Chemical and Kinematic Analysis of CN-strong Metal-poor Field Stars in LAMOST DR3

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Abstract

The large amount of chemical and kinematic information available in large spectroscopic surveys has inspired the search for chemically peculiar stars in the field. Though these metal-poor field stars ([Fe/H] < −1) are commonly enriched in nitrogen, their detailed spatial, kinematic, and chemical distributions suggest that various groups may exist, and thus their origin is still a mystery. To study these stars statistically, we increase the sample size by identifying new CN-strong stars with LAMOST DR3 for the first time. We use CN–CH bands around 4000 Å to find CN-strong stars, and further separate them into CH-normal stars (44) and CH-strong (or CH) stars (35). The chemical abundances from our data-driven software and APOGEE DR14 suggest that most CH-normal stars are N-rich, and this cannot be explained by an internal mixing process alone. The kinematics of our CH-normal stars indicate that a substantial fraction of these stars are retrograding, pointing to an extragalactic origin. The chemistry and kinematics of CH-normal stars imply that they may be stars dissolved from globular clusters, or accreted halo stars, or both.

Key words: stars: abundances – stars: chemically peculiar – stars: evolution – stars: kinematics and dynamics

1. Introduction

In recent years, large Galactic surveys with multi-object spectrographs have greatly improved our knowledge about the chemical and kinematic properties of the Milky Way. The Sloan Digital Sky Survey (SDSS) is a pioneer and active actor in this field. Beginning with SDSS-II/SEGUE (Yanny et al. 2009) and SDSS-III/SEGUE-2, SDSS observed stars in our Milky Way with low-resolution optical spectra (λ = 3850–9200 Å, R ∼ 2000). Later, the need for higher spectral resolution and the capability to see through the dusty part of our Galaxy inspired the Apache Point Observatory Galactic Evolution Experiment (APOGEE, Majewski et al. 2017) during SDSS-III (Eisenstein et al. 2011). The multi-object near-IR fiber spectrograph on the 2.5 m telescope at Apache Point Observatory (Gunn et al. 2006) delivers high-resolution (R ∼ 22,500) H-band spectra (λ = 1.51–1.69 μm). The APOGEE program was extended in SDSS-IV as APOGEE-2, which includes observations from both the Northern Hemisphere (Apache Point observatory) and the Southern Hemisphere (Las Campanas Observatory).

Searching for stars with peculiar chemistry in the field has recently become tractable, owing to the huge number of spectra/chemical abundances available in spectroscopic surveys. Martell & Grebel (2010) and Martell et al. (2011) (hereafter, M11 for these two papers) used CN and CH molecular bands to search for CN-strong stars in SDSS-II/SEGUE and SDSS-III/SEGUE-2. They suggested that these CN-strong stars come from globular clusters (GCs), and that a minimum of 17% of the present-day mass of the stellar halo was originally formed in GCs. Later, Carollo et al. (2013) showed that these CN-strong field stars and the majority of GCs exhibit kinematics and orbital properties similar to the inner-halo population. In fact, most of the scenarios (e.g., Decressin et al. 2007; de Mink et al. 2009; Ventura et al. 2011, 2013; Denissenkov & Hartwick 2014) that aim to explain multiple populations in GCs (e.g., Mézéras et al. 2015; Schiavon et al. 2017a; Tang et al. 2017, 2018; Fernández-Trincado et al. 2018) imply a significant mass loss before the enriched stellar generation is formed (Bastian et al. 2013; Renzini et al. 2015). Even if these multiple-population GC scenarios are not considered, the tidal force exerted by our Galaxy causes GCs to continuously lose stars, and some GCs may be disrupted and form observable stellar streams (e.g., Ibata et al. 2018; Malhan et al. 2018). In that sense, it is reasonable to expect to uncover stars now in the field that resemble so-called second generation (SG) stars with enhanced N and Na and depleted C, which presumably are only formed in the dense environments of GCs but then can escape and become field stars.

Schiavon et al. (2017b, hereafter S17) found a large group of N-rich stars in the inner Galaxy with N, C, and Al abundances that are typically found in GC SG stars using APOGEE data. They argued that these stars imply the absence of a mandatory genetic link between SG stars and GCs. Alternatively, these N-rich stars could be the by-products of chemical enrichment by the first stellar generations. Fernández-Trincado et al. (2016, 2017a) further discovered a group of stars with not only high N and Al abundances, but also depleted Mg abundances.
These authors separated their sample into two: a metal-rich sample \((\text{[Fe/H]} \gtrsim -1.0)\) and a metal-poor sample \((\text{[Fe/H]} < -1.0)\). The stars in the metal-poor sample may find their chemical counterparts in SG Galactic GC stars, but this is not so for the metal-rich sample. It was speculated that stars in the metal-rich sample may (1) migrate from nearby dwarf galaxies, and at the same time become contaminated by asymptotic giant branch (AGB) companion stars, or (2) come from dissolved extragalactic GCs.

While astronomers found an increasing number of N-rich stars using SDSS data, the LAMOST Galactic spectroscopic survey (Deng et al. 2012; Zhao et al. 2012) has not been explored in this regard. The LAMOST Galactic spectroscopic survey observes stars with low-resolution \((R \sim 1800)\) optical \((\lambda = 3700-9000 \text{ Å})\) spectra. Its ability to reach fainter objects and its large sample size make the LAMOST survey appropriate for studies of Galactic halo stars (e.g., Liu et al. 2017). The LAMOST Stellar Parameter pipeline (LASP, Wu et al. 2011; Luo et al. 2015) is able to determine radial velocity (RV), \(T_{\text{eff}}\), \(\log g\), and \([\text{Fe/H}]\). Luo et al. (2015) compared RVs and stellar parameters for stars in common between LAMOST DR1 and APOGEE. The typical uncertainties for these parameters derived from LAMOST data are 4 km s\(^{-1}\) for RV, 100 K for \(T_{\text{eff}}\), 0.25 dex for \(\log g\), and 0.1 dex for \([\text{Fe/H}]\). The LAMOST data release is now in its fifth phase (DR5), and mid-resolution spectral observations \((R \sim 7500)\) have been made recently. Here we use the public data release, DR5, which includes the data taken between 2011 October and 2015 May. DR3 was updated in 2017 June with a few minor corrections. More specifically, we use the A, F, G, and K type star catalog in our study, where more than 3 million stars are included.

In this work, we focus on the CN-strong metal-poor field stars from the LAMOST DR3 (Section 2). These CN-strong stars are further separated into CH-strong and CH-normal stars, because they show different properties. We examine these stars carefully using the chemical abundances derived by the APOGEE team and our data-driven software (Section 3). In Sections 4 and 5, the origins of CH-normal stars are discussed using their spatial distribution and orbital configuration. We further discuss the origins of these CH-normal stars using additional observational evidence as well as in Section 6. A brief summary is given in Section 7.

2. Sample Selection and Data Reduction

Given that we are interested in CN-strong metal-poor field stars, we first select metal-poor field stars from the A, F, G, and K type star catalog of LAMOST DR3, following these criteria:

1. \(4000 \text{ K} < T_{\text{eff}} < 5500 \text{ K}\)
2. \(\log g < 3.0\)
3. \(-1.8 < [\text{Fe/H}] < -1.0\)
4. \(S/\text{N}_{\text{H}} > 5.0\)

The last one indicates that the signal-to-noise ratio \((S/N)\) in the \(u\) band is greater than 5.0, which ensures that we have at least mid-quality spectra around 4000 Å for spectral analysis. The metallicity range is similar to that of M11. The stellar parameters and \(S/\text{N}_{\text{H}}\) are provided as part of LAMOST DR3. We further confirm that these stars are not members of known GCs by implementing the GC selection method described in Tang et al. (2017). Moreover, since the stars that we select are metal-poor \(([\text{Fe/H}] < -1.0)\), we do not expect them to be members of open clusters either. When correcting for RV in the spectra, we also consider the systematic RV shifts \((\sim 5 \text{ km s}^{-1})\) reported for the LAMOST spectra (Schönrich & Aumer 2017). Next, we measure the spectral indices of our sample stars. Here we use the definition of CN3839, CN4142, and CH4300 indices from Harbeck et al. (2003) and HK’ from Lim et al. (2015). To estimate the error in index measurement, we use the Monte Carlo (MC) simulation, where flux-associated error is used as the standard deviation of the random error in the MC approach. The final spectral index error is the quadratic sum of error caused by flux uncertainty and error caused by RV uncertainty.

Since the spectral indices that we use here are closely related to \(T_{\text{eff}}\), we plot them as a function of \(T_{\text{eff}}\) in Figure 1. To find the N-rich halo stars, we calculate the means and standard deviations (std for short) for CN3839 and CN4142 indices, in steps of 100 K, and fit the mean and mean \(+ 2.0 \times \text{std}\) as functions of \(T_{\text{eff}}\) with sixth-order polynomials (red and green solid lines, respectively, in Figure 1). We select stars above the green solid line for both CN3829 and CN4142 indices as our final sample of CN-strong stars. Seventy-nine stars are selected. We use both CN indices here to exclude stars whose spectra may be influenced by strange emission lines or other unwanted features around the CN bands. We also examine all 79 stars one-by-one to make sure that the absorption bands are reliable. For example, Figure 2 compares one CN-strong star (top panel) with one normal metal-poor field star (bottom panel). These two stars are chosen with similar stellar parameters to minimize the effects of different stellar parameters on the spectra. The stark difference between these two stars near the feature wavelengths of CN3839 and CN4142 confirms that our classification is based on real spectral signals.

Among these CN-strong stars, there are CH-strong and CH-normal stars. We determine the mean and std for CH4300, in steps of 100 K, and fit the mean and mean \(+ 1.0 \times \text{std}\) with sixth-order polynomials (red solid line and green dashed line, respectively, in Figure 1). We indicate the CH-strong stars with red dots, and the CH-normal stars with black dots. Later in this work, we show that these two groups of stars have other distinct properties. We note that distinguishing CH-normal stars from CH-strong stars has been done in other similar studies. For example, M11 excluded stars with a strong CH feature around 4350 Å and a strong C\(_2\) band at 4737 Å; S17 and Fernández-Trincado et al. (2017b) excluded stars with [C/Fe] > +0.15 dex. Next, we define \(\delta\)CH4300 as the CH4300 index value minus the mean polynomial fit value at \(T_{\text{eff}}\) of a given star. A similar definition is also applied to CN3839 and HK’. We use CN3839 in this work, because CN3839 is suggested to show higher sensitivity and smaller error than CN4142 (Harbeck et al. 2003; Pancino et al. 2010).

We notice that CH-strong stars tend to have lower \(\delta\)HK’ (Figure 3). These CH-strong stars occupy a different location in the \(\delta\)HK’–\(\delta\)CH4300 parameter space to the bulk of metal-poor field stars, while the CH-normal stars follow the trend defined by most of the metal-poor field stars. The HK’ index is carefully discussed in Lim et al. (2015), where they showed that this index measures only calcium lines, and the contamination from the CN band is minimized. Therefore, we do not expect \(\delta\)HK’ bias toward any of these three kinds of 12 \(\log g\) and metallicity also have minor effects. The effect of \(\log g\) is weakened when only giants are concerned.

13 Unless noted otherwise, we will refer to CN-strong CH-strong stars as CH-strong stars, and CN-strong CH-normal stars as CH-normal stars in this paper.
Furthermore, Li et al. (2018) recently identified 2651 carbon stars from more than 7 million spectra in LAMOST DR4. We match their results with our sample of CN-strong stars, and find five stars in common (green squares in Figure 4). Three are labeled as CH stars, while the other two are labeled as barium stars in their work. These five carbon stars are all CH-strong stars according to our definition. Therefore, we consider our method for distinguishing CH-strong stars from CH-normal stars to be efficient. CH-strong stars are different species of stars to CH-normal stars and most metal-poor field stars.

3. Careful Examination of the CN-strong Metal-poor Field Stars

3.1. Stellar Parameters

Metallicity plays an important role in determining the properties of a star. Do CH-strong and CH-normal stars have different metallicity distributions? The left panel of Figure 5 suggests that the two kinds of star do not show obviously different metallicity distributions. Next, we examine the $T_{\text{eff}}$–$\log g$ diagram (the middle panel of Figure 5). Our CN-strong stars have $T_{\text{eff}}$ and $\log g$ consistent with those of other red giants. Note that our CN-strong stars have a median $S/N$ of 120 in the $r$-band, where the uncertainties in determination of $\log g$ can be reduced to better than $\sim 0.1$ dex (Xiang et al. 2017). Finally, we examine their distributions in $\log g$. We notice that stars with lower $\log g$ tend to have slightly higher $\delta$CH4300, though the correlation between them is weak—a Spearman rank correlation coefficient of $-0.26$.

3.2. Chemical Abundances from APOGEE Pipeline and LAMOST Data-driven Software

The high-resolution spectroscopic survey APOGEE can provide 20–30 elemental abundances (Holtzman et al. 2015), which may improve our understanding of the CN-strong field stars. After we match our CN-strong field stars with the APOGEE DR14 database, we find eight stars in common (Table 1). Next, we take a closer look at the chemical abundances of these common stars given by the APOGEE Stellar Parameter and Chemical Abundances Pipeline (ASPCAP; García Pérez et al. 2016). Most of the stars have high $S/N$ APOGEE spectra ($S/N > 90$), except Star 4, partially because its $T_{\text{eff}}$ is greater than 5000 K. After visually inspecting the APOGEE spectra, we find that most of the CO, OH, and CN lines are detectable, and the ASPCAP best fits are reasonable. The exception is again found to be Star 4, where CNO
measurements are no longer reliable for stars hotter than 5000 K (Souto et al. 2016). We also visually examine the Mg and Al lines in these eight common stars; the ASPCAP fits looks reasonable. Therefore, we use the $\left[ \text{C}/\text{Fe} \right]_A$, $\left[ \text{N}/\text{Fe} \right]_A$, $\left[ \text{O}/\text{Fe} \right]_A$, $\left[ \text{Mg}/\text{Fe} \right]_A$, and $\left[ \text{Al}/\text{Fe} \right]_A$ from ASPCAP to study these common stars, without performing manual analysis. To define a control sample that represents the normal metal-poor field stars, we select stars that satisfy:

1. $-0.05 < \delta \text{CN3839} < 0.05$,
2. $-0.05 < \delta \text{CH4300} < 0.05$ (the red box in Figure 3), and
3. $T_{\text{eff}} < 5000$ K.

In total, 1314 stars are selected. We match this sample with APOGEE DR14, and find 115 stars in common.

Because we are using the ASPCAP results of these 115 stars without examining the details of each spectrum, we mainly use their statistical mean and standard deviation values.

Figure 6 shows a positive correlation between $\delta \text{CH4300}$ and $[\text{C}/\text{Fe}]_A$\textsuperscript{14}, but the correlation between $\delta \text{CN3839}$ and $[\text{N}/\text{Fe}]_A$ is more complicated. This means that $\delta \text{CH4300}$ is a good indicator of the C abundance, but $\delta \text{CN3839}$ depends on both C and N abundances. For the CH-normal stars, the N abundances are the highest of all (Star 1 and Star 7).

We will first compare CH-normal stars with normal metal-poor field stars, and turn to CH-strong stars toward the end of this section. The left panel of Figure 7 shows interesting physics in the N–C parameter space. Our normal metal-poor field stars, which are mostly giants, show an anticorrelation between $[\text{N}/\text{Fe}]_A$ and $[\text{C}/\text{Fe}]_A$. It is likely that these stars are going through extra mixing along the red giant branch (RGB) (Gratton et al. 2000), and thus N increases as C decreases. This anticorrelation is further discussed later with abundances derived from another approach. The normal metal-poor field stars and CH-normal stars show comparable C abundances, but CH-normal stars show much higher N abundances, which is similar to what is found in GC SG stars (Mészáros et al. 2015; Tang et al. 2017). We check the Na lines in the APOGEE spectra, but they are too weak for reliable analysis. Thus we lose the chance to use the classical Na–O diagnostic diagram to identify their GC origin.

Looking at $[\text{O}/\text{Fe}]_A$ (middle panel of Figure 7), CH-normal stars and normal metal-poor field stars have similar O abundances. On the other hand, CH-normal stars and normal metal-poor field stars generally show Mg enhancement ($[\text{Mg}/\text{Fe}]_A \sim 0.30$), consistent with the $\alpha$-enhancement seen in thick-disk or halo stars. Interestingly, CH-normal stars tend to show higher than average

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\textsuperscript{14} Subscript “A” denotes “ASPCAP.”
indicated by blue circles. Stars in common with Li et al. measurement uncertainties. Stars in common with APOGEE DR14 are shown as red and black symbols, respectively, where the error bars indicate the by green squares.

Figure 3. $\delta$CN3839 and $\delta$HK vs. $\delta$CH4300. The CH-strong and CH-normal stars are shown as red and black symbols, respectively, where the error bars indicate the measurement uncertainties. The metal-poor field stars are shown as small blue dots. A sample of normal metal-poor field stars are selected based on their $\delta$CH4300 and $\delta$CN3839 indices detailed by the red box.

Figure 4. $\delta$CN3839 vs. $\delta$CH4300. The CH-strong and CH-normal stars are shown as red and black symbols, respectively, where the error bars indicate the measurement uncertainties. Stars in common with APOGEE DR14 are indicated by blue circles. Stars in common with Li et al. (2018) are marked by green squares.

[Al/Fe]$_{\text{A}}$ compared to normal metal-poor field stars. Compared with Figure 1(a) of Fernández-Trincado et al. (2017b), our two CH-normal stars show neither depleted Mg nor high Al abundances like the stars in Fernández-Trincado et al. (2017b), but they do show similar Mg and Al abundances to the N-rich stars of S17. We will further discuss this in Section 6. To summarize, the [C/Fe], [N/Fe], [O/Fe], [Mg/Fe], and [Al/Fe] abundances from APOGEE support the idea that CH-normal stars are chemically peculiar compared to normal metal-poor field stars. We realize that our common sample size for CH-normal stars is small. High-resolution spectroscopic data (e.g., APOGEE) are necessary to increase our common sample size. Furthermore, optical high-resolution data are also necessary to derive abundances of Na and s-process elements, which are helpful in constraining their nature, e.g., SG origin or extragalactic origin.

Recently, data-driven software (e.g., The Cannon) has been applied to large data sets to derive chemical abundances (Ness et al. 2015; Ho et al. 2017; Ting et al. 2017). Another data-driven algorithm of stellar parameterization is SLAM (B. Zhang et al. 2018, in preparation). Similar to The Cannon, SLAM provides a forward model to produce a model spectrum from a set of given stellar parameters and then finds the best-fit stellar parameters for the observed spectrum in terms of chi-squared. Unlike The Cannon, SLAM applies a machine learning algorithm, rather than a polynomial, to set up the forward model, i.e., it produces the flux at each wavelength as a function of effective temperature, surface gravity, metallicity, $\alpha$-abundance etc. The advantage of a machine learning-based forward model is that it can handle well the situation of highly nonlinear data. As a consequence, SLAM is able to predict stellar parameters not only for late-type giant stars, but also for stars with a large range of effective temperature. In the current version of SLAM, which estimates stellar parameters of the K giant stars used in this work, a support vector regression algorithm is applied for the forward model. Meanwhile, SLAM uses about 9000 K giant stars common to LAMOST DR3 and APOGEE DR13 as the training data set with the spectra from LAMOST and the stellar parameters from APOGEE DR13. The precision of estimating stellar parameter from SLAM reaches $\sigma(T_{\text{eff}}) \sim 50$ K, $\sigma(\log g) \sim 0.13$ dex, $\sigma([\text{M/H}]) \sim 0.04$ dex, $\sigma([\alpha/\text{M}]) \sim 0.04$ dex, $\sigma([\text{C/Fe}]) \sim 0.09$ dex, and $\sigma([\text{N/Fe}]) \sim 0.1$ dex at $S/N \sim 40$. At $S/N \sim 100$, the precision increases to $\sigma(T_{\text{eff}}) \sim 40$ K, $\sigma(\log g) \sim 0.10$ dex, $\sigma([\text{M/H}]) \sim 0.03$ dex, $\sigma([\alpha/\text{M}]) \sim 0.03$ dex, $\sigma([\text{C/Fe}]) \sim 0.06$ dex, and $\sigma([\text{N/Fe}]) \sim 0.07$ dex.

We derived stellar parameters, [C/M], and [N/M] using SLAM. To avoid bad fits at the edges of the parameter space, we exclude stars with spectral S/N in the g band less than 50, and metallicity less than −1.4. The derived C and N
abundances are shown in Figure 8. Clearly, in the top panel, the CH-strong, CH-normal, and metal-poor field stars are separated, and their relative distribution in the N–C parameter space is similar to the case of APOGEE abundances (left panel of Figure 7): (1) metal-poor field stars form a sequence in the lower left of the top panel. As evolved stars ascend the RGB, C and N abundances may be changed by first dredge-up (Iben 1964, 1967) and extra mixing (Gratton et al. 2000; Charbonnel & Lagarde 2010). Given that for a typical halo/thick-disk star of 1 M$_\odot$, the first dredge-up occurs around $T_{\text{eff}} = 5200$ K (Boothroyd & Sackmann 1999), and most of our sample stars have $T_{\text{eff}} < 5000$ K and log $g < 2.5$, we infer that most stars have already undergone first dredge-up. On the other hand, the C and N abundances of these stars could be altered by extra mixing. Stars with brighter K-band absolute magnitudes tend to have higher [N/Fe] and lower [C/Fe] (middle and bottom panels of Figure 8), which is consistent with extra-mixing theory and observation (Gratton et al. 2000; Charbonnel & Lagarde 2010); (2) CH-normal stars show an enhanced median N abundance and slightly depleted median C abundance. Clearly, the median N abundance of CH-normal stars is enhanced compared to that of normal metal-poor field stars with similar C abundances. In other words, the enhanced N abundances in CH-normal stars cannot be explained by the extra-mixing effect alone. We notice that a few CH-normal stars may have low N abundances, probably due to large uncertainties when spectra of a particular type are scarce in the training set, i.e., high-N metal-poor stars. The statistical similarity between APOGEE C and N abundances and LAMOST-derived C and N abundances further strengthens our statement above.

Next, we take a look at chemical abundances of the CH-strong stars. We already know that these star have smaller $\delta$HK' than CH-normal and halo field stars. Figures 7 and 8 suggest that CH-strong stars show higher C, N, Mg, and Al abundances than normal metal-poor field stars. The chemistry of CH-strong stars supports the claim that they have a different origin than CH-normal stars.

During post-main-sequence phases of stellar evolution, carbon and nitrogen abundances may be changed by extra mixing, where the N abundance increases and the C abundance decreases. However, as shown earlier (Section 3), the

![Figure 5. Relations between $\delta$CH4300 and stellar parameters. Symbols have similar meanings as in Figure 1.](image-url)

| #  | APOGEE_ID       | $T_{\text{eff}}$ (K) | [C/Fe]   | [N/Fe]   | [O/Fe]   | [Mg/Fe]  | [Al/Fe]  | [Si/Fe]  | [Ca/Fe]  | Note       |
|----|-----------------|----------------------|----------|----------|----------|----------|----------|----------|----------|------------|
| 1  | 2M13233152+4931144 | 4847.0               | -0.28    | 0.78     | 0.10     | 0.15     | 0.10     | 0.17     | 0.12     | CH-normal  |
| 2  | 2M15590393+4139542 | 4399.2               | 0.50     | 0.28     | 0.38     | 0.33     | 0.04     | 0.40     | 0.26     | CH-strong  |
| 3  | 2M07330841+3837042 | 4254.3               | 0.51     | 0.34     | 0.37     | 0.36     | 0.13     | 0.33     | 0.25     | CH-normal  |
| 4  | 2M11394345+2708552 | 5193.4               | 0.78     | 0.71     | -0.14    | 0.28     | -0.30    | 0.38     | 0.20     | CH-strong; too hot |
| 5  | 2M15113274+3059083 | 4716.8               | 0.55     | 0.41     | 0.37     | 0.31     | 0.19     | 0.31     | 0.26     | CH-normal  |
| 6  | 2M13413240-0116003 | 4344.9               | 0.20     | 0.46     | 0.33     | 0.29     | 0.09     | 0.39     | 0.19     | CH-normal  |
| 7  | 2M12561260+2804017 | 4858.3               | -0.14    | 0.85     | 0.26     | 0.28     | 0.06     | 0.36     | 0.23     | CH-normal  |
| 8  | 2M19263774+4434325 | 4253.1               | 0.09     | 0.71     | 0.25     | 0.21     | -0.33    | 0.28     | 0.20     | CH-strong  |
CH-strong and CH-normal stars do not fall into the parameter space defined by normal metal-poor RGB stars undergoing extra mixing. Later, the C abundance may be changed during the AGB phase through third dredge-up, when a large amount of carbon is brought to the surface. However, AGB stars start to dredge-up carbon when they have $T_{\text{eff}} < 4000$ K and $\log g < 0$, which is not applicable to our sample stars.

How should we understand these carbon-enhanced stars? We should not label them as carbon-enhanced metal-poor (CEMP) stars, since CEMP stars have an upper limit of $[\text{Fe}/\text{H}] < -1.8$ as described by Lucatello et al. (2005). At $[\text{Fe}/\text{H}] > -1.8$ and $\log g < 3.0$, carbon-enhanced stars are mostly classical CH stars. The discovery of CH stars can be traced back to the work of Keenan (1942). Our definition of CH-strong stars in fact matches the original definition of CH stars. Therefore, we will also refer to our CH-strong stars as CH stars in the following paragraph and in future work. It has been clearly established that CH stars have a binary origin (McClure 1984; McClure & Woodsworth 1990). The peculiar abundance patterns seen in CH stars, combined with the high binary fraction indicate the accretion of material from an intermediate-mass AGB companion, either through Roche lobe overflow or through efficient stellar winds (Han et al. 1995).

4. Spatial Distribution of CH-normal Stars

Since CH stars may be related to different astrophysical process than CH-normal stars, and to avoid confusion in distinguishing two kinds of stars when calculating distances and orbits, we study the kinematics of only CH-normal stars. To visualize the spatial distribution of our CH-normal stars, we estimate stellar distances using three methods: (1) Bayesian
spectrophotometric distances with no assumptions about the underlying populations (Carlin et al. 2015), hereafter dist1; (2) Bayesian spectrophotometric distances with flexible Galactic stellar-population priors (Queiroz et al. 2018), hereafter dist2; (3) Bayesian Gaia DR2 parallax-based distances (Bailer-Jones et al. 2018), hereafter dist3. The basic idea of deriving a Bayesian spectrophotometric distance for a star is to first estimate stellar absolute magnitude in one band from fitting its stellar parameters ($T_{\text{eff}}, \log g,$ and $[\text{Fe/H}]$) to a given isochrone; then, the distance is given by the distance modulus: $m - M$, where $m$ and $M$ are apparent and absolute magnitudes, respectively. However, detailed treatments can be different between methods. For example, dist1 assumes no prior about the underlying populations, either due to predictions of the luminosity function from modeling of stellar evolution, or from Galactic models of stellar populations along each line of sight, while dist2 assumes flexible Galactic stellar-population priors. Figure 9 shows that the dist2 method predicts the most extended distance distribution, e.g., the maximum distance of our CH-normal stars is up to about 19 kpc; while the dist3 method predicts the most compact distance distribution, e.g., the maximum distance is less than 7.5 kpc; dist1 distances are between these two. Because dist3 is based on parallax from Gaia DR2, the uncertainties increase significantly for stars beyond $\sim 5$ kpc. The parallax-based distances of stars further than that are expected to be dominated by the prior assumed in Bailer-Jones et al. (2018).

Using the stars’ distances derived by the three different methods, we further calculate their positions in the meridional Galactic coordinate. The results are shown in Figure 10. The spatial distributions using distances from different methods are generally similar for stars within 5 kpc from the Sun, but the differences increase significantly when stars are located further...
away from the Sun. This is exactly what we expect from the distance distribution (Figure 9). To put our CH-normal stars into the context of our Galaxy, we assume the scale heights of the thin disk, thick disk, and halo to be 0.3 kpc, 1 kpc, and 2.5 kpc, respectively (Sparke & Gallagher 2007). Figure 10 indicates that no star belongs to the thin disk. Only a few stars have Galactic $Z$ comparable to the scale height of the thick disk. Most of the stars have Galactic $Z$ comparable to the scale height of the halo. In other words, our CH-normal stars are mostly halo stars. Note that our CH-normal stars are asymmetric in the $Z$-direction, because most of the LAMOST targets are located in the northern Galactic hemisphere.

5. Tracking Orbits of CH-normal Stars

In this work, we simulate the orbits of our CH-normal stars using a state-of-the-art orbital integration model in a (as far as possible) realistic Galactic gravitational potential. To do this, we employ the novel dynamical model called GravPot16 (J. G. Fernández-Trincado et al. 2018, in preparation), which has been adopted in a score of papers (Fernández-Trincado et al. 2016; Schiappacasse-Ulloa et al. 2018; Tang et al. 2018). The Galactic model of GravPot16 is briefly summarized in the Appendix of Tang et al. (2018). A long list of studies in the literature has presented different ranges for the bar pattern speeds (Monari et al. 2017a, 2017b; Portail et al. 2017). For our computations, we assume four pattern speeds, $\Omega_B = 35, 40, 45, 50$ km s$^{-1}$ kpc$^{-1}$. To obtain robust estimates of the orbits of our CH-normal stars, we employ recent high-quality data as input parameters for GravPot16. We use the RVs and absolute proper motions from the latest Gaia DR2 (Gaia Collaboration et al. 2018; Katz et al. 2018). The typical uncertainty of RVs of our CH-normal stars is 0.8 km s$^{-1}$, while the typical uncertainty of absolute proper motions is 0.05 mas yr$^{-1}$. Besides, we assume distances derived from three different methods as we mention above (dist1, dist2, and dist3).

After combining our Milky Way potential model with measurements of RV, absolute proper motion, distance, and sky position for the CH-normal stars, we run $N_{\text{total}} = 10^4$ orbit simulations for each of the CH-normal stars, taking into account the uncertainties in the input data considering $1\sigma$ variations in a Gaussian MC approach. For each generated set of parameters, the orbit is computed backward in time, up to 2.5 Gyr. The major assumptions and limitations in our computations are also discussed in Tang et al. (2018) and Schiappacasse-Ulloa et al. (2018). From the integrated set of orbits, we compute (1) $r_{\text{peri}}$, the perigalactic radius, (2) $r_{\text{apo}}$, the apogalactic radius, (3) the orbital eccentricity, defined as $e = (r_{\text{apo}} - r_{\text{peri}})/(r_{\text{apo}} + r_{\text{peri}})$, (4) the maximum vertical amplitude $Z_{\text{max}}$.

Figures 11 and 12 show $r_{\text{peri}}$, $r_{\text{apo}}$, $e$, and $Z_{\text{max}}$ of our sample stars. Each error bar indicates the mean of a given parameter for each star among the $10^4$ MC orbit realizations with uncertainty range given by the 16th and 84th percentile values. Each column of panels assumes the same pattern speed (from left to right: 35, 40, 45, and 50 km s$^{-1}$ kpc$^{-1}$), while each row of panels uses the distances derived from the same method (from top to bottom: dist1, dist2, and dist3, or LA, SH, and BJ for short). The medians over mean $e$ and mean $Z_{\text{max}}$ of our sample stars are shown on the top and left of each panel, respectively.
We find that (1) pattern speed has negligible impact on the four parameters that we investigate; (2) distance has negligible impact on $e$, and a small impact on $r_{peri}$; (3) distance has a substantial impact on $r_{apo}$ and $Z_{max}$. For example, $Z_{max}$ derived using dist2 (median $\sim 7.2$ kpc) are systematically greater than those of dist1 (median $\sim 4.9$ kpc) and dist3 (mean $\sim 4.7$ kpc). This is consistent with their distance distributions (Figure 9). Independent of which distance is assumed, most of our CH-normal stars lie on highly eccentric ($e \sim 0.8$) orbits with large $r_{apo}$ and $Z_{max}$, which is consistent with halo star kinematics.

We further employ the Toomre diagram to identify the origin of our CH-normal stars. Figure 13 shows that Galactic velocity distributions of stars depend strongly on the adopted stellar distances. In general, a few stars belong to the Galactic thick/thin disks, but most stars belong to the Galactic halo. This is similar to the conclusion that we draw from the spatial distribution in the meridional Galactic coordinate (Section 4).

We also find that a substantial fraction of stars lie in retrograde orbits—dist2 indicates more stars in retrograde orbits and a more extended distribution of $V$, while there are fewer retrograde orbiting stars in the case of dist3. Accordingly, dist1, dist2, and dist3 indicate 33%, 67%, and 25% of stars lying in retrograde orbits, respectively. The reader is reminded that dist3 is based on parallax of Gaia DR2, which is less certain for stars further than 5 kpc from our Sun.

Figure 12. Mean $r_{peri}$ vs. mean $r_{apo}$ (perigalactic and apogalactic radii) of 10^4 MC simulated orbits for our CH-normal stars. The 16th and 84th percentile values of each star are indicated by error bars. Each column of panels assumes the same pattern speed (from left to right: 35, 40, 45, and 50 km s^{-1} kpc^{-1}), while each row of panels uses the distances derived from the same method (from top to bottom: dist1, dist2, and dist3, or LA, SH, and BJ for short). The medians over mean $r_{peri}$ and mean $r_{apo}$ of our sample stars are shown on the top and right of each panel, respectively.

Figure 13. Toomre diagram. The thin-disk region is indicated by a constant velocity of 70 km s^{-1} (black dotted–dashed curve), and the thick-disk region is indicated by a constant velocity of 180 km s^{-1} (blue dashed curve). A constant Galactic rest frame velocity of 533 km s^{-1} is shown by the green curve. Finally, $V = -239$ km s^{-1} is used to distinguish prograde and retrograde orbits (red dotted line).

6. Discussion

6.1. Comparison with Literature

As we mentioned in Section 1, several literature studies have searched for N-rich stars or chemically peculiar stars. After matching our CN-strong stars with the sample of M11, we found no stars in common. Because Martell et al. (2016) and
Fernández-Trincado et al. (2016, 2017b) used APOGEE data, their stars should be available in APOGEE DR14. However, the eight CN-strong stars that we identified common to both LAMOST and APOGEE are not found in the aforementioned studies. S17 targeted stars in the inner Galaxy with $-20^\circ < l < 20^\circ$, $|b| < 16^\circ$. This part of the sky is not included in our work, and thus no common star is found. We further confirm that there is no overlap between our sample and the chemically peculiar stars found in Carretta et al. (2010), Ramírez et al. (2012), and Lind et al. (2015). To summarize, we find no stars in common between those in published studies and our sample stars. Therefore, we report for the first time 44 CN-strong CH-normal stars using LAMOST DR3, along with 35 stars identified as CN-strong CH-strong (five of them have been identified as carbon stars by Li et al. 2018).

M11 share a few similarities with our work, but our work has several major advantages: (1) a three times larger sample of metal-poor field stars, thanks to the superior data-collecting capability of LAMOST; (2) using both CN3839 and CN4142 to select CN-strong stars, followed by visual inspection; separating CH stars from CH-normal stars, and discussing the different chemical pattern of these CH stars; (3) including HK in the analysis; (4) combining the chemical abundances derived by high-resolution APOGEE data and our data-driven software to understand their origin, especially with the C–N parameter space; (5) a state-of-the-art orbital integration model with a realistic Galactic gravitational potential. We further note that Carollo et al. (2013) suggested that the stars in M11 are mostly in prograde orbits, while we find that a substantial fraction of stars (25%–67% depending on the adopted distances) lie in retrograde orbits. Finding no common stars to M11 and our CH-normal star sample is also unexpected, since the two works use similar experimental logic and search the northern sky. We checked the SDSS DR10 database, and found that none of the 44 CH-normal stars has an existing spectrum. In fact, the sky coverage of the LAMOST survey is much larger than that of SEGUE and SEGUE-2.

S17 found a large population of N-rich stars in the inner Galaxy with APOGEE data. A few C-enhanced stars ([C/Fe] > +0.15) are also seen in their work, and they excluded this group of stars to concentrate on the N-rich stars with normal C abundances. We also found a non-negligible number of CH stars in our study, and these stars show a chemistry distinct from other field stars.

The control sample of bulge field stars presented in S17 shows an N–C anticorrelation for $-0.5 < [C/Fe] < -0.1$ (Figure 2 of their paper), while their N-rich stars are above this sequence. S17 showed that this sequence follows the nitrogen lower envelope defined by the giants from several halo GCs. Thus, they suggested that this sequence is caused by the extra-mixing process during the RGB phase, while their N-rich stars cannot be produced by extra mixing alone due to their high N abundances. We see a similar configuration in the left panel of Figure 7. A lower N–C sequence is outlined by normal metal-poor field stars, where an anticorrelation is seen. The CH-normal stars are clearly above this sequence. On the other side, we obtain information on chemical abundances from low-resolution LAMOST data with our data-driven software, SLAM. A similar configuration is seen in the N–C parameter space (Figure 8). We further showed that brighter normal metal-poor field stars tend to have higher N abundances, which is consistent with extra-mixing theories (Charbonnel 1994; Boothroyd & Sackmann 1999; Charbonnel & Lagarde 2010). Thus the C and N abundances support the idea that these CH-normal stars have a different enrichment history than normal halo field stars, because the extra-mixing process cannot be fully responsible for the high N abundances.

Fernández-Trincado et al. (2017b) found a group of N- and Al-enhanced, but Mg-depleted stars. The stars in their metal-poor sample ([Fe/H] $<-1.0$) show a similar chemical pattern to some SG Galactic GC stars. In our stars in common with APOGEE, we did not find Mg-depleted stars, nor any with high Al abundance ([Al/Fe] > +0.5), as found in Fernández-Trincado et al. (2017b). From the chemical point of view, our CN-strong stars may not be of the same kind as their metal-poor sample.

6.2. Are CH-normal Stars Dissolved GC Stars?

If we assume that CH-normal stars are SG stars from dissolved GCs, we can estimate the contribution of dissolved GC members to the field. In this scenario, the first generation (FG) stars are buried inside the halo field stars, and they cannot be easily distinguished. Here we follow the minimal and maximal scenarios suggested by S17. The minimal scenario assumes that the present-day FG/SF ratio is about 1/2, and the maximal scenario assumes an extreme condition, where FG/SF is about 9/1. According to our study, we find 44 CH-normal stars out of 7723 field stars, which is 0.6%. This ratio is smaller than what was found in other studies, e.g., M11 and Ramírez et al. (2012) (2.5%–3%). We note that our sample selection requires that both CN3839 and CN4142 spectral indices are significantly (2σ) higher than for other normal metal-poor field stars, which is more stringent than other studies. In the minimal scenario, we expect to find a total of 66 dissolved GC member stars, which is ~0.9% of the field stars. This number is slightly smaller than the value found by S17, about 1.7%. Next, under the maximal scenario, early GCs are expected to lose ~90% of their mass before the formation of SG stars (Bastian & Lardo 2015). We expect to find a total of 440 stars as dissolved GC members, which account for ~6% of the field stars. However, the maximal scenario was basically ruled out in S17 due to (1) different metallicity distribution functions (MDFs) between their N-rich stars and the rest of the inner Galaxy population, and (2) the fact that the dissolved GC members outweigh the GC system by a factor of 80.

The maximal scenario needs revision in our work, because we are dealing with metal-poor field stars, not inner Galaxy field stars, like S17. First, we plot the MDFs of the CH-normal stars and of the metal-poor field stars in Figure 14. Both distributions have more stars towards higher metallicity. The metal-poor field stars seem to peak around [Fe/H] = −1.2, while the peak of CH-normal stars could be around [Fe/H] = −1.1, but it is not totally clear due to low statistics and limited metallicity range. At least from what we have, the two MDFs are not strongly different. Next, if we adopt the mass of the Galactic GC system from Kuij Jens & Portegies Zwart (2009) (~2.8 × 10^7 M_☉), and the mass of the luminous Galactic halo from Bland-Hawthorn & Gerhard (2016) (~(4–7) × 10^9 M_☉), then the mass of dissolved GC members (~1%–6% of the halo field stars) is comparable to that of the current GC system (the ratio is between 0.14 and 1.5).

Interestingly, the MDF of the N-rich stars found in the inner Galaxy peaks around [Fe/H] = −1.2 to −1.0, which shows no obvious contradiction with the MDFs of the CH-normal stars.
and of the metal-poor field stars in our work. Next, the ratio of the number of N-rich stars to the number of inner Galaxy field stars is similar to the ratio of the number of our CH-normal stars to the number of halo field stars. Better agreement may be reached if we consider that our method of selecting CN-strong stars is more stringent. Furthermore, our two CH-normal stars (common stars with APOGEE DR14) have compatible [C/Fe], [N/Fe], [Mg/Fe], and [Al/Fe] with the S17 N-rich stars. Is it possible that the N-rich stars found by Schiavon et al. are the same stellar population as the CH-normal stars that we find? Perhaps S17 N-rich stars are halo stars streaming toward the Galactic center? More observational evidence (e.g., kinematic analysis of the S17 sample stars, high-resolution spectra of our CH-normal stars) is needed to verify this statement. What about the M11 stars? We find that they share a similar MDF to our CH-normal stars (Figure 14), though their kinematic signatures may be different (Carollo et al. 2013). It would be interesting to run MC orbit simulations over all literature samples to eliminate the model dependence of different studies. If these stars are found over the whole Galaxy, it implies that they might form quite early, and now they have reached dynamic equilibrium.

6.3. Are CH-normal Stars Accreted Halo Stars?

Recent studies have shown that the Galactic halo stars ([Fe/H] < −0.9) may be separated into two populations with distinct chemical and kinematic signatures (Nissen & Schuster 2010; Ramirez et al. 2012; Hayes et al. 2018). The two populations of stars are called “high-α population” and “low-α population” based on their α-element abundances. The “low-α” stars tend to have lower O, Mg, Si, Na, Ni, Cu, and Zn and higher Eu abundances than those of the thick-disk stars and “high-α” stars at similar metallicity. Kinematically, the “low-α” stars have little to no net rotation (Hayes et al. 2018), and some of them may also lie in retrograde orbits (Nissen & Schuster 2010). These kinematics suggest that “low-α” stars are accreted from nearby dwarf galaxies, and thus they are also called accreted halo stars. In this work, we find that a substantial fraction of our CH-normal stars are retrograding (25%–67% depending on the adopted distances), which is a typical signature of accreted halo stars. Chemically, we find that our CH-normal stars are N-enriched compared to the bulk of metal-poor halo field stars. Further investigation of their chemical patterns must await high-resolution spectra for the whole sample of CH-normal stars.

Some GCs are suggested to be accreted from nearby dwarf galaxies, e.g., Sagittarius GCs (Law & Majewski 2010) and Canis Major GCs (Martin et al. 2004; Peñarrubia et al. 2005). The latter may also be referred as “Sausage” GCs (Myeong et al. 2018). Kruijssen et al. (2018) further proposed that 10–20 GCs were brought into the Milky Way by a massive satellite, Kraken, 6–9 Gyr ago. In particular, some of the Sagittarius GCs and “Sausage” GCs are in fact iron-complex (Da Costa 2015), for example the iron-complex Sagittarius GC, M54. Therefore, we speculate some of our CH-normal stars could be stars belonging to GCs accreted from a nearby dwarf galaxy and later dissolved into the field.

7. Conclusion

We have identified 79 CN-strong metal-poor ([Fe/H] < −1) field stars from LAMOST DR3 using CN spectral features around 3839 and 4142 Å. The sample was further separated into CH-normal (44) and CH (35) stars based on their CH spectral features around 4300 Å. This CH-normal star sample was identified for the first time in our study. We checked the high-resolution chemical abundances from APOGEE for eight common stars, and used our data-driven software, SLAM, to derive C and N abundances from LAMOST spectra for stars with high S/N. We found that CH stars, CH-normal stars, and normal metal-poor field stars have different chemical patterns, especially in the N–C parameter space.

We adopted distances derived from three methods for CH-normal stars, and integrated their orbits using GravPot16 with a Monte Carlo approach. Their orbital parameters and spatial distribution indicate that CH-normal stars are mostly halo stars. The Toomre diagram suggests that a substantial fraction of them (25% to 67%, depending on the adopted distance) are retrograding. The chemistry and kinematics of CH-normal stars imply that they may be GC-dissolved stars, or accreted halo stars, or both. In the future, we will increase our sample size by applying our technique to later LAMOST data releases. High-spectral-resolution follow-up observations of CH-normal stars are also planned.

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