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The assembly of the halo system of the Milky Way as revealed by SDSS/SEGUE – The CEMP star connection

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Abstract. In recent years, massive new spectroscopic data sets, such as the over half million stellar spectra obtained during the course of SDSS (in particular its sub-survey SEGUE), have provided the quantitative detail required to formulate a coherent story of the assembly and evolution of the Milky Way. The disk and halo systems of our Galaxy have been shown to be both more complex, and more interesting, than previously thought. Here we concentrate on the halo system of the Milky Way. New data from SDSS/SEGUE has revealed that the halo system comprises at least two components, the inner halo and the outer halo, with demonstrably different characteristics (metallicity distributions, density distributions, kinematics, etc.). In addition to suggesting new ways to examine these data, the inner/outer halo dichotomy has enabled an understanding of at least one long-standing observational result, the increase of the fraction of carbon-enhanced metal-poor (CEMP) stars with decreasing metallicity.

1. INTRODUCTION

For decades, "the halo" of the Galaxy has been thought of as a single entity, describable in terms of a single metallicity distribution function (MDF), single density profile, and a simple kinematical distribution that distinguishes it from the disk system. Indeed, much of the effort since its recognition as an important component of the Galaxy has concentrated on the effort to better specify these characteristics [2, 11, 12]. However, over this same period, numerous clues have emerged that this story is incomplete. Most of these clues were obtained in the form of disjoint small-n samples, making it difficult to "see the forest for the trees." This situation has now changed significantly.

Recently, Carollo et al. (2007, [5]) and Carollo et al. (2010, [6]) made use of large samples ($n > 30,000$) of "calibration stars" from SDSS/SEGUE, in order to directly test the nature of the halo component of the Galaxy, and elucidate its kinematic and chemical properties. Their results indicate that the halo consists of two broadly-overlapping structural components, an "inner halo" and an "outer halo". Note that these labels are not merely descriptors for the regions studied, but rather are labels for two individual stellar populations. These components exhibit different MDFs, spatial-density profiles, and stellar orbits, with the inner- to outer-halo transition occurring, according to these authors, at Galactocentric distances of 15–20 kpc. The inner halo was shown to comprise a population of stars exhibiting a flattened spatial-density distribution, with an inferred axial ratio on the order of $q_H \sim 0.6$, no net rotation at the level of $\sim 10\,\mathrm{km\,s^{-1}}$, and a MDF peaked at [Fe/H] ~ -1.6. The outer halo comprises stars that exhibit a more spherical spatial-density distribution, with an axial ratio $q_H \sim 0.9$,

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a clear retrograde net rotation ($\langle v_\Phi \rangle \sim -80\,\mathrm{km\,s^{-1}}$), a kinematically "hotter" distribution of space velocities than the inner halo, and a MDF peaked at [Fe/H] ~ -2.2. The fundamental demonstration of these results is contained in the original papers, as well as in [3], and will not be repeated here. We note, however, that the dual-halo model for the Milky Way has received considerable recent theoretical support, based on simulations for galaxy formation including baryons (as opposed to previous pure dark-matter-only simulations), e.g., [9, 19], and [22].

In this brief communication, we highlight how recognition of the inner/outer halo structure of the Milky Way's halo has provided the means for understanding at least one long-standing "mystery" concerning the nature of a specific class of very metal-poor stars, the so-called carbon-enhanced metal-poor (CEMP) stars.

2. THE CEMP STARS

The CEMP stellar classification was originally defined as the subset of very metal-poor ([Fe/H] ≤ -2) stars that exhibit elevated carbon abundances relative to iron, [C/Fe] $> +1.0$ [2]. More recently, other criteria have been used, e.g., [C/Fe] $> +0.7$ [1], which appear to be better supported by the bulk of the available data.

In the last two decades it has been recognized that roughly 20% of stars with [Fe/H] < -2.0 exhibit enhanced [C/Fe] ratios (which we refer to as "carbonicity"), up to several orders of magnitude larger than the solar ratio [16, 17]. The fraction of CEMP stars rises to 30% for [Fe/H] < -3.0, 40% for [Fe/H] < -3.5, and 75% for [Fe/H] < -4.0 ([2], the fraction would have been 100%, until the recent discovery of an SDSS turnoff star with [Fe/H] ~ -5.0, reported by [4]); definitive explanations for the origin of this increase have yet to be offered. Regardless of the ultimate reason, these results indicate that significant amounts of carbon were produced in the early stages of chemical evolution in the Universe.

There exist a number of sub-classes of CEMP stars, some of which have been associated with proposed progenitor objects. The CEMP-*s* stars (those with *s*-process-element enhancement), for example, are the most commonly observed type to date. High-resolution spectroscopic studies have revealed that around 80% of CEMP stars exhibit *s*-process-element enhancement [1]. The favored mechanism invoked to account for these stars is mass transfer of carbon-enhanced material from the envelope of an asymptotic giant-branch (AGB) star to its binary companion; it is this surviving companion that is now observed as a CEMP-*s* star.

The sub-class of CEMP-*no* stars (which exhibit no strong neutron-capture-element enhancements) is particularly prevalent among the lowest metallicity stars (Fe/H < -2.5). Possible progenitors for this class include massive, rapidly rotating, mega metal-poor ([Fe/H] < -6.0) stars, which models suggest have greatly enhanced abundances of CNO due to distinctive internal burning and mixing episodes, followed by strong mass loss [20]. Another suggested mechanism for the production of the material incorporated into CEMP-*no* stars is pollution of the interstellar medium by so-called faint supernovae associated with the first generations of stars, which experience extensive mixing and fallback during their explosions [24].

The increasing frequency of CEMP stars with declining metallicity, as well as the suggested increase of the fraction of CEMP stars with increasing distance from the Galactic plane [10], can be explained in the context of an inner/outer halo dichotomy, and the dominance of *different carbon production mechanisms* (the processes associated with the progenitors of the CEMP-*s* and CEMP-*no* stars) being linked to these two populations.

3. THE INNER/OUTER HALO, CEMP-STAR CONNECTION

The recent study of Carollo et al. (2011, [7]) illuminates the intimate connection between the nature of the halo system and the observed facts concerning CEMP stars. Among other results, these authors find that:

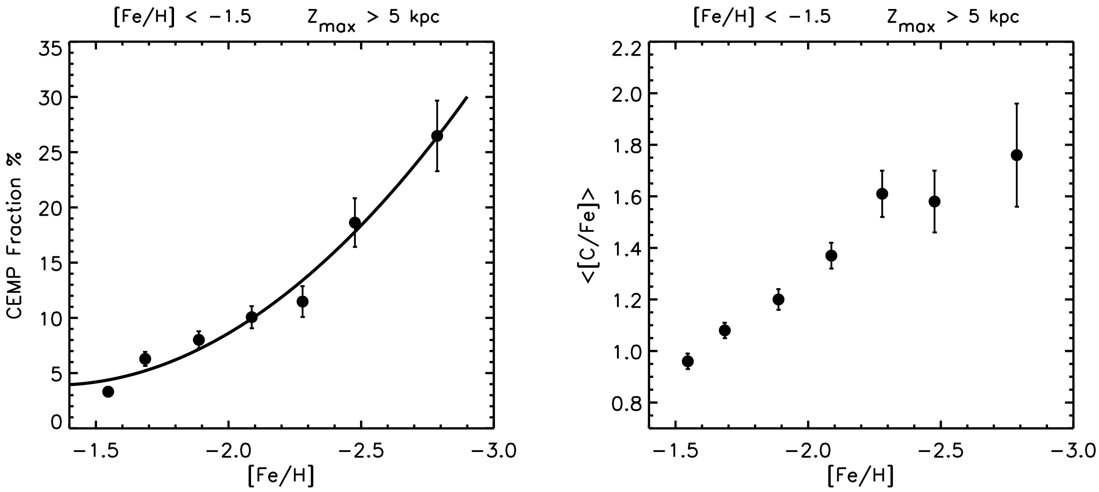

Figure 1. Left panel: Global trend of the CEMP fraction, as a function of [Fe/H], for the low-metallicity SDSS calibration stars with $Z_{max} > 5$ kpc. Each bin of metallicity has width Δ[Fe/H] = 0.2 dex, with the exception of the lowest-metallicity bin, which includes all stars with [Fe/H] < −2.6. The error bars are evaluated with the jackknife method. A second-order polynomial fit to the observed distribution is shown by the dot-dashed line. Right panel: Global trend of the mean carbonicity, ⟨[C/Fe]⟩, as a function of [Fe/H]. Only those stars with detected CH G-bands are used. The bins are the same as used in the left panel. Errors are the standard error in the mean.

- *Almost all* of the CEMP stars are located in the halo components of the Milky Way.
- At low metallicities ([Fe/H] < −1.5), the distribution of derived distances and rotational velocties for the CEMP and non-CEMP stars differ significantly from one another.
- In the low-metallicity regime, [Fe/H] < −1.5, and at vertical distances $Z_{max} > 5$ kpc (where Z_{max} refers to the maximum distance from the Galactic plane reached during the course of a stellar orbit), a continued increase of the fraction of CEMP stars with declining metallicity is found (Figure 1, left panel). A second-order polynomial provides a good fit to the CEMP star fraction as a function of [Fe/H].
- In the same metallicity regime, the mean carbonicity, ⟨[C/Fe]⟩, increases with declining metallicity (Figure 1, right panel).
- In the low-metallicity regime, for both −2.0 < [Fe/H] < −1.5 and [Fe/H] < −2.0, Carollo et al. find a clear increase in the CEMP star fraction with distance from the Galactic plane, |Z| (Figure 2). At these low metallicities, significant contamination from the disk populations is unlikely, and would only reasonably have a small effect for the bin with 0 kpc < |Z| < 4 kpc and −2.0 < [Fe/H] < −1.5; this is an observed property of the halo system. *Such a result would be difficult to understand in the context of a single halo population*.
- At low metallicity, −2.0 < [Fe/H] < −1.5, where the dominant component is the inner halo, a kinematic decomposition of this population from the outer-halo population reveals no significant difference in the CEMP star fraction between the inner/outer halo. In contrast, at very low metallicity, −2.5 < [Fe/H] < −2.0, where the dominant component is the outer halo, there is evidence for a significant difference in the CEMP star fraction between the inner halo and the outer halo (Figure 3); the fraction of CEMP stars associated with the outer halo in this metallicity interval is roughly twice that associated with the inner halo. This difference is also confirmed in the lowest metallicity bin, −3.0 < [Fe/H] < −2.5, even though it is less remarkable, due to the smaller numbers of stars and proportionately larger error bars. Carollo et al. conclude that the difference in CEMP frequency at very low metallicity is driven *not by metallicity itself, but rather, by the stellar populations present.*

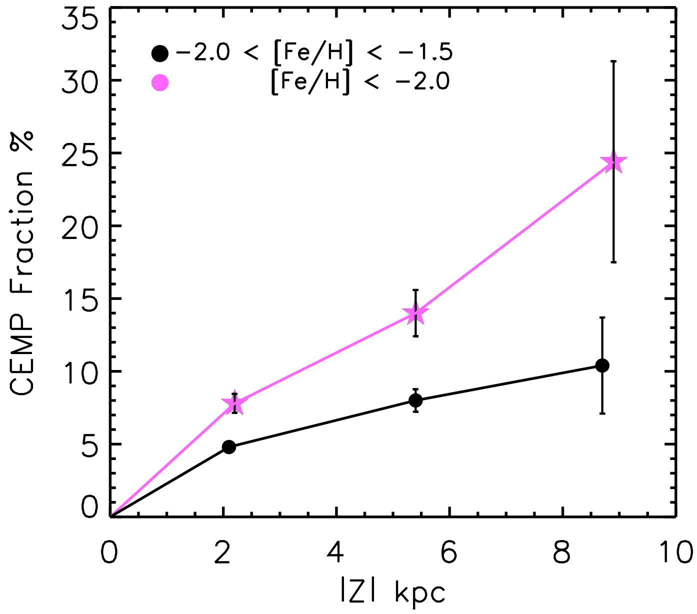

Figure 2. Global trend of the CEMP star fraction, as a function of distance from the Galactic plane, |Z|, for the low-metallicity stars of the Extended Sample described by [7]. The stars with $-2.0 < [\mathrm{Fe/H}] < -1.5$ are shown as filled black circles; those with $[\mathrm{Fe/H}] < -2.0$ are shown as magenta stars. Each bin has a width of $\Delta|Z| = 4$ kpc, with the exception of the last bin, which cuts off at 10 kpc, the limiting distance of the Extended Sample. Note the clear dependence of CEMP fraction on height above the Galactic plane, for both metallicity regimes.

4. IMPLICATIONS FOR GALAXY FORMATION

The large fractions of CEMP stars in both halo components indicates that significant amounts of carbon were produced in the early stages of chemical evolution in the Universe. The observed contrast of CEMP star fractions in the inner- and outer-halo populations strengthen the picture that the halo components had different origins, and supports a scenario in which the outer-halo component has been assembled by the accretion of small subsystems. In this regard, it is interesting that the MDF of the inner halo (peak at $[\mathrm{Fe/H}] \sim -1.6$) is in the metallicity regime associated with the CEMP-*s* stars, which are primarily found with $[\mathrm{Fe/H}] > -2.5$, while the MDF of the outer halo (peak at $[\mathrm{Fe/H}] \sim -2.2$), might be associated with the metallicity regime of the CEMP-*no* stars, which are primarily found with $[\mathrm{Fe/H}] < -2.5$.

The fact that, in the metal-poor regime, the outer halo exhibits a fraction of CEMP stars that is larger than the inner halo suggests that multiple sources of carbon, besides the nucleosynthesis of AGB stars in binary systems, were present in the pristine environment of the outer-halo progenitors (lower mass sub-halos). These sources could be the fast massive rotators and/or the faint supernovae mentioned above. If the CEMP stars in the outer halo are predominantly CEMP-*no* stars (which has yet to be established), it might suggest that non-AGB-related carbon production took place in the primordial mini-halos. The predominance of CEMP-*s* stars in the inner halo, if found, would suggest that the dominant source of carbon was the nucleosynthesis in AGB stars in a binary system. This would place important constraints on the primordial IMF of the sub-systems responsible for the formation of the two halo components.

Recent efforts to model, from the population synthesis standpoint, the fractions of observed CEMP stars in the halo have struggled to reproduce results as high as 15–20% for metallicities $[\mathrm{Fe/H}] < -2.0$ [13, 21]. Note, however, that these predictions are based solely on carbon production by AGB stars. While such calculations may prove meaningful for the inner-halo population, they may not be telling

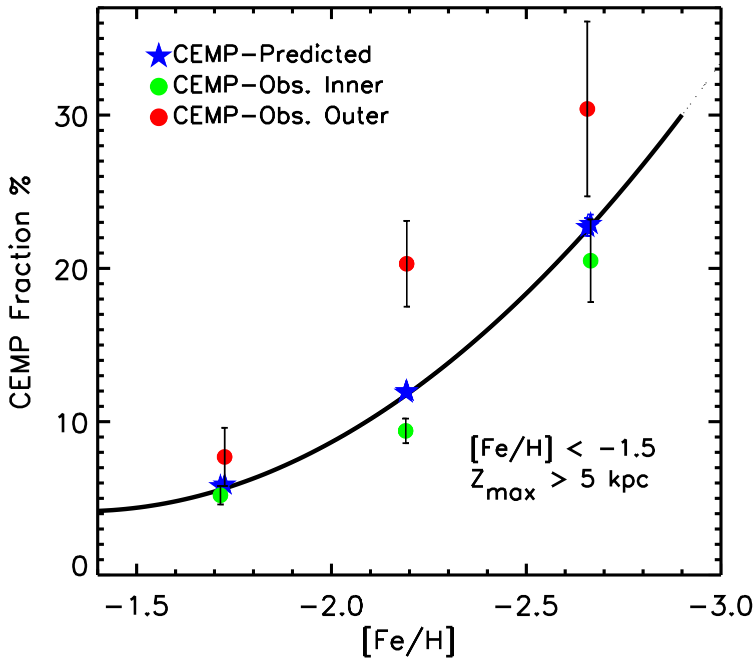

Figure 3. Global trend of the CEMP star fraction as a function of [Fe/H] for the low-metallicity stars of the Extended Sample with $Z_{max} > 5$ kpc. The dashed curve is a second-order polynomial fit representing the global trend. The blue filled stars represent the predicted values of the CEMP fractions in each bin of metallicity, having a width of Δ[Fe/H] $= 0.5$ dex. The green and red filled circles show the location of the observed CEMP star fractions for the inner halo and outer halo, respectively, based on the kinematic deconvolution method described by [7].

the full story for carbon production associated with the progenitors of the outer-halo population. The lower CEMP fraction in the inner halo may relieve some of the tension with current model predictions.

The fact that the CEMP star fraction exhibits a clear increase with $|Z|$ suggests that the relative numbers of CEMP stars in a stellar population is not driven by metallicity alone. The proposed coupling of the cosmic microwave background to the IMF [14, 23] is one mechanism for imposing a temporal dependence on the IMF. This effect, coupled with chemical evolution models, predicts that the CEMP fraction would be expected to increase as the metallicity decreases, but with similar metallicity regimes forming carbon according to the expected yields of the predominant mass range available at that time. In the hierarchical context of galaxy formation, star-forming regions are spatially segregated, and their chemical evolution can proceed at different rates, with stars at the same metallicity forming at different times. Depending on the source(s) of carbon, this trend could lead to a spatial variation of the CEMP fraction at the same metallicity, increasing in older populations and decreasing in younger ones.

5. THE PATH FORWARD

We have used this article to illustrate one application of the dual-halo model to understand the formerly unexplained increase in the fraction of CEMP stars with declining metallicity, demonstrating that it arises from the differing nature of the stellar populations associated with the inner/outer halo.

Further exploration of the CEMP stars, in particular the CEMP-*no* sub-class, which may well have arisen from non-AGB sources of carbon production, should prove of great interest. Connections of such stars with chemical production in early epochs are now being made. For example, the recently reported high-redshift ($z = 2.3$), extremely metal-poor Damped Lyman-α system ([8], [Fe/H] ~ -3.0) exhibits enhanced carbonicity ([C/Fe] = +1.5) and other elemental abundance signatures that are quite similar to those of the CEMP-*no* stars, and which [15] associate with production by faint supernovae. It is also of interest that evidence for strong carbon production in the early Universe has been reported [18], based on analysis of the optical spectrum of the most distant known radio galaxy, TN J0924-2201, with $z = 5.19$. When viewed in this light, the CEMP-*no* stars may well prove to be our local touchstone to the abundance patterns produced by the very FIRST generations of stars, an exciting prospect!

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