A POSSIBLE SIGNATURE OF NON-UNIFORM Be–α RELATIONSHIPS FOR THE GALAXY∗

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ABSTRACT

Most of the previous studies on beryllium (Be) abundances in metal-poor stars have taken different Galactic populations as a whole when investigating the production and evolution of Be. In this Letter, we report on the detection of systematic differences in [α/H]–A(Be) relationships between the low- and high-α stars which were identified by previous works. We remind that one should be more careful in investigating the Galactic evolution of Be with a sample comprising different Galactic populations, because such a mixed sample may lead to inaccurate Be–Fe/Be–O relationships.

Key words: Galaxy: formation – Galaxy: halo – stars: abundances

Online-only material: color figures

1. INTRODUCTION

During the past two decades, astronomers have been working on beryllium (Be) abundances in metal-poor stars to investigate the production and evolution of Be in the early Galaxy. Most of these studies have taken different Galactic populations (halo and thick-disk stars, if included) as a whole when investigating the Be–Fe and Be–O relationships. This may be partly due to that the production of Be is thought to be a global process across the Galaxy, and therefore Be abundances should show small scatter at a given metallicity (Suzuki & Yoshii 2001), no matter which population the stars belong to. Boesgaard & Novicki (2006) presented, for the first time, some evidences of Be abundance dispersions. Smiljanic et al. (2008) and Tan et al. (2009) also found some Be-rich stars which are obviously above the general Be–Fe and Be–O trends. In their Be abundance survey with the largest sample to date, Smiljanic et al. (2009, hereafter S09) found a marginal statistical detection of a real scatter in the [Fe/H]–A(Be) diagram. They proposed two possible explanations for this: one is that the halo and the thick-disk stars have different [Fe/H]–A(Be) relationships; the other is that Be abundance dispersions exist at any given metallicity.

It is now generally believed that the Galaxy was formed through hierarchical merging, which means that different components of the Galaxy may have experienced different chemical evolution histories. Since α-elements are mainly produced by core collapse supernovae, they are closely associated with the star formation history of the Galaxy. In this regard, Galactic components with different α-element abundance patterns may show different behaviors in Be abundances. Nissen & Schuster (1997) found evidence of a bimodal distribution of [α/Fe] (α refers to the average abundance of Mg, Si, Ca, and Ti) for about a dozen halo stars. Gratton et al. (2003a, 2003b) found that the accretion component of the Galaxy tends to have lower [α/Fe] than the dissipative component. S09 also claimed two distinct components of the Galactic halo, but in the log(Be/H)–[α/Fe] diagram, which seems to make the division clearer than in the [Fe/H]–[α/Fe] diagram. Recently, Nissen & Schuster (2010, hereafter NS10) performed a precise abundance analysis for a sample of 94 thick-disk and halo stars in the solar neighborhood. They confirmed that, in the [Fe/H]–[α/Fe] diagram, the halo stars separate into two distinct populations, i.e., the low- and high-α halo populations. The very high precision of stellar parameters and α-element abundances make the sample of NS10 ideal for studying the possible different Be abundance patterns for different Galactic components in a systematic way. In this Letter, we report on the detection of two systematically different Be–α relationships for the stars from the sample of NS10.

2. THE SAMPLE

Among the 94 stars in the sample of NS10, high-resolution and high signal-to-noise ratio Very Large Telescope (VLT)/Ultraviolet and Visual Echelle Spectrograph (UVES) spectra covering the Be ii 3130 Å resonance doublet were available from the ESO/ST-ECF Science Archive for 40 stars. We downloaded the reduced spectra for these stars and then determined their Be abundances using the same technique as described in Tan et al. (2009). In addition, another three stars have Be abundances from the literature (two from Rich & Boesgaard 2009 and one from Boesgaard & King 1993). For these three stars, in order to keep our analysis consistent, we first derived their equivalent widths of the Be ii 3130 Å resonance lines based on the Be abundances and stellar parameters from the literature, and then re-calculated their Be abundances. For all the sample stars, stellar parameters given by NS10 were adopted in the determination of Be abundances. The uncertainty of Be abundance mainly comes from the uncertainties of stellar parameters and pseudo-continuum location. NS10 estimated the uncertainties of effective temperature, surface gravity, and metallicity to be ±30 K, ±0.05 dex, and ±0.04 dex, respectively, which leads to a total uncertainty of about ±0.03 dex in Be abundance. The typical uncertainty of Be abundance introduced by pseudo-continuum location was estimated to be ±0.05 dex. In total, the typical internal uncertainty of Be abundance is around ±0.06 dex. Abundances and uncertainties for the α-elements were taken from NS10 directly. The abundance results for the sample stars are given in Table 1. We noted that, among the 40 stars whose Be abundances were determined directly from the VLT/UVES spectra, 33 stars were included in the sample

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As mentioned in NS10, the classification of thick disk and halo stars in NS10, which is in reasonable agreement within uncertainties. Our results and that of S09 will be 0.37 2 1.49 59.03 2 (low-α)
G05-40 -0.81 -0.50 0.96 1 1.90 2 0.44 10.45 2 high-α
G18-28 -0.83 -0.52 0.89 1 ≤0.10 2 0.15 8.57 2 high-α
G18-39 -1.39 -1.06 0.21 1 2.23 6 0.79 12.52 1 high-α
G21-22 -1.09 -1.00 0.12 3 2.48 7 0.74 16.98 1 low-α
G46-31 -0.83 -0.68 0.49 1 2.09 2 1.02 8.65 2 low-α
G63-26 -1.56 -1.19 0.64 1 2.40 1 3.12 9.50 1 (high-α)
G121-12 -0.93 -0.83 0.25 1 2.55 2 0.13 43.31 2 low-α
G159-50 -0.93 -0.62 0.77 1 1.00 2 0.40 12.82 2 low-α
G188-22 -1.32 -0.97 0.40 1 2.21 8 2.48 14.28 1 high-α
HD 3567 -1.16 -0.95 -0.01 1 2.42 2 0.19 10.72 2 low-α
HD 17820 -0.67 -0.38 0.95 1 1.28 2 6.03 18.39 2 high-α
HD 22879 -0.85 -0.54 0.82 1 1.45 2 3.74 9.93 2 high-α
HD 25704 -0.85 -0.61 0.62 1 1.89 2 4.30 11.06 2 high-α
HD 51754 -0.58 -0.32 0.84 1 1.10 2 1.74 14.68 2 high-α
HD 70932 -0.58 -0.58 0.79 1 2.06 2 3.95 8.75 2 high-α
HD 97320 -1.17 -0.89 0.42 1 2.32 4 6.20 10.80 4 high-α
HD 103723 -0.80 -0.67 0.49 1 2.22 4 0.30 9.20 4 low-α
HD 105004 -0.82 -0.68 0.40 1 1.95 2 0.56 8.54 2 low-α
HD 111980 -1.08 -0.74 0.74 1 2.19 2 0.33 21.76 2 high-α
HD 113679 -0.65 -0.33 0.97 1 1.99 2 1.67 9.70 2 high-α
HD 114762A -0.70 -0.46 0.72 1 2.01 2 4.58 9.52 2 high-α
HD 120559 -0.89 -0.59 0.60 1 ≤0.25 2 5.82 8.75 2 high-α
HD 121004 -0.70 -0.38 1.02 1 ≤0.34 2 0.59 9.01 2 high-α
HD 126681 -1.17 -0.82 0.90 1 1.54 2 6.14 8.50 2 high-α
HD 132475 -1.49 -1.11 0.60 1 2.23 4 3.90 8.90 4 (high-α)
HD 148816 -0.73 -0.46 0.76 1 1.53 2 0.70 9.70 2 high-α
HD 160693 -0.49 -0.30 0.80 5 1.20 5 2.51 16.15 1 high-α
HD 163810 -1.20 -0.99 0.02 1 1.67 2 0.94 21.21 2 low-α
HD 175179 -0.65 -0.36 0.92 1 ≤0.87 4 1.73 9.83 2 high-α
HD 179626 -1.04 -0.73 0.67 1 1.81 2 1.92 11.42 2 high-α
HD 189558 -1.12 -0.79 0.70 1 2.15 2 2.34 9.31 2 high-α
HD 193901 -1.09 -0.93 0.01 1 1.92 2 0.45 10.59 2 low-α
HD 194598 -1.09 -0.91 0.08 1 2.02 2 0.97 8.88 2 low-α
HD 199289 -1.04 -0.74 0.57 1 2.00 2 4.94 8.75 2 high-α
HD 205650 -1.17 -0.87 0.41 1 1.70 4 3.70 10.20 4 high-α
HD 219617 -1.15 -1.17 -0.37 1 2.25 2 1.49 59.03 2 (low-α)
HD 222766 -0.67 -0.37 0.97 1 ≤0.10 2 1.22 22.74 2 high-α
HD 233511 -1.55 -1.21 -0.17 3 2.19 8 0.54 10.17 1 (high-α)

Note. Parentheses means the classification is uncertain for stars with [Fe/H] < −1.4 according to NS10.

References. (1) Determined by this work; (2) S09; (3) Rich & Boesgaard 2009; (4) Tan et al. 2009; (5) Boesgaard & King 1993; (6) Charbonnel & Primas 2005; (7) Boesgaard & Novicki 2006; (8) Shi et al. 2007.
gin as oxygen. Similar approximation has also been adopted by S09. It can be seen clearly in Figure 1(a) that Be abundances of the low-\(\alpha\) stars are systematically lower than that of the high-\(\alpha\) stars, and the differences are obviously larger than the uncertainties of Be abundances. Even so, one may still expect a uniform \(A(\text{Be})\) versus \([\alpha/\text{H}]\) relationship for the sample stars because the production of Be is thought to be correlated directly with oxygen (and thus \(\alpha\)-elements) rather than iron. However, as can be seen in Figure 1(b), Be abundances of the low-\(\alpha\) stars are still systematically lower than that of the high-\(\alpha\) stars. As the differences in Be abundances in the \([\alpha/\text{H}]/A(\text{Be})\) diagram are not as obvious as that in the \([\text{Fe}/\text{H}]/A(\text{Be})\) diagram, we performed a statistical test to confirm whether the division is a real feature or just caused by the uncertainties of the analysis. We made linear fits, in the common \([\alpha/\text{H}]\) range \((-1.2 < [\alpha/\text{H}] < -0.6)\), to the high-\(\alpha\) stars, to the low-\(\alpha\) stars, and to the whole sample,\(^2\) and then calculated the root-mean-square (rms) deviations from the fits, respectively. The rms deviations from the fits for the high- and low-\(\alpha\) stars are 0.07 and 0.06 dex, respectively, which are comparable to the Be abundances uncertainty (0.06 dex); while the rms deviation for the whole sample is 0.18 dex, which is obviously larger than the error of Be abundances. Therefore, we conclude that systematic differences in \([\alpha/\text{H}]/A(\text{Be})\) relationships do exist between the low- and high-\(\alpha\) stars in our sample. One may think that Be in the low-\(\alpha\) stars have been depleted and thus the abundances are lower than that of the high-\(\alpha\) stars. This is, however, not the case. As shown in Figure 2, Li abundances of the low-\(\alpha\) stars are in the upper range of the sample, but their [Be/\(\alpha\)] values (solar Be abundance \(A(\text{Be}) = 1.32\) recommended by Lodders 2010 was adopted in the calculation) are systematically lower than that of the high-\(\alpha\) stars. As the destruction temperature for Li is lower than that of Be, if Be is depleted, then Li should have been depleted more than Be. The possibility that the gas from which the low-\(\alpha\) stars formed had been exposed to the cosmic-rays shorter than that of the high-\(\alpha\) stars and thus has lower Be abundance can also be excluded, because the low-\(\alpha\) stars are on average 2–3 Gyr younger than the high-\(\alpha\) stars (W. J. Schuster et al. 2011, in preparation). Pasquini et al. (2005) proposed the possibility that some stars may form at very large Galactocentric radii with lower cosmic-ray fluxes and thus lower production of Be and heavy elements. However, as shown in Figure 3, we did not find any gradient in Be abundances for the sample stars. In the Be abundance survey with the largest sample to date by S09, no decreasing trend in Be abundance with increasing Galactocentric distance was found, either.

S09 identified four pairs of stars with similar atmospheric parameters and metallicities but different Be abundances to testify the existence of scatter in Be abundances. We suggest that one of the main reasons for the scatter is the composition of the pairs. Among these four pairs of stars, three pairs are included in our sample, and each pair is comprised of one low-\(\alpha\) star and one high-\(\alpha\) star. According to the definition of NS10, at a given \([\text{Fe}/\text{H}]\), low-\(\alpha\) stars have lower \([\alpha/\text{Fe}]\) (and thus \([\alpha/\text{H}]\)) than high-\(\alpha\) stars. Moreover, at a given \([\alpha/\text{H}]\), low \([\alpha/\text{Fe}]\) stars have less Be than high \([\alpha/\text{Fe}]\) stars as shown in Figure 1(b). Therefore, it is natural that low-\(\alpha\) stars have lower Be abundances than high-\(\alpha\) stars with the same metallicities. Also, it can be easily understood that the separation between the low- and high-\(\alpha\)

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\(^2\) All through this Letter, G63–26, HD 132475, and HD 126681 are not included in any linear fits; please refer to the last paragraph but one of this Letter for more discussions about these three stars.
stars in the [Fe/H]–A(Be) diagram is clearer than that in the
[α/H]–A(Be) diagram (compare the two panels of Figure 1). S09 noted the impression of two parallel relations in the Be–Fe
diagram. However, they did not detect the different [α/H]–A(Be)
relationships. This may be partly due to the relatively large abun-
dance uncertainties of S09 (note that the stellar parameters and
α-element abundances adopted by S09 were taken from differ-
cent works and had not been homogenized).

As suggested by NS10, the high-α stars may form in regions
with rapid chemical evolution, while the low-α stars may
originate from dwarf galaxies with lower star formation rates.
In this case, the energy spectrum for the cosmic rays may
be different in the regions where the low- and high-α stars
formed, and thus the production rate of Be could be different
(as the effective spallation cross sections are dependent on the
energies of the cosmic rays). Therefore, systematic differences
in Be abundances between the low- and high-α stars can be
a natural prediction from the explanation of NS10. We note
that the bimodal distribution of [α/Fe] observed by NS10 is
consistent with the theoretical results of Zolotov et al. (2009,
2010), which are based on the assumption that the inner halos of
the galaxies contain both stars accreted from satellite galaxies
and stars formed in situ. However, Nissen & Schuster (2011)
show that abundance patterns of the low-α stars do not match
that of the present-day dwarf galaxies. They suggest that the
low-α stars may have been accreted from more massive satellite
galaxies at early times.

As shown in Figure 1(b), in the common [α/H] range
(−1.2 < [α/H] < −0.6), A(Be) of the high-α stars increases
with [α/H] faster than that of the low-α stars; however, if the
"metal-rich" end of the high-α stars are included, then the
[α/H]–A(Be) relationship for the high-α stars will be flatter than
that for the low-α stars. Such a break in the [α/H]–A(Be) re-

Figure 3. [Be/α] as a function of (a) perigalactic and (b) apogalactic distances
for the sample stars. The symbols have the same meanings as in Figure 1.
(A color version of this figure is available in the online journal.)
consistent. Nevertheless, we hope that the results presented in this work could stimulate more research on Galactic evolution of Be and related fields, both observational and theoretical.

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