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Abundance Analyses of r-Process Elements in Very Metal-Poor Stars

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Abstract

We obtained high resolution, high S/N spectra for two very metal-poor stars with the Subaru Telescope High Dispersion Spectrograph. One object shows large overabundances of neutron-capture elements relative to iron in general, and the other shows excesses only in light neutron-capture elements. By using the recent atomic line data including hyperfine splitting effects, the chemical abundance patterns were investigated in detail the range of a wide atomic number. These results will provide strong constraints on the models of the r-porcess nucleosynthesis, and give hints for the astrophysical site of r-process, which are still unknown to date.

Keywords:

metal-poor star, abundance analysis, r-process element, spectroscopy, nucleosynthesis

1. Introduction

The chemical composition of extremely metal-poor stars are expected to reflect the yields from very small number of nucleosynthesis processes. Recent abundance analyses for extremely metal-poor stars have provided very valuable information on the origin of the elements, and the individual nucleosynthesis processes involved [1].

The rapid neutron capture process (r-process) is known to be responsible, in solar system material, for about half of the abundances of elements beyond the iron-peak. However, the site where r-process is occurring is still unclear. In order to clarify the origin of r-process elements, it is important to obtain the abundance pattern of many neutron-capture elements covering a wide range of atomic number in metal-poor stars.

We previously obtained high resolution, high quality spectra of 40 metal-poor stars for abundance studies, and inspected the elemental abundance patterns of heavy elements in detail for seven of them that show excesses of neutron-capture elements relative to lighter metals like Fe [2]. We confirmed the fact that the abundance patterns of the *heavy* neutron-capture elements ($56 \leq Z \leq 70$) in metal-poor stars are similar to that of the solar system r-process component, which has already been found by previous studies. This result proves that heavy neutron-capture elements in these very metal-poor stars are primarily synthesized by the r-process, and the elemental abundance pattern produced by the r-process is universal at least in this atomic number range [3]. By way of contrast, the abundance ratios of *light* neutron-capture elements ($38 \leq Z \leq 46$) to heavier ones ($56 \leq Z \leq 70$) show a large dispersion [2], suggesting another process that largely contributes only to the light neutron-capture elements.

In order to investigate the processes that are corresponding to heavy and light neutron-capture (r-process) elements, we selected two bright stars from our previous sample for more detailed chemical abundance study: one star (HD 6268) shows large overabundances of neutron-capture elements relative to iron in general, and the other (HD 122563) shows excesses only in light neutron-capture elements.

2. UV observations and measurement of elemental abundances

Though most of transitions of neutron-capture elements exist in the UV region, observations using ground-based telescopes for this wavelength region are difficult due to the low atmospheric transmission. We selected the bright metal-poor stars HD 6268 and HD 122563 to obtain very high quality spectra (S/N > 500 at 3800 Å) with high spectral resolution ($R = 90,000$) using the High Dispersion Spectrograph (HDS) for the Subaru Telescope. Figure 1 shows examples of the observed spectra. Very weak lines of neutron-capture elements are successfully detected in these high-quality spectra.

Since the atmospheric parameters (*e.g.*, effective temperature, metallicity) of those two objects are al-

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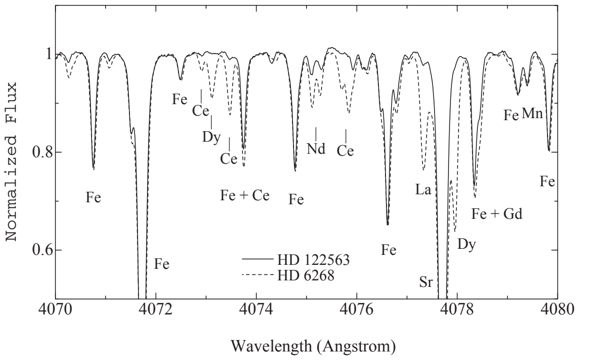

Fig. 1 Comparison of spectra between HD 6268 (dashed line) and HD 122563 (solid line).

most the same, the absorption features of Fe and Mn are very similar in both stars (Fig. 1). However, the absorption features of heavy neutron capture elements (*e.g.*, La, Ce, Dy) are much stronger in HD 6268 than in HD 122563, clearly indicating a large difference in abundances of heavy neutron-capture elements. The absorption of the light neutron-capture element Sr in HD 122563 has similar strength of that in HD 6268, suggesting that both objects have similar abundances of light neutron-capture elements.

Accurate atomic data of neutron-capture elements are indispensable in the study of these extremely metal-poor stars. Recent progress in measurements of the transition probabilities, including hyperfine splitting effect, for neutron-capture elements [4] enables us to determine accurate abundances of these elements in metal-poor stars.

3. New detections of light and heavy neutron-capture elements:

Figure 2 shows the abundance patterns of neutron-capture elements for the two stars. Compared to the previous studies that determined the elemental abundances near the abundance peaks at $Z \sim 40$, 56 and 76, our new measurements cover the elements between the abundance peaks ($Z \sim 45$, 70) for both objects. These detailed abundance patterns are crucial to constrain the modeling of the r-process.

Figure 2 compares the elemental abundances of our objects with that of r-process component in solar-system material. The elemental abundances of HD 6268 are basically in agreement with the solar-system r-process pattern. However, some disagreement in the light neutron-capture elements is found, as has been reported by previous works[2, 5]. We also found a small departure of the abundances of heavy elements with odd atomic number (Tb and Tm) from the solar-system r-process abundance pattern. This point will be studied

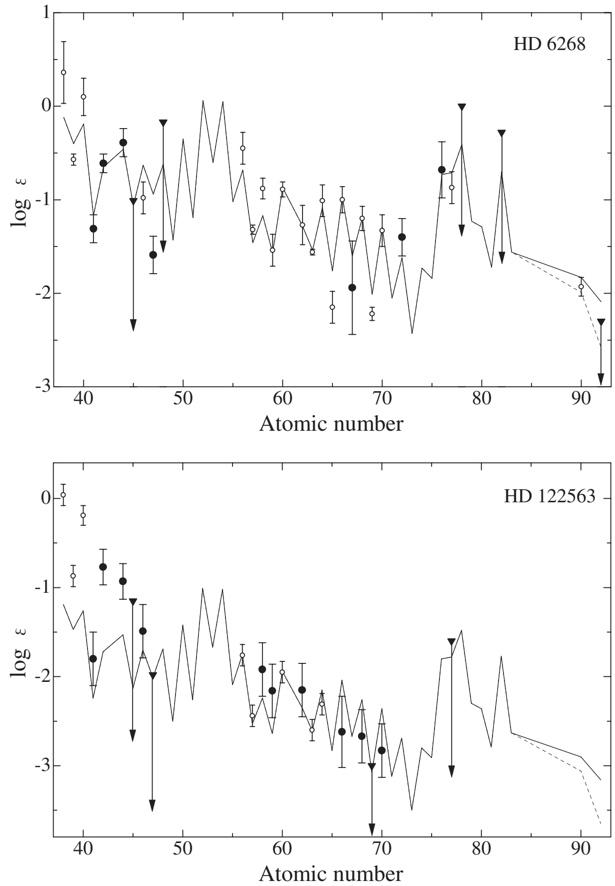

Fig. 2 The abundances in HD 6268 and HD 122563 (dots) compared with the solar system r-process abundance. The present results are shown by filled circles, and previous studies [2] are also shown by open circles. The arrow shows the value of upper limit. Th ($Z = 90$) is radioactive; the dashed lines indicate the solar-system Th abundance at present, while the solid lines mean the estimate of the initial Th abundance of the solar-system. Log ϵ means $\log_{10}(X/H) + 12.0$ for elements X. Error bars indicates the $1-\sigma$ uncertainty in the abundance determination.

in more detail in our future work. We note that we used reliable atomic line data of Tb that have been quite recently provided by Lawler *et al.* [6].

HD 122563 has a significantly different abundance patterns from that of HD 6268: the abundance of light neutron-capture elements ($38 \leq Z \leq 47$) are much higher than that of heavy ones. However, our new measurements clearly demonstrate that the elemental abundances gradually decreases with increasing atomic number. Especially, the tendency that the abundance continuously decreases in the region of $38 \leq Z \leq 47$ does not agree with any neutron-capture processes known (i.e., main s-process, weak s-process, or main r-process). Since the abundance pattern of such very metal-poor stars, in contrast to that of solar system material, is expected to be formed by a small number of nucleosynthesis events another process yielding elements with $38 \leq Z \leq 47$ would be required. The abundance pattern of HD 122563 will provide a very new constraint on modeling of the process that contributed to the production of light neutron-capture elements in the early galaxy [7], which is sometimes referred to as "weak r-process".

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