Two Populations of Carbon-enhanced Metal-poor Stars in the Disk System of the Milky Way

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Abstract

We present a chemodynamical analysis of low-resolution (R ~ 1300) spectroscopy of ~50,000 stars from the AAOmega Evolution of Galactic Structure survey, focusing on two key populations of (in total) 650 carbon-enhanced metal-poor (CEMP) stars within the disk system of the Milky Way; a mildly prograde population \( L_c < 1000 \text{ kpc km s}^{-1} \) and a strongly prograde population \( L_c > 1000 \text{ kpc km s}^{-1} \). Based on their chemical and kinematic characteristics, and on comparisons with similar populations found in the recent literature, we tentatively associate the former with an ex situ inner-halo population originating from either the Gaia Sausage or Gaia–Enceladus. The latter population is linked to the metal-weak thick disk. We discuss their implications in the context of the formation history of the Milky Way.

 Unified Astronomy Thesaurus concepts: Milky Way disk (1050); Milky Way evolution (1052); Milky Way formation (1053); CEMP stars (2105); Stellar kinematics (1608)

1. Introduction

The Milky Way’s disk system is the most highly populated region of our Galaxy, and our position within this system enables the accumulation of a wealth of data to produce highly detailed characterizations to compare with numerical simulations of the thin- and thick-disk populations.

The thick-disk component was first formally proposed by Yoshii (1982) and confirmed by Gilmore & Reid (1983), who demonstrated the need for an additional disk component when constructing Galactic stellar-density models. Since then, studies have uncovered a rich substructure within the disk system, including the identification (Morrison 1990) and subsequent confirmation (Chiba & Beers 2000; Beers et al. 2014) of the metal-weak thick disk (MWTD). However, for almost three decades, despite numerous analyses, it remained unclear whether the MWTD was a separate population, or the metal-poor tail of the canonical thick disk. This situation may now be resolved; two recent analyses indicate that the MWTD comprises a distinct component with its own unique formation history.

Carollo et al. (2019) used a sample of 9258 local stars from the Sloan Extension for Galactic Understanding and Exploration (SEGUE; Yanny et al. 2009) program of the Sloan Digital Sky Survey (SDSS; York et al. 2000) to separate the MWTD from the thick disk, finding the two populations to possess different characteristic kinematics, metallicities, and α-element abundances. An & Beers (2020) constructed a chemodynamical “blueprint” of Galactic components using photometric data from SDSS DR14 supplemented with deeper \( \alpha \)-band photometry from the South Galactic Cap \( \alpha \)-band Sky Survey (SCUSS; Gu et al. 2015) and astrometry from Gaia DR2 (Gaia Collaboration et al. 2018), which is less subject to bias compared to targeted spectroscopic data. These authors identified several key stellar populations in their chemodynamical maps, including a MWTD component that is clearly separable from the canonical thick-disk stellar population.

The origin story for the disk system has also become more complex with the discovery of a relatively massive accreted satellite, known alternatively as the Gaia Sausage or Gaia–Enceladus (the exact characteristics and potentially overlapping origins of these two proposed progenitors are still under debate; see, e.g., Evans 2020), which may have contributed to the formation of the thick disk via dynamical heating as it merged with the Milky Way (Belokurov et al. 2018; Helmi et al. 2018). The identification of a Splashed Disk population of stars (An & Beers 2020; Belokurov et al. 2020) that may be connected with the proposed satellite collision(s) contributes an additional feature that could help constrain models for the formation of the disk system.

Recent reports of larger-than-expected populations of metal-poor stars within the disk system are also raising new questions about the assembly history of the Galaxy. The thin- and thick-disk metallicity distribution functions (MDFs) peak at approximately \( [\text{Fe}/\text{H}] = -0.1 \) and \( [\text{Fe}/\text{H}] = -0.6 \), respectively, with the MWTD covering an approximate range of \( -1.8 < [\text{Fe}/\text{H}] < -0.8 \) (Carollo et al. 2007, 2010). However, Sestito et al. (2019) identified a significant population of ultrametal-poor stars (UMP; \( [\text{Fe}/\text{H}] < -4.0 \)), well outside of the disk system’s usual metallicity range, traveling on prograde orbits within 3 kpc of the Galactic plane. They followed up on this finding in Sestito et al. (2020), using a combined sample of 1027 very metal-poor (VMP) stars with \( [\text{Fe}/\text{H}] < -2.5 \) observed with the Large Sky Area Multi-Object Fibre Spectroscopic Telescope (Cui et al. 2012) and the Pristine survey (Youakim et al. 2017; Aguado et al. 2019), demonstrating a statistically significant overdensity of prograde VMP stars residing in the disk region. Similarly, Cordoni et al. (2021) find ~11% of their 475 VMP stars from the SkyMapper survey (Wolf et al. 2018) are within 3 kpc of the plane and have prograde orbits with low eccentricities. Di Matteo et al. (2020)
even find an “ultra metal-poor thick disk,” extending as far down as [Fe/H] ~ -6, within their sample of 54 VMP stars from the ESO Large Programme “First Stars” (Bonifacio et al. 2009), with interesting implications for the early dynamical history of the Galaxy.

Complementary to these discoveries of metal-poor disk populations, numerous carbon-enhanced metal-poor (CEMP; [Fe/H] < -1, [C/Fe] > +0.7) stars have been identified in the disk system as well. In their analyses of metal-poor stars from the Hamburg/ESO survey, Beers et al. (2017) noted a population of CEMP-s,6 stars in a kinematic and metallicity region usually associated with the MWTD. J. Yoon et al. (2021, in preparation) find preliminary results indicating significant populations of CEMP stars in regions of energy–momentum space associated with the disk system, including a prograde population and a population with little to no angular momentum. Most notably, their sample includes a subset of UMP ([Fe/H] < -4) CEMP-no 7 stars mainly found within the low-angular-momentum population. These differences in kinematic and chemical characteristics suggest that at least two separate formation scenarios (e.g., from two accretion events) may be necessary to explain the presence of the CEMP stars in the disk populations.

Continuing to probe the disk for metal-poor and CEMP stars provides us with valuable tracer populations to better understand the history of the disk system. In this paper, we continue this study of disklike CEMP stars using low-resolution (R ~ 1300) spectroscopy obtained by the AAOmega Evolution of Galactic Structure (AEGIS) survey (P.I. Keller), originally commissioned to study the evolutionary history of the thick-disk and halo systems of the Milky Way. As we demonstrate below, this sample includes two relatively nearby populations of CEMP stars, with potential implications for our understanding of the formation histories of the canonical thick disk and MWTD. We introduce the AEGIS data set in Section 2, and describe its chemical abundances (Sections 2.1 and 2.2) and kinematics (Sections 2.3 and 2.4). Section 3 presents our analyses of this sample with results. We discuss the implications of our results in the context of the Galactic formation history in Section 4. A brief summary of this work and our key findings are provided in Section 5.

2. Data

AEGIS is a spectroscopic survey conducted at the Australian Astronomical Telescope (AAT), using the dual beam (blue and red arms, covering ranges λ = 3700–5800 Å and λ = 8400–8800 Å) AAOmega multijob spectrograph to target populations of interest selected from the SkyMapper photometric survey. The resulting data set comprises ~70,000 stars with low-resolution spectroscopy (R ~ 1300 for blue-arm spectra, R ~ 10,000 for red-arm spectra) and spans ~4900 deg² of sky in the Southern Hemisphere. A more complete description of the data set can be found in Yoon et al. (2018), along with a detailed examination of the metallicity ([Fe/H]) and carbonicity ([C/Fe]) of the Galactic halo through the lens of the AEGIS survey. The full AEGIS catalog can be found in D.A. Shank et al. (2021, in preparation).

6 CEMP-s stars exhibit overabundances of elements associated with the slow neutron-capture process: [Ba/Fe] > +1.0, [Ba/Eu] > +0.5 (Beers & Christlieb 2005).

7 CEMP-no stars exhibit no overabundances of elements associated with the neutron-capture processes: [Ba/Fe] < 0 (Beers & Christlieb 2005).

2.1. Stellar Parameters and Chemical Abundances

Stellar atmospheric parameters and a limited set of chemical abundances were derived with the non-SEGUE stellar parameter pipeline (n-SSPP; Beers et al. 2014, 2017). Effective temperature (Teff), surface gravity (log g), metallicity ([Fe/H]), and carbon abundances ([C/Fe]) for the AEGIS sample have been corrected to be more consistent with external high-resolution estimates, following the procedure described in Beers et al. (2014). Additionally, we apply the evolutionary carbon corrections developed by Placco et al. (2014) to take into account the surface carbon-abundance depletion expected to occur on the upper red giant branch. For this sample, mean errors on Teff, log g, [Fe/H], and [C/Fe] are approximately 75 K, 0.2 dex, 0.1 dex, and 0.1 dex, respectively.

2.2. CEMP-s and CEMP-no Classification

In the past, high-resolution spectroscopy was required to divide CEMP stars into the CEMP-no and CEMP-s sub-classes, because it was necessary to obtain barium and europium abundances to do so. However, Yoon et al. (2016) showed that this separation can be reliably (with a ~90% success rate) made using only the absolute carbon abundance, A(C), making larger, low/medium-resolution data sets available for analysis. Because the division between CEMP-no and CEMP-s stars can vary based on temperature and luminosity class, here we limit ourselves to the two categories for which the A(C) divisions are most apparent in this sample: (1) giants and subgiants (G/SG), and (2) main-sequence dwarfs and turn-off stars (D/TO). We use divisions of A(C) = 7.1 and A(C) = 7.6 for the G/SG and D/TO classes, respectively, as suggested by Yoon et al. (2018) in their analysis of the AEGIS data set. After removing duplicate measurements and measurements with signal-to-noise ratios <10, there are 1061 G/SG CEMP stars and 421 D/TO CEMP stars identified in the AEGIS sample in total. The combined sample of these classes comprises 660 CEMP-no and 822 CEMP-s stars.

We note that stellar temperature can affect our ability to adequately derive a star’s carbon abundance. Compared to stars with strong carbon enhancements, those with moderate carbon enhancements can be difficult to detect in warmer (Teff ≥ 5750 K) stars, producing a spurious overabundance of high-A(C), high-Teff stars (in other words, a higher CEMP-s to CEMP-no ratio). The application of such a cut on temperature would substantially reduce our CEMP sample size, so we choose to present the sample without temperature restriction in the following analyses, but make note of the effects that a temperature limit might have on our results, where appropriate.

2.3. Kinematic Parameters

Radial velocities were derived using the n-SSPP analysis of the high-resolution red arm of the AEGIS spectra. A correction of −24.6 km s⁻¹ was applied to all radial velocity values to account for an offset between the n-SSPP values and radial velocities derived using Ca triplet lines (at λ = 8498, 8542, 8662 Å) from the red-arm spectra (C. A. Navin 2021, private communication). Proper motions from Gaia DR2 (Gaia Collaboration et al. 2018) are available for the majority (~98%) of the sample. For the remaining ~2%, proper motions
were averaged from a variety of catalogs (including Hipparcos, Tycho-1, and Tycho-2, as described in Beers et al. 2014). We adopt a +0.054 mas correction to all Gaia parallaxes as prescribed by Schönrich et al. (2019), and derive distances from the inverted parallaxes for all stars with <20% relative parallax uncertainty (~54% of the sample). The remaining ~46% of the stars in our sample are assigned photometrically derived distances, following the procedure outlined in Beers et al. (2000), as modified by Beers et al. (2012). For this sample, mean errors on radial velocities, proper motions, and distances are approximately 17.1 km s⁻¹, 0.16 mas yr⁻¹, and 0.45 kpc, respectively.

2.4. Kinematic Derivations

Galactocentric positions and velocities are derived using the galpy Galactic dynamics package (Bovy 2015). In this work, we use $R_0 = 8.2$ kpc for the distance to the center of the Galaxy (Bland-Hawthorn & Gerhard 2016), $v_{LSR} = 236$ km s⁻¹ for the local standard of rest (LSR) velocity (Kawata et al. 2019), and $(U, V, W)_0 = (-11.10, 12.24, 7.25)$ km s⁻¹ for the motion of the Sun with respect to the LSR (Schönrich et al. 2010). Orbital parameters are derived with the Galactic potential code used by Chiba & Beers (2000), which adopts the Stäckel potential described in Sommer-Larsen & Zhen (1990).

To estimate uncertainties on the orbital parameters, we follow a Monte Carlo sampling procedure, as in Dietz et al. (2020). A new set of kinematic input parameters is selected for each star from a corresponding set of random distributions (with the assumption that the given kinematic uncertainties are normally distributed about their observed values). This process is repeated 1000 times per star, and the standard deviations of the resulting orbital-parameter distributions are taken as the uncertainties.

We note here that this sampling process should take into account the correlations between the input parameters in order to derive the most accurate uncertainty. However, correlation coefficients are not available for the kinematic parameters given in the original AEGIS data set (as noted above, we use the original kinematic parameters given in the AEGIS data set for 100% of our radial velocities, ~2% of our proper motions, and ~46% of our distances). Including correlation coefficients in our calculations for stars with Gaia kinematics results in (at most) a median difference of ~1% and mean difference of ~6% in derived uncertainties for the orbital parameters used in this work when compared to uncertainties calculated without correlation coefficients. Because this difference is minor, we choose to neglect correlations between input parameters in order to treat the subsets of our data with AEGIS and Gaia kinematics in the same manner.

To avoid identifying any potentially spurious features, we limit our sample to stars with uncertainties on $Z_{max}$ less than 1 kpc and uncertainties on $L_c$ less than 250 kpc km s⁻¹ (that is, no greater than our chosen bin size in Figure 1). After applying this restriction, we have a total of 51,946 stars in the $Z_{max} < 5$ kpc region, 427 of which are CEMP-s stars and 223 of which are CEMP-no stars.

3. Analysis

We begin our analysis by identifying populations of interest close to the Galactic plane. Angular momentum ($L_c$) distributions for the sample are divided into sections based on maximum orbital extent from the Galactic plane, $Z_{max}$, as shown in Figure 1.

From left to right, the columns of Figure 1 show the distributions for all stars, the CEMP stars, and the CEMP-s (blue) + CEMP-no (red) stars.

In the full sample (left column of panels), the disk clearly dominates at all $Z_{max}$ ranges, producing a strongly prograde peak at $L_c > 1000$ kpc km s⁻¹. This peak includes both thin- and thick-disk stars, but it should be noted that the thin disk is not fully represented here due to the metallicity upper limit within the AEGIS sample ([$\text{Fe}/\text{H}$] $\leq 0.3$). The inner-halo component ($L_c \sim 0$ kpc km s⁻¹) becomes more visible at $3 \leq Z_{max} < 5$ kpc, although the disk system still retains a robust peak even at these heights.

In the CEMP subsample (middle column of panels in Figure 1), at least two populations appear to be present for all $Z_{max}$ ranges. We have fitted the $L_c$ distributions with Gaussians using the scikit-learn (Pedregosa et al. 2011) mixture package in order to approximate the general features of these populations (we have also performed similar fits on the total sample so that we can compare the characteristics of the total sample to the CEMP subsamples). Each range contains a mildly prograde peak and a strongly prograde peak—we refer to these as populations “A” (dotted curve) and “B” (dashed-dotted curve), respectively, for the remainder of this work. The low-momentum peak is likely associated with the inner-halo population, a rich source of CEMP stars, which would account for the larger relative proportion of population A at high $Z_{max}$.

Population B displays a strong net rotation and decreases in relative significance with increasing $Z_{max}$, which suggests it may be a part of the thick disk/MWTD. The fits for population A peak at 905, 396, and 315 kpc km s⁻¹, from the low to high $Z_{max}$ ranges. The fits for population B peak at 1625, 1398, and 1167 kpc km s⁻¹, from the low to high $Z_{max}$ ranges. These fits are mainly meant to provide an overview of the characteristics of our CEMP populations, not to create a strict definition for each population, so it is understandable that the location of the peaks varies somewhat with $Z_{max}$ (especially at $Z_{max} < 1$ kpc, where population A is weakly represented). It is interesting to note here that population B lags an average of ~170 kpc km s⁻¹ behind the dominant, strongly prograde peak of the total sample.

Populations A and B appear to possess different relative fractions of CEMP-s and CEMP-no stars, as can be seen in the right column of panels in Figure 1. The $L_c$ region dominated by population A possesses a more balanced CEMP-s/CEMP-no ratio than the $L_c$ region dominated by population B, which is more heavily dominated by CEMP-s stars than population A. The CEMP-s to CEMP-no ratios for each population are listed in Table 1, as well as a complementary set of ratios for a limited-temperature cut of the sample (see Section 2.2 for details on the effect of $T_{eff}$ on relative CEMP ratios). These ratios are also obtained using the scikit-learn mixture package, which allows us to predict population membership fractions for the CEMP stars in our sample based on our fits by predicting which Gaussian component each input star most probably belongs to.

Both populations are dominated by CEMP-s stars, which is not surprising, given that we currently understand CEMP-no stars to have predominantly ex situ origins (e.g., Lee et al. 2017, 2019; Yoon et al. 2018, 2019, 2020), though the relative
The strength of this ratio appears to vary based on the subsample being considered. In the full sample, the ratio of CEMP-s to CEMP-no stars is roughly twice as large in population B as it is in population A, which could suggest different origins for the CEMP stars within these populations.

When we consider the sample restricted to $T_{\text{eff}} < 5750$ K, CEMP-s stars still dominate both populations, but the CEMP-s to CEMP-no ratio varies much more unpredictably, making it challenging to make any definitive statement on the chemical origins of population A versus population B. Note that the low-temperature sample contains significantly fewer CEMP stars than the full sample; a larger sample of cool CEMP stars in this region may be needed to more fully explore these populations.

The presence of a large number of CEMP stars in a region of the Galaxy usually associated with disk stars is worthy of further investigation. To aid in interpretation of these data, we...
present the same samples of stars shown in Figure 1 in a set of MDFs in Figure 2. Rows are subdivided into the same Z_{max} ranges used in Figure 1, while columns are separated into L_Z ranges. Population counts and statistics are given in the upper left-hand corner of each panel.

Inspection of Figure 2 shows that the strongly prograde stars in our sample are generally more metal-rich than the mildly prograde or retrograde stars, as expected for a disk-dominated sample. As in Figure 1, the disk is robustly represented (high metallicity, strongly prograde) at both low and high Z_{max}, and here too we observe the growing inner-halo contribution ([Fe/H] \sim -1.6, L_z \sim 0 \text{ kpc km s}^{-1}) in the highest Z_{max} range.

Figure 2 also includes CEMP, CEMP-s, and CEMP-no counts for the each kinematic range, listed in black, blue, and red, respectively.

| Table 1: CEMP-s to CEMP-no Ratios (and Total CEMP Counts) for Figure 1 |
| --- |
| Pop. | 0 < Z_{max} \leq 1 \text{ kpc} | 1 < Z_{max} \leq 3 \text{ kpc} | 3 < Z_{max} \leq 5 \text{ kpc} |
| All $T_{eff}$ | | | |
| A | 1.8 (17) | 1.3 (143) | 1.1 (110) |
| B | 3.7 (47) | 2.7 (241) | 2.5 (92) |
| $T_{eff} < 5750 \text{ K}$ | | | |
| A | 3.7 (14) | 1.9 (60) | 1.1 (68) |
| B | 2.0 (6) | 2.1 (56) | 1.8 (14) |

Note. The CEMP-s to CEMP-no ratios for populations A and B are given in bold for each range shown in Figure 1, for the full sample and for a temperature-limited sample. The total number of CEMP stars in each population for the given range is listed in parentheses.
red, respectively. The relative percentage of CEMP stars compared to all stars is noted in parentheses next to the CEMP count. Although the strongly prograde stars (two right-most columns) have the most CEMP stars by number, they possess the smallest relative percentages of CEMP stars compared to the total population. We find a relatively large number of CEMP stars in these regions simply because these regions of the kinematic space were sampled the most in the observations. Nevertheless, the presence of even a small relative percentage of CEMP stars moving in tandem with the disk is interesting, and may provide insight into the disk’s formation history. These subsamples correspond to the CEMP-s-rich population B noted above.

Population A can be seen more clearly in the lower-$L_z$ ranges (two left-most columns). These regions contain small absolute numbers of CEMP stars, but possess the highest CEMP percentages. A feature of note here is the double metallicity peak seen in both the $Z_{\text{max}} \leq 1$ kpc and $1 < Z_{\text{max}} < 3$ kpc plots within the $-250 < L_z < 750$ kpc km s$^{-1}$ range. Peaks at approximately $[\text{Fe}/H]=-1.0$ and $[\text{Fe}/H]=-1.7$ are present in the $Z_{\text{max}} \leq 1$ kpc subsample, becoming less distinct as we move farther from the plane. It should be noted that the shape of this component varies somewhat with binning, though a feature similar to the $[\text{Fe}/H]=-1.0$ peak can also be seen in Figure 4 of An & Beers (2020); the authors suggest the Splashed Disk, presented in Belokurov et al. (2020), as one possible source.

4. Discussion

We have identified two CEMP populations of interest in the disk system of the Milky Way: the mildly prograde population A ($L_z < 1000$ kpc km s$^{-1}$) and the strongly prograde population B ($L_z > 1000$ kpc km s$^{-1}$), both containing an enhancement of CEMP-s stars relative to CEMP-no stars.

Although many population A stars orbit close to the Galactic plane, this population may be linked to the inner-halo population, particularly since it possesses a similar relative percentage of CEMP-s stars (53%–65%, depending on $Z_{\text{max}}$) to that given by Carollo et al. (2014) for this component (57%). An & Beers (2020) found a strong inner-halo population even at slices of $|Z|$ close to the plane, estimating two-thirds of the metal-poor stars in the $1 < |Z| < 2$ kpc region of their data to be Gaia–Enceladus stars. Although the mildly prograde motion of population A is at odds with the slightly retrograde motion derived by Helmi et al. (2018) for Gaia–Enceladus, a common origin cannot be ruled out. Both population A and Gaia–Enceladus span a range of velocities, including both prograde and retrograde rotation, and the latter presumably carries a similar CEMP-s percentage to that quoted in Carollo et al. (2014), as Gaia–Enceladus is proposed to make up a large portion of the inner-halo population. It is also possible that population A is instead a part of the Gaia Sausage, which possesses a slightly higher mean $L_z$ ($L_z \sim 0$ kpc km s$^{-1}$) than Gaia–Enceladus (bounded by $-1500$ kpc km s$^{-1} < L_z < -500$ kpc km s$^{-1}$ in Helmi et al. (2018)). The scientific community has not yet come to a consensus on which scenario better describes the formation of the ex situ inner-halo population, the Gaia Sausage or Gaia–Enceladus; it would be interesting to revisit the characteristics of population A in the future, when more is known about the nature of the main inner-halo progenitor(s).

Population B possesses kinematic characteristics more in line with the thick-disk system ($L_z \sim 1500$ kpc km s$^{-1}$, close to the Galactic plane), and the low metallicity of our CEMP stars (by definition) necessarily designate them as members of the MWTD, which spans an approximate range of $-1.8 < [\text{Fe}/H] < -0.8$ (Carollo et al. 2010). Beers et al. (2017) and J. Yoon et al. (2021, in preparation) also noted significant CEMP-s populations in MWTD-associated regions of their samples. It is unclear whether these stars formed in situ or were imported into the disk system. CEMP stars are not expected to be common in a well-mixed, gas-rich environment like the disk, but peak B makes up a very small percentage of the total disk-system stars within its kinematic region, so in situ formation is not out of the question. For instance, Sesito et al. (2020) propose a possible in situ formation pathway for their population of disk VMP stars, involving pockets of pristine gas in the protodisk and radial migration. On the other hand, both Carollo et al. (2019) and An & Beers (2020) find evidence in their data clearly indicating a separate MWTD population, which suggests a potential ex situ origin for population B stars. We note here that while speculation on the origin of the MWTD might inform our interpretation of population B, our overall results are independent of the issue of the separability of the MWTD. Lian et al. (2020) propose a two-pronged formation scenario for the thick disk, including a late starburst in the outer disk, potentially caused by the accretion of a gas-rich dwarf galaxy. Although the abundance-space explored in their analyses ($[\text{Fe}/H] > -1$) does not extend to the low-metallicity regimes probed here, it is possible that this ex situ outer thick disk is linked to population B. In the case of an accreted origin, the high relative fraction of CEMP-s stars in population B could indicate a (relatively) massive, gas-rich progenitor satellite, which would have preferentially formed more CEMP-s stars than CEMP-no stars, the latter being mostly accreted from less-massive progenitors such as ultrafaint dwarf (UFD) galaxies (Yoon et al. 2019).

An investigation into the morphological groups introduced by Yoon et al. (2016) present in our CEMP subpopulations could be of interest, especially an analysis of the two groups dominated by CEMP-no stars, “Group II” and “Group III.” These groups are thought to have different progenitors due to their distinct $A(C)$–$[\text{Fe}/H]$ and $A(C)$–$A(\text{Na}, \text{Mg})$ relations, which could provide insight into the origins of population A versus B, but our sample does not possess sufficient numbers of potential Group III stars (which can be difficult to identify, due the overlap between Groups II and III) to make any statistically interesting statements about the Group II/Group III ratio in either population. However, J. Yoon et al. (2021, in preparation) find a strong Group III population in a region of energy–momentum space potentially associated with population A (low-energy, $L_z < 1000$ kpc km s$^{-1}$) based on a high-resolution literature sample of Group III CEMP-no stars. Yoon et al. (2019) found Group III stars to be preferentially accreted from UFDs, so further sampling of the population A region may help constrain the assembly history of the nearby halo, as well as potentially contribute to the as-yet sparsely populated Group III region of the $A(C)$–$[\text{Fe}/H]$ space.

5. Summary and Conclusions

We present a chemodynamical analysis of $Z_{\text{max}} < 5$ kpc stars from the AEGIS survey, focusing on CEMP populations within this region. We find two key CEMP populations of
interest close to the Galactic plane: a mildly prograde ($L_z < 1000$ kpc km s$^{-1}$) population (population “A”) and a strongly prograde ($L_z > 1000$ kpc km s$^{-1}$) population (population “B”). Population A contains a mild overabundance of CEMP-s compared to CEMP-no stars ($\sim$53%–65% CEMP-s), which, in combination with its kinematic characteristics (low $L_z$, dominant farther from the Galactic plane), lead us to associate this population with the inner-halo component. These stars could belong to either of the proposed ex situ inner-halo progenitors: the Gaia Sausage or Gaia–Enceladus.

Population B also contains preferentially more CEMP-s stars than CEMP-no stars (potentially with a higher ratio than population A, but a larger number of low-$T_{	ext{eff}}$, $Z_{\text{max}} < 5$ kpc CEMP stars than our current sample ($\sim$200) is needed to more fully explore this possibility), and can be kinematically and chemically associated with the MWTD. This clump of (mainly) CEMP-s stars within the MWTD has been seen in other samples as well, including in Beers et al. (2017) and J. Yoon et al. (2021, in preparation). We propose both in situ and ex situ origins for this population, such as pockets of pristine gas in the protodisk (in situ), as suggested by Sestito et al. (2020), and a relatively massive merger of a gas-rich progenitor satellite (ex situ).

Although the stellar halo (and the outer-halo component in particular) contains the highest relative ratio of metal-poor and CEMP stars compared to other Galactic components, a surprising number of these ancient tracer populations are emerging in recent surveys of the disk system. We present our own findings within the AEGIS data set as potentially useful constraints for evolutionary models of the Milky Way, particularly with regards to the creation of the ex situ inner halo and the formation of the MWTD. Future surveys of the disk and halo systems will undoubtedly aid in interpretation of the CEMP behaviors noted here, and ongoing efforts to increase the number of known Group III stars could provide further constraints on the origins of these populations.

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References
Aguado, D. S., Youakim, K., González Hernández, J. I., et al. 2019, MNRAS, 490, 2241
An, D., & Beers, T. C. 2020, AAS Meeting, 235, 158.01
Beers, T. C., Carollo, D., Ivezić, Ž, et al. 2012, ApJ, 746, 34
Beers, T. C., Chiba, M., Yoshii, Y., et al. 2000, AJ, 119, 2866
Beers, T. C., & Christlieb, N. 2005, ARA&A, 43, 531
Beers, T. C., Norris, J. E., Placco, V. M., et al. 2014, ApJ, 794, 58
Beers, T. C., Placco, V. M., Carollo, D., et al. 2017, ApJ, 835, 81
Belokurov, V., Erkal, D., Evans, N. W., Koplowsky, S. E., & Deason, J. A. 2018, MNRAS, 478, 611
Belokurov, V., Sanders, J. L., Fattahi, A., et al. 2020, MNRAS, 494, 3880
Bland-Hawthorn, J., & Gerhard, O. 2016, ARA&A, 54, 529
Bonifacio, P., Andersen, J., Andrievsky, S. M., et al. 2009, Science with the VLT in the ELT Era (Dordrecht: Springer), 31
Bovy, J. 2015, ApJS, 216, 29
Carollo, D., Beers, T. C., Chiba, M., et al. 2010, ApJ, 712, 692
Carollo, D., Beers, T. C., Lee, Y. S., et al. 2007, Natur, 450, 1020
Carollo, D., Chiba, M., Ishigaki, M., et al. 2019, ApJ, 887, 22
Carollo, D., Freeman, K., Beers, T. C., et al. 2014, ApJ, 788, 180
Chiba, M., & Beers, T. C. 2000, AJ, 119, 2843
Cordoni, G., Da Costa, G. S., Yong, D., et al. 2021, MNRAS, 503, 2539
Cui, X.-Q., Zhao, Y.-H., Chu, Y.-Q., et al. 2012, A&A, 536, L115
Dietz, S. E., Yoon, J., Beers, T. C., & Placco, V. M. 2020, ApJ, 894, 34
Evans, N. W. 2020, in IAU Symp. 353, Galactic Dynamics in the Era of Large Surveys, ed. M. Valluri & J. A. Sellwood (Cambridge: Cambridge Univ. Press), 113
Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2018, A&A, 616, A11
Gilmore, G., & Reid, N. 1983, MNRAS, 202, 1025
Gu, J., Du, C., Jia, Y., et al. 2015, MNRAS, 452, 3092
Helmi, A., Babusiaux, C., Koppelman, H. H., et al. 2018, Natur, 563, 85
Hunter, J. D. 2007, CSE, 13, 22
Lee, Y. S., Beers, T. C., Kim, Y. K., et al. 2017, ApJ, 836, 91
Lee, Y. S., Beers, T. C., & Kim, Y. K. 2019, ApJ, 885, 102
Lian, J. Thomas, D. Maraston, C., et al. 2020, MNRAS, 497, 2371
Morris, H. L. 1990, JRAAC, 84, 107
Pedregosa, F., Varoquaux, G., Gramfort, A., et al. 2011, J. Mach. Learn. Res., 12, 2825
Placco, V. M., Frebel, A., Beers, T. C., & Stanchfield, R. J. 2014, ApJ, 797, 21
Schönrich, R., Binney, J., & Dehnen, W. 2010, MNRAS, 403, 1829
Schönrich, R., McMillan, P., & Eyer, L. 2019, MNRAS, 487, 3568
Sestito, F., Longeard, N., Martin, N. F., et al. 2019, MNRAS, 484, 1216
Sestito, F., Martin, N. F., Starkenburg, E., et al. 2020, MNRAS, 497, L7
Sommer-Larsen, J., & Zhen, C. 1990, MNRAS, 242, 10
van der Walt, S., Colbert, S. C., & Varoquaux, G. 2011, CSE, 13, 22
Wolf, C., Onken, C. A., Luvaul, L. C., et al. 2018, PASA, 35, e010
Yanny, B., Rockosi, C., Newberg, H. J., et al. 2009, AJ, 137, 4377
Yoon, J., Beers, T. C., Dietz, S., et al. 2018, ApJ, 861, 146
Yoon, J., Beers, T. C., Placco, V. M., et al. 2016, ApJ, 833, 20
Yoon, J., Beers, T. C., Tian, D., & Whitten, D. D. 2019, ApJ, 878, 97
Yoon, J., Whitten, D. D., & Beers, T. C. et al. 2020, ApJ, 894, 7
York, D. G., Adelman, J., Anderson, J. E. J., et al. 2000, AJ, 120, 1579
Yoshii, Y. 1982, PASJ, 34, 365
Youakim, K., Starkenburg, E., Aguado, D. S., et al. 2017, MNRAS, 472, 2963