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LAMOST-Subaru exploration of chemical relics of first stars

Haining Li[1,2], Wako Aoki[3,4], Gang Zhao[1], Takuma Suda[5], Satoshi Honda[6], Norbert Christlieb[7] and Tadafumi Matsuno[4]

[1]Key Lab of Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China
[2]email: lhn@nao.cas.cn

[3] National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo, 181-8588, Japan

[4] School of Physical Sciences, The Graduate University of Advanced Studies (SOKENDAI), 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan

[5] Research Center for the Early Universe, The University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo 113-0033, Japan

[6] University of Hyogo, 407-2, Nishigaichi, Sayo-cho, Sayo, Hyogo, 679-5313, Japan

[7] Zentrum für Astronomie der Universität Heidelberg, Landessternwarte, Königstuhl 12, D-69117 Heidelberg, Germany

Abstract. Very metal-poor (VMP) stars preserve chemical signatures of early generations of stars, and are crutial to understand the early nucleosynthesis and first stars. Millions of stellar spectra obtained by LAMOST provide an unprecedented chance to enlarge the currently limited VMP star sample. Since 2014, a joint project on searching for VMP stars has been conducted based on the LAMOST survey and Subaru follow-up observations. So far, the project has obtained chemical abundances for about 250 VMP stars and a number of chemically interesting objects, e.g., three ultra metal-poor stars with [Fe/H] ~ -4.0, a dozen Li-rich VMP stars distributed in a wide range of evolutionary stages. Statistics of the large homogeneous sample of VMP stars will be of great interest and importance to probe the chemical enrichment in the early Galaxy and low-mass star evolution.

Keywords. star:abundances, stars:Population II, nucleosynthesis

1. Introduction

Low-metallicity stars in the Milky Way record information on the time and place of their formation. In particular, chemical compositions of very metal-poor ([Fe/H]† < -2.0, VMP) stars provide with unique constraint on the chemical yields of the first generations of stars, which enables us to estimate the masses of first stars, and also early chemical evolution of the Milky Way (see Bromm & Yoshida 2011, Nomoto *et al.* 2013, and Frebel & Norris 2015 for more complete review). Elemental abundances of these old stars also constrain the evolutionary models of low-mass stars that we are currently observing.

In the past decade, several studies have provided chemical abundance data based on high-resolution spectra for several hundred VMP stars (e.g., Cayrel *et al.* 2004, Norris *et al.* 2013, Aoki *et al.* 2013, Roederer *et al.* 2014, Jacobson *et al.* 2015). However, the number of stars with extremely low-metallicity is still limited, e.g., the number of ultra metal-poor (UMP) stars with [Fe/H] < -4.0 is about two dozen. Therefore, it is needed

† $[A/B] = \log(N_A/N_B)_\star - \log(N_A/N_B)_\odot$, where N_A and N_B are the number densities of elements A and B respectively, and $\star$ and $\odot$ refer to the star and the Sun respectively.

to establish a large and homogeneous sample of VMP stars to improve our understanding of the early nucleosynthesis process and chemical evolution.

Lithium is a product of Big-Bang nucleosynthesis (BBN) but can be easily destroyed by nuclear reactions inside stars with $T_{\rm eff} \geqslant 2.5 \times 10^6$ K. Observations of metal-poor stars have detected a plateau of lithium abundances around A(Li)$\sim$ 2.2[‡], which gives an important constraint on the primordial Li production through the determination of the Li abundances in metal-poor main-sequence stars (Spite *et al.* 2013). On the other hand, the surface Li is diluted by more than one order of magnitude by mixing with Li-depleted materials when a star evolves into a red giant. However, in both globular clusters and Galactic halo field stars, a number of metal-poor giants are found to show unusually high Li abundances (e.g., Ruchti *et al.* 2011, Kirby *et al.* 2016). These peculiar objects request modifications of the standard evolution model of low-mass stars (e.g., Sackmann & Boothroyd 1999, Charbonnel & Balachandran 2000, Nollett *et al.* 2003).

2. Joint searching project with LAMOST and Subaru

To obtain a large homogeneous sample of VMP stars by extending previous efforts, a joint project to search for metal-poor stars was initiated to obtain high-resolution spectra for hundreds of VMP star candidates selected from LAMOST (Large sky Area Multi-Object fiber Spectroscopic Telescope) low-resolution spectroscopic survey (Zhao *et al.* 2012, Cui *et al.* 2012). The 4-meter LAMOST telescope is capable of obtaining about 3400 targets simultaneously in a 5 degree diameter field of view, and has already obtained more than 5 million stellar spectra by the third data release (DR3). The spectra cover $3700 - 9100$ Å with a resolution of R$\sim$1800, and thus allow us to directly identify candidates of VMP stars out of millions of stars in the survey mode.

More than 500 candidates of VMP stars have been selected from LAMOST DR3, based on metallicities derived from LAMOST low-resolution spectra for all stars with signal-to-noise ratio (SNR) higher than 15 in the g-band, using methods and procedure described in Li *et al.* (2015a). To systematically search for low-mass stars which show excess of Li, we have selected about 30 candidates of Li-rich metal-poor stars with strong absorption line at Li 6708 Å from the sample of VMP stars. About 300 of the above selected candidates were followed-up using the High Dispersion Spectrograph (HDS) mounted at the Subaru telescope to obtain high-resolution (R=36,000) "snapshot" spectra covering $4000-6800$ Å. The spectra were taken with exposure times of $10-20$ minutes during six runs from May 2014 and November 2016. For a few interesting objects with [Fe/H] < -4.0 or with peculiar elemental abundances, spectra with higher SNR and/or resolving power (R=60,000) were then obtained for more detailed analysis.

3. Abundance analysis and preliminary results

For about 250 VMP stars whose Subaru spectra are with reasonable SNR, we have derived atmospheric parameters and elemental abundances using similar procedure as Li *et al.* (2015a). The resulted metallicities confirm that over 90% of the measured objects have [Fe/H] < -2.0, indicating a very efficient selection.

The abundances for about 20 elements have been measured for the VMP sample, including four representative elements shown in Figure 1. Our sample covers a wide metallicity range from [Fe/H] ~ -1.5 through ~ -4.0, including three UMP stars. All three UMP stars are carbon-enhanced metal-poor (CEMP) stars, but show no enhancement in

‡ $A(\mathrm{Li}) = 12 + \log[n(\mathrm{Li})/n(\mathrm{H})]$ where n is the number density of atoms

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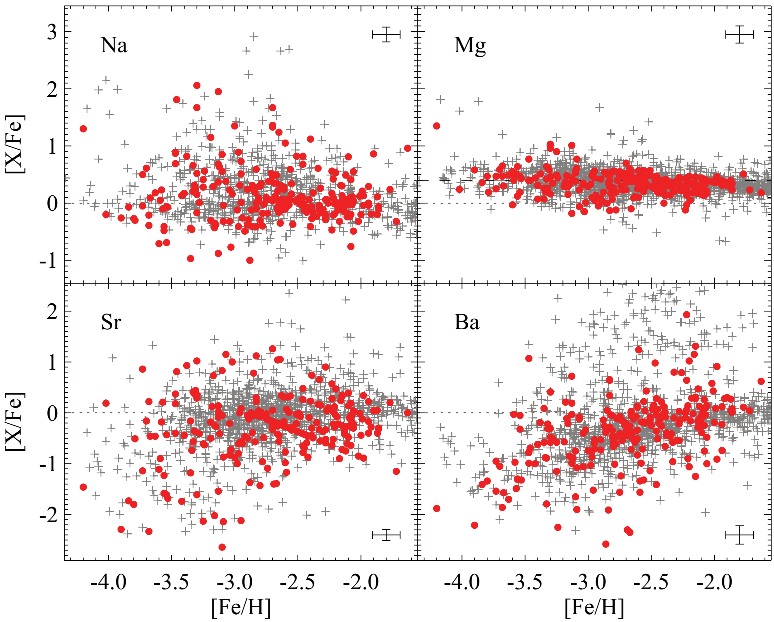

Figure 1. [X/Fe] vs. [Fe/H] for Na, Mg, Sr, and Ba. For Mg, the dashed line refers to the canonical value of $[\alpha/\mathrm{Fe}] \sim +0.4$ for the halo stars. Red dots correspond to LAMOST-Subaru targets, and crosses to literature metal-poor stars taken from the SAGA database (Suda *et al.* 2008, the version on June 26, 2017).

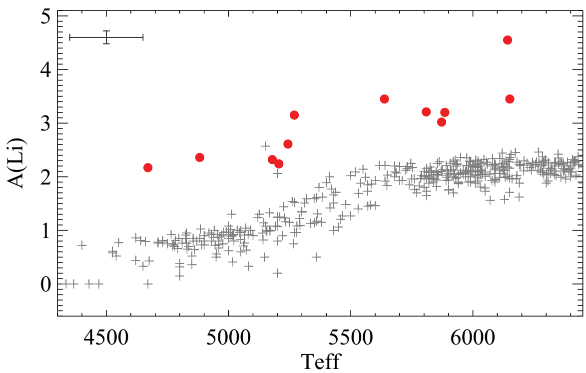

Figure 2. Distribution of A(Li) with $T_{\rm eff}$. Symbols are same as Figure 1.

heavy elements, and thus belong to CEMP-no stars. For one of the newly discovered UMP stars LAMOST J1253+0753, the Li 6707 line is clearly detected to derive $A(\mathrm{Li}) \sim 1.80$, which is the second UMP turnoff star with accurate Li abundance (Li *et al.* 2015b). The sample also includes a newly discovered $r-$II star LAMOST J1109+0754 (Li *et al.* 2015c), which shows extreme enhancements in $r-$process elements (e.g. $[\mathrm{Eu/Fe}] \sim +1.2$). A UV spectrum has also been obtained for this bright $r-$II star, and analysis for more heavy elements is still ongoing.

We discovered 12 new Li-rich metal-poor stars by our observations, with the distribution of their Li abundances over $T_{\rm eff}$ shown in Figure 2. These objects cover wide range in metallicity ($[\mathrm{Fe/H}] \sim -1.7$ through -3.3), including the first super Li-rich EMP star LAMOST J0705+2552 ($T_{\rm eff}{\sim}5270$ K, $\log g{\sim}2.5$, $[\mathrm{Fe/H}] \sim -3.2$, and A(Li)$\sim 3.0$). The

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Li-rich metal-poor stars are also widely distributed in evolutionary stages, and of special interest, five of them are turnoff/subgiant stars. This is the first time to find Li-rich turnoff/subgiant stars in field halo stars, and no models have been established to explain enhancement of Li in stars before evolving into red giants. More detailed investigation of this kind of peculiar objects will provide important clues to solve the origin of Li-rich low-mass stars.

More than 7 million high SNR stellar spectra will be obtained when LAMOST accomplishes the first 5-year spectroscopic survey, and the joint project with Subaru will provide us with a homogeneous sample for about 500 VMP stars with stellar parameters and abundanes determined based on high-resolution spectroscopy. Combined with kinematical data from Gaia, it will enable us to explore the origins of these ancient stars and the nature of earliest generations of stars.

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