PROCEEDINGS OF SCIENCE

PoS(NIC-IX)059

Neutron-Capture Processes in the Early Galaxy

Wako Aoki[*]
National Astronomical Observatory of Japan
E-mail: `aoki.wako@nao.ac.jp`

Many observational studies of metal-poor stars that exhibit large excesses of r-process elements have been made in the past decade, and have provided useful constraints on modeling this process. Recent abundance studies have revealed the existence of extremely metal-poor stars that have large enhancements exclusively of the light neutron-capture elements, indicating that a nucleosynthesis process that efficiently yields these elements operated in the very early Galaxy. We review these recent measurements of light neutron-capture elements in the field halo stars, including the most iron-deficient star known, as well as stars in metal-poor globular clusters. The abundance pattern produced by this process and possible astrophysical sites are discussed. We also discuss a group of metal-poor stars that exhibit double enhancements of s- and r-process elements, which have been recently discovered through observations of carbon-enhanced metal-poor stars. Observational constraints on the corresponding processes responsible for this signature are presented.

International Symposium on Nuclear Astrophysics — Nuclei in the Cosmos — IX
June 25-30 2006
CERN, Geneva, Switzerland

---

[*] Speaker.

1. Introduction

Chemical abundance studies based on high-resolution spectroscopy of very metal-poor stars in the past decade have revealed that a small fraction of these objects exhibit large excesses of neutron-capture elements, whose abundance patterns agree very well with that of the r-process component of solar-system material (e.g. CS 22892–052 [1], CS 31082–001 [2]). Very metal-poor stars are believed to have formed in the very early Galaxy, and the chemical composition of such objects were determined by the elemental yields of a few (or possibly a single) supernova nucleosynthesis events. The agreement of the abundance pattern of neutron-capture elements in very metal-poor stars with that of the r-process component in the Solar System suggests that the abundance pattern produced by the r-process is possibly unique. This phenomenon is referred to as the universality of the r-process, and has been confirmed at least for heavy neutron-capture elements (Ba–Ir) by the abundance measurements for several r-process-enhanced stars [3, 4, 5, 6, 7, 8]. This observational result has a large impact on studies of the mechanism and the astrophysical sites of the r-process.

Although abundance measurements have been extended to stars with lower metallicity by recent observations, r-process-enhanced stars are found only in the range of [Fe/H]$\gtrsim -3$ [1] (e.g. Barklem et al. [9]). In particular, the stars having extremely large overabundances of r-process elements (e.g. [Eu/Fe]$> +1$) appear at around [Fe/H]$= -3.0$. The metallicity distribution of the r-process- enhanced stars should reflect the characteristics (mass, metallicity, etc.) of the progenitor objects, although the astrophysical sites responsible for the r-process are still not understood (see the review on r-process nucleosynthesis by Wanajo & Ishimaru [10]).

Recent abundance studies have also revealed the existence of objects that have quite different abundance patterns from that of the solar-system r-process component, in particular for light neutron-capture elements. Detailed abundance measurements for CS 22892–052 [11] showed that the abundances of the light neutron-capture elements (Sr–Cd) deviate from the r-process abundance pattern of the Solar System. This deviation is also found for other r-process-enhanced stars [12, 7]. Moreover, the abundance ratios between light and heavy neutron-capture elements (e.g. Sr/Ba) exhibit a large spread in very metal-poor stars [13, 7]. These observational results indicate the existence of a process (or processes) that produced significant amount of light neutron-capture elements, and have contributed to the r-process component of solar-system material. This process is sometimes referred to as the “weak r-process” [10], while the r-process that creates the bulk of the heavy neutron-capture elements is called the “main r-process” [14]. In this paper, our recent observational studies of the production of light neutron-capture elements in the early Galaxy are reviewed, and constraints on models for this process obtained from these data are discussed.

The abundances of the actinides (such as Th and U) produced by the r-process are also of interest. The Th abundance of the r-process-enhanced star CS 22892–052 is well explained by the assumption that the initial abundance pattern of heavy neutron-capture elements, including the actinides, of this object is identical to that of the r-process component in the Solar System, with Th undergoing radioactive decay by a factor of two over the time since this element was formed (~ 14 Gyr, that is, the age of the universe; [1, 6]. Similar results have been obtained for other r-process-enhanced stars. However, a few stars exhibit Th abundances that are higher than the value expected from the above assumption (e.g., CS 31082–001 [2, 12]; CS 30306–132 [7]). Although the spread

---

[1] [A/B] = $\log(N_{\rm A}/N_{\rm B}) - \log(N_{\rm A}/N_{\rm B})_{\odot}$, and $\log\varepsilon_{\rm A} = \log(N_{\rm A}/N_{\rm H}) + 12$ for elements A and B.

of the abundance ratios between the actinides and the stable heavy neutron-capture elements (e.g., Th/Eu) is not large (at most 0.4 dex), this factor is crucial when the abundance ratios are applied to obtain limits on stellar ages. This topic have been discussed extensively in the literature [7, 15] and in this volume [16].

Another interesting result related to neutron-capture processes in the early Galaxy is found for carbon-enhanced metal-poor (CEMP) stars, the majority of which exhibit large excesses of s-process elements. The nucleosynthesis in thermally pulsing Asymptotic Giant Branch (AGB) stars is believed to be responsible for the s-process elements, in particular for those heavier than Ba (see a recent review by Herwig [17]). Since the timescale for significant contribution of AGB nucleosynthesis to Galactic enrichment is longer than that of massive stars, the effect of the s-process appears clearly in relatively metal-rich (young) stars. Therefore, the s-process-enhanced, very metal-poor stars are explained by a scenario that assumes mass transfer across a binary system; that is, the AGB star responsible for the s-process was once the primary of a binary system, and the yields were transferred to the envelope of its companion prior to the primary evolving to become a faint white dwarf. Detailed abundance measurements of neutron-capture elements have shown that a significant fraction of such objects also exhibit excesses of Eu, which is an almost pure r-process element in the Solar System. This result suggests a large contribution of r-process, as well as s-process, to such objects, and they are called “CEMP r/s stars”[18]. In section 5, recent observational studies for these stars are reviewed.

2. Production of light neutron-capture elements in the early Galaxy

Figure 1 shows the abundances of Sr and Ba measured for very metal-poor ([Fe/H]< -2.5) field halo stars and objects in the metal-poor ([Fe/H]~ -2.3) globular cluster M15. Here Sr and Ba are regarded as elements representing light and heavy neutron-capture yields, respectively. Carbon-rich stars, most of which show excesses of s-process elements and would be affected by mass transfer in binary systems, are excluded from the sample. Hence, the origin of Sr and Ba for the stars shown in the figure is expected to be solely due to the r-process.

Inspection of Figure 1 indicates that (1) there is no object that has both a high Ba abundance and a low Sr abundance; (2) a large scatter of Sr abundances is found in stars with low Ba abundances [7, 19, 20]. These results are naturally explained by assuming two processes producing high and low Sr/Ba ratios. That is, one process that produces large amount of Sr with little Ba is responsible for the stars having high Sr and low Ba abundances, while the other process yields both elements in similar amounts, and formed stars with high Ba (and Sr) abundances. Since Sr is produced by both processes, all Ba-enhanced stars also show excesses of Sr. Moreover, the contribution of the latter process diminishes the spread of Sr abundances in Ba-enhanced stars.

The latter process, which produces heavy neutron-capture elements, corresponds to the main r-process (section 1). Although the astrophysical origin of Sr-enhanced stars is still unclear, this investigation clearly shows the existence of a process that efficiently yielded light neutron-capture elements at very low metallicity. For convenience, hereafter we regard this process as the weak r-process (section 1).

Aoki et al. [20] have suggested that the distribution of Sr and Ba abundances is dependent on the metallicity of the star. In the metallicity range [Fe/H]< -3.1, most objects have low Ba abun-

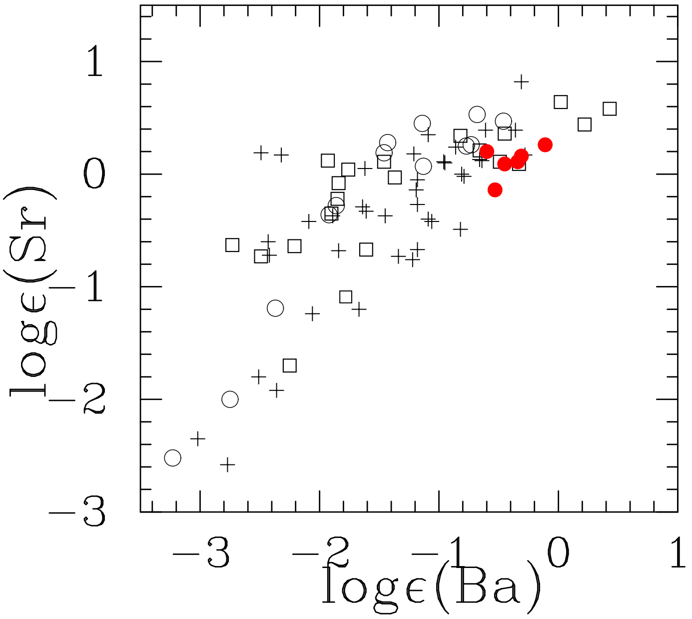

Figure 1: Sr abundances as a function of the Ba abundance for very metal-poor stars ([Fe/H]$\lesssim -2.5$). Stars having significant excesses of carbon and s-process elements are excluded. The results of our studies for field stars are shown by open circles [20] and open squares [7]. Results of previous studies are also shown by plus symbols (see Aoki et al. [20] for references). Stars in the globular cluster M15 are shown by filled circles.

dances ($\log\varepsilon$(Ba)$\lesssim -1.5$), while a large scatter of Sr abundances exists. In contrast, most stars with higher metallicity ($-2.9 <$[Fe/H]< -2.5) have high Ba (and Sr) abundances. A clear transition occurs at [Fe/H]$= -3.0$. This phenomenon corresponds to the fact that r-process-enhanced stars only appear in the range of [Fe/H]> -3 (see section 1). An important result of the above inspection is that Sr-enhanced stars exist at lower metallicity ([Fe/H]< -3), suggesting that the weak r-process operated even at extremely low metallicity, or that the process is related to supernova explosions that are responsible for the elements observed in extremely metal-poor stars.

Since singly ionized Sr and Ba have very strong resonance doublet lines in the optical range, these two elements are preferable for investigating the abundance distribution of large samples of metal-poor stars, including objects with very low abundances of these elements. However, the accuracy of abundance measurements for Sr and Ba in stars is somewhat compromised when these lines are used, because strong absorption lines are less sensitive to abundance differences than weak lines. In particular, no weak Sr line that is ideal for abundance analysis exists in the optical range. Hence, for a more detailed investigation of the abundance distributions of light and heavy neutron-capture elements, Aoki et al. [20] consider the Y, Zr, and Eu abundances. Figure 2 shows the Y and Eu abundances for the field stars of their study, as well as stars in three metal-poor globular clusters (M15, M30, and M92).

Because of the relatively high detection limit of Eu lines, only stars with large abundances of heavy neutron-capture elements can be discussed. However, note that a spread of Y abundances is found in stars with low Eu abundances ([Eu/Fe]< -2). This indicates that the contribution of the

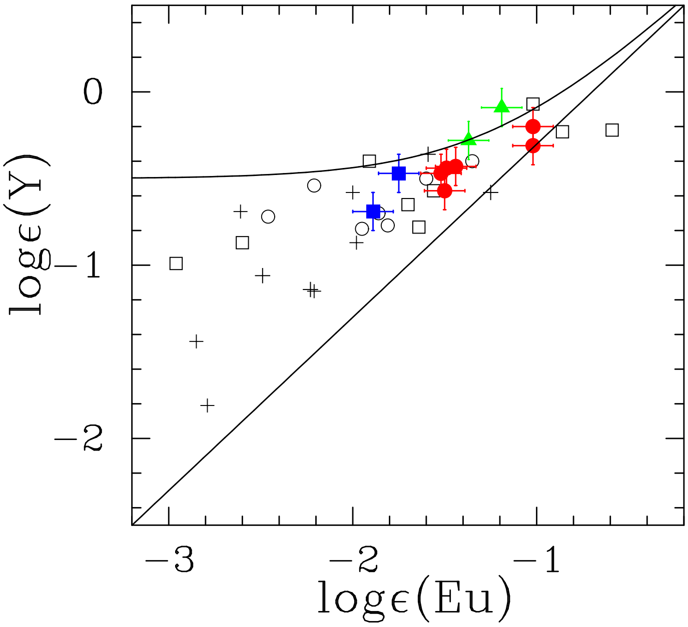

Figure 2: Y abundance as a function of Eu abundance for field stars (open circles [20], open squares [7] and plus symbols), and for three metal-poor globular clusters – M15 (filled circles), M92 (filled squares) and M30 (filled triangles). The lines show the enrichment of related elements, assuming different initial abundances and a constant Y/Eu ratio in the yields of the main r-process. See text for details.

weak r-process appears in these stars, although the main r-process also has clearly contributed. The two solid lines show the enrichment of these two elements by the main r-process (here we assume a fixed Y/Eu ratio of 5 for the yields) for two different initial Y abundances, which represents the variation of the contribution of the weak r-process (see Aoki et al. [20] for details). Most field stars appear between the two lines, implying that the abundance distributions are explained by the contributions of the two processes. The effect of the weak r-process also appears in these objects, as well as in the extremely metal-poor, Sr-rich, Ba-poor stars shown in Figure 1.[2]

Otsuki et al. [22] studied neutron-capture elements in six bright giants of the metal-poor ([Fe/H]~ -2.3) globular cluster M15. The Sr and Ba abundances of these stars are plotted in Figure 1. The neutron-capture elements in this cluster exhibit some abundance spread [23], and the values are relatively high compared to field stars of similar metallicity. The Y and Eu abundances of these stars are shown in Figure 2. We recently have extended the measurements to include two stars in M30 and another two in M92, whose metallicity is similar to M15. The results are also shown in the Figure. If there is no (or only a very small) contribution of weak r-process to the stars in these clusters, a correlation represented by the lower solid line should appear. The result is, however, that the Y abundances are *higher* than this line, indicating the contribution of the weak r-process to globular clusters, or their progenitors, as in the field halo stars (see Otsuki et al. [24]).

Thus, the weak r-process generally contributes to metal-poor stars over a wide metallicity

---

[2] It should be noted that the [Y/Zr] abundance ratios measured for field stars are almost constant ([Y/Zr]~ -0.4), and the value is not explained by the weak s-process [21].

range, although the contribution is not uniform. This suggests that the progenitor stars responsible for this process are different from those of the main r-process, which affects only a limited number of extremely metal-poor stars. Travaglio et al. [25] investigated the role of this process in Galactic chemical evolution, and estimate the contribution to the solar-system abundances of light neutron-capture elements to be on the order of 8–25%, depending on the elements under dicussion.[3] The role of this process appears to be quite significant in the early Galaxy.

3. The abundance pattern produced by the weak r-process

For modeling the weak r-process, observational constraints on the detailed abundance pattern produced by this process are vital. Unfortunately, however, the solar-system composition does not provide useful constraints, because the contribution by the main r-process is not well separated from the weak r-process. Hence, abundance patterns of very metal-poor stars that preserve the yields of this process provide a unique opportunity to examine model predictions. Stars having a high Sr abundance without the presence of a Ba excess are candidate targets for this study.

Honda et al. [26] obtained a detailed abundance pattern for neutron-capture elements in the very metal-poor ($[\mathrm{Fe/H}]=-2.7$) star HD 122563, which has a relatively high abundance of light neutron-capture elements ($\log\varepsilon(\mathrm{Sr})=0.1$) and low abundances of the heavy ones ($\log\varepsilon(\mathrm{Ba}) = -1.7$, see Figure 1). This star is a very bright red giant (visual magnitude of 6.2), for which a number of abundance studies have been made. However, since heavy neutron-capture elements are less abundant in this object, a very high quality spectrum is required in order to obtain accurate abundance measurements. Most spectral lines of neutron-capture elements that are useful for abundance studies exist in the ultraviolet region, in which stellar flux rapidly declines and the transparency of the earth's atmosphere degrades. Honda et al. [26] obtained a very high quality ultraviolet spectrum of HD 122563 using the 8.2 m Subaru Telescope, and determined abundances of 19 neutron-capture elements, as well as upper limits for other five elements.

Such measurements were recently extended to another bright, very metal-poor red giant, HD 88609, by Honda et al. [27]. Figure 3 shows the abundance patterns of neutron-capture elements in these two stars, compared with that of the solar-system r-process component. If the pattern is normalized to the Eu abundance, these two stars clearly show large excesses of light neutron-capture elements compared to the solar pattern. Since these stars are very metal-poor and only one or a few massive stars and supernovae should have contributed to their chemical composition, the light neutron-capture elements of these stars can be regarded as representing the yields of the weak r-process.

The abundances of the elements with $Z\sim 46$, which exist between the first and second abundance peaks produced by neutron-capture processes, would strongly constrain the nucleosynthesis models. Most r-process models with parameters that are *not* appropriate for production of heavy r-process elements ($Z\geq 52$) predict a rapid decline of abundances after the first peak ($Z\sim 40$). Some parameter range of r-process models could possibly reproduce the abundance patterns of HD 122563 and HD 88609 [26]. However, these objects are rather *normal* stars in the low metallicity range, in contrast to the r-process-enhanced stars (Figure 1). Hence, fine tuning of the pa-

---

[3] Travaglio et al. [25] call this process the "lighter element primary process (LEPP)".

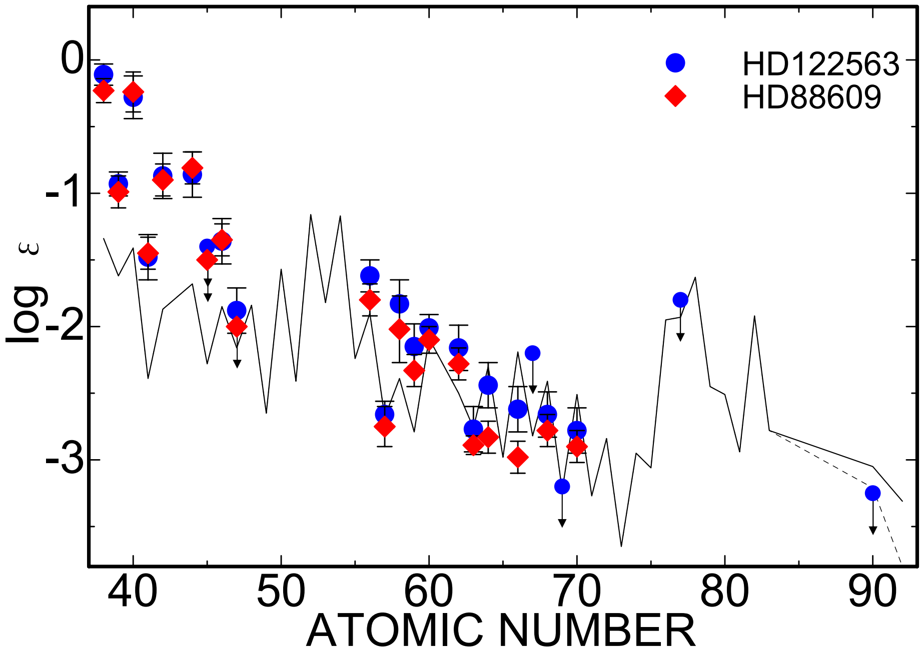

Figure 3: Chemical abundance pattern of the very metal-poor stars HD 122563 and HD 88609 [27], comparing with the solar-system r-process abundance pattern.

rameters of r-process models is unlikely to provide a solution for the origin of the weak r-process elements.

The abundance patterns of the heavy neutron-capture elements ($Z \geq 56$) in the above two stars are similar to that of the solar-system r-process component. However, detailed inspection for these elements in HD 122563 [26] shows that the elemental abundances of this star more rapidly decrease with increasing atomic number than the abundances of the solar-system r-process component. This discrepancy is not fully explained by assuming a (small) contribution of the s-process. Honda et al. [26] argued that the abundances of heavy neutron-capture elements in this star possibly reflect the yields of the weak r-process. There is no established model for this process at present, and further measurements of neutron-capture elements for metal-poor stars like HD 122563 and HD 88609 are desired to reveal the abundance pattern produced by the weak r-process.

4. Neutron-capture elements in the most iron-deficient star HE 1327–2326

A clue to the astrophysical site for the production of light neutron-capture elements in the very early Galaxy was obtained from the recent discovery of HE 1327–2326, the most iron-deficient star known to date [28]. This star was identified as a candidate metal-poor star by the Hamburg/ESO survey [29]. High-resolution spectroscopy of this star was obtained in an ongoing observing program for candidate extremely metal-poor stars using the Subaru Telescope [30] to determine the detailed abundances [28, 31]. This star appears to be either a main-sequence or subgiant star, based on available photometric data and its measured proper motion. The Fe abundance derived by the detailed abundance analysis is [Fe/H]$= -5.4$, which is lower than the iron abundance of HE 0107–

5240, the previously known most iron-poor star [32], and more than one order of magnitude lower than those of other ultra metal-poor halo stars ([Fe/H]$\gtrsim -4$).

The low iron abundance strongly suggests that this star formed from material that had been polluted by only a first-generation (massive) star and its supernova explosion. An important abundance property of this object is the large excess of light elements like carbon, nitrogen and sodium with respect to iron ([C/Fe]$\sim$ [N/Fe]$\sim +4$ and [Na/Fe]$\sim +2.5$). To explain this peculiar abundance pattern, several models, including a supernova model involving the effects of mixing and fallback as parameters [33, 34], stellar wind from rotating very massive stars [35], etc. have been proposed.

One unanticipated result from spectroscopy of HE 1327–2326 is the overabundance of Sr in this object ([Sr/Fe]=$+1.3$), along with a non-detection of Ba. Although the upper limit on the Ba abundance ([Ba/Fe]$< +1.7$) is still weak, the limit for the [Sr/Ba] ratio ([Sr/Ba]> -0.4) provides some constraints on the origin of neutron-capture elements in this star. The main s-process at low metallicity is excluded, because the [Sr/Ba] ratios produced by this process are quite low ([Sr/Ba]$\lesssim -1$)[4]. This limit is not inconsistent with the [Sr/Ba] ratios produced by the main r-process ([Sr/Ba]~ -0.4), as estimated from the abundance ratios of a few extremely r-process-enhanced stars (see section 1). This possibility should be investigated by obtaining the Ba abundance for HE 1327-2326, or a stronger upper limit for it, from higher quality spectra in future.

Another possibility to explain the overabundance of Sr is to assume that the weak r-process operates in the progenitor of this object. Indeed, as discussed in Section 2, overabundances of light neutron-capture elements are found in extremely metal-poor stars, whose heavy elements are believed to be provided by first generation massive objects. The r-process nucleosynthesis in jets of collapsars [36] or in the outflow from the gamma-ray burst objects [37] have been investigated. On the other hand, Fröhlich et al. [38] argued a possible production of heavy elements by the νp process. Efforts to include such processes in the models proposed to explain the lighter elements in HE 1327–2326 are strongly desired.

5. Stars with double enhancements of s- and r-process elements

In this section we discuss recent observational results on the r/s stars. As mentioned in Section 1, all known examples of these stars are carbon-rich (hence they are often referred to as CEMP-r/s), and the excesses of s-process elements are attributed to the nucleosynthesis in thermally pulsing AGB stars. By way of contrast, the origin of the r-process elements, such as Eu, is still unclear.

The classification of such stars mostly relies on the Ba and Eu abundance ratios. The [Ba/Eu] ratios of the r- and s-process components in the Solar System are -0.7 and 1.0, respectively [39]. Beers & Christlieb [18] defined this class of objects to have $0.0 <$[Ba/Eu]< 0.5. While the estimate of the s-process contribution is supported by the abundances of several elements other than Ba (e.g., La), the r-process contribution has been estimated only from the Eu abundances, although the abundances of elements from Gd to Lu also provide some constraints on the origin of neutron-capture elements for a limited number of stars [40].

Aoki et al. [41] quite recently determined the abundances of Os and Ir, species that are located at the third peak of the r-process yields, for the CEMP star CS 31062–050, as well as upper limits

---

[4] The weak s-process yields a quite high abundance ratio of [Sr/Ba]. However, the process is not expected to be efficient at low metallicity due to the lack of neutron sources.

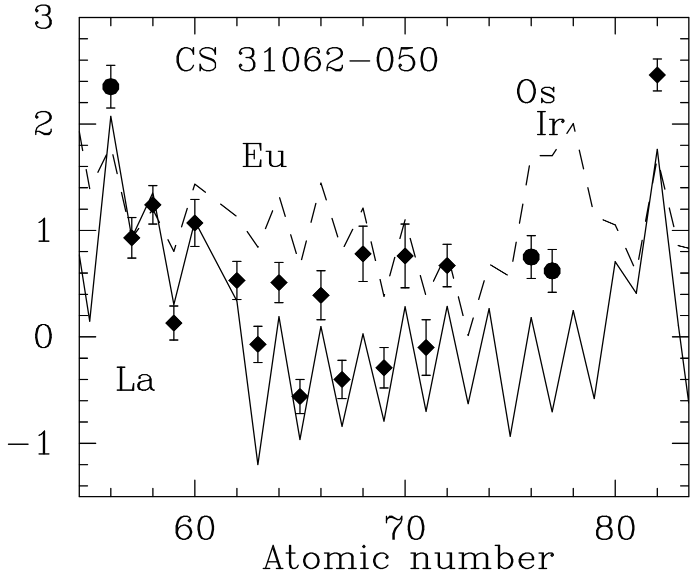

Figure 4: Chemical abundance pattern of the r/s star CS 31062–050, comparing with the solar-system r-process and s-process abundance patterns (dashed and solid lines, respectively).

on their abundances for another CEMP star, LP 625–44. These stars are very metal-poor ([Fe/H]$\sim$ -2.5) subgiants. Moreover, variations of radial velocities are detected in these stars, indicating that these stars belong to binary systems. Figure 4 compares the elemental abundance pattern of CS 31062–050 [42, 41] with the r- and s-process components of solar-system material, which are normalized to La. While the overall abundance pattern of heavy neutron-capture elements agree with the s-process abundance pattern, Eu shows a clear excess from that. The Os and Ir abundances are also much higher than the values of the s-process abundance pattern. Since Os and Ir are almost pure r-process elements, the result confirms a significant contribution of r-process to thes stars.

It should be noted that the upper limits of Os and Ir abundances in LP 625–44 are lower than the abundances of these elements in CS 31062–050 [41]. The La/Eu ratio of LP 625–44 ([La/Eu]$= +0.74$) is also higher than that of CS 31062–050 ($+0.33$). Although these two stars have similar enhancements of carbon and neutron-capture elements, the processes responsible for their enrichment might be quite different.

Observational results for neutron-capture-enhanced stars are complied by Jonsell et al. [43]. One important fact is that a significant fraction of s-process-enhanced stars are r/s stars [43], while the r-process-enhanced stars with no excess of s-process elements are quite rare among very metal-poor stars ($\sim$ 5% [9]). Another interesting result is that the r/s stars have larger enhancements of heavy neutron-capture elements on average than the stars having only s-process enhancements. These results suggest a close relation between the s- and r-processes that form the abundance patterns of r/s stars.

One interpretation for such r/s stars is to assume that the binary system including the low-mass star we currently observe was formed from a cloud polluted by a supernova that yielded r-process elements, and which might trigger the formation of next-generation, lower-mass stars. The s-process elements were then provided by the former primary star during its AGB phase. However, this simple idea might *not* be able to naturally explain the two observational results mentioned in the previous paragraph.

A possible alternative scenario for the r-process contribution is to assume pollution by r-process-enhanced material on the surface of the low-mass star after the s-process has already occured. Wanajo et al. [44] proposed a model that the progenitor is an 8–10 $M_\odot$ star which operated the s-process during its AGB phase, followed by the r-process during the supernova explosion. However, it is not clear how much of the s-process material may be produced by such massive AGB stars [45].

Thus, there is still no established model that explains the abundance patterns of r/s stars, nor their frequency of occurence. Further modeling of these stars, as well as more observational studies, are required for understanding the origins of these stars.

6. Summary and concluding remarks

Recent abundance studies for very metal-poor stars have uncovered a variation of the abundance patterns of neutron-capture elements produced in the early Galaxy. In this paper, observational studies for objects having large excesses in their light neutron-capture elements and the r/s stars have been summarized. These studies suggest that further variation of neutron-capture processes may result from future observations of larger samples. Further systematic surveys of extremely metal-poor stars, and detailed abundance measurements for selected stars are both strongly desired.

The author thanks Dr. T. C. Beers for reading carefully the paper and improving the presentation.

References

[1] Sneden, C., McWilliam, A., Preston, G. W., Cowan, J. J., Burris, D. L., Armosky, B. J. 1996, *The Ultra–Metal-poor, Neutron-Capture–rich Giant Star CS 22892-052., Astrophysical Journal* **467** 819

[2] Cayrel, R., and 12 colleagues 2001, *Measurement of stellar age from uranium decay, Nature* **409** 691

[3] Westin, J., Sneden, C., Gustafsson, B., Cowan, J. J. 2000, *The r-Process-enriched Low-Metallicity Giant HD 115444, Astrophysical Journal* **530** 783

[4] Johnson, J. A., Bolte, M. 2001, *Th Ages for Metal-poor Stars, Astrophysical Journal* **554** 888

[5] Cowan, J. J., et al. 2002, *The Chemical Composition and Age of the Metal-poor Halo Star BD +17°3248, Astrophysical Journal* **572** 861

[6] Sneden, C., et al. 2003, *The Extremely Metal-poor, Neutron Capture-rich Star CS 22892-052: A Comprehensive Abundance Analysis, Astrophysical Journal* **591** 936

[7] Honda, S., Aoki, W., Kajino, T., Ando, H., Beers, T. C., Izumiura, H., Sadakane, K., Takada-Hidai, M. 2004, *Spectroscopic Studies of Extremely Metal-Poor Stars with the Subaru High Dispersion Spectrograph. II. The r-Process Elements, Including Thorium, Astrophysical Journal* **607** 474

[8] Christlieb, N. et al. 2004, *The Hamburg/ESO R-process Enhanced Star survey (HERES). I. Project description, and discovery of two stars with strong enhancements of neutron-capture elements, Astronomy and Astrophysics* **428** 1027

[9] Barklem, P. S., Christlieb, N., Beers, T. C., Hill, V., Bessell, M. S., Holmberg, J., Marsteller, B., Rossi, S., Zickgraf, F.-J., Reimers, D. 2005. *The Hamburg/ESO R-process enhanced star survey (HERES). II. Spectroscopic analysis of the survey sample*, *Astronomy and Astrophysics* **439** 129

[10] Wanajo & Ishimaru 2006, *r-Process Calculations and Galactic Chemical Evolution Nuclear Physics A*, in press, [`astroph/0511518`]

[11] Sneden, C., Cowan, J. J., Ivans, I. I., Fuller, G. M., Burles, S., Beers, T. C., Lawler, J. E. 2000, *Evidence of Multiple R-Process Sites in the Early Galaxy: New Observations of CS 22892-052*, *Astrophysical Journal* **533** L139

[12] Hill, V. et al. 2002, *First stars. I. The extreme r-element rich, iron-poor halo giant CS 31082-001. Implications for the r-process site(s) and radioactive cosmochronology*, *Astronomy and Astrophysics* **387** 560

[13] McWilliam, A. 1998, *Barium Abundances in Extremely Metal-poor Stars*, *Astronomical Journal* **115** 1640

[14] Truran, J. W., Cowan, J. J., Pilachowski, C. A., Sneden, C. 2002, *Probing the Neutron-Capture Nucleosynthesis History of Galactic Matter*, *Publications of the Astronomical Society of the Pacific* **114** 1293

[15] Inese I. Ivans, Jennifer Simmerer, Christopher Sneden, James E. Lawler, John J. Cowan, Roberto Gallino, Sara Bisterzo 2006, *Near-UV Observations of HD221170: New Insights into the Nature of r-Process-Rich Stars*, *Astrophysical Journal*, in press, [`astro-ph/0604180`]

[16] Cowan et al., this volume

[17] Herwig, F. 2005, *Evolution of Asymptotic Giant Branch Stars*, *Annual Review of Astronomy and Astrophysics* **43** 435

[18] Beers, T. C., Christlieb, N. 2005, *The Discovery and Analysis of Very Metal-Poor Stars in the Galaxy*, *Annual Review of Astronomy and Astrophysics* **43** 531

[19] Aoki, W. 2005, *Elemental and isotopic abundances in metal-deficient stars*, *Nuclear Physics A* **758** 209

[20] Aoki, W., Honda, S., Beers, T. C., Kajino, T., Ando, H., Norris, J. E., Ryan, S. G., Izumiura, H., Sadakane, K., Takada-Hidai, M. 2005, *Spectroscopic Studies of Very Metal-poor Stars with the Subaru High Dispersion Spectrograph. III. Light Neutron-Capture Elements*, *Astrophysical Journal* **632** 611

[21] Raiteri, C. M., Gallino, R., Busso, M., Neuberger, D., Kaeppeler, F. 1993, *The Weak s-Component and Nucleosynthesis in Massive Stars*, *Astrophysical Journal* **419** 207

[22] Otsuki, K., Honda, S., Aoki, W., Kajino, T., Mathews, G. J. 2006, *Neutron-Capture Elements in the Metal-poor Globular Cluster M15*, *Astrophysical Journal* **641** L117

[23] Sneden, C., Kraft, R. P., Shetrone, M. D., Smith, G. H., Langer, G. E., Prosser, C. F. 1997, *Star-To-Star Abundance Variations Among Bright Giants in the Metal-Poor Globular Cluster M15*, *Astronomical Journal* **114** 1964

[24] Otsuki et al., this volume

[25] Travaglio, C., Gallino, R., Arnone, E., Cowan, J., Jordan, F., Sneden, C. 2004, *Galactic Evolution of Sr, Y, And Zr: A Multiplicity of Nucleosynthetic Processes*, *Astrophysical Journal* **601** 864

[26] Honda, S., Aoki, W., Ishimaru, Y., Wanajo, S., Ryan, S. G. 2006, *Neutron-Capture Elements in the Very Metal Poor Star HD 122563*, *Astrophysical Journal* **643** 1180

[27] Honda et al., this volume

[28] Frebel, A. et al. 2005, *Nucleosynthetic signatures of the first stars*, *Nature* **434** 871

[29] Christlieb, N. 2003, *Finding the Most Metal-poor Stars of the Galactic Halo with the Hamburg/ESO Objective-prism Survey*, *Reviews of Modern Astronomy* **16** 191

[30] Aoki et al., this volume

[31] Aoki, W. et al. 2006, *HE 1327-2326, an Unevolved Star with [Fe/H]*< -5.0. *I. A Comprehensive Abundance Analysis*, *Astrophysical Journal* **639** 897

[32] Christlieb, N., Bessell, M. S., Beers, T. C., Gustafsson, B., Korn, A., Barklem, P. S., Karlsson, T., Mizuno-Wiedner, M., Rossi, S. 2002, *A stellar relic from the early Milky Way*, *Nature* **419** 904

[33] Umeda, H., Nomoto, K. 2003, *First-generation black-hole-forming supernovae and the metal abundance pattern of a very iron-poor star*, *Nature* **422** 871

[34] Iwamoto, N., Umeda, H., Tominaga, N., Nomoto, K., Maeda, K. 2005, *The First Chemical Enrichment in the Universe and the Formation of Hyper Metal-Poor Stars*, *Science* **309** 451

[35] Meynet, G., Ekström, S., Maeder, A. 2006, *The early star generations: the dominant effect of rotation on the CNO yields*, *Astronomy and Astrophysics* **447** 623

[36] Nagataki, S., Wanajo, S., *r-Process nucleosynthesis in a collapsar*, this volume

[37] Surman, R., McLaughlin, G., *Neutrinos and nucleosynthesis in gamma-ray bursts*, this volume

[38] C. Frhlich, G. Martnez-Pinedo, M. Liebendrfer, F.-K. Thielemann, E. Bravo, W. R. Hix, K. Langanke, N. T. Zinner, *Neutrino-induced nucleosynthesis of* $A > 64$ *nuclei: The nu p-process*, *Phys.Rev.Lett.* **96** 142502, [`astro-ph/0511376`]

[39] Arlandini, C., Käppeler, F., Wisshak, K., Gallino, R., Lugaro, M., Busso, M., Straniero, O. 1999, *Neutron Capture in Low-Mass Asymptotic Giant Branch Stars: Cross Sections and Abundance Signatures*, *Astrophysical Journal* **525** 886

[40] Ivans, I. I., Sneden, C., Gallino, R., Cowan, J. J., Preston, G. W. 2005, *Near-Ultraviolet Observations of CS 29497-030: New Constraints on Neutron-Capture Nucleosynthesis Processes*, *Astrophysical Journal* **627** L145

[41] Aoki, W., Bisterzo, S., Gallino, R., Beers, T. C., Norris, J. E., Ryan, S.G., Travaglio, S. 2006, *Astrophysical Journal*, submitted

[42] Johnson, J. A., Bolte, M. 2004 *The s-Process in Metal-Poor Stars: Abundances for 22 Neutron-Capture Elements in CS 31062-050*, *Astrophysical Journal* **605** 462

[43] Jonsell, K., Barklem, P. S., Gustafsson, B., Christlieb, N., Hill, V., Beers, T. C., Holmberg, J. 2006. *The Hamburg/ESO R-process enhanced star survey (HERES). III. HE 0338-3945 and the formation of the* $r + s$ *stars*, *Astronomy and Astrophysics* **451** 651

[44] Wanajo, S., Nomoto, K., Iwamoto, N., Ishimaru, Y., Beers, T. C. 2006, *Enrichment of Very Metal Poor Stars with Both r-Process and s-Process Elements from 8-10* $M_\odot$ *Stars*, *Astrophysical Journal* **636** 842

[45] Siess, L. 2006 *Evolution of massive AGB stars. I. Carbon burning phase*, *Astronomy and Astrophysics* **448** 717