PROCEEDINGS OF SCIENCE

Neutron Capture Elements in Globular Cluster M15

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We used high-resolution, high signal-to-noise ratio spectra obtained with the Subaru Telescope to determine neutron-capture elemental abundances in metal-poor globular cluster M15. We confirmed that there are star-to-star abundance variations in the abundance of heavy neutron-capture elements and there is no significant s-process contribution. We have found that there are anti-correlations between the abundance ratios of light to heavy neutron-capture elements and the abundance of heavy neutron-capture elements. Our observaitonal results indicates that at least two different processes have enriched light neutron-capture elements in the M15 progenitor. It has been pointed out that light neutron-capture elements in field stars should have been enriched by more than one process although astrophysical sites for such processes are still uncertain. Abundance distributions of neutron-capture elements in M15 give clues to understand the origin of light and heavy r-process elements.

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1. Introduction

The r-process is a rapid neutron-capture process which probably occurs in explosive astrophysical events such as Type II supernovae. Thanks to the development of observational technology, r-process elements in the atmosphere of dozens of metal-poor stars have been detected. Those data indicate interesting features of r-process abundance distributions; (1)Universal abundance pattern of Z>56 r-process elements [1], (2)dispersion of the abundance ratio of Z>56 r-process elements to Fe around [Fe/H]< -2.5 [2], and (3)dispersion of the abundance ratio of light neutron-capture elements (Z<56) to heavy r-process elements(Z>56) around [Fe/H]~ -3 [3]. The last one implies there were at least two different processes which enriched Z<56 elements, one forms both heavy and light neutron-capture elements, the other forms only light neutron-capture elements. For the sake of convenience, we call the former 'the main r-process', the latter 'the weak r-process' here after[4]. We should note, however, that 'the weak r-process' is just the name for convenience, and it does not have to be *rapid* neutron-capture process[e.g., 5].

Globular clusters are thought to be among the oldest Galactic objects. M15 is one of the most metal-poor Galactic globular clusters. Although its formation process is still unknown, stars in metal-poor globular clusters were probably formed from less contaminated ISM compared to ones in relatively metal-rich globular clusters. In addition, the chemical component of stars in globular clusters was not enriched by explosive event after their formation. Hence, we can expect the abundances of neutron-capture elements in metal-poor globular clusters will help to understand their origin.

Sneden et al.(1997, 2002) reported dispersion of the [Ba/Fe] ratios within the metal-poor globular cluster M15[5, 6]. They also obtained high dispersion spectroscopic data of three giants in M15 and conclude there is no significant s-process contribution in M15 stars[7]. Their results indicate there was chemical inhomogeneity in the progenitor of M15 when stars were formed. Our purpose of this study is to obtain the constraints on the origin of r-process elements via M15 stellar abundances. For this purpose, we obtained high quality data to confirm Sneden et al.'s results and to measure weak r-process elements in M15 which have not been seen in previous studies.

2. Observational results

We have measured neutron-capture elements of 6 giants in M15 using Subaru/HDS. Details of abundance analyses are found in [8] and forthcoming paper. We have confirmed that there are star-to-star abundance variations of heavy neutron-capture elements in M15 (Fig. 1). Clearly, there are high Eu abundance stars and low Eu abundance stars. Here, we have to note that we choose stars with relatively higher and lower Ba abundance from Sneden et al. (1997). We cannot conclude if this abundance variation is bimodal or continuous at this point. Figure 2 shows the ratios of [La/Eu] in each stars. We conclude that there is no significant s-process contribution in comparison with solar r-process [La/Eu] ratio[9].

Furthermore, we have found that there are anti-correlations between the ratios of light neutron-capture elements to heavy ones and the abundance of heavy neutron-capture elements (Fig. 3). These results suggest that two different processes had enriched light neutron-capture elements in M15, similarly to field stars. Assuming that these two processes are the same as main r-process

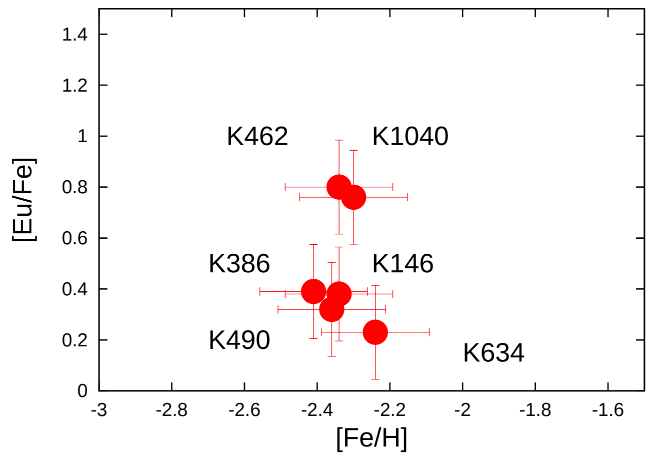

Figure 1: [Eu/Fe] of M15 stars as a function of [Fe/H]. There are clear scatter of the [Eu/Fe] ratios ($\sim$ 0.6dex) although the [Fe/H] ratios agree within $\pm$ 0.08 dex.

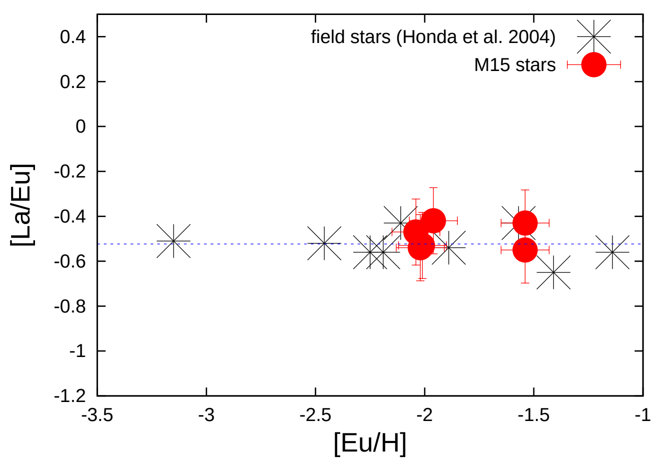

Figure 2: [La/Eu] as a function of [Eu/H]. The red circles indicate M15 stars and the black stars are field stars from Honda et al. 2004. [La/Eu] ratio of solar r-process abundances from Simmerer et al. 2003 are shown as the dotted line.

and weak r-process which enriched the field stars, observed abundances were explained by uniform weak r-process enrichment ($\log_\varepsilon(Y)_{weak} \sim -0.57$) and non-uniform main r-process enrichment ($\log_\varepsilon(\mathrm{Y})_{main} \sim -0.7$ for Eu-rich stars and $\sim$ -1.2 for Eu-poor stars). There were chemical inhomogeneities within the M15 progenitor cloud. Main r-process elements were less dispersed than weak r-process elements at star formation period in M15 progenitor.

3. Discussion

There is no widely accepted globular cluster formation model or its chemical enrichment model. Here, we assume a simple supernovae-induced self-enrichment model for further discussion[10]. This model starts at the point when the first generation of stars are formed with some mass distribution at the center of metal-free proto-globular cluster clouds. SNe of the first generation induce

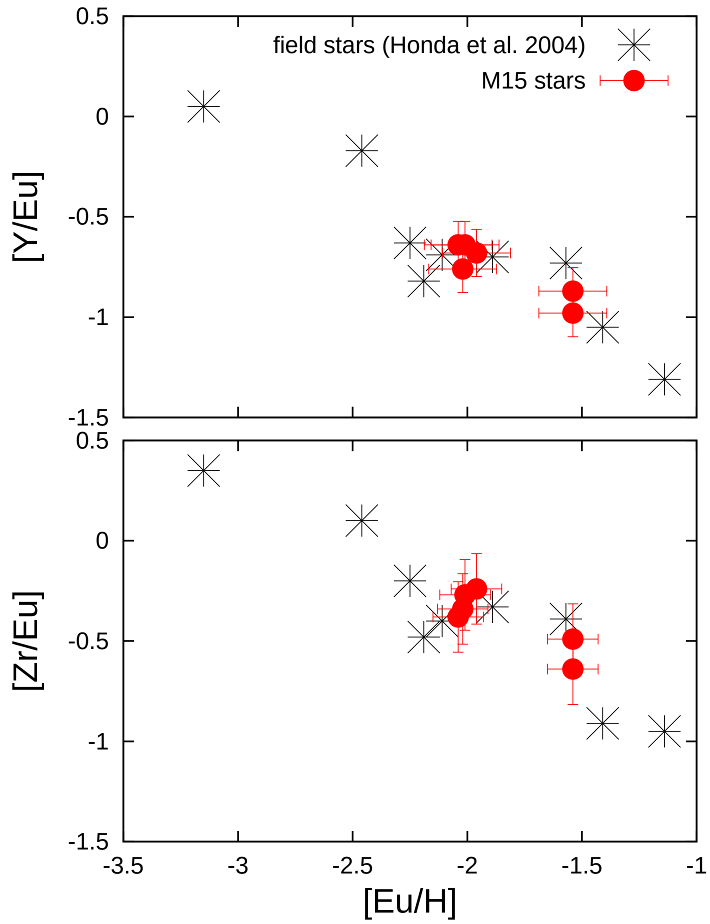

Figure 3: (a)[Y/Eu] and (b)[Zr/Eu] as functions of [Eu/H]. The red circles indicate M15 stars and the black stars indicate field stars from Honda et al. 2004. There are clear anti-correlations between the ratios of light neutron-capture elements to heavy r-process elements and the abundance of heavy r-process elements.

formation of the second generation of stars, i.e., those which are observed today. The chemical components of the supershell correspond to primordial abundance of second generation stars. Second generation supernovae then blow off the remaining gas in a cluster. To reproduce uniform [Fe/H], all supernovae must form a super shell and the ejected material must be mixed completely in that shell before the second generation of stars is formed.

Based on this chemical enrichment model, uniform weak-r and non-uniform main-r abundances suggest that the main r-process occurred later than the weak r-process. If the weak r-process enriched supershell uniformly followed by the main r-process, which is not mixed completely with supershell material, the observed abundances can be reproduced. Since Fe from a single supernova ($\sim$ 0.1 $M_{\odot}$) does not change [Fe/H] of the supershell significantly after it is enriched more than [Fe/H]$\sim$-2.5, the main r-process at the later stage of chemical enrichment is consistent with uniform Fe and dispersed heavy r-process elements.

If the astrophysical site for the weak and main r-process are different progenitor mass supernovae, our observational results suggest that the progenitor mass of main r-process supernova is lighter than progenitor mass of weak r-process supernova since massive stars have shorter lifetime. The lifetime of a supershell in a typical proto-globular cluster cloud, which is estimated using analytic treatment, is same order of the lifetime of low mass supernovae ($\sim 10^7 yrs$ for ~ 8 $M_\odot$)[11, 12]. Therefore, our results seems to support the main r-process in low mass supernovae. We have to note, however, that there is a possibility of enrichment from second generation supernovae, especially for massive globular clusters. Massive supernovae of second generation could also explode in similar timescale if the timescale of cluster star formation is order of 10^6 yrs as believed. If first few supernovae of second generation contributed to chemical enrichment of M15, the main r-process should occur in massive supernovae to explain abundance variations. Main r-process enrichment from first generation supernovae and second generation supernovae are indistinguishable because main r-process is metallicity independent. Hence, at this point, we can not conclude yet whether the origin of main r-process elements is massive supernova or low mass supernova. More detailed study of dynamics of supershell to constrain the mass range of progenitors of main r-process supernova is ongoing now.

The fraction of Eu-rich stars in M15 is an important point for further discussion of chemical enrichment of globular clusters as well as whether these abundance variations are bimodal or continuous. More observations of r-process elements in M15 stars to increase the sample are strongly desired. Unfortunately, not so many measurements of neutron-capture elements in globular clusters have been reported. There are few measurements of weak r-process elements. So far, only M15 shows abundance variations of heavy r-process elements. Comparison with neutron-capture elements in other metal-poor globular clusters can be clues to understand the origin of r-process elements. Measurement of neutron-capture elements in other globular clusters are also desired.

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