

Chemical Abundance Patterns of Extremely Metal-Poor Stars with $[\text{Fe}/\text{H}] \lesssim -3.5^\dagger$

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Abstract. We present preliminary results on the chemical abundance patterns of extremely metal-poor stars obtained during an ongoing observing program with Subaru/HDS. High-resolution, high signal-to-noise spectra have been obtained for 14 stars with $[\text{Fe}/\text{H}] \lesssim -3$. Five of them exhibit clear overabundances of carbon, a remarkable characteristic found only in the most metal-poor range. One of the carbon-rich stars, HE 1327-2326, has $[\text{Fe}/\text{H}]_{\text{NLTE}} = -5.4$, the lowest Fe abundance known. No stars with $-5 < [\text{Fe}/\text{H}] < -4$ have yet been found in our program, suggesting that quite different enrichment processes were responsible for stars with $[\text{Fe}/\text{H}] < -5$ and $[\text{Fe}/\text{H}] > -4$. While neutron-capture elements are deficient in most of our stars, one star (BS 16550-087) exhibits large enhancements of its light neutron-capture elements (Sr, Y and Zr), providing a strong constraint on models for the production of such elements in the very early Galaxy.

Keywords. Stars: abundances, stars: Population II, Galaxy: halo

1. Introduction

Extremely metal-poor stars ($[\text{Fe}/\text{H}] < -3$; hereafter EMP stars) of the old halo population of our Galaxy provide useful probes of the formation and evolution of the first heavy elements in the Galaxy. The most metal-deficient stars known until 2001 had iron abundances down to $[\text{Fe}/\text{H}] \sim -4.0$. From this observational fact, a rapid decline of the metallicity distribution function for stars with $[\text{Fe}/\text{H}] < -4.0$ has been inferred.

[†] Based on data collected with the Subaru telescope, which is operated by the National Astronomical Observatory of Japan.

However, the recent discovery of the extraordinarily iron-poor star, HE 0107–5240, with $[\text{Fe}/\text{H}]_{\text{NLTE}} = -5.2$ has had a large impact on the studies of the formation and nucleosynthesis of first-generation stars (Christlieb *et al.* 2002). Further searches for stars of the lowest metallicity are now one of the most important observational approaches to understanding the very early stages of Galaxy evolution.

Recent abundance studies of EMP stars have revealed that their chemical abundance patterns are sometimes quite different from those of stars with higher metallicity ($[\text{Fe}/\text{H}] > -3.0$). For example, HE 0107–5240 shows significantly high overabundances of C, N, and O (Christlieb *et al.* 2002; Bessell *et al.* 2004; Christlieb *et al.* 2004). Two other stars with $[\text{Fe}/\text{H}] < -3.5$ also show enormous overabundances of C, N, O, and Mg (e.g. Norris *et al.* 2001; Aoki *et al.* 2002), while several others appear to have rather similar relative abundances that extend the observed trends of higher metallicity stars (e.g. Cayrel *et al.* 2004; Honda *et al.* 2004). These abundance characteristics seem to appear only in the range of metallicity lower than $[\text{Fe}/\text{H}] = -3.5$.

Previous large programs to study metal-deficient stars revealed the abundance patterns of stars with $[\text{Fe}/\text{H}] \sim -3$ (e.g. Honda *et al.* 2004). Though the VLT ‘First Stars’ program studied abundance patterns of metal-poor stars covering $[\text{Fe}/\text{H}] = -4$ to -2.5 , the number of newly found stars with $[\text{Fe}/\text{H}] < -3.5$ is quite small. In order to investigate the chemical abundance patterns of stars with $[\text{Fe}/\text{H}] \lesssim -3.5$, we initiated a program to observe candidate EMP stars in 2003. Here we report preliminary results for the abundance patterns of a subsample of our ongoing program.

2. Chemical Abundance Studies of EMP Stars with Subaru/HDS

Candidate metal-poor stars in our program were initially selected by objective-prism surveys – the HK-survey (Beers *et al.* 1985, 1992; Beers 1999) and the Hamburg/ESO survey (Christlieb 2003). The targets for our present program were those stars judged to have $[\text{Fe}/\text{H}] \leq -3.0$, based on medium- and high-resolution spectroscopy obtained with the ESO 1.5 m and 3.6 m, the SSO 2.3 m, the KPNO 2.3 m and 4.0m, the CTIO 4.0 m, and the AAT 3.9 m telescopes. *BVRI* photometry was obtained for most of our targets using the ESO/Danish 1.5 m, KPNO 0.9 m, CTIO 0.9 m, and MAGNUM 2 m telescopes, while *JHK* data were taken from 2MASS (Cutri *et al.* 2003). Several objects were also selected from the HERES sample (Barklem *et al.* 2005; Barklem *et al.*, this volume).

High-resolution spectroscopy for our targets was obtained with the High Dispersion Spectrograph (HDS, Noguchi *et al.* 2002) of the Subaru Telescope. We have carried out four observing runs from December 2003 to June 2005, and have obtained spectra of 19 stars with a resolving power of $R = 60,000$ covering 4000–6800 Å. The typical signal-to-noise ratio achieved in these observations is 100/1 at 4500 Å. We here discuss preliminary results on the chemical abundances of our targets observed until February 2005.

3. Carbon, Magnesium, and Iron

Figure 1 shows the abundance ratios of carbon ($[\text{C}/\text{Fe}]$) and magnesium ($[\text{Mg}/\text{Fe}]$) as functions of the iron abundance ($[\text{Fe}/\text{H}]$). The iron abundances of our objects are distributed between $[\text{Fe}/\text{H}] = -3$ and -3.8 . An exception is HE 1327–2326, which has $[\text{Fe}/\text{H}]_{\text{NLTE}} = -5.4$ (Frebel *et al.* 2005). Details of the chemical abundance pattern of this star, and astrophysical interpretation of its origin, are discussed separately by Frebel *et al.* (this volume). It should be noted that, although a large fraction of our stars have iron abundances slightly higher than $[\text{Fe}/\text{H}] = -3.5$, the iron abundance depends on the adopted effective temperature scale. We applied the empirical scale determined by Alonso

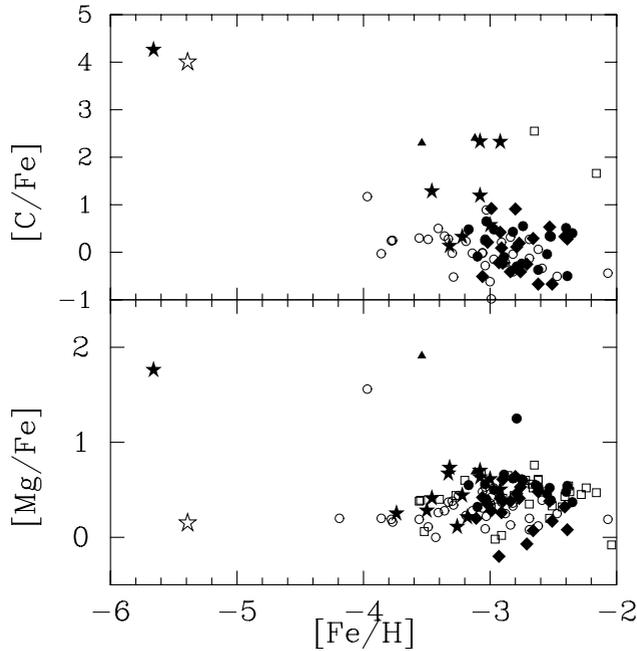


Figure 1. Abundance ratios of C and Mg as functions of $[\text{Fe}/\text{H}]$. Filled stars indicate the results of the present work, while others are from the literature (the open star: Christlieb *et al.* 2002; open circles: Cayrel *et al.* 2004; open squares: Carreta *et al.* 2002 and Cohen *et al.* 2004; filled diamonds: Honda *et al.* 2004; filled circles: Aoki *et al.* 2005; Filled triangles: Aoki *et al.* 2002)

et al. (1996, 1999), which is known to give slightly higher temperatures than spectroscopic methods (e.g. excitation equilibrium, Balmer line profiles), resulting in relatively higher derived iron abundances.

Our sample includes 5 carbon enhanced ($[\text{C}/\text{Fe}] \gtrsim +1$) stars, one of which is HE 1327–2326. One star at $[\text{Fe}/\text{H}] \sim -3$ with a very large enhancement of carbon ($[\text{C}/\text{Fe}] > +2$) also shows an excess of Ba, suggesting significant contribution from AGB nucleosynthesis, while the others show no clear excesses of neutron-capture elements. It should be noted that excesses of carbon were revealed by the high-resolution spectroscopy in at least two newly-studied stars, including HE 1327–2326. This result confirms the suggestion from previous studies that a large fraction of EMP stars have overabundances of carbon.

The existence of two Hyper Metal-Poor (HMP) stars with $[\text{Fe}/\text{H}] < -5$ (HE 1327–2326 and HE 0107–5240), along with the absence of stars with $-5 < [\text{Fe}/\text{H}] < -4$, may have important implications on the formation mechanisms of the most metal-deficient stars. The large overabundances of carbon in the two HMP stars, which cannot be attributed to any biases in the sample selection, provide another key to modeling the nucleosynthesis processes responsible for these two stars (Frebel *et al.* 2005; Aoki *et al.*, in preparation).

A large overabundance of Mg was also found in HE 1327–2326, in contrast to the relatively low magnesium abundance in HE 0107–5240. The Mg abundance of HE 1327–2326 possibly indicates a connection between this object and other Mg-enhanced stars with somewhat higher iron abundances ($[\text{Fe}/\text{H}] = -3.5 - -4.0$), for which so-called ‘faint supernovae’ are proposed as the source of the high Mg/Fe ratios (e.g. Nomoto *et al.*, this volume).

The Mg abundances of stars with $[\text{Mg}/\text{Fe}] \sim -3$ appear to show some scatter. Indeed, a comparison of the spectra of two stars in our program having very similar atmospheric

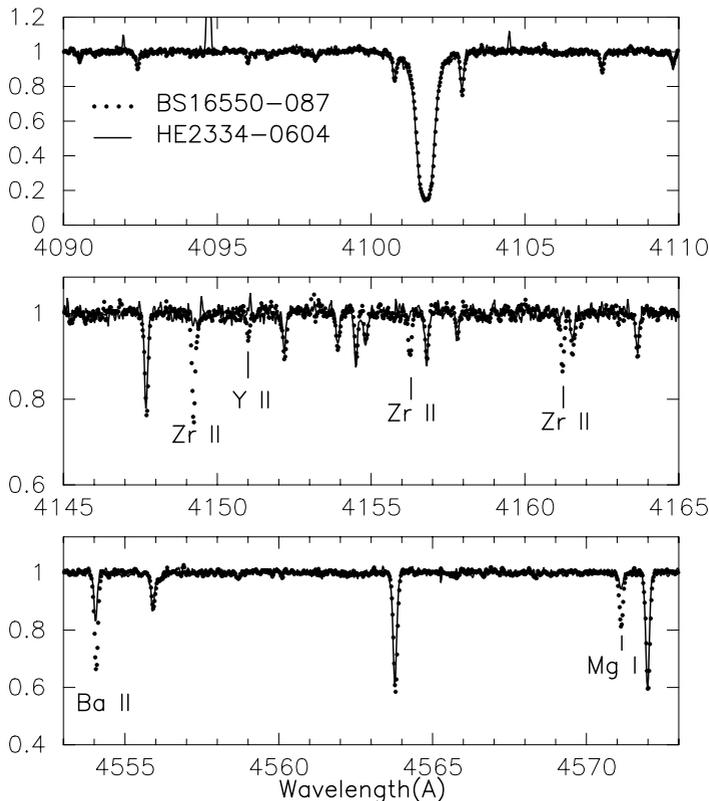


Figure 2. Comparison of the spectra of two giants having similar atmospheric parameters and metallicity ($[\text{Fe}/\text{H}] \sim -3.3$). The absorption features, including the $\text{H}\delta$ line, are very similar between the two stars (top panel). However, the absorption lines of the light neutron-capture elements Y and Zr are significantly stronger in the spectrum of BS 16550-087 (middle panel). The Ba absorption line is stronger in BS 16550-087 (bottom panel), but the difference is not as significant as for the features of light neutron-capture elements. The strengths of the Mg I 4571 Å line are also quite different.

parameters and iron abundances demonstrates large differences in their Mg absorption lines, as shown in Figure 2. This result might contradict the result of a recent study on Mg abundances in very metal-poor stars (Arnone *et al.* 2005), which suggested a very small scatter in Mg/Fe ratios. In order to derive definitive conclusions, further studies for larger sample of stars, in particular for stars with $[\text{Fe}/\text{H}] \sim -3.5$, are required.

4. Neutron-Capture Elements

Previous studies of very metal-poor stars have revealed the existence of large observed scatter in the abundances of neutron-capture elements at a given iron abundance. This large scatter indicates that the sources of neutron-capture elements and iron are quite different, at least in the early Galaxy. The behavior of the abundance ratios of neutron-capture elements is, however, still unclear in the lowest metallicity range ($[\text{Fe}/\text{H}] < -3$).

Figure 3 shows the abundance ratios of Sr and Ba as functions of $[\text{Fe}/\text{H}]$. A large scatter, more than 2 dex, is found in Sr abundance ratios even for $[\text{Fe}/\text{H}] < -3$. Large scatter in the abundances of light neutron-capture elements can be seen in the direct comparison of the spectra of two giants from our program (Figure 2). While these two

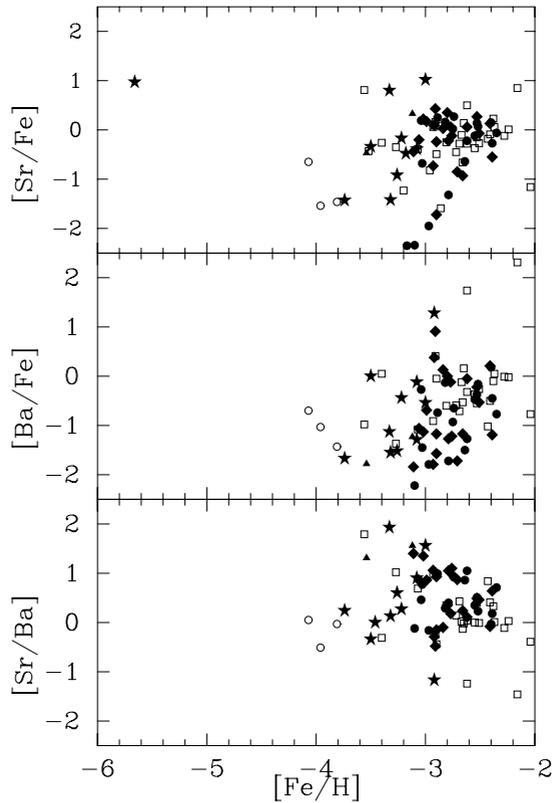


Figure 3. Same as Figure 1, but for $[\text{Sr}/\text{Fe}]$, $[\text{Ba}/\text{Fe}]$, and $[\text{Sr}/\text{Ba}]$.

stars have quite similar strengths of absorption features in general, clear differences are found in the features of the light neutron-capture elements Y and Zr. It should be noted that Sr absorption lines are even detected in the HMP star HE 1327–2326.

The scatter in Ba abundances for stars with $[\text{Fe}/\text{H}] < -3$ is also quite large, though that seems to be smaller than the scatter in the Sr abundances. We note that one star in our program with an extremely large excess of Ba at $[\text{Fe}/\text{H}] \sim -3$ also shows a large enhancement of carbon abundance, indicating a significant contribution of the AGB nucleosynthesis to this object.

In contrast, the abundance ratios between Sr and Ba in stars with $[\text{Fe}/\text{H}] < -3.2$ show relatively small scatter; most stars have $[\text{Sr}/\text{Ba}] \sim 0$. This trend might be explained by the yields of the so-called ‘main’ r-process (Aoki *et al.* 2005). However, there are a few stars having exceptionally high Sr/Ba ratios. The most remarkable example is BS 16550–087, which has $[\text{Sr}/\text{Ba}] \sim +2.0$. The nucleosynthesis process that yields light neutron-capture elements such as Sr with almost no heavier species (e.g. Ba) has been recently studied by Travaglio *et al.* (2004) and Gallino *et al.* (this volume). The existence of stars having very high Sr/Ba ratios at $[\text{Fe}/\text{H}] < -3$ indicates that this process operates efficiently even in the lowest metallicity ranges.

5. Lithium Abundances

The lithium abundances measured for EMP dwarfs and subgiants are presently the subject of some controversy (Bonifacio *et al.*, this volume; Ryan, this volume). The

measured values are significantly lower than the prediction from standard Big Bang nucleosynthesis, when one adopts the baryon density determined by WMAP (Coc *et al.*, this volume). The Li abundances in halo stars have been known for many years to exhibit the so-called Spite plateau, but a weak decreasing trend of Li abundance with decreasing iron abundance has also been reported (e.g. Ryan *et al.* 1999).

Our sample includes only three stars having effective temperatures higher than 6000 K, and hence useful for study of the Li abundances in the early Universe. Our preliminary result on the Li abundances of the two stars with $[\text{Fe}/\text{H}] = -3.2$ and -3.5 shows a good agreement with the values determined by Ryan *et al.* (1999) for stars with similar metallicity. Namely, our results support the decreasing trend of the Li abundance with decreasing metallicity, although a more detailed study, in particular careful determination of effective temperatures, is required.

One interesting result is the non-detection of Li in HE 1327-2326. The upper limit on its Li abundance is $\log \epsilon(\text{Li}) = +1.5$, significantly lower than the values found in most EMP dwarfs and subgiants (Frebel *et al.* 2005; Aoki *et al.* 2005, in preparation).

6. Concluding Remarks

Preliminary results for the abundance analysis for EMP stars observed with Subaru/HDS have been presented. We are in the process of extending this analysis to the full sample of stars observed in our program. Our analysis will provide new data on the abundance of EMP stars ($-5.5 < [\text{Fe}/\text{H}] < -3$). It is already evident that EMP stars exhibit significant variations in their abundance patterns. In order to reveal the chemical nature of the most metal-poor stars, further observations with VLT/UVES are planned.

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