ISM where the dominant contributing source is HNe and not normal SNe II. Thus the previously-designated L source

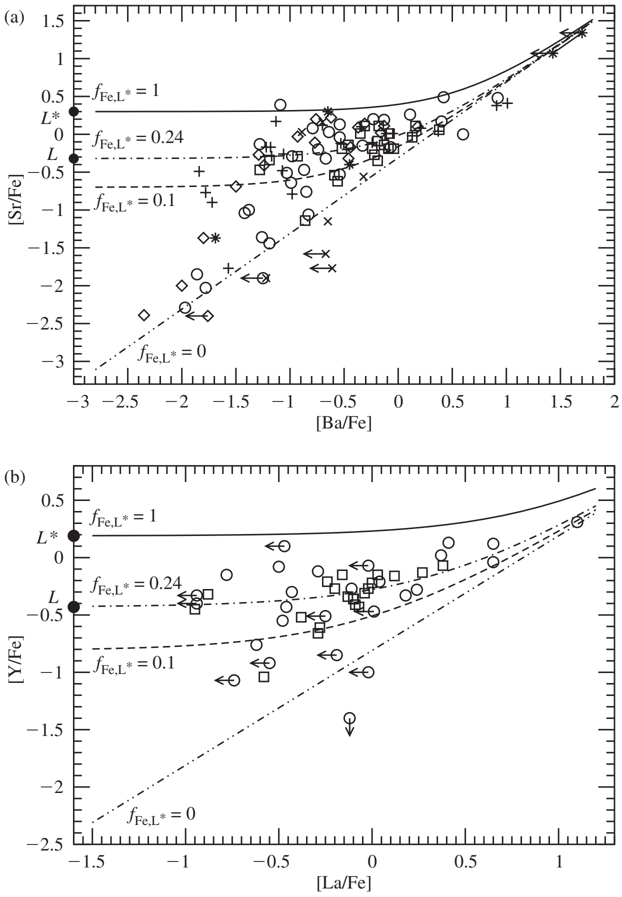

Figure 6 (a) Similar to Figure 4b but with the L source being a blend of normal SNe II (L^*) and HNe (i.e., $L = L^* + \mathrm{HNe}$). (b) Same as (a) but for [Y/Fe] versus [La/Fe]. The L^* yield ratios $(\mathrm{Sr/Fe})_{\mathrm{L^*}}$ and $(\mathrm{Y/Fe})_{\mathrm{L^*}}$ are higher than the corresponding L yield ratios in the two-component model as the latter ratios include the contributions from HNe producing Fe but no CPR elements. Note that there are no data points lying above the $f_{\mathrm{Fe,L^*}} = 1$ curves (cf. Figure 4b). Only one data point lies below the $f_{\mathrm{Fe,L^*}} = 0$ curve for [Y/Fe] versus [La/Fe].

is not a pure SN II source but a blend of HNe and normal SNe II: $L = L^* + \mathrm{HNe}$, where L^* represents normal SNe II. For the estimated yields and relative rates given above, it follows that the $\sim\frac{1}{3}$ of the solar Fe inventory previously assigned to normal SNe II is in considerable error. Taking $\sim\frac{2}{3}$ of the solar Fe inventory to be from SNe Ia, we find that of the remaining $\sim\frac{1}{3}$, ~24% is from HNe with only ~9% from normal SNe II. Thus with the proper assignment of Fe contributions for the L blend with $[\mathrm{Sr/Fe}]_{\mathrm{L}} = -0.32$, we obtain $[\mathrm{Sr/Fe}]_{\mathrm{L^*}} = 0.3$ for the L^* source. Using the proper yield ratios for the L^* source (see Table 3 in Qian & Wesserburg 2008) and equations similar to Equation (3), we obtain the results shown in Figure 6. It is seen that the data for all the elements appear to be described very well by the three-component (H, L^* and HNe) model. We further note that the clump of data above the $f_{\mathrm{Fe,L}} = 1$ curve in Figure 4b are now absent in Figure 6a with diminished Fe contribution from normal SNe II. It is also important to note that as amply testified to by gamma-ray bursts (e.g. Galama et al. 1998), HNe are active in the present epoch. Consequently, it is evident that HNe have been ongoing major contributors to the chemical evolution of the ISM/IGM during and beyond the early epochs. The stellar sources for the three-component model are summarized in Table 2.

4 General Discussion

From the results reviewed above it appears that the whole chemical evolution in the 'juvenile epoch' of the first $\sim 10^9$ yr after the Big Bang, which was dominated by massive stars, may be explained by the concurrent contributions of massive stars associated with low-mass and normal SNe II and HNe with a standard IMF and that this same relative contribution continues into the present epoch. It is possible that the mass range could go up to $\sim 100\,\mathrm{M}_\odot$ (e.g. Wooseley et al. 2002). The efforts to seek Pop III stars that only occur in early epochs and then stop are considered by us to be invalid as were our earlier efforts to find a P-inventory in the ISM/IGM. It follows that models for the formation of the 'first' stars, which has been the focus of intensive studies with due consideration of the complex condensation and cooling processes at zero to low metallicities (e.g. Abel, Bryan & Norman 2002; Bromm & Larso 2004), should consider the stellar populations inferred here with HNe ($\sim$25–50 $\mathrm{M}_\odot$, possibly up to $\sim 100\,\mathrm{M}_\odot$) being the dominant metal source. It is possible that more massive stars may have occurred during the very early stages, but their contributions to the ISM/IGM are quite small at $-5.5 < [\mathrm{Fe/H}] < -3$. HN explosions are highly disruptive and certainly can disperse debris through the IGM until halos of substantial mass have formed. The apparent sudden onset of heavy r elements, which motivated our earlier search for a P-inventory, is most plausibly related to the formation of halos of sufficient mass that remain bound following both SN II and HN explosions (Qian & Wasserburg 2004). We no longer consider our hypothesis of a P-inventory to be valid. It also follows that the earlier models of GCE that aimed to provide $\sim\frac{1}{3}$ of the solar Fe inventory by normal SNe II must now be subject to reinvestigation. The observational evidence for ongoing HNe in the current epoch cannot be ignored in models of galactic chemical evolution.

There is further the fact that production of heavy (true) r-nuclei is strongly decoupled from Fe production. It is also worth noting that quantitative yields of the CPR elements have not been obtained. These issues and the true site of the r process itself are not resolved and present a further challenge to future stellar models. Insofar as the proposed phenomenological three-component model is concerned, more high-resolution data on the CPR elements (e.g. Sr, Y and Zr) and heavy r elements (e.g. Ba and La) are needed to provide a stricter test. It is extremely important to obtain data for those stars that appear to represent mixtures of H and HN contributions only ($f_{\mathrm{Fe,L^*}} = 0$).

With regard to the r process, certainly the possibility that shocked surface layers of the core in low-mass SNe II may experience rapid expansion to enable the production of heavy r elements must be investigated further (Ning et al. 2007). As there is only limited knowledge on the complex evolution of the progenitors of $\sim$8–11 $\mathrm{M}_\odot$ for low-mass SNe II, more extensive and intensive studies of these stars are required. The problem of explaining the meteoritic data on ^{129}I and ^{182}Hf, which launched the investigation into multiple r processes, is still not resolved. As emphasized by K.-L. Kratz (e.g. Ott & Kratz 2008), from the point of view of nuclear systematics, there is substantial difficulty in understanding a break in the production between these two nuclei (but see Qian et al. 1998). These and other issues discussed above provide ample stimulus for future studies of the r process in particular and GCE in general. In the phenomenological approach used by us, it is assumed that stars themselves have correctly calculated the yields of stellar nucleosynthesis. Theory is the important guide in illuminating the path to understanding. The stars tell us the facts.

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