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The Detailed Abundance Patterns of Light Neutron-Capture Elements in Very Metal-Poor Stars

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We report the detailed abundance patterns of neutron-capture elements in four very metal-poor stars. The abundance patterns of heavy neutron-capture elements in the two objects HD 6268 and HD 115444 are quite similar to that of the r-process component in the Solar-System, while their abundances of light neutron-capture elements show deviation from that. The actinide element thorium is detected in these objects. These stars well represent the abundance pattern produced by the so-called main r-process. The other two stars, HD 88609 and HD 122563, have quite low abundances of heavy neutron-capture elements. However, the light neutron-capture elements in these stars show large excesses with respect to heavy ones, indicating a contribution of another process than the main r-process. These results provide useful for investigations of the neutron-capture nucleosynthesis in the early universe.

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1. Introduction

Chemical compositions of extremely metal-poor stars are believed to reflect a quite small number of nucleosynthesis processes in the early Universe. The detailed abundance studies for neutron-capture elements in such objects have been performed in the past decade, providing useful information on the r-process nucleosynthesis in the early Galaxy. The survey of metal-poor stars like HK survey (e.g.,[1]) in the past two decades have been providing good sample for abundance studies based on high resolution spectroscopy (e.g., [2, 3]).

Sneden et al.[4, 5] have studied the abundances of the extremely metal-poor star CS 22892–052, the first example of a growing class of metal-poor stars that exhibit very large excesses of r-process elements relative to iron. An important result of this work is that the relative abundance pattern of the neutron-capture elements from the 2nd to the 3rd peak ($56 \leq Z \leq 76$) in this star is identical (within observational errors) to that of the (inferred) solar system r-process component. This phenomenon is sometimes referred to as the "universality" of the r-process.

They also have successfully detected the actinide element Th in this star. Since Th is a radioactive element with a half-life of about 14 Gyr, it can be used to determine the age of the star, which is the lower limit of the age of the Universe, if its initial abundance is estimated. Moreover, Cayrel et al. [6] reported the detection of U as well as Th for another r-process-enhanced star CS 31082–001, enabling to use the U/Th ratio to estimate the age of the object.

While such new observational finding has been reported, the astrophysical site of r-process is still unclear, and many hypotheses have been proposed. For instance, neutrino-heated ejecta of core-collapse supernovae (e.g., [7]), neutron star mergers (e.g., [8]), etc., have been investigated as a source of the r-process. The studies for detailed abundance patterns in r-process-enhanced stars like CS 22892–052 and CS 31082–001 have large impact on the argument on the r-process mechanism, though no definitive constraint has been obtained. Detailed abundance studies for larger sample of r-process-enhanced stars are strongly desired.

On the other hand, abundance studies for a large sample of metal-poor stars have revealed that a significant fraction of stars show abundance patterns of neutron-capture elements that are quite different from the solar-system r-process pattern . Honda et al. [9] and Aoki et al. [10] showed the existence of metal-poor stars that have quite high abundance ratios between light and heavy neutron-capture elements (e.g. Sr/Ba), suggesting the existence of the second component of the r-process (or some other processes that efficiently produce light neutron-capture elements in the early Galaxy: see Aoki [11]). The bright metal-poor star HD 122563 is one of such objects. The detailed abundance pattern of HD 122563 were obtained by our recent study [12], which showed that the elemental abundances of HD 122563 more steeply decrease with increasing atomic number than those of the r-process component in solar-system material.

We recently obtained high resolution spectroscopy for three bright metal-poor stars. Two of them (HD 115444 and HD 6268) show moderate enhancements of heavy neutron-capture elements, while the other (HD 88609) shows excesses only in light neutron-capture elements like HD 122563. In this paper, we report the abundances of neutron-capture elements in HD 122563 and the preliminary results of abundance analyses for the above three stars.

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2. Observations and Abundance Analyses

High resolution spectroscopy for the near-UV range (from 3100Å to 4700Å), where many lines of neutron-capture elements exist, have been obtained using High Dispersion Spectrograph (HDS) [13] for the Subaru Telescope. Although our targets are bright metal-poor stars, relatively long exposures (> 1 hour) with the 8m Subaru telescope are required, because of the low atmospheric transmission in the UV range.

The targets of this study (HD 6268, HD 88609, HD 115444, and HD 122563) were selected from the sample of Honda et al. [9]. In order to maximize the possibility to detect many elements in the UV range, where spectral lines are crowded in general, a high resolving power ($R = 90,000$) was chosen. The obtained signal-to-noise ratios (S/N) of the spectra are 720/1 at 4000 Å for HD 6268, 240/1 at 4000Å for HD 88609, 440/1 at 4000Å for HD 115444, and 900/1 at 4000Å for HD 122563.

We adopted the model atmosphere parameters derived by previous study [9] for abundance analyses. The adopted atmospheric parameters are (1) $T_{\rm eff} = 4600K$, $\log g$ = 1.0, $v_{\rm micro}$ = 2.1 km s^{-1}, and [Fe/H] = –2.63 for HD 6268; (2) $T_{\rm eff} = 4550K$, $\log g$ = 1.1, $v_{\rm micro}$ = 2.4 km s^{-1}, and [Fe/H] = –3.07 for HD 88609; (3) $T_{\rm eff} = 4720K$, $\log g$ = 1.5, $v_{\rm micro}$ = 1.7 km s^{-1}, and [Fe/H] = –2.85 for HD 115444; and (4) $T_{\rm eff} = 4570K$, $\log g$ = 1.1, $v_{\rm micro}$ = 2.2 km s^{-1}, and [Fe/H] = –2.77 for HD 122563. The abundance analyses were performed for 26 neutron-capture elements from Sr to Th, though only upper-limits of the abundances were obtained for some of them. The effects of hyperfine splitting and/or isotopic shifts were taken into account in the analysis of Ba, La, Eu, and Yb.

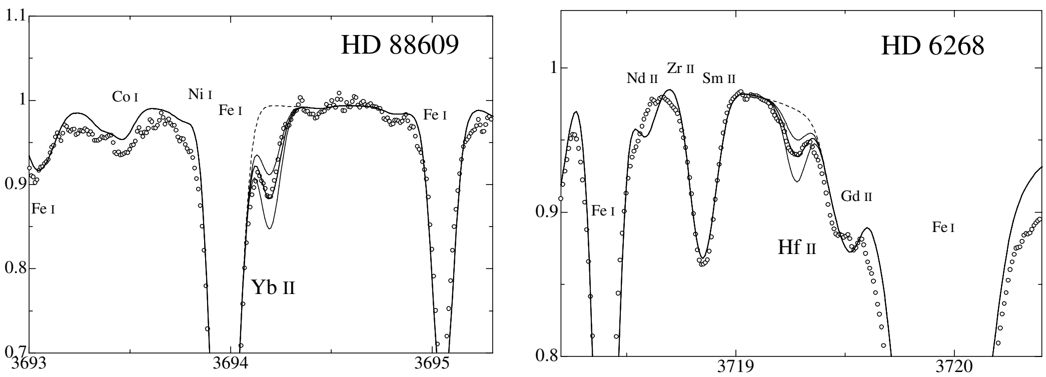

Figure 1: Observed Subaru/HDS spectra and synthetic ones in the regions of the Yb II 3694Å and Hf II 3719Å lines. The synthetic spectra show the case of best fit and the change of 0.15 dex for Yb and 0.2 dex for Hf.

HD 6268 and HD 115444 show over-abundances of (heavy) neutron-capture elements (e.g., $+0.5 <$[Eu/Fe]), while HD 88609 and HD 122563 have very low abundances of heavy neutron-capture elements (e.g., $0 >$[Eu/Fe]). The Ba/Eu (or La/Eu) ratios in these stars agree with the value of the solar system r-process component within the measurement errors. This means the neutron-capture elements in these stars are exclusively determined by the r-process and the contribution of s-process is very small if any.

3. Overall Abundance Patterns of Neutron-Capture Elements and their implications

The derived abundance patterns are shown in Figure 2. The abundance patterns of HD 6268 and HD 115444, which show enhancements of neutron-capture elements, are similar to the solar system r-process pattern, though their Ag and Tb abundances are significantly lower. Such abundance patterns are also found in some neutron-capture-enhanced stars recently investigated (see Cowan [14] and Ivans [15]). The overall abundance pattern from light to heavy neutron-capture elements will be useful in the future investigations for the main r-process.

The Th/Eu ratios of such objects are potentially useful to estimate the age of stars [4, 16, 17, 18]. Recent studies based on high quality spectra have shown that more than one Th lines are detectable if the abundance is sufficiently high [19, 20]. Three lines of Th (3539Å, 4019Å, and 4094Å) are detected in HD 6268, and results from individual lines agree well. The abundance ratio of Th and other heavy neutron-capture elements in HD 115444 is slightly higher than HD 6268, though the result relies on only one Th line (4019 Å). The distribution of the abundance ratios between Th and stable neutron-capture elements (e.g. Th/Eu) is currently in controversy, and further investigation is strongly desired.

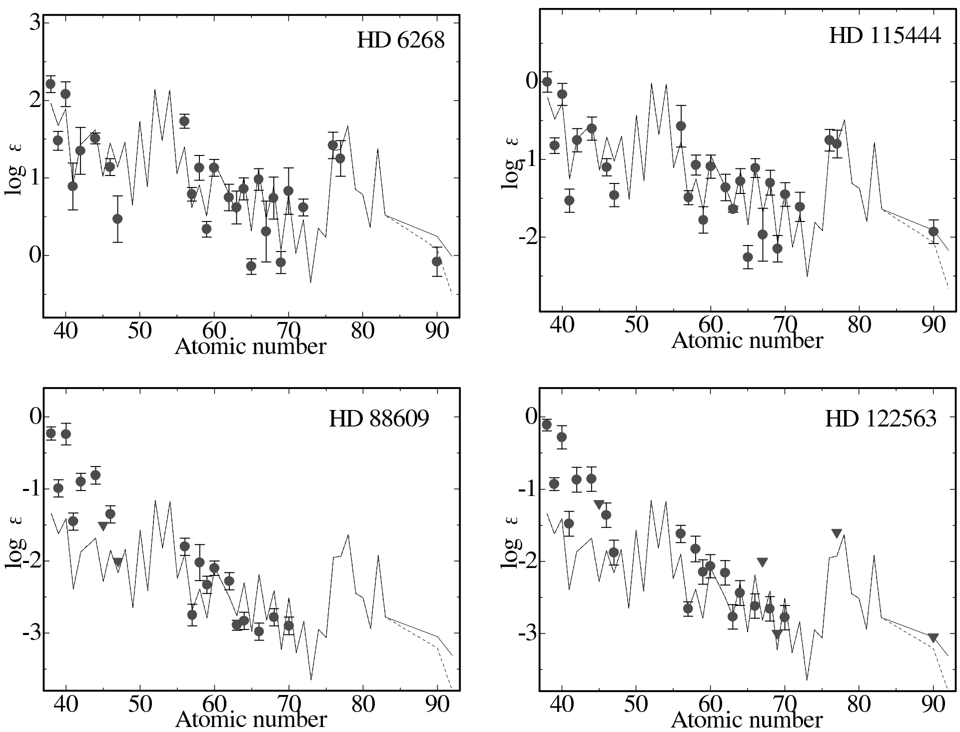

Figure 2: Abundance patterns of HD 6268, HD 88609, HD 115444 and HD 122563. The line indicates the solar system r-process abundance pattern [21], scaled to the measured Eu abundance for each object. The triangles represent the upper limits of the abundances.

While abundance studies for several r-process-enhanced stars have been made, very few attempts have been made to obtain detailed abundance patterns for objects which have low abundances of heavy neutron-capture elements. Very high quality data are required to measure abundances of heavy neutron-capture elements. Our analyses for HD 122563 and HD 88609 determined the abundances of 19 and 18 neutron-capture elements, respectively. The abundance patterns of these "neutron-capture-poor" objects are clearly different from neutron-capture-rich stars. These stars would represent the pattern produced by weak r-process, and provide a new, useful constraint on the study of the process that produces light neutron-capture elements in the early Galaxy.

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