Subaru/HDS Studies of r-Process Elements in Metal-Poor Stars from Near-UV Spectra

S. Honda[1], W. Aoki[1], Y. Ishimaru[2], S. Wanajo[3], S. G. Ryan[4], T. Kajino[1], H. Ando[1], and T. C. Beers[5]

[1]National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo, 181-8588, Japan
email: honda@optik.mtk.nao.ac.jp

[2]Department of General Education, Kogakuin University, 2665-1 Nakano-Cho, Hachioji, Tokyo 192-0015, Japan

[3]Graduate School of Science, University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan

[4]Department of Physics and Astronomy, Open University, Walton Hall, Milton Keynes MK76AA, UK

[5]Department of Physics and Astronomy and JINA: Joint Institute for Nuclear Astrophysics, Michigan State University, East Lansing, MI 48824, USA.

Abstract. We present detailed abundance measurements of neutron-capture elements for the two very metal-poor stars HD 6268 and HD 122563, based on very high-quality, near-UV spectra (S/N >140 @3100A) using Subaru/HDS. Abundances have been obtained for a total of 26 and 19 neutron-capture elements in these two stars, respectively, including Nb, Mo, Ru, Pd, Ag, Pr, and Sm. We have confirmed that the abundance pattern of neutron-capture elements in HD 6268 agrees very well with that of previously known r-process-enhanced stars. In contrast, the elemental abundances of HD 122563 are found to steeply decrease with increasing atomic number than those of HD 6268, and are much lower than than the r-process pattern in solar-system material. This result provides a new, strong constraint on models of the nucleosynthetic process that has provided light neutron-capture elements in the very early Galaxy.

Keywords. Stars: abundances, ultraviolet: stars, nuclear reactions, nucleosynthesis, abundances

1. Introduction

Essentially all elements heavier than the iron peak are synthesized by neutron-capture processes. About half of the neutron-capture elements in the solar system are thought to have been provided by the r-process. However, details of the nuclear reactions and the astrophysical site(s) of the r-process are still unclear. An effective method to investigate the nature of r-process is to measure the chemical abundances of very metal-poor stars, in which the heavy elements are considered to have been provided by only a few supernovae. Their surface chemical composition would well preserve the results of individual nucleosynthesis processes.

One remarkable example is CS 22892-052, which exhibits large excesses of r-process elements relative to iron (Sneden *et al.* 2003). An important result of this and studies of other similar stars (e.g., Hill *et al.* 2002, Christlieb et al. 2004, Honda *et al.* 2004) is the discovery of the "universality" of the r-process. The abundance pattern of heavy neutron-capture elements ($56 \leqslant Z \leqslant 76$) in r-process-enhanced, metal-poor stars is in excellent agreement with that of the r-process component in the solar-system. This fact has had a large impact on the modeling of r-process nucleosynthesis (e.g., Otsuki *et al.* 2003). However, these studies also revealed that the abundance patterns of light neutron-capture elements ($38 \leqslant Z \leqslant 48$) are not in agreement with that of the solar system r-process.

429
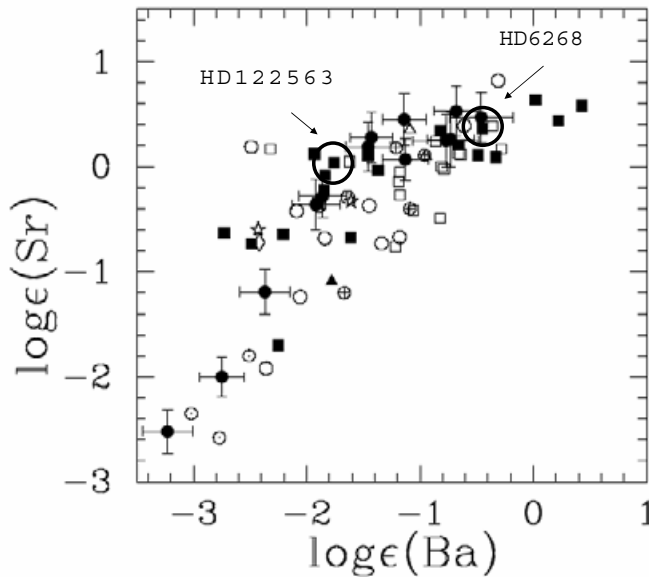
Figure 1. Sr abundances as a function of the Ba abundance for very metal-poor stars with [Fe/H] $\leqslant -2.5$ from McWilliam 1998; Burris et al 2000; Carretta *et al.* 2002; Depagne *et al.* 2002; Johnson & Bolte 2002; Ishimaru *et al.* 2004; Cohen *et al.* 2004; Honda *et al.* 2004, and Aoki *et al.* 2005. Stars having significant excesses of carbon and s-process elements are excluded. The targets discussed in the present work are labelled.

2. Previous observations and sample selection

We have observed 40 very metal-poor stars using the High Dispersion Spectrograph (HDS, Noguchi *et al.* 2002) of the Subaru Telescope, and determined the abundances of numerous neutron-capture elements (Honda *et al.* 2004, Aoki *et al.* 2005). We confirmed that the abundance patterns of the heavy neutron-capture elements ($56 \leqslant Z \leqslant 70$) in seven objects with excesses of these elements are similar to that of the solar system r-process component. However, the light neutron-capture elements ($38 \leqslant Z \leqslant 47$) exhibit large deviations from the solar pattern.

We adopt Sr ($Z = 38$) and Ba ($Z = 56$) as representatives of the light and heavy neutron-capture elements, respectively. Figure 1 shows the correlation between Sr and Ba abundances in very metal-poor stars. This figure shows that (1) there is no Sr-poor star with high Ba abundance, and that (2) the dispersion of Sr abundance is remarkable in Ba-poor stars. This trend can be explained by hypothesizing following two nucleosynthesis processes. One is a process which produces Sr and Ba with similar proportions. The other is a process producing Sr without Ba. While the former is known as the "main" r-process associated with the production of heavy neutron-capture elements, the latter process has been observationally and theoretically studied only quite recently (e.g., Burris et al. 2000; Wasserburg & Qian 2000; Truran *et al.* 2002; Travaglio *et al.* 2004).

In order to further investigate the two likely processes, we selected two bright metal-poor stars which are thought to be representative examples of the two processes: HD 6268 exhibits overabundances of heavy neutron-capture elements such as Ba, while HD 122563 shows high abundances of light neutron-capture elements with no excess of heavier ones.
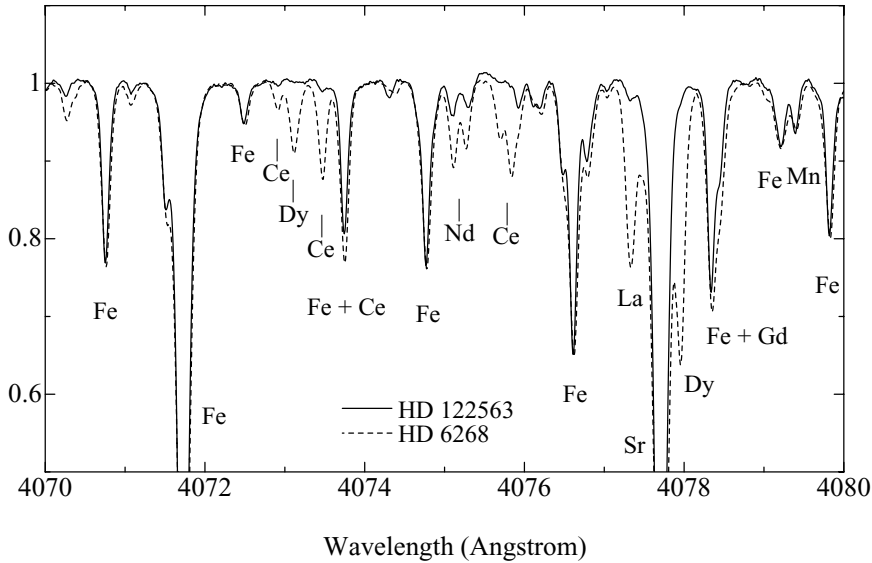
Figure 2. Comparison of a red portion of the spectra for HD 6268 (dashed line) and HD 122563 (solid line).

3. Near-UV observations with Subaru/HDS

High-resolution, near-UV spectroscopy (3000 – 4000 Å) was obtained for these two stars with Subaru/HDS in order to measure the absorption lines of neutron-capture elements. Although our targets are bright stars, a large telescope is required because near-UV observations with ground-based telescopes is made difficult due to strong absorption by the Earth's atmosphere. In order to maximize our ability to detect as many lines as possible in this crowded spectral region a high resolving power ($R = 90,000$) was chosen. The signal-to-noise ratios (S/N) of the spectra are 350/1 at 3500 Å; 700/1 at 4000 Å for HD 6268, and 480/1 at 3500 Å; and 900/1 at 4000 Å for HD 122563.

Figure 2 shows a comparison of a red portion of the spectra of the two stars. The absorption features of iron and manganese are very similar in these spectra, indicating the atmospheric parameters of HD 6268 and HD 122563 are very similar ($T_{\rm eff} = 4600K$, $\log g = 1.0$, $v_{\rm micro} = 2.1$ km s^{-1}, and [Fe/H] = –2.63 for HD 6268; $T_{\rm eff} = 4570K$, $\log g = 1.1$, $v_{\rm micro} = 2.2$ km s^{-1}, and [Fe/H] = –2.77 for HD 122563). However, those of the neutron-capture elements (e.g., La, Dy, Ce) are clearly much stronger in HD 6268 than in HD 122563.

In contrast, the strengths of the Sr line are quite similar in these two stars, confirming an excess of Sr in HD 122563 as well as in HD 6268. In order to investigate the abundance patterns between heavy and light neutron-capture elements, we searched for features of elements with $38 \leqslant Z \leqslant 47$. We have detected several light neutron-capture elements (e.g., Nb, Mo, Ru, Pd, Ag, etc.) which have not been observed by many previous studies.

4. Abundance Patterns of HD 6268 and HD 122563

We adopted the model atmosphere parameters derived by Honda *et al.* (2004) for conducting our abundance analyses. The derived abundance patterns are shown in Figure 3. We have detected 26 elements from Sr ($Z = 38$) to Th ($Z = 90$) in the spectrum of
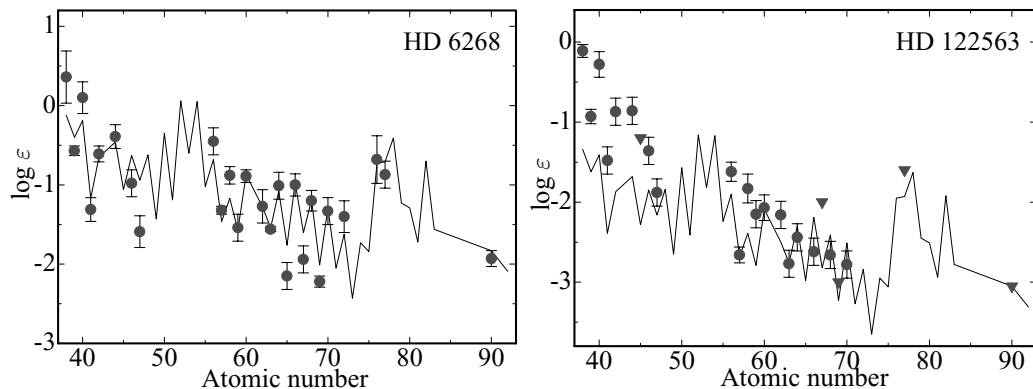
Figure 3. Abundance patterns of HD 6268 and HD 122563. The line is the solar system r-process abundance pattern (Burris *et al.* 2000), scaled to fit the measured Eu abundance. The triangles represent upper limits for several elements.

HD 6268. We confirmed that the abundance pattern of heavy neutron-capture elements in HD 6268 shows good agreement with the solar-system-r-process pattern, while that of the light ones shows several deviations. We should also note that some departure is found at odd elements (Tm, Ho, Tb). In addition, abundance ratios between Th and other heavy neutron-capture elements (e.g., Eu) of this object is slightly higher than CS 22892-052. These should be investigated in more detail in future work.

Although heavy neutron-capture elements are deficient in HD 122563, we have detected 11 elements with $56 \leqslant Z \leqslant 70$ from our high-quality spectrum. In An additional eight elements with $38 \leqslant Z \leqslant 47$ are also detected. HD 122563 exhibits a significantly different abundance pattern from that of the solar system r-process component; the abundances of light neutron-capture elements are much higher than those of the heavier ones.

In order to display these behaviors more clearly, Figure 4 shows the difference of the abundances between these stars and the solar system r-process pattern, as a function of atomic number. The abundance pattern of HD 6268 are basically in agreement with the solar system r-process pattern, although the agreement is not as good as that of CS 22892-052 found by Sneden *et al.* (2003), and other previously observed r-processed-enhanced, metal-poor stars.

In contrast, our new measurements for HD 122563 clearly demonstrate that the elemental abundances steeply decrease with increasing atomic number, in particular as one moves from the elements near the first abundance peak of the r-process ($Z \leqslant 40$) to those near the second peak ($\leqslant 56$). This decreasing trend in the region of $38 \leqslant Z \leqslant 47$ provides an important constraint on modeling the nucleosynthesis process responsible for the light neutron-capture elements (see below).

5. What is the source of the light neutron-capture elements in HD 122563 ?

The abundance pattern produced by the "main" r-process can be represented by the elements observed in HD 6268, which have a similar distribution the abundance patterns of many previously studied r-process-enhanced, metal-poor stars. The ratios between light neutron-capture elements and the heavier ones in HD 122563 are clearly very different from those in HD 6268, which indicates that the "main" r-process is not an important source of the light neutron-capture elements in HD 122563.
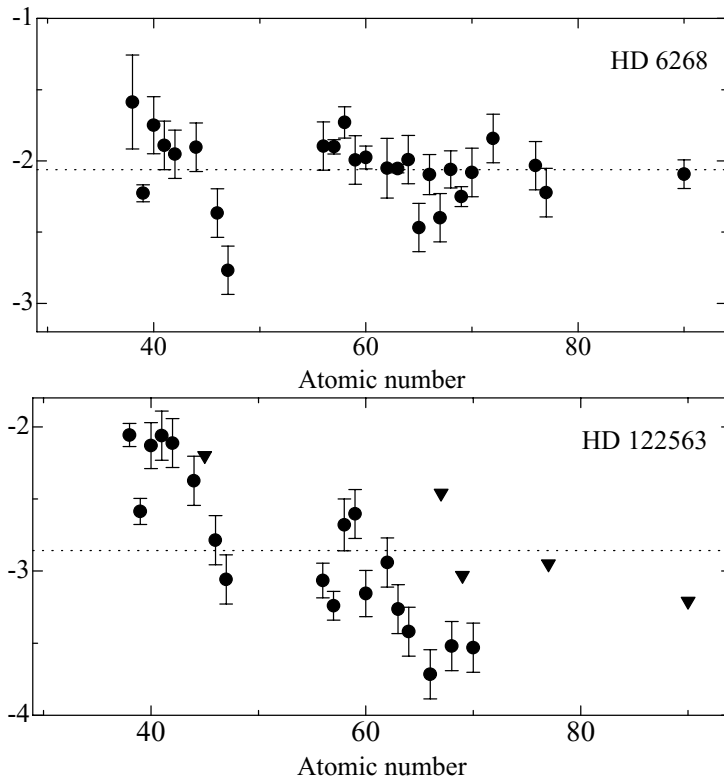
Figure 4. Logarithmic differences from the solar system r-process pattern of HD 6268 and HD 122563. The triangles represent upper limits.

The main s-process is also excluded from the possible source of light neutron-capture elements in HD 122563, because this process is expected to yield predominantly heavy neutron-capture elements (Ba-Pb) compared to light ones (Sr-Zr) (e.g. Busso *et al.* 1999; Aoki *et al.* 2002).

The weak component of the s-process has been introduced in order to account for the abundances of the light s-process nuclei in the Solar System. However, the gradually decreasing trend of elemental abundances from Sr to Ba found in HD 122563 does not agree with the that of the weak s-process, which predicts a rapid decrease of abundances at $A \sim 90$ (e.g., Y or Zr). It should be noted that the weak s-process is also expected to be ineffective at low metallicity, because of the lack of neutron sources such as ^{22}Ne.

Thus, another process that has efficiently produced light neutron-capture elements at low metallicity is required to explain the abundance pattern of neutron-capture elements in HD 122563. The elemental abundances of HD 122563 provide a new constraint on this process. Recently, the operation of a "weak" r-process has been discussed as one possibility (e.g., Wanajo *et al.*, this volume).

6. Conclusions

We have obtained the abundance patterns, covering a wide range of atomic numbers, for the two very metal-poor stars HD 6268 and HD 122563, concentrating on the large number of neutron-capture elements detectable in the near-UV region. Our abundance study revealed that HD 122563 has a significantly different abundance pattern from that

of HD 6268, which exhibits a similar abundance pattern to previously known r-process-rich stars. The elemental abundances of HD 122563 more steeply decrease with increasing atomic number than those of HD 6268, and also with respect to the r-process component in solar-system material. Further theoretical and observational studies to understand the process that is responsible for the light neutron-capture elements in HD 122563, as well as in other halo stars, are strongly desired.

Acknowledgements

References

Aoki, W., *et al.* 2005, *ApJ* in press

Aoki, W., Norris, J.E., Ryan, S.G., Beers, T.C., & Ando, H. 2002, *ApJ*, 567, 1166

Burris, D.L., Pilachowski, C.A., Armandroff, T.A., Sneden, C., Cowan, J.J., & Roe, H. 2000, *ApJ* 544, 302

Busso, M., *et al.* 1999, *ARA&A* 37, 239

Carretta, E., Gratton, R., Cohen, J.G., Beers, T.C., & Christlieb, N. 2002, *AJ* 124, 481

Christlieb, N., Beers, T.C., Barklem, P.S., Bessell, M., Hill, V. *et al.*, 2004, *A&A* 428, 1027

Cohen, J.G., Christlieb, N., McWilliam, A., Shectman, S., Thompson, I. *et al.*, 2004, *ApJ* 612, 110

Depagne, E., Hill, V., Spite, M., Spite, F., Plez, B. *et al.*, 2002, *A&A* 390, 187

Hill, V., Plez, B., Cayrel, R., Beers, T.C., Nordström, B., *et al.* 2002, *A&A* 387, 560

Honda, S., Aoki, W., Kajino, T., Ando, H., Beers, T.C., *et al.* 2004, *ApJ* 607, 474

Ishimaru, Y., Wanajo, S., Aoki, W., & Ryan, S.G., 2004, *ApJ* 600, L47

Johnson, J.A. & Bolte, M. 2002, *ApJ* 579, 616

McWilliam, A. 1998, *AJ* 115, 1640

Noguchi, K., Aoki, W., Kawanomoto, S., Ando, H., Honda, S., *et al.* 2002, *PASJ* 54, 855

Otsuki, K., Mathews, G., & Kajino, T., 2003, *NewA* 8, 767

Sneden, C., Cowan, J., Lawler, J., Ivans, I., Burles, S., *et al.* 2003, *ApJ* 591, 936

Travaglio, C., Gallino, R., Arnone, E., Cowan, J., Jordan, F., & Sneden, C. 2004, *ApJ* 601, 864

Truran, J.W., Cowan, J., Pilachowski, C., & Sneden, C., 2002, *PASP* 114, 1293

Wanajo, S., *et al.* 2005, *This Volume*

Wasserburg, G.J. & Qian, Y.-Z. 2000, *ApJ* 529, L21