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Chemical abundances of field halo stars - Implications for the building blocks of the Milky Way

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Abstract. I would like to review recent efforts of detailed chemical abundance measurements for field Milky Way halo stars. Thanks to the advent of wide-field spectroscopic surveys up to a several kpc from the Sun, large samples of field halo stars with detailed chemical measurements are continuously expanding. Combination of the chemical information and full six dimensional phase-space information is now recognized as a powerful tool to identify cosmological accretion events that have built a sizable fraction of the present-day stellar halo. Future observational prospects with wide-field spectroscopic surveys and theoretical prospects with supernova nucleosynthetic yields are also discussed.

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

1. Introduction

Chemical abundances in the photosphere of ancient stars provide fossil records to link field stars with their original birth places and thus serve as an essential tool to re-construct the merging history of our Milky Way Galaxy (Freeman & Bland-Hawthorn 2002). The stellar halo, which predominantly consists of old stellar populations, is a particularly interesting target because orbital velocities of the stars are largely preserved over the Galactic history due to the long dynamical time. This makes the Milky Way stellar halo an ideal laboratory to test theories of galaxy formation and evolution in the context of the currently standard ΛCDM cosmology (Bullock & Johnston 2005; Robertson *et al.* 2005; Font *et al.* 2006; Cooper *et al.* 2010) based on spatial position, kinematics and chemistry of individual stars.

Since the stellar halo is an extremely diffuse component where $\sim 10^9$ $M_\odot$ of stars are distributed in a large volume over $\sim 150-200$ kpc from the Galactic center and the local density is much less than 1% (Juric *et al.* 2008), studies of chemical abundances in field halo stars take significant advantages from wide-field spectroscopic surveys. Large samples of candidate halo stars with low metallicity have been built by prism spectroscopic surveys (the *HK survey* or the *Hamburg/ESO survey*). Their follow-up high-resolution spectroscopy have revealed characteristic chemical abundances among stars with [Fe/H] lower than -3 (Beers & Christlieb 2005 and reference therein; Section 4).

More recently, wide-field low-to-medium resolution spectroscopic surveys such as the Sloan Extension for Galactic Understanding and Exploration (SEGUE; Yanny *et al.* 2009), Radial Velocity Experiment (RAVE; Steinmetz *et al.* 2006), the Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) survey (Deng *et al.* 2012), and the APOGEE survey (Majewski *et al.* 2017) have significantly improved survey volumes for stellar samples with line-of-sight velocity and chemical abundance measurements. Wide-field photometric surveys employing narrow-band filters sensitive to the calcium

H and K lines, such as SkyMapper Southern Sky Surveys (Keller *et al.* 2007) and Pristine survey (Starkenburg *et al.* 2017) have also been successful in discovering the most chemically pristine stars. High-resolution spectroscopic follow-up observations are accumulating a number of interesting chemical signatures in field halo stars (e.g., Li *et al.* 2016) that could potentially update the current understanding of the chemical structure of our Galaxy and on the nature of the earliest generations of stars in the Universe (Frebel & Norris 2015)

The large spectroscopic data sets are particularly powerful when they are combined with accurate parallax and proper motion data provided by satellite missions such as *Hipparcos* in studying the chemodynamical structure and evolution of our Galaxy (see Feltzing & Chiba 2013 for a review of this subject). Furthermore, the measured chemical abundances provide further insights into the stellar birth environment making use of Galactic chemical evolution models (e.g. Kobayashi *et al.* 2006) and with individual supernova yield models (e.g., Woosley & Weaver 1995; Heger & Woosley 2010; Nomoto, Kobayashi, & Tominaga 2013).

In this article, I would like to focus on how the chemical information help distinguishing the origin of individual field halo stars in the following three different categories: (1) local halo stars that characterize the gross chemodynamical structure of the halo (Section 2), (2) halo stars with full space motions measured and identified as candidate members of kinematically coherent streams (Section 3), and (3) metal-poor stars that show peculiar chemical abundance patterns (Section 4). Finally, future prospects with on-going and planed large spectroscopic surveys of the Milky Way are discussed (Section 5).

2. The global chemodynamical structure of the stellar halo

Thanks to the recent wide-field photometric surveys, our understanding of the stellar distribution in the halo has been dramatically changed over the last few decades (Ivezić *et al.* 2012). It was clearly demonstrated that the stellar halo is far from a smooth and static distribution of a single stellar population but it exhibits various spatially coherent substructures. While the spatial coherence of stars could be washed out in about 10 Gyrs, as a result of dynamical evolution of the Galaxy, kinematics and chemical abundances are preserved for a longer time scale and thus provide information on the early Galactic history (Helmi & White 1999).

Dating back to the pioneering work by Eggen, Lynden-Bell, & Sandage (1962), the strength of combining kinematics and chemistry of field halo stars has been widely recognized (e.g. Norris & Ryan 1989; Chiba & Beers 2000). One of the global nature of the stellar halo revealed by full space motions and [Fe/H] of nearby field halo stars is the presence of at least two structural components, the inner and outer halo populations (Carollo *et al.* 2007).

Detailed elemental abundances in nearby halo stars have provided crucial information on the nucleosynthesis and chemical evolution of the early Universe. At $[\mathrm{Fe/H}] \lesssim -2$, α-element-to-iron ratios ([(Mg, Si, Ca)/Fe]) have found to be enhanced by $\sim$0.4 dex relative to the solar values, and trend and scatter seen in other elements have been interpreted as the dependence of Type II supernova yields on progenitor metallicity or on explosion physics (e.g., McWilliam *et al.* 1995; Ryan, Norris, & Beers 1996; Cayrel *et al.* 2004). At higher [Fe/H], the enhancement of the α-elements was thought to continue up to $[\mathrm{Fe/H}] \sim -1$, whose behavior was found to be different from the majority of stars in dwarf spheroidal satellite galaxies with measured elemental abundances (e.g., Venn *et al.* 2004). Exception to the [α/Fe]-[Fe/H] trends were also reported (e.g., Carney *et al.* 1997) in particular for halo stars whose orbit reaches the outer Galactic halo (Nissen & Schuster 1997).

Subsequent studies analyzed a larger samples of stars with known kinematics (Fulbright 2000; Fulbright 2002; Stephens & Boesgaard 2002; Zhang *et al.* 2009; Ishigaki *et al.* 2010). Among others, Nissen & Schuster (2010) have expanded their original sample of Nissen & Schuster (1997) to ∼100 stars carefully selected to have similar stellar parameters (effective temperature, surface gravity and [Fe/H]) and have full space motions. They have shown that the sample of nearby halo stars can be separated into the two chemically different populations; namely, high-α and low-α stars. In addition to the alpha elements, the two populations show systematic difference in various elemental abundances including C, Ni, Zn (Nissen & Schuster 2011) and in the neutron capture elements (Fishlock *et al.* 2017).

An intriguing question is whether the inner and the outer halo populations identified by kinematics and [Fe/H] reported by Carollo *et al.* (2007) exactly correspond to the high-α and low-α components, respectively, reported by Nissen & Schuster (2010). Ishigaki *et al.* (2012) carried out high-resolution spectroscopic analyses of stars from Chiba & Beers (2000) to study the difference in detailed elemental abundances among those selected to have characteristic kinematics of the thick disk, inner and outer halo stars reported by Carollo *et al.* (2007). They have shown that the [Mg/Fe] ratios in stars kinematically compatible with the inner and outer halo stars in Carollo *et al.* (2007) show a decreasing trend with [Fe/H] at $[\mathrm{Fe/H}] > -1.5$ on average. Ishigaki *et al.* (2013) further analyzed Fe-peak and neutron-capture elemental abundances and have found that [Eu/Fe] ratios are higher for the stars with low [Mg/Fe], mostly comprised of the outer halo stars, at $[\mathrm{Fe/H}] > -1.5$.

The high-resolution spectroscopic survey by the APOGEE project significantly increased the sample size, thus providing an updated view on the nature of the two chemically distinct components seen in the local halo stars. Based on elemental abundances of ∼3200 giant stars from the APOGEE data in the SDSS Data Release 12, Hawkins *et al.* (2015) identified the α-rich and the α-poor sequences of stars in the $[\alpha/\mathrm{Fe}]$-[Fe/H] plane at $-1.2 < [\mathrm{Fe/H}] < -0.55$. By analyzing chemical abundance trends with [Fe/H] for fourteen elements, including CNO, α, and Fe-peak elements, they also showed that the two sequences of stars are distinguished by the abundance ratios of O, Mg, S, Al, C+N. Furthermore, the two groups of stars show systematically different kinematics identified in the Galactic longitude (l) versus Galactic rest-frame radial velocity (GRV) space, suggesting different origins for the two groups. With the updated chemical abundance estimates for an expanded sample of ∼62, 000 stars from SDSS Data Release 13, Hayes *et al.* (2018) confirmed the presence of the high and low-Mg sequences similar to the previous findings. The studies of halo stars either with precision differential analysis (e.g., Nissen & Schuster 2010) or with a large statistical sample (e.g., Hayes *et al.* 2018), demonstrate that, with homogeneously measured various elemental abundances, the chemistry alone could be used to separate different stellar populations for moderately metal-poor halo stars ($-2 \lesssim [\mathrm{Fe/H}] \lesssim -0.5$). The APOGEE data, in particular, probe a much larger volume than previous high-resolution spectroscopic studies. Indeed, Fernández-Alvar *et al.* (2017) have analyzed chemical abundances of ∼400 stars in the range $5 < r < 30$ kpc and demonstrate that the stars at $r > 15$ kpc show different trends in elemental abundance ratios ([X/Fe]) at $[\mathrm{M/H}] > -1.1$. It has become clear that the chemical dichotomy seen in the solar neighborhood is part of a global structure, extending to at least up to several kpc from the Sun.

In summary, the key improvement in the last 20 years has been the recognition that the chemistry of field halo stars is not represented by a homogeneous α/Fe-enhancement over a wide [Fe/H] range but exhibits variation depending on local space motions and/or Galactocentric distances. Whether this chemical diversity corresponds to the global accretion events that are now suggested to make up a large fraction of the local halo

(Helmi *et al.* 2018; Belokurov *et al.* 2018) remains to be investigated in the next generation surveys. The origin and the fraction of the high-α halo component remain elusive. It has been found that the high-α halo stars are chemically indistinguishable from the thick disk stars (Hawkins *et al.* 2015). Further studies incorporating all the six dimensional phase space coordinates together with more detailed neutron capture elemental abundances are needed to put more constraints on the origin of high- and low-α stars and their connection to the thick disk population. Another remaining question is nucleosynthetic origin of the chemical difference between the high- and low-α populations. As has been pointed out by previous studies (e.g., Nissen & Schuster 1997; Fishlock *et al.* 2017), an additional contribution of elements from Type Ia supernovae to the gas initially enriched by core-collapse supernovae does not fully explain the observed chemical difference.

3. Chemistry of kinematically interesting stars

Along with the global structure, substructures in kinematic spaces have been identified in the solar neighborhood (Helmi *et al.* 1999; Chiba & Beers 2000; Arifyanto & Fuchs 2006; Dettbarn *et al.* 2007; Kepley *et al.* 2007; Klement *et al.* 2008; Klement *et al.* 2009; Smith *et al.* 2009; Smith 2016 and Liang *et al.* 2018 for recent reviews of this subject). These kinematically interesting halo stars, that are often referred to as “kinematic streams” are considered to have originated from accretion of dwarf galaxies or globular clusters to the Milky Way halo. Chemistry has provided the most stringent test to distinguish the origin of these streams.

One of the best known kinematic streams is the H99 stream, which was identified by kinematics mostly provided by the Hipparcos satellite (Helmi *et al.* 1999; Chiba & Beers 2000). Roederer *et al.* (2010) analyzed high-resolution spectra of 13 candidate member stars selected to have kinematics consistent with the H99 stream. It was shown that the candidate member stars have a wide range of [Fe/H], which rules out the possibility that the H99 is originated from a dissolved star cluster. Instead, the [X/Fe] ratios are nearly homogeneous and their scatter is found to be small. While the Galactic dwarf satellite galaxies that have metallicity similar to the H99 stream show evolution in [X/Fe] with [Fe/H], the abundance ratios of the H99 stars are nearly constant with [Fe/H] except for neutron capture elements. No signature of chemical enrichment by Type Ia supernovae or AGB stars are found. The observed abundance pattern do not stand out compared to the bulk of field halo stars that have similar [Fe/H].

Another well studied kinematic stream is KFR08, which was originally discovered by Klement *et al.* (2008) based on velocities from the RAVE survey. Follow up studies have confirmed the presence of this stream (Klement *et al.* 2009; Bobylev *et al.* 2010) based on independent data sets. The nature of the stream, however, remains elusive due to the uncertainties in distances and kinematics as well as the small number of candidate member stars (Klement *et al.* 2011). Liu *et al.* (2015) analyzed high-resolution spectra for 16 candidate member stars of the KFR08 stream and estimated detailed elemental abundances of 14 elements. They have found that the 16 stars have a scatter in [Fe/H] as large as 0.29 dex and therefore, it is unlikely they originated from the same star cluster. By quantifying similarity in chemical abundances among these stars by the method proposed by Mitschang *et al.* (2013), three of the 16 stars are found to show [X/Fe] ratios close each other. On the other hand, their vertical velocities (W) exhibit a large dispersion, which does not support the hypothesis that the three chemically similar stars were formed in the same star cluster. Instead, the observed elemental abundances as well as the estimated ages are similar to those seen in the thick disk stars. Liu *et al.* (2015) therefore conclude that the KFR08 stream is a kinematic stream that formed as a result of dynamical interactions among the Galactic disk stars.

Recently, Zhao *et al.* (2018) analyzed high-resolution spectra obtained by Subaru/HDS for six candidate member stars of another kinematic stream, LAMOST-L1, discovered by the LAMOST survey. They have found that the six stars show a large [Fe/H] dispersion and only small dispersion for [X/Fe]. The large [Fe/H] dispersion is not reproduced if the member stars were formed in a same star cluster. On average, the member stars of LAMOST-L1 show lower [α/Fe], [Na/Fe] and [Ni/Fe] ratios and higher [Ba/Y] ratio compared to the bulk of the field halo stars that share a similar [Fe/H] (Suda *et al.* 2008). The amount of the offset from the trend of field stars is similar to that found for low-α stars as reported by Nissen & Schuster (2010). The direction of the offsets in [X/Fe] from the field stars is similar to those reported for dwarf spheroidal galaxies, which might suggest that they were originally born in a dwarf galaxy that was accreted to the Milky Way in the past.

The origin of nearby field halo stars on highly retro-grade orbits has been debated for a while. It has been proposed that the stars are tidal debris of a galaxy which once hosted the ω-Centauri (ω Cen) globular cluster (e.g., Mizutani *et al.* 2003). Majewski *et al.* (2012) analyzed high-resolution ($R \sim 55,000$) spectra of giant stars within ∼5 kpc from the Sun which have been found to belong to a kinematic substructure with a highly retrograde orbit. It was found that the majority of these stars show enhanced [Ba/Fe] ratios compared to the field halo stars similar to those observed in ω Cen stars. This finding suggests that these retro-grade stars are likely tidal debris of ω Cen itself. With a large compilation of ∼800 literature abundance data in the SAGA database (Suda *et al.* 2008) cross matched with Gaia DR2, Matsuno *et al.* (2019) show that the highly retro-grade stars show a different trend in the [α-Fe]-[Fe/H] space from that seen among high-energy orbit stars. These retrograde stars show a [α/Fe]-[Fe/H] down turn, which is often called "knee", at [Fe/H] ∼0.5 dex lower than that corresponding to the high-energy orbit stars. Myeong *et al.* (2019) demonstrate that the sequence seen in the chemical abundance plane in Matsuno *et al.* (2019) is likely tidal debris of a dwarf galaxy, named "Sequoia" galaxy, which is suggested to be the second-largest galaxy which has contributed to the halo stars in the solar neighborhood.

These studies have clearly demonstrated that, when the identification with accurate kinematics are available, detailed chemical information provided by high-resolution spectroscopy is powerful in discriminating the origin of individual substructures. It is often the case, however, that the chemical differences from the bulk population are as small as typical observational uncertainties. Therefore, the interpretation is often limited by uncertainties in chemical abundance estimates, a small sample size and contamination of field halo stars. Homogeneously analyzed high-resolution spectra that will be made available with the ongoing Gaia-ESO survey (Gilmore *et al.* 2012), GALAH survey (De Silva *et al.* 2015) as well as WEAVE (Dalton *et al.* 2014) in the future will alleviate these difficulty.

4. Using chemistry to directly identify accreted stars

Stars that exhibit chemistry similar to those found in dwarf spheroidal galaxies currently orbiting the Milky Way have been known for a while, although they are relatively rare. The most remarkable classical example is the three stars, BD + 80°245 ([Fe/H] = −2.07), G 4-36 ([Fe/H] = −1.94), and CS 22966-043 ([Fe/H] = −1.91). Ivans *et al.* (2003) have carried out a detailed chemical abundance analysis and have found that they show extremely low α (Mg, Si, and Ca) -to-iron and [(Sr, Ba)/Fe] ratios with large variations in Fe-peak elements.

Thanks to the large spectroscopic surveys, candidate stars with extreme chemical patterns are more efficiently found. Xing *et al.* (2019) have analyzed one of the candidates of stars that have very low [α/Fe] ratios identified by the LAMOST survey. A follow-up spectroscopy with Subaru/HDS has confirmed that this star shows the [Mg/Fe] ratio of -0.4 at [Fe/H]$=-1.2$. Such a low [Mg/Fe] ratio is unusual for halo stars with comparable metallicity, while it is similar to stars in classical dwarf spheroidal galaxies such as Ursa Minor. On the other hand, the star shows a remarkable enhancement in r-process elements, with the abundance pattern comparable to the solar-system r-process pattern.

Sakari *et al.* (2019) reported a low-α and mildly r-process enhanced star, RAVE J093730.5-062655, originally identified in the RAVE survey. Sakari *et al.* (2019) made detailed comparison of the observed abundances with yield models of Type Ia supernovae to investigate whether the abundances are explained by contribution of Fe from Type Ia supernovae. Although the existing yield models of Type Ia supernovae do not exactly reproduce all the observed elemental abundances, this is more likely formed out of gas enriched with Fe from Type Ia supernovae. Its retro-grade orbit clearly suggests that this star has come from an accreted dwarf galaxy.

Both of the low-α stars of Sakari *et al.* (2019) and Xing *et al.* (2019) exhibit enhancement of r-process elements that are more frequently seen among much lower [Fe/H] stars. In fact there is a growing evidence that r-process enhanced stars are originated from dwarf galaxies (Roederer *et al.* 2018).

For the case of stars with metallicity lower than [Fe/H] ~ -3, that are collectively called extremely metal-poor (EMP) stars, the observed abundances are generally believed to be the result of only one or a few supernovae of the very first stars in the Universe (e.g., Audouze & Silk 1995).

A sign of stochastic chemical enrichment has been seen among EMP stars as a large scatter in observed elemental abundance ratios. The most remarkable feature is the presence of carbon enhanced stars that do not show enhancement in s-process elements (CEMP-no; Yong *et al.* 2013, Placco *et al.* 2014 but see Norris & Yong 2019 for the effect of 3D/NLTE effects on the Fe and C abundance measurements for EMP stars). Since the fraction of binary stars among the CEMP-no is not particularly high compared to normal EMP stars, it is unlikely their atmospheric composition was modified by a binary mass transfer and thus are thought to reflect the abundance of gas from which these stars formed. The origin of the CEMP-no stars has been debated for a while. The proposed scenarios include rotating massive first stars (Maeder *et al.* 2015), faint supernovae (Umeda & Nomoto 2003; Iwamoto *et al.* 2005), inhomogeneous metal-mixing (Hartwig & Yoshida 2019) or the result of the properties of dusts that were responsible for cooling the gas from which these stars have formed (Chiaki *et al.* 2017). As the detailed elemental abundances become available for EMP stars, it becomes clear that some fraction of CEMP-no stars also show enhancement of intermediate-mass elements, including Na, Mg, Al, or Si (Bonifacio *et al.* 2018; Aoki *et al.* 2018). The diversity in other elemental abundance seen in CEMP-no stars suggests that multiple mechanisms are required to fully explain the carbon enhancement (Yoon *et al.* 2016).

Recent large statistical sampling of EMP stars have identified stars that show significantly lower [α/Fe] ratios than the majority of halo stars with similar metallicities (Cohen *et al.* 2013; Caffau *et al.* 2013; Bonifacio *et al.* 2018). Unlike the low-α stars with [Fe/H] ~ -1 which are, at least in part, more likely related to the Type Ia enrichment, the origin of the EMP stars with sub solar [α/Fe] ratios remain largely unknown. Kobayashi *et al.* (2014) proposed that the stars have been enriched by supernovae of low-mass first stars. It has also been demonstrated by Hartwig *et al.* (2018) that some of the low-α stars in the sample of Bonifacio *et al.* (2018) are more likely to have been enriched by more than one supernova of the first stars.

These studies imply that the chemically peculiar EMP stars have formed in the environment dominated by stochastic chemical enrichment. Such characteristic patterns are frequently reported in ultra-faint dwarf galaxies currently orbiting around the Milky Way (e.g., Koch *et al.* 2008; Tolsty *et al.* 2009; Salvadori *et al.* 2015) and some of the classical dwarf galaxies (e.g. Venn *et al.* 2012).

5. Key questions for the future

The observations of chemistry of field halo stars have yielded various intriguing questions to be addressed in the next generation observing facilities. One of such questions would be how to quantify the relative contribution of substructures to the smooth halo component. Quantification of halo populations that have different birth places (e.g., in-situ, kicked-out, accreted) is the central issue to test the Galaxy formation model as has been addressed by Unavane *et al.* (1996). Detailed chemical information is essential to make further progress in this issue since phase-space coordinates can be largely washed out as the result of the dynamical evolution of the Galaxy. A drawback of the chemical analysis is that observations tend to be incomplete compared to the photometric sample and thus frequently suffer from selection bias. In this case it would be difficult to obtain a quantitative conclusion about the fraction of stars with given chemistry in the whole stellar halo population.

Cosmological simulations incorporating the chemical evolution in the building blocks of the Galaxy provide a powerful tool to quantify and interpret the emerging chemical observations (e.g., Font *et al.* 2006; Zolotov *et al.* 2010; Tissera *et al.* 2013). Techniques to compare observations with these theoretical predictions have been investigated by e.g., Schlaufman *et al.* (2012) and Lee *et al.* (2015). These studies provide a step forward to make full use of spectroscopic data from large surveys on-going and planed in the near future such as WEAVE (Dalton *et al.* 2014), 4MOST (de Jong *et al.* 2014), *Milky Way Mapper* survey planned as part of SDSS-V (Kollmeier *et al.* 2017), and the PFS (Takada *et al.* 2014).

For the theoretical side, some of the chemical signatures seen in field halo stars are likely connected to specific nucleosynthesis mechanisms in supernovae of the earliest generation of stars (e.g., Ezzeddine *et al.* 2019). Further investigations of theoretical yield models are crucial to better understand the stellar birth environment. In fact, it has been pointed out that the elemental abundances of the Sun are not fully explained by neither traditional nor modern core-collapse and Type Ia supernova yield models (Simionescu *et al.* 2019).

With increasingly large sample of high-resolution spectroscopic samples, it would be interesting to compare the elemental abundance patterns to grids of supernova yield models to obtain their statistical properties (Tominaga *et al.* 2014; Placco *et al.* 2015; Ishigaki *et al.* 2018). These studies have been used to investigate the possible origin of extremely metal-poor stars in terms of the physical properties of the very first generation of stars. It is still difficult to reproduce observed abundances of all the key elements by any given supernova yield models. This is partly due to the still unknown physical mechanism of stellar evolution and supernova nucleosynthesis.

6. Summary

Important observational results on the chemistry of field halo stars described in this article can be summarized as follows:

- The chemistry of nearby field halo stars with $[\mathrm{Fe/H}] \gtrsim -1.5$ consist of at least two populations that are distinguished in the trend in [X/Fe]-[Fe/H] plane for α-elements as well as several other elements. This is likely connected to the global structural components such as the dual halo structure and hints at the formation of the Milky Way with accretions of dwarf galaxies.

- Some of the kinematic streams show characteristic abundance patterns that have helped distinguishing their birth places (dwarf galaxies, star clusters or the Galactic disk).
- Chemically interesting field halo stars at $[\mathrm{Fe/H}] \gtrsim -3$ show characteristic chemical signature of an accreted dwarf galaxy which is likely, at least in part, connected to additional Fe enrichment by Type Ia supernovae. Among the lower [Fe/H] stars, scatter in elemental abundance ratios are prominent, particularly for light-to-intermediate mass elements, C, Mg, or Si, which could be a signature of the stochastic chemical enrichment in the early Universe as well as the properties of the earliest generation of stars in the Universe.

These observations have lead to a transition of our understanding of the nearby halo stars from a traditional picture of a predominantly α-enhanced stellar population down to $[\mathrm{Fe/H}] \sim -1$, that is distinct from currently surviving dwarf satellite galaxies, to a new picture of highly complex stellar populations in both kinematics and chemistry. At the same time, these findings provide intriguing questions to be answered in future observational and theoretical efforts.

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