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A Statistical Model for Predicting the Average Abundance Patterns of Heavier Elements in Metal-Poor Stars

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Abstract We have collected nearly all the available observed data of the elements from Ba to Dy in halo and disk stars in the metallicity range $-4.0 <$[Fe/H]< 0.5. Based on the observed data of Ba and Eu, we evaluated the least-squares regressions of [Ba/Fe] on [Fe/H], and [Eu/H] on [Ba/H]. Assuming that the heavy elements (heavier than Ba) are produced by a combination of the main components of s- and r-processes in metal-poor stars, and choosing Ba and Eu as respective representative elements of the main s- and the main r-processes, a statistical model for predicting the Galactic chemical evolution of the heavy elements is presented. With this model, we calculate the mean abundance trends of the heavy elements La, Ce, Pr, Nd, Sm, and Dy with the metallicity. We compare our results with the observed data at various metallicities, showing that the predicted trends are in good agreement with the observed trends, at least for the metallicity range [Fe/H]≥ -2.5. Finally, we discuss our results and deduce some important information about the Galactic chemical evolution.

Key words: stars: abundances — stars: Population II — Galaxy: evolution — method: statistical

1 INTRODUCTION

Since the pioneering work on stellar nucleosynthesis by Burbidge et al. (1957), nuclei heavier than iron have been recognized to be produced through both the slow (s-) and the rapid (r-) neutron-capture (hereafter n-capture) processes. It is believed that the s- and r-processes occur at different sites. The r-process nuclei are primary nucleosynthesis products, presumed to have been formed in an environment associated with the evolution of massive stars ($M \geq 10\,M_{\odot}$)

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to supernova explosions of Type II and the formation of neutron star remnants (Mathews & Cowan 1990; Mathews, Bazan & Cowan 1992). The s-process nuclei are generally thought to be products of n-captures on preexisting silicon "seed" nuclei, occurring during the hydrostatic He-burning phases of stellar evolution (Meyer 1994). The s-process is further divided into two categories: the weak s-component (s_w) and the main s-component (s_m). The weak s-process occurs during the core He-burning of massive stars with $M \geq 10M_{\odot}$ (Lamb et al. 1977; Prantzos et al. 1990; Raiteri et al. 1993). The main s-process happens during the double-shell burning phase of low $(1-3M_{\odot})$ and intermediate-mass $(4-7M_{\odot})$ AGB stars (Gallino et al. 1988; Käppeler et al. 1990), which is mainly responsible for the production of heavier s-process elements (especially heavier than Ba).

The abundances of n-capture elements in very metal-poor halo stars provide vital clues to the chemical evolution and early history of the Galaxy, and the production mechanisms for n-capture elements in metal-poor stars have been the subject of some debate in the literature for twenty years. Spite & Spite (1978) showed from observations of Ba and Eu that metal-poor stars exhibit r-process abundance distributions. Truran (1981) provided a theoretical basis for the result by noting that the s-process need pre-stellar seed nuclei, whereas the r-process site would produce its own seed nuclei. For this reason, metal-poor stars would be poor producers of s-process nuclei. It is common to regard n-capture elements in metal-poor stars only due to the r-process, at least for the heavier such elements with $Z \geq 56$ (r_h component). This view has been strongly supported by later observational works (Sneden & Parthasarathy 1983; Sneden & Pilachowski 1985; Gilroy et al. 1988; Gratton & Sneden 1991, 1994; Sneden et al. 1996, 1998; McWilliam et al. 1995a, b; Cowan et al. 1995, 1996; Ryan et al. 1996). The latest observations in the ultra-metal-poor halo star CS 22892–052 (Sneden et al. 2000) revealed that the abundances of the heavier ($Z \geq 56$) stable n-capture elements are in remarkable agreement with the scaled solar system r-process pattern. The theory is demonstrated numerically in the Galactic chemical evolution calculations of Travaglio et al. (1999; see also Busso, Gallino & Wasserburg 1999) which showed that s-process products do not feature significantly in newly forming stars until [Fe/H] ≥ -1.5.

Many studies have found that the case for an r-process origin of the n-capture elements to be less certain. The survey of Burris et al. (2000) presented new abundances of eight n-capture elements (Sr, Y, Zr, Ba, La, Nd, Eu, Dy) in 43 metal-poor stars with [Fe/H] ranging from -2.93 to -0.91. Their observations revealed that the onset of the main r-process can be seen at [Fe/H] ≈ -2.9 and no main s-process contribution for stars more metal-poor than [Fe/H] ≤ -2.75. However, contributions from the main s-process can be first seen in some stars with metallicities as low as [Fe/H] ≈ -2.75, and in increasing amounts in most stars with metallicities [Fe/H]> -2.3. They pointed out that between $50-80\%$ of Ba in most stars in their halo sample with [Fe/H]≥ -2.0 is produced by the main s-process. Cowan et al. (1996) measured the abundances of heavy elements in the metal-poor halo giant HD 126238 ([Fe/H]$= -1.7$). They found that the best-fit heavy element abundance pattern of this star contains 80% r-process and 20% s-process solar system mixture. Magain (1995) measured the abundances of Ba isotopes in the classical metal-poor subgiant HD 140283 in order to estimate the relative contribution of r- and s-processes, his result shows that the Ba isotopic ratios in that star is in agreement with a pure s-process production, and excludes any significant enhancement of the r-process contribution. François (1996) also disputed the claimed r-process source of halo heavy elements, based on a plot of [Eu/H] versus [Ba/H], arguing against the break in slope of the ϵ (Ba) versus ϵ (Eu) seen by Gilroy et al. (1988). Gratton & Sneden (1994) have given accurate abundances of heavy elements in a large sample of metal-poor stars with $-2.8 \leq$ [Fe/H] < 0. They found that the abundance patterns of n-capture elements in the metal-poor stars show clear difference with respect to scaled solar system r-process nucleosynthesis predictions (e.g., there is a relative excess of Ba), and suggested the patterns can be explained if there was an early onset of the contribution by the main component of the s-process at metallicity slightly lower than [Fe/H] ~ -2.5.

Previous studies of the Galactic evolution of elements produced by s- and r-processes were made only at a semiquantitative level (see Travaglio et al. 1999 for a review). Travaglio et al. (1999) presented a model for the chemical evolution of the Galaxy and calculated the evolution of n-capture elements from Ba to Eu in the interstellar gas of the Galaxy. They discussed in detail the s- and r-process contributions to these elements, based on the AGB models computed with the FRANEC code (see Chieffi & Straniero 1989) and their standard Galactic chemical model. Their results are in good agreement with the observational data. Therefore, they concluded that the abundance of Ba is dominated by the s-process for [Fe/H]≥ -1.5, while the primary r-process contribution plays a dominant role at lower metallicities.

Up to now, only the solar system nuclide abundance distribution has been obtained in some detail, so it usually serves as the standard pattern or basis when investigating the abundance distribution of n-capture elements. For example, for population I stars, the general abundance distribution is taken to be similar to the solar system pattern (Busso et al. 1992), that is,

$$N_i = N_{i,\odot} \times Z/Z_{\odot}, \tag{1}$$

where Z denotes stellar metallicity. This formula has been popular for many years. However, the observational studies have shown that the abundance patterns of heavy elements in population II stars differ obviously from the solar (Spite & Spite 1978; Gratton et al. 1994), and the same is true even for population I stars (Woolf et al. 1995). Generally, the n-capture elements are produced by a mixture of r- and s-processes, at least for stars with [Fe/H]≥ -2.5 (Zhang et al. 1999). Based on this idea, Zhang et al. (1999) presented a model for calculating the abundances of heavy elements in metal-poor stars. Their results showed that the observed abundances of heavy elements of the sample of Gratton & Sneden (1994) can be well matched by an abundance mix of the solar r- and s-processes, especially for elements heavier than Ba. The solar s-component is the accumulated consequence of s-process nucleosynthesis over the long Galactic chemical evolution, therefore whether or not it is still representative at low metallicity is still a moot question. Since the solar r-component is the r-residual obtained after subtracting the s-component from the total solar composition, it is not an independent parameter from the main s-component at other metallicities. Investigations of the r_h component (r-process nuclei with nuclear charge number $Z \geq 56$, see Wasserburg et al. 1996; Qian et al. 1998) indicate that the abundance pattern of the r_h component is similar to the corresponding solar component for stars with [Fe/H]< -2.5 (e.g., the observation of CS 22892–052 given by Sneden et al. 1994, 1996; Cowan et al. 1995, 1997; Norris et al. 1997; Sneden et al. 1998). For stars with $-2.5 <$[Fe/H]< 0.0, however, the abundance of n-capture elements is a mix of some nucleosynthesis processes. In these cases, because there is no direct evidence to test whether or not the r_h-component is similar to the solar r_h distribution, the abundance patterns are merely extrapolated to be similar to the solar r_h pattern (Cowan et al. 1996). Given the average abundance distributions of s_{mh} (in the range $140 \leq A \leq 204$) agreeing with the solar s_{mh} pattern at any metallicity, and the observational stellar heavy element (especially those heavier than Ba) abundance being fitted by a combination of the solar r-process and s-process in certain proportions, the r_h-component should be similar to the solar r_h pattern in the range

$140 \leq A \leq 204$. Moreover, the previous results given by Cowan et al. (1996) and Zhang et al. (1999) can strongly support this point. Thus the solar r_h-component is typical and can work as an independent parameter, and not only the *r-residuals*, it also may be contributed by the bottleneck effect (Clayton et al. 1967).

With observational data of n-capture elements rapidly increasing both in volume and precision, it is now feasible to make a statistical analysis of the chemical evolution of the Galaxy. Here we present a statistical model to determine the average contributions from the s- and r-processes to the n-capture elements at different metallicities. We only concentrate on elements from Ba to Dy (el_h), not only because they have sufficient observational data but also because they contain species of very different origins ranging from almost pure r-process production, as in the case of Eu, to a dominant s-process origin, as in the case of Ba. This paper is organized as follows: in Section 2 we describe the observational results used in the present work, in Section 3 we present our statistical model for the chemical evolution of n-capture elements in metal-poor stars, the discussion of the calculated results and their implications are given in Section 4. Finally, in Section 5 we summarize the main conclusions and point out a few aspects deserving further analysis.

2 OBSERVATIONS

In order to obtain a more reliable statistical model for the chemical evolution of the Galaxy, we adopted nearly all the available observed data to date of the elements from Ba to Dy in halo and disk stars.

The first evidence for a plateau with [heavy element/Fe] ~ 0.0, followed by a systematic trend of decreasing [heavy element/Fe] below [Fe/H] ~ -2.5, was presented by Spite & Spite (1978) (see McWilliam 1997 for a review). Since then, many observations of the heavy elements in metal-poor stars have been reported. In this paper, we choose a large sample of metal-poor stars in the metallicity range $-4.0 <$[Fe/H]< 0.5 from Gilroy et al. (1988) to Burris et al. (2000). Gilroy et al. (1988) studied 20 very metal-poor halo stars, 17 of which are giants, and confirmed the operation of the r-process at low metallicities. They also showed significant star-to-star scatter in the overall abundance level of the n-capture elements with respect to iron for stars with [Fe/H]< -2.0. The ubiquitous subsolar [Ba/Eu] ratios in halo stars (e.g. Magain 1989; Gratton & Sneden 1994; McWilliam et al. 1995b) show that halo stars must contain a larger fraction of r-process material than the solar composition.

Edvardsson et al. (1993) analyzed the chemical evolution of the Galactic disk from nearly 200 F and early disk G dwarfs. They found that [Ba/Fe] ratios increased with time and were very roughly independent of metallicity. This trend in [Ba/Fe] suggests that there is a source that produced Ba on a time scale longer than the time scale for Fe production, which is consistent with the idea that s-process nucleosynthesis is dominated by AGB stars over the mass range $1 - 3M_\odot$ or $1 - 4M_\odot$. Zhao (1993) determined the abundances of a number of heavy elements (Y, Zr, Ba, La, Ce, and Eu) in 27 metal-poor dwarfs and subgiants. Gratton & Sneden (1994) presented 19 stars in the interval $-2.8 \leq$ [Fe/H]≤ -0.5. The abundance measurements indicated a heavy element dispersion of less than 0.1 dex for the sample, which is consistent with their measurement uncertainties. McWilliam et al. (1995a, b) analyzed a large sample of 33 ultra-metal-poor stars in the interval $-4 \leq$ [Fe/H]≤ -2. They found a decline in [heavy element/Fe] below [Fe/H]$= -2.5$, accompanied by a considerable scatter in [Sr/Fe] and [Ba/Fe] abundances ratios, and their typical measurement uncertainties were ± 0.2

dex. McWilliam (1998) refined the barium abundances in the same sample stars, and found the mean [Ba/Eu] ratio for stars with [Fe/H]≤ -2.4 is -0.69 ± 0.06 dex, consistent with pure r-process nucleosynthesis within the measurement uncertainties, although [Sr/Fe] and [Ba/Fe] ratios span a range of 2.6 dex, the mean values are approximately constant with [Fe/H]. Woolf et al. (1995) measured [Eu/Fe] ratios of 81 nearby field F and G disk dwarf stars with $-0.9 \leq$ [Fe/H]$\leq +0.3$ in the solar neighborhood and their results showed increasing [Eu/Fe] ratios with decreasing [Fe/H] although there was some considerable scatter about the mean relation.

François (1996) has found from 16 metal-poor stars that the case for an r-process origin of the n-capture elements is less certain. Since the scatter in n-capture element abundances with respect to iron is so large for stars with [Fe/H]< -1.0, much of the disagreement can be traced to the small number and particular selection of stars included. Jehin et al. (1999) surveyed a sample of 21 mildly metal-poor stars in the range of $-1.2 \leq$ [Fe/H]≤ -0.6, with the measurement uncertainties of [heavy element/Fe] below 0.1 dex. Tomkin et al. (1999) reported the abundances of the elements Rb, Y, Zr, and Ba in 44 dwarfs and giants with metallicities spanning the range $-2.0 <$[Fe/H]< 0.0.

Burris et al. (2000) presented n-capture element abundances for 43 metal-poor Bond giants, and Ba abundances only for an additional 27 Bond giants on a uniform system of metallicity. Sneden et al. (2000) determined the abundances of more than 30 n-capture elements ($Z > 30$) in the ultra-metal-poor ([Fe/H]$= -3.1$) halo field giant star CS 22892–052, and found that the abundances of the heavier ($Z \geq 56$) stable n-capture elements in this star match well the scaled solar system r-process abundance distribution, but the concordance breaks down for the lighter n-capture elements. They concluded that their results support the previous suggestion that different r-process production sites are responsible for the lighter and heavier n-capture elements. From the above observational studies, we obtain the observed abundance ratio of [Ba/Fe] versus [Fe/H] shown in Figure 1. Figure 2 shows the run of [Eu/H] versus [Ba/H].

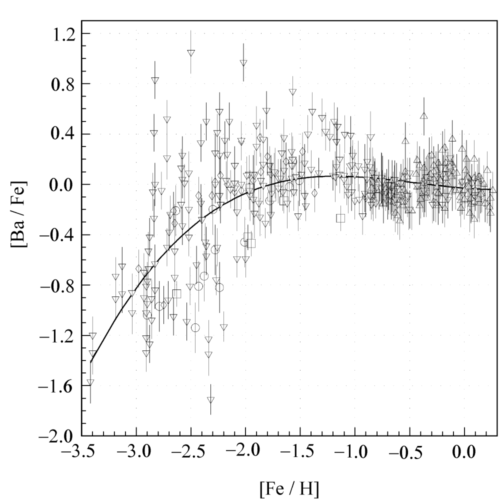

Fig. 1 Comparison of the observed abundances of [Ba/Fe] vs. [Fe/H] with the third-order cubic spline fit (solid line).

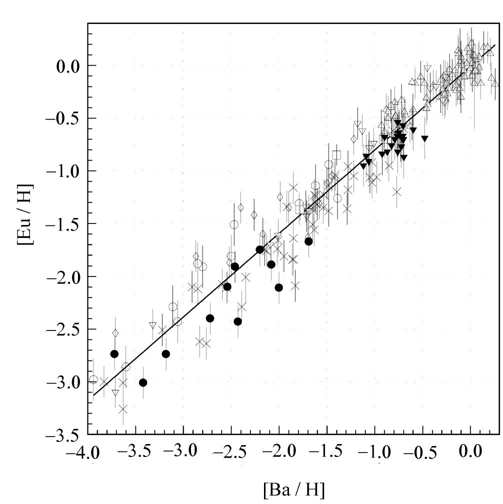

Fig. 2 Comparison of the observed abundances of [Eu/H] vs. [Ba/H] with the linear regression line (solid line).

Figures 4–9 show the trends of [La/H], [Ce/H], [Pr/H], [Nd/H], [Sm/H], and [Dy/H] versus [Fe/H], respectively. Different symbols refer to the different sources: open pentagons for Gilroy (1988), open diamonds for Magain (1989), open squares for Zhao (1993), open triangles for Edvardsson (1993), open upside-down triangles for Gratton & Sneden (1994), filled pentagons for McWilliam et al. (1995a, 1995b, 1998), filled diamonds for Woolf et al. (1995), filled squares for François (1996), filled triangles for Tomkin (1999), filled upside-down triangles for Jehin et al. (1999), and crosses for Burris et al. (2000).

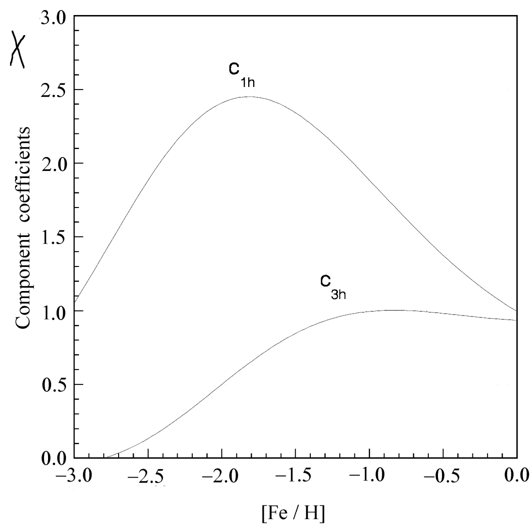

Fig. 3 Runs of C_{1h} and C_{3h} as function of [Fe/H] according to our model.

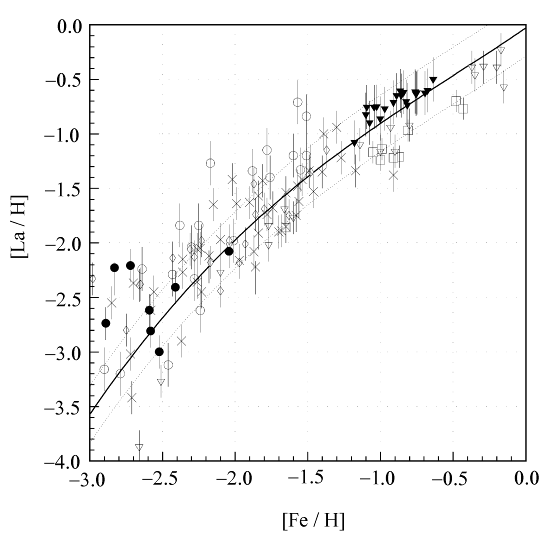

Fig. 4 Evolution of [La/H] in metal-poor stars as function of [Fe/H] according to our model (solid line).

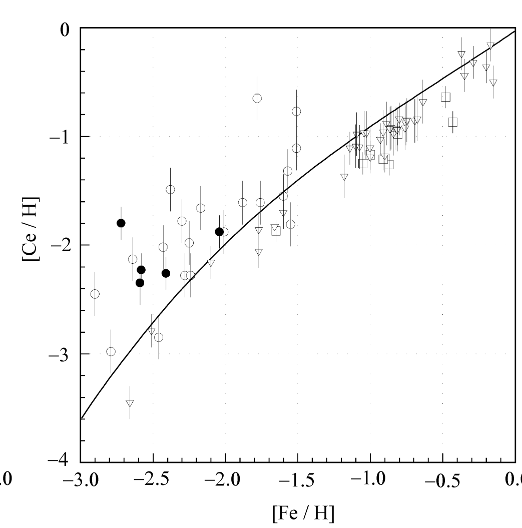

Fig. 5 Evolution of [Ce/H] as function of [Fe/H] (solid line).

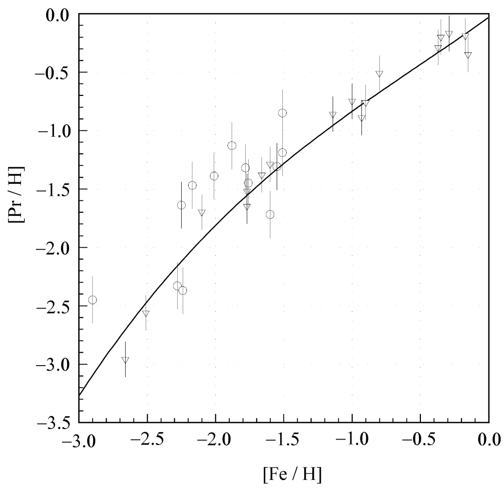

Fig. 6 Evolution of [Pr/H] as function of [Fe/H] (solid line).

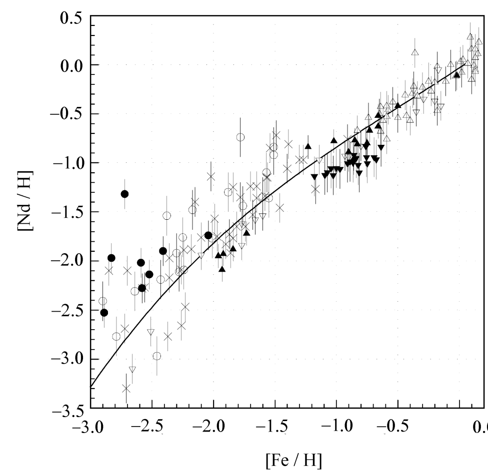

Fig. 7 Evolution of [Nd/H] as function of [Fe/H] (solid line).

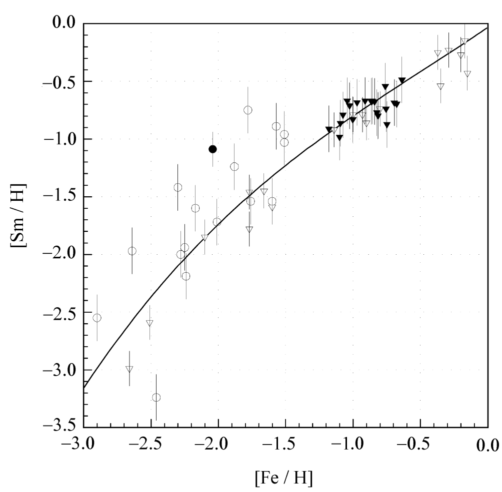

Fig. 8 Evolution of [Sm/H] as function of [Fe/H] (solid line).

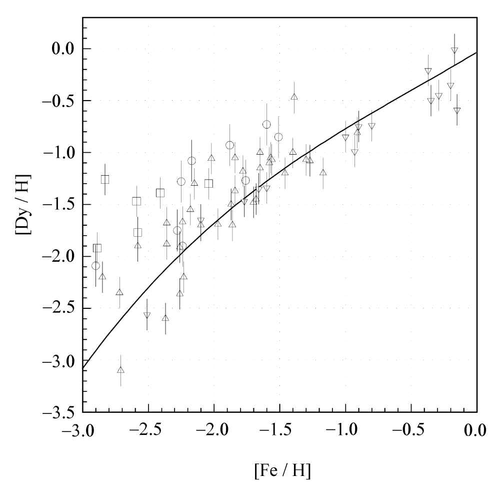

Fig. 9 Evolution of [Dy/H] as function of [Fe/H] (solid line).

3 STATISTICAL MODEL

3.1 Model of the Heavier Element Abundance Distribution

Detailed comparisons of solar system meteoritic abundances of n-capture isotopes (Anders & Ebihara 1982; Anders & Grevesse 1989; Käppeler et al. 1989; Arlandini et al. 1999) have yielded an accurate breakdown into r- and s-process parts for each isotope. These elemental

s- and r-process abundances in solar system material have served as the standard pattern in chemical evolution models. Burris et al. (2000) and Sneden et al. (1996) have calculated the solar system s- and r-process fractions for each element. From the solar abundance pattern, we note that no n-capture element with $Z \leq 83$ can be identified solely with the r-process or the s-process but some are clearly dominated by one of the two: for example, Ba has an 81% s-process fraction, and Eu, a 94.2% r-process fraction (Arlandini et al. 1999). Such elements are usually labeled as s- process or r-process, regardless of their synthesis history in non-solar Galactic material. Similarly, the n-capture elements in metal-poor stars are usually synthesized by a combination of the r- and s-processes. In this paper, we take Ba as the representative element of the main s-process component and Eu, as that of the primary r-process component, and, following the above discussion, we adopt the new abundance distribution in the solar system (Arlandini et al. 1999), and so present our model for the chemical evolution of the heavy elements with $Z \geq 56$ as follows:

$$N_{ih}(Z) = (C_{1h}N_{i,r} + C_{3h}N_{i,sm})10^{[\mathrm{Fe/H}]}, \tag{2}$$

$$C_{1h} = 1.0765 \times 10^{[\mathrm{Eu/Fe}]} - 0.0765 \times 10^{[\mathrm{Ba/Fe}]}, \tag{3}$$

$$C_{3h} = 1.2522 \times 10^{[\mathrm{Ba/Fe}]} - 0.2522 \times 10^{[\mathrm{Eu/Fe}]}, \tag{4}$$

where $N_{i,r}$ and $N_{i,sm}$ are the i-th heavier n-capture element abundance produced by the r-process and the main s-process in solar system material, respectively; C_{1h} and C_{3h} are the component coefficients of the r_h-process and the main s_{mh}-process for the heavier n-capture elements in metal-poor stars, respectively.

To obtain the runs of C_1 and C_3 with [Fe/H], we should first know the average trends of [Ba/Fe] and [Eu/Fe] with [Fe/H]. François (1996) suggested that there is a tight linear correlation between [Eu/H] and [Ba/H]. Based on the observational data of [Ba/Fe] and [Eu/H] in Figure 1 and Figure 2, we come to a similar conclusion, and evaluate the least-squares regressions of [Ba/Fe] on [Fe/H], and of [Eu/H] on [Ba/H]. We obtain

$$\left.\begin{array}{rcl}
[\mathrm{Ba/Fe}] &=& -0.03049 - 0.06829 \times [\mathrm{Fe/H}] \quad +0.00883 \times [\mathrm{Fe/H}]^2 \quad +0.06637 \times [\mathrm{Fe/H}]^3, \\
&& \pm 0.02568 \pm 0.08439 \qquad\qquad\quad \pm 0.07074 \qquad\qquad\qquad \pm 0.01597, \\
&& (s = 0.2615,\ 406\ \text{elements}), \\
[\mathrm{Eu/H}] &=& -0.01105 + 0.79174 \times [\mathrm{Ba/H}] \\
&& \pm 0.02159 \pm 0.01372, \\
&& (s = 0.2017,\ 203\ \text{elements}),
\end{array}\right\} \tag{5}$$

where s is the residual scatter. The solid lines in Figures 1 and 2 are the regression curves. Using the F-test and the correlation coefficient r to determine the goodness of fit, we compute that r has the values 0.7185, 0.9828 for the data in Figures 1 and 2 and that the two larger values correspond to a confidence level above 99%. So Equation (5) can be considered as reliable.

4 RESULTS AND DISCUSSION

4.1 Results

Substituting Equation (5) in Equations (3) and (4), we obtain the runs of the two component coefficients C_{1h} and C_{3h} with metallicity [Fe/H], shown in Figure 3. Using the two curves, we can predict the trends of the mean abundance distribution of the n-capture elements in metal-poor stars at any metallicity through Equation (2). We choose to consider the heavier elements La, Ce, Pr, Nd, Sm, Dy; their predicted mean abundance distributions are separately shown by the solid lines in Figures 4–9.

4.2 Discussion

The mean patterns of component coefficients C_{1h} and C_{3h} with metallicity [Fe/H], as illustrated in Figure 3, contain some important information for the chemical evolution of the Galaxy. First, that $C_{1h} > C_{3h}$ means that the productions of the main r-process are more remarkable than those of the main s-process in metal-poor stars. Secondly, for the very metal-poor stars with [Fe/H] < -2.0, the main r-process for the synthesis of the $Z \geq 56$ elements is extremely robust, while the main s-process for these elements is less so. Thirdly, the trends of the r-process and the main s-process productions are obviously different. As the metallicity increases, the r-process productions first increase and reach a maximum value at ~ -2.0, then begin to decrease, while the main s-process productions increase all the time. However, both the r-process productions and the main s-process productions reach their solar system abundances as the metallicity approaches the solar value, i.e., $C_{1h} = C_{3h} \approx 1$ at [Fe/H]=0. Not only are these results in agreement with previous observational and theoretical studies, they are also consistent with the conclusions of the theory of galactic chemical evolution (e.g., Truran 1981; Mathews & Cowan 1990; Mathews et al. 1992; Gratton & Sneden 1994; Sneden et al. 1996, 2000; Travaglio et al. 1999; Burris et al. 2000). According to this theory, the r-process nuclei are produced during the stage of massive supernova explosions, whereas the manufacture of the r-process elements is independent of Fe-seed sources. The r-process elements can be synthesized directly from the elements C, N, and O, and the oxygen abundance is higher than the iron abundance by a factor of $3-4$ in the early Galaxy, therefore the r-process contributions to the heavy elements are dominant at low metallicities. In contrast, the main s-process occurs during the phase of thermal pulsation in intermediate and low mass AGB stars, and the production of the s-process elements needs Fe-seed source, so its contributions to the heavy elements are very small in the early Galaxy. Figure 3 clearly shows that contributions from the main s-process can be first seen at [Fe/H] ≈ -2.90, and increase in most stars with metallicities [Fe/H]> -2.3; at the same time, the contributions from the r-process begin to decrease with increasing [Fe/H]. These results are in good agreement with the suggestions of Burris et al. (2000).

Figures 4–9 show that the predictions of the model for the heavier elements La, Ce, Pr, Nd, Sm, and Dy (solid lines) fit the mean trends of the observations well. This agreement strongly suggests that our statistical model is workable for predicting the mean abundances of the heavy elements ($Z \geq 56$) in metal-poor stars. It also means that these heavier elements are truly produced by the main r-process and the main s-process, and each of the main r- and s-process abundance patterns in metal-poor stars are consistent with its corresponding solar system pattern.

We also note from Figures 4-9 that, for samples with [Fe/H]< -2.5, the predicted trends of [heavy element/H] versus [Fe/H] do not reproduce the mean abundances of the available spectroscopic observations. For instance, the predicted trend of [Ce/H] vs. [Fe/H] is clearly lower than the observed mean abundances for [Fe/H]< -2.5. Since Ce is mainly produced through the s-process in solar material, this deviation means that the efficiency of the s-process in extremely metal-poor stars is too low to contribute significantly to the chemical enrichment of Ce, and a larger r-process production is needed to match the observed data of Ce. This result sustains the previous conclusion that the heavy element abundance patterns in very metal-poor stars are compatible with r-process origin (Truran 1981; Sneden et al. 1996, 2000; Burris et al. 2000). On the other hand, this result indicates that our statistical model will not be suitable for the very metal-poor stars due to the chemical inhomogeneity in the Galactic halo. However, we argue that even in this case, our model predictions still provide a reference point when we compare the abundance patterns in metal-poor stars with the solar pattern and gather more information of the Galactic chemical evolution. We do not attempt to discuss the lighter n-capture elements in this paper because the production mechanisms of the lighter elements are more complex and still uncertain at present. Various possibilities are still under discussion (see Travaglio et al. 2000; Burris et al. 2000; Qian et al. 2001).

5 CONCLUSIONS

We have presented a statistical model for predicting the mean trends of heavy element abundances with metallicity. This model is based on two reasonable assumptions: (1) the heavy elements (heavier than Ba) are produced by a combination of the main components of the s- and r-processes in metal-poor stars; (2) either the main r-process(r_h) abundance distribution or the main s-process(s_{mh}) abundance distribution for these heavy elements at any metallicity is in accordance with its corresponding solar distribution. The reasonableness of our assumptions has been discussed in Sections 2 and 3. The agreement between the model predictions and the observed data further validates our assumptions and strongly confirms that the statistical model is reliable at least in the regime of [Fe/H]≥ -2.5.

As described above, the results of our model provide some important information for the chemical evolution of the Galaxy, which we now itemize as follows:

1. The productions of the main r-process are more remarkable than those of the main s-process in metal-poor stars. For the very metal-poor stars with [Fe/H]< -2.0, the main r-process for the synthesis of the $Z \geq 56$ elements is extremely robust, while the main s-process for these elements is less so.
2. Although both the main s-process and r-process abundance distributions for the heavy elements in metal-poor stars are in accordance with their corresponding solar pattern, the relative yields of the two processes are obviously different. As the metallicity increases, the r-process productions first increase and reach a maximum value at [Fe/H]~ -2.0, then begin to decline; while the main s-process productions monotonously increase.
3. For the extreme metal-poor stars with [Fe/H] < -2.5, the heavy element abundance patterns may be compatible with a pure solar r-process origin.

In summary, our model provides an approach to determine the mean contributions from the r-process and the main s-process to the heavy elements at any metallicity. The model predictions can be used as initial stellar abundances when calculating the elemental nucleosynthesis. With the improvement of the observed data in quantity and quality, especially the data of Ba and Eu in the regime of [Fe/H]< -2.5, the model predictions will be more and more precise, and our model will also be expected to be more reliable.

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