The puzzling abundance pattern of HD134439 and HD134440

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ABSTRACT

Abundances of 18 elements are determined for the common proper-motion pair, HD 134439 and HD 134440, which shows high [Mn/Fe] and low [α/Fe] ratios as compared to normal halo stars. Moreover, puzzling abundances are indicated from elements whose origins are normally considered to be from the same nucleosynthesis history. Particularly, we have found that [Mg/Fe] and [Si/Fe] are lower than [Ca/Fe] and [Ti/Fe] by 0.1-0.3 dex. When elemental abundances are interpreted in term of their condensation temperatures ($T_C$), obvious trends of [X/Fe] vs. $T_C$ for α elements and probably iron-peak elements as well are shown. The hypothesis that these stars have formed from a dusty environment in dSph galaxy provides a solution to the puzzling abundance pattern.

Key words: stars: abundances – stars: individual: HD134439, HD134440 – stars: Population II – stars: late-type – Galaxy: evolution

1 INTRODUCTION

It is well accepted that metal-poor halo stars have the enhanced $[\alpha/\text{Fe}]$ ratio of 0.4 dex while this ratio decreases with increasing metallicity for stars with $[\text{Fe/H}] > -1$. In contrary to this traditional view, a few metal-poor stars showing relatively low $[\alpha/\text{Fe}]$ in the metallicity...
range of $-2.0 < \text{[Fe/H]} < -0.7$ have been reported \cite{NissenSchuster1997, Ivans2003}, and abundances and kinematics accumulated in spectroscopic observations indicate that some of these low-$\alpha$ stars could be accreted from nearby dwarf galaxies which have a lower star formation rate than the Galactic halo \cite{GilmoreWyse1998}.

Recently, \cite{ShigeyamaTsujimoto2003} have proposed a new possible origin for low-$\alpha$ stars in the metallicity of $-2.0 < \text{[Fe/H]} < -1.0$. They suggested that some metal-poor stars harbor planetary systems and show low-$\alpha$ ratios due to engulfing planetesimals. Inspired by this conjecture, we attempt to investigate the abundance pattern of HD 134439 and HD 134440, which are the best test samples with the reported low $[\alpha/\text{Fe}]$ \cite{King1997} and the metallicity in the middle of $-2.0 < \text{[Fe/H]} < -1.0$. \cite{Ivans2003}’s sample of low-$\alpha$ stars is close to $\text{[Fe/H]} = -2.0$ while most low-$\alpha$ stars in \cite{NissenSchuster1997} have $\text{[Fe/H]} > -1.0$. Moreover, these two stars are a common proper-motion pair and abundance difference between this pair provides a way to inspect the possibility of harboring planetary systems.

Two previous works on abundance determination of this pair \cite{King1997, Fulbright2000} gave inconsistent results for some important elements. The abundance ratios of $[\text{Na}/\text{Fe}]$, $[\text{Mg}/\text{Fe}]$ and $[\text{Si}/\text{Fe}]$ show deviations of 0.15-0.25 dex. Since these ratios provide crucial information on the formation environment of this pair, it is desirable to make a new analysis with high quality spectra from UVES/VLT and HDS/SUBARU by an updated analysis method in the present work. **Moreover, our work will derive abundances for more elements based on more lines. In particular**, abundances of a few interesting elements, such as K, Sc, Mn, Cu, Co and Zn, are not available in the literature. The abundance ratios of these elements provide key clues to their origin and give new information on their nucleosynthesis history.

## 2 Observations and Data Reductions

In order to reduce analysis error and to facilitate the interpretation of resulting abundance, we select HD 211998 as a standard star for comparison. HD 211998 is a subgiant, which is expected to be immune to the planet (if existed) formation process according to \cite{ShigeyamaTsujimoto2003}, and its metallicity is the same as our target stars.

High resolution UVES spectra were retrieved from the ESO archive \footnote{http://www.eso.org} with the resolving
power of 40,000 and the signal-to-noise ratio of 200 for HD 134439/40 and R~60 000 and S/N~400 for HD 211998. Subaru archive data \(^3\) (Baba et al. 2002) supplied additional HDS (Noguchi et al. 2002) spectra for HD 134439 with R~90 000 and S/N~300. Note that the resolution and signal-to-noise of our HDS spectra for HD 134439 are higher than those of King (1997) and Fulbright (2000), while UVES spectra have similar resolution and signal-to-noise ratio as those of King (1997). In comparison with Fulbright (2000), the signal-to-noise of our UVES spectra is significantly higher.

The spectra were reduced by using standard routines in MIDAS software for order identification, background subtraction, flat-field correction, order extraction and wavelength calibration. Bias, dark current and scattered light corrections are included in the background subtraction. The spectra were then normalized by a continuum function determined by fitting a spline curve to a set of pre-selected continuum windows estimated from the solar atlas. Finally, correction of radial velocity shift, measured from 20 lines, was applied and the equivalent widths were measured by Gaussian fitting.

Fig. 1 shows the comparison of equivalent widths between this work and King (1997). Note that two points showing significant deviations as large as 15 mÅ are Mg lines at \(\lambda_{5711}\) Å for HD 134439 and HD 13440 respectively. We have checked that our spectra of HD 134439 from UVES and HDS give the same equivalent widths for this line. Since our HDS spectra have very high quality, and the agreement indicates that our values for this line are reliable. The comparison of equivalent widths of HD 134439 from our UVES and HDS spectra for 189 lines in common in Fig. 2 also gives consistent values with a deviation of \(\Delta EW(HDS - UVES) = -2.01 \pm 3.18\) mÅ.

3 ABUNDANCE ANALYSIS

3.1 Stellar Parameters

The effective temperatures are based on Alonso et al. (1996)’s IRFM \(T_{\text{eff}}\) scale and (b-y) color indices. Reddening is assumed to be negligible since all stars are within 30 pc from the Sun. We have checked that the slopes of iron abundances versus excitation potential are small. Gravities are derived from Hipparcos parallaxes (Chen et al. 2000) and metallicities are iterated by abundance analysis. Microturbulences are determined by forcing FeI lines

\(^{3}\) http://smoka.nao.ac.jp
with different strengths to give consistent abundances. Stellar parameters and resulting abundances are presented in Table 1.

Our temperatures are generally consistent with those in King (1997) with deviations of 21 K and 67 K for HD 134439 and HD 134440, respectively, but they are significantly higher than those in Fulbright (2000). As noticed in Chen & Zhao (2006), spectrscopically-derived
Table 1. Atmosphere parameters and [X/Fe] ratios for HD 134439(1), HD 134440(2) and HD 2119988(3). X indicates different elements.

<table>
<thead>
<tr>
<th>Element</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>(T_{\text{eff}}) (K)</td>
<td>5021</td>
<td>4852</td>
<td>5241</td>
</tr>
<tr>
<td>(\log g)</td>
<td>4.66</td>
<td>4.64</td>
<td>3.34</td>
</tr>
<tr>
<td>(\xi_t)</td>
<td>1.10</td>
<td>1.10</td>
<td>1.10</td>
</tr>
<tr>
<td>Sc</td>
<td>−0.03</td>
<td>−0.04</td>
<td>0.01</td>
</tr>
<tr>
<td>Ti</td>
<td>0.18</td>
<td>0.20</td>
<td>0.34</td>
</tr>
<tr>
<td>V</td>
<td>0.01</td>
<td>0.05</td>
<td>−0.07</td>
</tr>
<tr>
<td>Cr</td>
<td>0.01</td>
<td>0.06</td>
<td>−0.07</td>
</tr>
<tr>
<td>Mn</td>
<td>0.41</td>
<td>−0.37</td>
<td>−0.59</td>
</tr>
<tr>
<td>Al</td>
<td>−1.43</td>
<td>−1.45</td>
<td>−1.46</td>
</tr>
<tr>
<td>Si</td>
<td>0.04</td>
<td>0.04</td>
<td>0.33</td>
</tr>
<tr>
<td>K</td>
<td>0.10</td>
<td>0.08</td>
<td>0.77</td>
</tr>
<tr>
<td>Ca</td>
<td>0.09</td>
<td>0.08</td>
<td>0.36</td>
</tr>
</tbody>
</table>

Temperatures for solar type stars show systematically deviations in opposite directions in different works, and they strongly depend on stellar model atmosphere, the selection of lines, the adopted atomic data, and so on. We thus prefer the IRFM-based photometric temperatures. Furthermore, surface gravities in the present work are derived from parallaxes which are more reliable than those in King (1997) and Fulbright (2000). Finally, we note that the microturbulences of this pair adopted by Fulbright (2000) are 0.7 km s\(^{-1}\) which are quite low as compared with the usually adopted value of 1.5 km s\(^{-1}\) for metal-poor stars in the literature.

The internal error in \(T_{\text{eff}}\) derived in the present work is around 70 K as shown in Nissen et al. (2004). Considering the significant discrepancy with spectroscopically-derived value in Fulbright (2000), we adopted the error of 150 K in \(T_{\text{eff}}\) as the maximum value of temperature error. Errors of other atmospheric parameters are estimated to be 0.15 dex in \(\log g\), 0.1 dex in [Fe/H] and 0.3 km s\(^{-1}\) in \(\xi_t\).

3.2 Abundances and Error Analysis

The unblended lines with strength strong enough for measurement were carefully selected by using the solar atlas of Moore (1966). The oscillator strengths are mainly the same or taken from the same sources as those in Chen et al. (2000), which are checked for consistency with the Sun being one of ”standard” stars. The atomic line data and equivalent widths for HD 134439, HD 134440 and HD 211998 are presented in Table A1, which is published electronically only.

The model atmospheres were interpolated from a grid of plane-parallel, LTE models.
provided by Kurucz (1995) in which convective overshoot is switched off. The ABONTEST8 program, developed by P. Magain in the Liège group, was used to carry out the calculations of theoretical equivalent widths of lines and abundance was derived by matching the theoretical equivalent widths to the observed values. Hyperfine structures for Sc, Mn, Cu and Ba are checked to have small effects since the adopted lines are weak in metal-poor stars. Solar abundances from Grevesse & Sauval (1998) are adopted to derive the relative abundances. Since Si and Zn lines correspond to high excitation levels and are weak in our stars, they are formed from deep in the stellar atmospheres which is similar as that of FeII lines. In view of this, iron abundances from FeII lines were adopted to derive [Si/Fe] and [Zn/Fe] ratios. On the contrary, iron abundances from FeI lines were used to obtain [Ba/Fe] ratio because BaII lines behave more like FeI lines rather than FeII lines. In this way, we can expect that errors of [X/Fe] ratios can be greatly reduced. For other elements, we follow the general rule that elemental abundances derived from neutron lines are relative to FeI lines and abundances from ionized lines are relative to FeII lines.

The uncertainties estimated by a change of 150 K in $T_{\text{eff}}$, 0.2 dex in $\log g$, 0.1 dex in [Fe/H] and 0.3 km s$^{-1}$ in $\xi_t$ are shown in Table 2, where numbers with brackets indicate the internal errors by using 70 K as an error in temperature. It shows that abundance errors...
are 0.12 dex for iron abundances and less than 0.1 dex for [X/Fe] ratios even the external error of 150 K is used. Clearly, main errors in abundances of most elements come from the uncertainty of temperature. The abundance errors will be greatly reduced (about 0.07 dex) when the internal error in temperature of 70 K is adopted.

The comparisons of our abundances with those in King (1997) and Fulbright (2000) are shown in Fig. 3. Generally, our values are quite similar with King (1997). The [Na/Fe] and [Ca/Fe] show the largest deviations around 0.1 dex. Note that more lines are used in the present work to derive abundances while only one line for Na and three lines for Ca are adopted in King (1997). In comparison with Fulbright (2000), there is a large disagreement by 0.2-0.3 dex in [Na/Fe] and [Si/Fe]. Since our abundances are derived with a more reasonable atmospheric parameters based on spectra with higher signal-to-noise, they may be more reliable.

## 4 ABUNDANCES AND DISCUSSIONS

The common proper-motion pair is presumed to be formed out from the same cloud, and thus we can expect that HD 134439 and HD 134440 have the same age and chemical history.
Unfortunately, it is difficult to determine their ages since they are on the main sequence. For chemical composition, identical abundances between these two stars have been found by King (1997) for six elements and are confirmed in the present work for more elements as shown in Fig. 4. One exception is the lithium abundance. We obtained the abundance of 0.48 dex for HD 134439 which is close to the value (0.53 dex) in King (1997). The LiI line at λ6708Å is undetected for HD 134440 and an upper limit of Li abundance is 0.06 dex based on the assumed equivalent width of 3.0 mÅ.

Some common proper-motion pairs, e.g. 16 Cyg and HD 219542, are reported to harbor planets and abundance differences in planet host stars have been suggested (Laws & Gonzalez 2001; Gonzalez et al. 2001; Sadakane et al. 2003). However, Desidera et al. (2004) recently studied 23 common proper motion pairs with solar metallicity, some of which harbor planets, and suggested that differences in iron abundances between the pairs are less than 0.07 dex. Presently, it is premature to exclude the possibility of the presence of planets on the HD 134439/40 pair based on their identical abundances.

As reported by King (1997) and confirmed in the present work, this pair has lower [α/Fe] ratio than normal stars at [Fe/H] \sim −1.5. According to Shigeyama & Tsujimoto (2003), low-α metal-poor stars might harbor planets and they accreted planetesimals which enhanced the surface content of Fe and thus reduced the [α/Fe] ratios. In this regard, we would expect an increasing enhancement of elements with higher condensation temperatures (hereafter, $T_C$). Simply, we adopted the condensation temperature of the solar system from Lodders (2003) since there is no better source in the literature. However, there is no any clear trend in Fig. 4 where abundances, relative to the comparison star HD 211998, versus $T_C$ are shown for both.
HD 134439 and HD 134440. Especially, Zn has low $T_C$ but does not show underabundant $[X/Fe]$ ratio as much as Mg and Si elements which have higher $T_C$. Moreover, $[\text{Mn/Fe}]$ is higher than HD 211998 which is contrary to the prediction by Shigeyama & Tsujimoto (2003) that low $[\alpha/Fe]$ stars with low $[\text{Mn/Fe}]$ harbor planetary systems. In addition, our abundances of Mn, Co, Cr and Ni elements, as presented in Table 1, do not support the suggestion by Tsujimoto & Shigeyama (2006) that HD 134439/40 are relics of a population III SNIIIa in which they predicted the deficiency of odd-number elements, Mn and Co, relative to even-number elements, Cr and Ni.

HD 134439/40 have the same and special kinematic parameters ($R_{apo}=45\text{ kpc}, V_{LSR}=-315\text{ km s}^{-1}, Z_{max}=1.7\text{ kpc}$) which are thought to be a evidence of accreted substructure in the halo field according to Carney et al. (1996). Similarly, other eight low $[\alpha/Fe]$ stars found by Nissen & Schuster (1997) also show large $R_{apo}$ and $Z_{max}$ and they were related to the accretion of our Galaxy from nearby dwarf spheroidal (dSph) galaxies. The inspection of our resulting abundances of HD 134439/40 with stars in dSph galaxies by Shetrone et al. (2001, 2003) shows generally similar abundance pattern. For example, the $[\text{Na/Fe}]$ ratio in our stars is lower than $[\text{Al/Fe}]$, which is consistent with the Fig. 2 of Shetrone et al. (2003) for stars in dSph galaxies. Moreover, the $[\text{Ni/Fe}]$ of this pair is lower than that of the reference star HD 211998 by 0.1 dex, indicating a Na-Ni correlation in low $[\alpha/Fe]$ field stars found by Nissen & Schuster (1997) and in dSph galaxies by Venn et al. (2004). Thus, to a large sense, this pair is related to an chemical evolution history like dSph galaxies. Particularly, this is further witnessed by the higher $[\text{Mn/Fe}]$ than the comparison star HD 211998 by 0.2 dex. As noted by Nissen et al. (2000), low $[\alpha/Fe]$ stars in Nissen & Schuster (1997) have higher $[\text{Mn/Fe}]$ than normal stars. This is consistent with their origins from dSph galaxies because Mn is mainly produced by SN Type Ia (Samland 1998) which starts to contribute the chemical evolution of dSph galaxies at lower than usual $[\text{Fe/H}]$ values in the Galaxy.

However, the suggestion that they are accreted from dSph galaxy may not be the whole story of this common proper-motion pair. With careful inspection of the abundances in Table 1, some interesting features, which are not found stars of dSph galaxies, are shown. The most obvious feature is that $[\text{Mg/Fe}]$ is lower than $[\text{Ca/Fe}]$ by 0.2 dex and than $[\text{Ti/Fe}]$ by 0.3 dex, and $[\text{Si/Fe}]$ is also slightly lower than $[\text{Ca/Fe}]$ and $[\text{Ti/Fe}]$. Note that the low-$\alpha$ young globular cluster Rup 106, presumably accreted from the Sagittarius dwarf galaxy, do not show difference between Mg-Si and Ca-Ti abundances (Brown et al. 1997). On the
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Figure 5. The $[X/Fe]$ vs. $T_C$ for $\alpha$ elements and iron group elements. Elements are indicated in order of increasing $T_C$.

contrary, Venn et al. (2004) found even lower $[\text{Ca,Ti}/\text{Fe}]$ ratios than $[\text{Mg}/\text{Fe}]$ in metal-poor dSph systems. Furthermore, there is a underabundant $[\text{Ba}/\text{Y}]$ by 0.1 dex in HD 134439/40, which is inconsistent with most dSph stars according to Venn et al. (2004), who found a large overabundance in $[\text{Ba}/\text{Y}]$ in the comparison of stars from seven dSph galaxies with Galactic stars. It seems that additional mechanism is required to explain the abundance pattern of this pair.

Since the two stars were formed in a low supernova Type II environment as indicated by their low $\alpha$ ratios, it is natural that dust accretion provides a possible solution to these unexpected features. Probably, the two field low $\alpha$ stars have formed from a dusty environment where dust from the late stages of stellar evolution in a prior generation of stars contaminated the pro-stellar material of this pair. In connection with the dust observations, this suggestion is promising since the existence of very cold dust in low metallicity galaxy has been reported (Galliano et al. 2003) which indicates that the mass ratio of dust-to-gas ratio is significantly higher than normal value in the Galaxy (Li 2004). It is well known that the depletion pattern of gas onto dust in a prior generation of stars shows a decreasing depletion factor for elements with higher condensation temperatures (Jenkins 2004). Therefore, if the proto-cloud of this pair is polluted by material with a usually high dust-to-gas ratio, we would expect an increasing enhancement of elements with higher condensation temperatures. The relation of $[X/Fe]$ vs. $T_C$ for $\alpha$ elements and Fe-group elements in Fig. 5 respectively, so that small trends can be detected by comparing elements which are thought to be formed from the same nucleosynthesis site. In this plot, the average values of HD 134439
and HD 134440 are adopted as representative abundances of this pair. Here, Zn is included in iron group elements since it follows Fe at \([\text{Fe/H}] \sim -1.5\) \(\text{(Nissen et al. 2004)}\) while Mn is excluded due to the odd-even effect of this element found in Galactic stars \(\text{(Nissen et al. 2000)}\) and Ni is also excluded due to the Na-Ni correlation described above. As expected, a positive slope in the \([X/\text{Fe}]\) vs. \(T_C\) for \(\alpha\) elements is clear. This trend is also visible based on abundances of \(\alpha\) elements from \(\text{King (1997)}\) as shown by open squares in Fig. 5. For Fe group elements, the trend is generally masked within the abundance uncertainty, but there is a hint that \([\text{Zn/Fe}]\), being an element least contained in dust, is lower than the average \([X/\text{Fe}]\) of other Fe group elements such as V and Cr. Alternatively, the hypothesis of accreting planetesimals, which also gives rise to a positive slope in the \([X/\text{Fe}]\) vs. \(T_C\), is difficult to be accepted since there is a low probability for both stars in this common proper motion pair have accreted the same mass of planetesimals with the same composition. It seems that these abundances favor the dust pollution hypothesis. Interestingly, two blue metal-poor stars from \(\text{Ivans et al. (2003)}\), CS 22966-043 and CS 22941-012, have lower Mg and Si ratios than Ca and Ti ratios. However, it is unclear if the dust pollution can explain \(\text{Ivans et al. (2003)}\)’s result since CS 22966-043 is a low \(\alpha\) stars while CS 22941-012 has high \([\alpha/\text{Fe}]\) (with the mean value of Mg, Si, Ca and Ti above 0.3 dex). More observational data and knowledge on dust formation and evolution are desirable to understand these results.

5 CONCLUSIONS

We have derived abundances of 18 elements for the HD 134439/40 common proper-motion pair. With new determined abundances of Mn, Co and Zn, our result do not favor the accretion of planetesimals suggested by \(\text{Shigeyama & Tsujimoto (2003)}\) and \(\text{Tsujimoto & Shigeyama (2006)}\) as a possible origin of their low \([\alpha/\text{Fe}]\) ratios. Instead, abundance results of low \([\alpha/\text{Fe}]\) ratios, high \([\text{Mn/Fe}]\) and the Na-Ni relationship are generally consistent with the kinematical evidence of a discrete accretion from dSph galaxy. Furthermore, the hint of positive slopes of \([X/\text{Fe}]\) vs. \(T_C\) for \(\alpha\) elements and probably iron group elements for this pair may indicate that the proto-cloud of this common proper pair is polluted by material with a usually high dust-to-gas ratio in a low SN Type II environment such as dSph galaxy.
ACKNOWLEDGEMENTS

Dr. Liang Yanchun is thanked for help on data collection from UVES archive, and Dr. Li Aigen is thanked for useful discussion on dust observations. This research is supported by the NSFC under grant No. 10433010, No. 10521001 and No. 10203002, and by the Chinese Academy of Sciences under grant No. KJCX2-SW-T06.

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