CARBON-ENHANCED METAL-POOR STARS IN SDSS/SEGUE. II. COMPARISON OF CEMP-STAR FREQUENCIES WITH BINARY POPULATION-SYNTHESIS MODELS

YOUNG SUN LEE1, TAKUMA SUDA2, TIMOTHY C. BEERS3,4, AND RICHARD J. STANCLIFFE5

1 Department of Astronomy, New Mexico State University, Las Cruces, NM 88003, USA; yslee@nmsu.edu
2 National Astronomical Observatory of Japan, Osawa 2-21-1, Mitaka, Tokyo 181-8588, Japan
3 National Optical Astronomy Observatory, Tucson, AZ 85719, USA
4 Joint Institute for Nuclear Astrophysics (JINA), Michigan State University, East Lansing, MI 48824, USA
5 Argelander-Institut für Astronomie, Auf dem Hügel 71, D-53121 Bonn, Germany

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ABSTRACT

We present a comparison of the frequencies of carbon-enhanced metal-poor (CEMP) giant and main-sequence turnoff (MSTO) stars with predictions from binary population-synthesis models involving asymptotic giant-branch (AGB) mass transfer. The giant and MSTO stars are selected from the Sloan Digital Sky Survey and the Sloan Extension for Galactic Understanding and Exploration. We consider two initial mass functions (IMFs)—a Salpeter IMF, and a mass function with a characteristic mass of 10 M⊙. For giant stars, the comparison indicates a good agreement between the observed CEMP frequencies and the AGB binary model using a Salpeter IMF for [Fe/H] > −1.5, and a characteristic mass of 10 M⊙ for [Fe/H] < −2.5. This result suggests that the IMF shifted from high- to low-mass dominated in the early history of the Milky Way, which appears to have occurred at a “chemical time” between [Fe/H] = −2.5 and [Fe/H] = −1.5. The CEMP frequency for the turnoff stars with [Fe/H] < −3.0 is much higher than the AGB model prediction from the high-mass IMF, supporting the previous assertion that one or more additional mechanisms, not associated with AGB stars, are required for the production of carbon-rich material below [Fe/H] = −3.0. We also discuss possible effects of first dredge-up and extra mixing in red giants and internal mixing in turnoff stars on the derived CEMP frequencies.

Key words: Galaxy; halo – methods: data analysis – stars: abundances – stars: AGB and post-AGB – stars: carbon – techniques: imaging spectroscopy

Online-only material: color figures

1. INTRODUCTION

Numerous spectroscopic studies of metal-poor ([Fe/H] < −1.0) candidates identified by the HK survey (Beers et al. 1985, 1992) and the Hamburg/ESO Survey (Wisotzki et al. 1996; Christlieb et al. 2001, 2008; Christlieb 2003) have revealed that the frequency of carbon-enhanced stars increases greatly with decreasing [Fe/H]. These stars, now known as carbon-enhanced metal-poor (CEMP) stars, were originally defined as stars with metallicity [Fe/H] ≤ −1.0 and carbon-to-iron ratios [C/Fe] ≥ +1.0 (Beers & Christlieb 2005). Generally, the frequency of C-rich stars increases from a few percent at higher metallicity to on the order of 20% for [Fe/H] < −2.0, 30% for [Fe/H] < −3.0, 40% for [Fe/H] < −3.5, and 75% for [Fe/H] < −4.0 (Beers et al. 1992; Norris et al. 1997, 2007, 2013; Rossi et al. 1999, 2005; Beers & Christlieb 2005; Cohen et al. 2005; Marsteller et al. 2005; Frebel et al. 2006; Lucatello et al. 2006; Carollo et al. 2012; Spite et al. 2013; Yong et al. 2013). This increasing trend of CEMP-star frequency with declining [Fe/H] is again confirmed from the many thousands of CEMP stars found among the several hundred thousand stars with available spectra from the Sloan Digital Sky Survey (SDSS; Fukugita et al. 1996; Gunn et al. 1998, 2006; York et al. 2000; Stoughton et al. 2002; Abazajian et al. 2003, 2004, 2005, 2009; Pier et al. 2003; Adelman-McCarthy et al. 2006, 2007, 2008; Aihara et al. 2011; Ahn et al. 2012) and the Sloan Extension for Galactic Understanding and Exploration (SEGUE-1; Yanny et al. 2009), and SEGUE-2 (C. Rockosi et al., in preparation), as described by Lee et al. (2013).

There exist a number of subclasses within the CEMP classification, as originally defined by Beers & Christlieb (2005), which may provide direct clues to the nature of their likely progenitors. Stars in the CEMP-s subclass exhibit over-abundances of s(low)-process elements such as Ba and Sr, the CEMP-r/s subclass includes stars with enhanced r(apid)-process elements such as Eu, and the CEMP-r/s stars exhibit elemental abundance patterns associated with both the r-process and the s-process. The CEMP-no subclass exhibits no over-abundances of the neutron-capture elements.

The CEMP-s (and CEMP-r/s) subclasses of CEMP stars are the most common found to date; high-resolution spectroscopic studies show that around 80% of the CEMP stars are categorized as CEMP-s (or CEMP-r/s; Aoki et al. 2007, 2008). The favored mechanism for the production of the high [C/Fe] ratios found for CEMP-s (CEMP-r/s) stars is mass transfer of carbon-enhanced material from the envelope of a now-defunct asymptotic giant-branch (AGB) star to its (presently observed) binary companion (Suda et al. 2004; Herwig 2005; Komiya et al. 2007; Sneden et al. 2008; Stancliffe 2009; Masseron et al. 2010; Bisterzo et al. 2011, 2012; Lugger et al. 2012). Observational evidence now exists to suggest that the CEMP-r/s stars (and other r-process-element rich stars) were enhanced in r-process elements in their natal gas clouds by previous generations of supernovae (SNe), and did not require a contribution of r-process elements from a binary companion (see Hansen et al. 2013).

The limited amount of long-term radial-velocity monitoring available for CEMP stars indicates radial-velocity variations
for almost all of the CEMP-s stars, confirming their binary status (Lucatello et al. 2005b). In addition, the CEMP-s stars are mostly, though not exclusively (e.g., Norris et al. 2013 and references therein), found among metal-poor stars with [Fe/H] > −3.0. On the other hand, CEMP-no stars are found most commonly among the extremely metal-poor (EMP) stars, with [Fe/H] < −3.0 (Aoki et al. 2007; Norris et al. 2013). Existing radial-velocity monitoring of these objects indicates that they are found in binary systems no more frequently than other metal-poor stars (T. Hansen et al., in preparation). Norris et al. (2013) found no CEMP-s stars among 18 CEMP stars with [C/Fe] ≥ +0.7 and [Fe/H] < −3.1, as well as no discernible variations of their radial velocities. The recent study by Starkenburg et al. (2014) has confirmed that the majority of CEMP-no stars are not binaries.

Although there is general consensus on the origin of CEMP-s stars, the likely progenitor (or progenitors) of the CEMP-no stars is still under discussion. Suggested models include massive, rapidly rotating, mega metal-poor (MMP; [Fe/H] < −3.0) stars, which produce large amounts of C, N, and O due to distinctive internal burning and mixing episodes (Meynet et al. 2006, 2010; Chiappini 2013), and faint (low-energy) SNe associated with the first generations of stars, which experience extensive mixing and fallback during their explosions, and eject large amounts of C and O, but not heavier metals (Umeda & Nomoto 2003, 2005; Tominaga et al. 2007, 2014; Ito et al. 2009, 2013; Nomoto et al. 2013). Nevertheless, the origin of the CEMP-no star phenomenon is yet to be fully resolved (see Norris et al. 2013, which summarizes other possible progenitors of the C-rich stars).

Previous authors have attempted to understand the different subclasses of the CEMP stars, as well as the large fractions of CEMP stars at low metallicity, by invoking AGB models with different masses. Furthermore, there have been several efforts to constrain the form of the early initial mass function (IMF) by reproducing the observed frequencies of CEMP stars, as well as the number ratios of the different CEMP subclasses. Abia et al. (2001), for example, claimed that the large number of carbon-enhanced stars found among stars of very low metallicity could be accounted for if the IMF in the early history of the Galaxy was dominated by higher-mass stars. Lucatello et al. (2005a) and Komiyama et al. (2007) utilized population-synthesis models with an IMF biased toward massive stars to compare with the fractions of observed CEMP stars, and concluded that an IMF comprising a larger number of intermediate- to high-mass stars could reproduce the larger fraction of the CEMP stars among metal-poor stars ([Fe/H] < −2.5) better than the present-day (Salpeter) IMF. Recently, Suda et al. (2013) made use of the number ratios of CEMP/EMP, CEMP-no/CEMP, and NEMP/CEMP giant stars (where NEMP stands for nitrogen-enhanced metal-poor) from the Stellar Abundances for Galactic Archaeology (SAGA; Suda et al. 2008) database to constrain the parameters in their binary population-synthesis model. They considered several IMFs, and proposed that the IMF changed from high-mass dominated in the early Galaxy to low-mass (M < 0.8 M☉) dominated at present, and that this transition occurred around a metallicity of [Fe/H] ∼ −2.0.

The CEMP stars that have been studied with high-resolution spectroscopy are mostly giants (for which it is simpler to obtain high signal-to-noise ratio (S/N) spectra, due to their relative brightness and moderate temperatures, which allows for lines of interest to be measured with less uncertainty). The numbers of observed dwarf and turnoff stars with similar observations are in any case too small to derive statistically meaningful results for different subclasses of CEMP stars, and these stars are mostly restricted to very low metallicity ([Fe/H] < −2.0).

In this study, we make use of stars with available carbon-to-iron ratios ([C/Fe]) and [Fe/H], based on medium-resolution (R ∼ 2000) spectroscopy obtained during the course of SDSS, SEGUE-1, and SEGUE-2, in order to derive accurate frequencies of CEMP stars among giants and turnoff stars as a function of metallicity, over a wide range of [Fe/H]. The derived CEMP frequencies are then compared with the predictions from AGB binary-synthesis models that employ the two different IMFs explored by Suda et al. (2013). The results of these comparisons should provide more stringent constraints on the IMF of the Milky Way, and clues to the existence of progenitors other than AGB stars that are capable of producing large amounts of carbon-enhanced material in the early universe.

This paper is outlined as follows. In Section 2, we describe the selection criteria used to assemble the sample for this study, Section 3 presents and discusses results of the comparison of the CEMP frequencies for giants and main-sequence turnoff (MSTO) stars with the binary-synthesis model predictions, and describes a procedure for correcting the anticipated undercounts of CEMP stars among warm, metal-poor turnoff stars. Our conclusions are presented in Section 4.

2. CARBON-ENHANCED SDSS/SEGUE STARS

The SDSS, SEGUE-1, and SEGUE-2 surveys have produced an unprecedented number of high-quality medium-resolution stellar spectra, covering stars in various evolutionary stages, and spanning a wide range of metallicity (−4.0 < [Fe/H] < +0.5). A total of about 600,000 stars from these surveys are potentially suitable for examination of the properties of the Milky Way’s stellar populations. The resolving power of the spectra is R ∼ 2000, over the wavelength range 3820–9100 Å. Below, we simply refer to these stars (spectra) as SDSS/SEGUE stars (spectra). Accurate estimates of the atmospheric parameters for most of the SDSS/SEGUE stars are derived using the latest version of the SEGUE Stellar Parameter Pipeline (SSPP; Lee et al. 2008a, 2008b, 2011; Allende Prieto et al. 2008; Smolinski et al. 2011). The typical external errors obtained by the SSPP are 180 K for log Teff, 0.24 dex for log g, and 0.23 dex for [Fe/H], respectively (Smolinski et al. 2011). In addition, estimates of the carbonicity, [C/Fe], are obtained following the prescription of Lee et al. (2013), for stars with 4400 ≤ T eff ≤ 6700 K, where accurate [C/Fe] can be determined. As reported by Lee et al., uncertainties in the determination of [C/Fe] are smaller than 0.35 dex for SDSS/SEGUE spectra with S/N ≥ 15 Å−1.

In order to derive reliable frequencies of the CEMP stars among the stellar field populations, we follow the selection criteria of Lee et al. (2013). Briefly, we first exclude all stars located in the directions of known open and globular clusters. For stars that were observed more than once, we keep only the parameters derived from the highest S/N spectrum. We then restrict the sample to stars with spectra having S/N ≥ 20 Å−1, effective temperatures in the range 4400 K ≤ T eff ≤ 6700 K, and metallicities in the range −4.0 ≤ [Fe/H] ≤ +0.5, so that our estimates of [C/Fe] are as reliable as possible. We then visually inspect each spectrum with [Fe/H] ≤ −2.0, in order to reject spectra for stars such as cool white dwarfs, or those with emission-line features in the cores of their Ca ii lines, or other spectral defects that could lead to spurious determinations of metallicity by the SSPP. Additionally, we visually examine...
the spectra for all stars with $[\text{C/Fe}] > +0.7$, and exclude stars with poor estimates of $[\text{Fe/H}]$ and/or $[\text{C/Fe}]$. Following Lee et al., for the purpose of deriving the CEMP frequencies we do not consider stars with $[\text{C/Fe}] > +0.7$ and a flag indicating that the measurement is an upper limit as CEMP stars, but rather, consider these stars to have unknown carbon status. By application of the above procedures, we are left with a sample of about 247,350 stars.

For the purpose of our analysis, we consider stars with $4400 \, \text{K} \leq T_{\text{eff}} \leq 5600 \, \text{K}$ and $1.0 \leq \log g < 3.2$ as giants, and stars with $5600 \, \text{K} \leq T_{\text{eff}} \leq 6600 \, \text{K}$ and $3.2 \leq \log g < 4.5$ as MSTO stars. The distance to each star is estimated following the prescriptions of Beers et al. (2000, 2012), which obtains photometric distance estimates with errors on the order of 10%–20%.

Note that we have added stars to our sample from Table 1 of Yong et al. (2013), and one object from Caffau et al. (2011), with determinations based on high-resolution spectroscopic analyses, in order to increase the number of stars with $[\text{Fe/H}] < -3.0$. This results in better number statistics for the calculation of the CEMP frequencies in the extremely and ultra metal-poor regime.

3. RESULTS AND DISCUSSION

3.1. Differences in Average $[\text{C/Fe}]$ Between Giants and Turnoff Stars

Figure 1 shows the distribution of $[\text{C/Fe}]$ for SDSS/SEGUE stars in various bins of metallicity, decreasing from the upper to lower panels. MSTO stars are shown as solid histograms; giants are shown as dashed histograms. Inspection of this figure reveals that the overall distribution of $[\text{C/Fe}]$ gradually shifts (for both turnoff stars and giants) to higher $[\text{C/Fe}]$ with decreasing $[\text{Fe/H}]$, with a tail extending toward higher $[\text{C/Fe}]$ appearing as the metallicity decreases. As the metallicity decreases below $[\text{Fe/H}] = -3.0$, this trend becomes less evident for both samples due to small-number statistics.

Another interesting feature seen in Figure 1 is that for $[\text{Fe/H}] < -3.0$, the turnoff stars are distributed over a wide range of $[\text{C/Fe}]$, whereas the giants are mostly concentrated in the region of $[\text{C/Fe}] < +1.0$. The red vertical lines in Figure 1 indicate the mean values of $[\text{C/Fe}]$ for the turnoff stars (solid lines) and giants (dashed lines), respectively. On average, the giants appear to exhibit lower carbonicity (by about 0.2 dex) than the turnoff stars, down to $[\text{Fe/H}] = -2.0$. The mean value of $[\text{C/Fe}]$ appears to increase with decreasing metallicity, as also found by Carollo et al. (2012), their Figure 11. They reported that the degree of carbon enhancement significantly increased from $[\text{C/Fe}] \sim +1.0$ at $[\text{Fe/H}] = -1.5$ to $[\text{C/Fe}] \sim +1.7$ at $[\text{Fe/H}] = -2.7$, somewhat higher than our values (it should be noted that a different sample of stars, as well as a different method for determination of $[\text{C/Fe}]$, were employed by these authors).

Bonifacio et al. (2009) also noted a difference in the mean $[\text{C/Fe}]$ between giants and turnoff stars of similar metallicities, finding a difference of about 0.2 dex (giants being lower) for stars with $[\text{Fe/H}] < -2.5$. A similar result was also obtained by Denissenkov & Pinsonneault (2008). The difference in the distribution of $[\text{C/Fe}]$ between the turnoff stars and the giants may be explained by the different masses of the convective envelopes between the two evolutionary stages. Because a giant has a much deeper convective envelope, its surface material experiences more mixing, leading to reduction of the carbonicity. On the other hand, the turnoff stars have shallower convective envelopes, so that their surface abundances may not be expected to greatly change, unless some non-convective mixing mechanism, such as thermohaline mixing (Stancliffe et al. 2007), rotation (e.g., Sweigart & Mengel 1979; Charbonnel et al. 1998; Denissenkov et al. 2006), or other diffusive processes (Richard et al. 2005; Lind et al. 2008; Korn et al. 2007; Gruyters et al. 2013) are active. More details on these mixing processes are provided in the following sections.

Bonifacio et al. (2009) also suggested the stellar models employed in the analysis could contribute to this discrepancy: they found a smaller difference between the giants and turnoff stars when deriving $[\text{C/Fe}]$ from a three-dimensional, rather than a one-dimensional model atmosphere.

3.2. Comparison of the Frequencies of C-rich Giants with Model Predictions

The black filled circles in Figure 2 represent the derived differential frequencies for C-rich giants, as a function of $[\text{Fe/H}]$. 

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Distribution of $[\text{C/Fe}]$ for SDSS/SEGUE stars over different ranges of $[\text{Fe/H}]$, decreasing from the upper to lower panels. Main-sequence turnoff stars are shown as solid histograms; giants are shown as dashed histograms. The metallicity range in each panel is indicated by the legends, along with the total number of stars shown in the histograms. The solid and dashed red vertical lines indicate the mean values of $[\text{C/Fe}]$ for the turnoff stars and giants, respectively. On average, the turnoff stars exhibit higher carbon enhancement than the giants. (A color version of this figure is available in the online journal.)

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et al. (2005, 2006), Lucatello et al. (2006), and Aoki et al. (2007), this may be in part due to CN-processing, both from the action of first dredge-up (FDU) and subsequently from the occurrence of extra mixing along the upper part of the giant branch. The C-rich material at the surface of a giant could be easily diluted by the deepening of the convective envelope as the star begins to ascend the giant branch, which also dredges up CN-processed material from its interior during the FDU episode, leading to a decrease in the carbon abundance. In addition, the more luminous red giant branch (RGB) stars can suffer from additional mixing of material by convective overshooting, rotation, internal gravity waves, or thermohaline instabilities. Stancliffe & Lattanzio (2011) provide a recent review of each of these processes. Such extra mixing processes, apart from the FDU, might further reduce the carbon abundance.

However, it has also been argued that for CEMP stars, the reduction of the observed carbon abundances by these processes (FDU and extra mixing) may not be significant. For example, Stancliffe et al. (2009) showed that as a result of thermohaline mixing in their stellar-evolution models, while carbon-normal ([C/Fe] < +1.0) stars experienced a significant reduction of the carbon abundance, their carbon-rich counterparts did not, suggesting that extra mixing may not affect the calculated fraction of CEMP stars. Observational studies (e.g., Gratton et al. 2000; Smith & Martell 2003; Martell et al. 2008; Denissenkov & Pinsonneault 2008) support the larger effect of extra mixing on C-normal stars on the upper RGB. These studies also suggested that extra mixing is more efficient at lower metallicity. Whether or not a giant experienced such mixing can be tested by measuring its $^{12}\text{C}/^{13}\text{C}$ or [C/N] ratios, as both will be lower for an object that has gone through such an event (see, for example, the models presented by Stancliffe et al. 2009). Unfortunately, these ratios are difficult to assess from the SDSS/SEGUE spectra over the full range of metallicities we consider.

The effect of FDU on the dilution of accreted material is very dependent on the composition and mass of the accreted material, as well as on the assumed physics of the mixing. Because material ejected from an AGB star experienced significant nuclear processing, it has a notably higher mean molecular weight than the pristine material of the mass-receiving star. The situation of higher mean molecular weight material lying on top of lower mean molecular weight material is unstable to the process of thermohaline mixing. In the context of CEMP stars, the effects of thermohaline mixing were first noted by Stancliffe et al. (2007). They showed that in some circumstances, thermohaline mixing could lead to the accreted material being mixed throughout about 90% of the secondary star. In such cases, the depth of mixing is crucially greater than the depth that the convective envelope reaches during the FDU. Thus, there is no subsequent dilution of material at FDU, and little decline in the surface carbon abundance is found. However, if the accreted material is not mixed so deeply, there can still be dilution of the accreted material at FDU, but the change in the surface carbon abundance is not so great as in the case that the material is unmixed (e.g., Stancliffe & Glebbeek 2008; Stancliffe et al. 2013).

Suda et al. (2004) also noticed the insignificant effect of carbon dilution at FDU, in the case of a large amount of carbon material being accreted—too large to be significantly depleted by the relatively small amount of matter in the hydrogen-burning shell, $M < 0.02 \, M_\odot$. Even in cases of EMP stars for which the initial carbon abundance is small, Suda & Fujimoto (2010) suggested that extra mixing is more efficient at lower metallicity. Whether or not a giant experienced such mixing can be tested by measuring its $^{12}\text{C}/^{13}\text{C}$ or [C/N] ratios, as both will be lower for an object that has gone through such an event (see, for example, the models presented by Stancliffe et al. 2009). Unfortunately, these ratios are difficult to assess from the SDSS/SEGUE spectra over the full range of metallicities we consider.

Figure 2. Differential frequencies of CEMP giants (defined as stars with 4400 K < $T_{\text{eff}}$ < 6500 K and 1.0 < log $g$ < 3.2), as a function of [Fe/H]. Bin sizes of 0.5 dex in [Fe/H] are used for stars with [Fe/H] > −3.5; a single bin for stars with [Fe/H] < −3.5 is used. Each bin is represented by the average [Fe/H] of stars in the bin. Filled circles show the derived frequencies of the CEMP stars for all giants, while the filled squares represent the subsample of CEMP stars for giants located more than 5 kpc from the Galactic plane, $|Z| > 5$ kpc. The filled triangles indicate stars located closer to the plane, with $|Z| < 5$ kpc. The prediction of the CEMP frequencies as a function of [Fe/H], based on an AGB nucleosynthesis model with IMF peaked at 10 $M_\odot$, is indicated by the open circles, while the open squares denote the prediction assuming a Salpeter IMF. The definition of [C/Fe] > +0.7 as a C-rich object is adopted for both the model predictions and the derived frequencies. Error bars are based on Poisson statistics.

(A color version of this figure is available in the online journal.)
showed that the effect of the FDU is also limited, due to the shallower convective envelopes in metal-poor (as compared to metal-rich) stars. According to their model calculation, the change of the CNO abundances before and after the FDU was on the order of one percent. Therefore, they did not notice a large impact on the surface carbon abundances after FDU for stars with [Fe/H] < −2.3. On the other hand, Denissenkov & Pinsonneault (2008) noticed a small reduction, by about 0.4 dex, in [C/H] from the turnoff to RGB stars from the sample by Lucatello et al. (2006), which they took as due to the effects of the FDU.

Thus, FDU and extra mixing do not seem to greatly influence the surface carbon abundance for CEMP stars; as a result, the fraction of the CEMP giants would not be expected to be altered by these processes. Hence, it is challenging to explain the constant trend of the CEMP frequencies with [Fe/H] in Figure 2. However, we recognize that a small reduction by FDU and extra mixing in the C-abundance for stars with [C/Fe] < +1.0 could influence the derived CEMP frequencies, depending on the definition of a C-rich star that is adopted. In this study, we regard to a star with [C/Fe] ≥ +0.7 as a C-rich star. Should we have chosen the criterion of [C/Fe] ≥ +1.0, we notice a slightly increasing trend of the CEMP frequency with decreasing metallicity. If the stars having [C/Fe] between +0.7 and +1.0 were instead converted to C-normal stars due to FDU and extra mixing, we would obtain lower numbers of C-rich stars. Hence, the declining trend of the CEMP frequency below [Fe/H] = −3.0 is possibly caused by the adopted definition of the C-rich star, and the effects of FDU and metallicity-dependent extra mixing.

The blue open circles in Figure 2 are the predicted frequencies of CEMP giants, as a function of metallicity, from AGB binary-synthesis models with an IMF peaked at 10 M⊙, while the open squares are the predicted frequencies from models using a Salpeter IMF, adopted from Suda et al. (2013). In their model, they included a mechanism referred to as “pulsation-driven mass loss” (Wood 2011), which was argued to suppress the previously predicted over-production of NEMP stars by Izzard et al. (2009) and Pols et al. (2012). It appears that the predicted CEMP frequencies for the high-mass dominated IMF are in relatively good agreement with the observed CEMP giant frequencies for [Fe/H] < −2.5, but the model predicts too many C-rich stars above [Fe/H] = −2.5. The predicted CEMP frequencies from a Salpeter IMF are in good agreement with our derived frequencies for the metal-rich region ([Fe/H] > −1.5), while the predicted CEMP frequencies are far too low for stars with [Fe/H] < −2.5.

These are similar results to those found by Suda et al. (2013), who used the giants in the SAGA database to compare the observed CEMP frequencies with their model predictions. One of the reasons that Suda et al. (2013) employed giants to derive the CEMP frequency is that one can ignore effects such as atomic diffusion, which can alter the surface abundances of dwarfs and turnoff stars more significantly than in giants (e.g., Richard et al. 2002a, 2002b; Korn et al. 2007; Lind et al. 2008; Stancliffe & Glebbeek 2008; Gruyters et al. 2013). Our derived frequencies show a much better agreement for the Salpeter IMF in the metallicity region [Fe/H] > −1.5. In the study of Suda et al. (2013), the model-predicted frequency of the CEMP stars above [Fe/H] = −2.0 was not well-constrained, most likely due to the selection biases associated with the assembly of their sample from previous high-resolution spectroscopic studies (which tended to emphasize the more metal-poor and/or carbon-enhanced stars). In contrast, the good agreement of the frequencies calculated from our considerably less-biased SDSS/SEGUE sample with the model prediction for [Fe/H] > −1.5 suggests that the AGB binary-synthesis model with a Salpeter mass function used by Suda et al. (2013) works well, at least in this metallicity regime.

Based on the results from the comparisons of the observed CEMP frequencies with model predictions from the two different IMFs, we conjecture that for very low-metallicity ([Fe/H] < −2.5) stars, the distribution of the stellar masses was dominated by rather massive stars (~10 M⊙ or higher), while for the relatively more metal-rich stars ([Fe/H] > −1.5), it appears that the IMF did not much differ from a Salpeter IMF, which is biased toward low-mass progenitor stars (M < 0.8 M⊙). As previously claimed by Suda et al. (2013), our results also support the idea that there must exist a shift in the IMF from a high-mass dominated to low-mass dominated form in the early history of the Milky Way, corresponding to a “chemical time” between [Fe/H] = −2.5 and [Fe/H] = −1.5.

However, by way of comparison, the binary population-synthesis model of Izzard et al. (2009) was able to reproduce the ratio of NEMP to very metal-poor (VMP; [Fe/H] < −2.0) stars (that is, C- and N-normal stars) without introducing an IMF dominated by higher-mass stars, but not the high frequency of the CEMP stars. Pols et al. (2012) also argued, by comparing the observed number ratio of NEMP to CEMP stars with their model predictions, that they could derive a similar number ratio from a Salpeter IMF, and ruled out an IMF peaked at 10 M⊙, as claimed by Komiyama et al. (2007).

3.3. Behavior of Derived CEMP Frequencies with Distance from the Galactic Plane

Another interesting result emerges when one partitions the giant sample based on distance from the Galactic plane. The green squares in Figure 2 are the CEMP frequencies for giants with distances from the Galactic mid-plane (|Z|) larger than 5 kpc, whereas the red triangles represent frequencies based on those with |Z| < 5 kpc.8 The figure clearly indicates that the more distant halo giants exhibit higher frequencies of C-rich stars, while the stars closer to the Galactic plane tend to have lower frequencies of C-rich stars. This same trend with vertical distance was only hinted at (due to small-number statistics) in Frebel et al. (2006), but strongly confirmed in the much larger sample of SDSS/SEGUE calibration stars considered by Carollo et al. (2012). Carollo et al. argued that this result was likely due to the fact that the outer-halo population has about twice the frequency of CEMP stars, at a given low metallicity, as the inner-halo population.

A few possible reasons for the observed differences in the CEMP frequencies between the two spatial regions might be suggested within the context of the AGB model predictions. First, the progenitors of the inner-halo population (which dominates for |Z| < 5 kpc) and the outer-halo population (which, at |Z| > 5 kpc, includes more outer-halo stars) might have formed their stars at different times, with different IMFs. Because the outer-halo population has more CEMP stars than the model prediction for [Fe/H] < −2.5, it is possible that the outer-halo population might have had an IMF with more intermediate-mass stars than considered by the model. On the other hand, since the CEMP frequencies of the inner-halo stars are lower

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8 A more quantitative analysis of the variation of CEMP frequencies with |Z| will be considered in an upcoming paper in this series.
than the model estimate, the inner-halo population might have had an IMF with less intermediate-mass stars than the proposed IMF. Related ideas are discussed by Tumlinson (2007).

Suda et al. (2013) assumed that all CEMP stars, including CEMP-no stars, formed from the AGB binary scenario. If there were to exist other channels of carbon production at [Fe/H] $< -2.5$, such as faint SNe or rapidly rotating massive stars (producing CEMP-no stars in the subsequent generation), as suggested by several studies, we then might expect larger frequencies of CEMP stars than the AGB binary-synthesis model prediction (as seen in Figure 2), even if the carbon dilution of the giants due to FDU events is taken into account. A more detailed discussion of this is provided in Section 3.6.

In any event, the frequency difference we find can be understood (as argued by Carollo et al. 2012) as the result of a change in the dominant population with distance above the plane, from the inner-halo population to the outer-halo population. Carollo et al. further argued that the inner halo is dominated by stars with modest carbon enhancement ([C/Fe] $\sim +0.5$), while the outer halo has a greater portion of stars with large carbon enhancements ([C/Fe] $\sim +2.0$), although considerable overlap still exists. They interpreted these results, as well as the increase in the global frequency of CEMP stars with distance from the Galactic plane, as evidence for the possible presence of additional astrophysical sources of carbon, beyond AGB production alone, associated with the progenitors of the outer-halo stars.

It is difficult to separate CEMP-s and CEMP-no stars from our medium-resolution SDSS/SEGUE spectra, but determination of the ratio of CEMP-s/CEMP-no for stars in the inner- and outer-halo populations, based on high-resolution spectroscopy, will provide not only very strong constraints on the binary-synthesis model, but clues to the origin of the different CEMP frequencies between the inner- and outer-halo populations (see, e.g., Carollo et al. 2014).

### 3.4. Correcting the CEMP Frequencies for Main-sequence Turnoff Stars

Above, we have compared the derived CEMP frequencies from our sample of giants with the predicted CEMP frequencies from AGB binary-synthesis models by Suda et al. (2013). However, as previously mentioned, observations suggest that giants can suffer from dilution of the carbon-rich material in its envelope by mixing during the FDU event (or by extra mixing along the RGB), resulting in a lower overall carbon abundance, and (as a population) lower frequencies of CEMP stars. If such dilution were absent, we would expect that the actual frequencies of CEMP stars among giants would be higher than shown in Figure 2.

The main-sequence stars do not experience such dredge-up episodes; rather, they are presumed to preserve unpolluted (or accreted) material on their surfaces. Therefore, the best way forward would be to compare model predictions with the observed CEMP frequencies based on unevolved stars. However, such stars are not without possible complications. In the context of the AGB mass-transfer scenario, the accreted material onto the surviving secondary star may be mixed into the interior via the action of thermohaline mixing (Stancliffe et al. 2007). It might also be possible that the surface abundances are affected by atomic diffusion (e.g., Lind et al. 2008; Korn et al. 2007) or rotation (e.g., Sweigart & Mengel 1979; Charbonnel et al. 1998; Denissenkov et al. 2006; Masseron et al. 2012).

For instance, Stancliffe et al. (2007) found that the carbon-to-iron ratio could decrease by about 0.8 dex for turnoff stars, when considering the effects of thermohaline mixing. Stancliffe & Glebbeek (2008) further showed that depletion of [C/H] by over 1 dex was possible when gravitational settling was included, although it should also be noted that such models were expected to be too efficient, and some additional turbulent process was necessary to reduce the effect (see Richard et al. 2005 for a full discussion of this point). Lind et al. (2008) obtained medium-high resolution spectroscopy of giant and turnoff member stars of the globular cluster NGC 6397, reporting that the giants exhibited higher abundances in Fe and Mg than the turnoff stars, confirming the conclusion by Korn et al. (2007) that diffusion processes likely caused the discrepancy.

These results indicate that the surface abundances of some elements on the surface of an MSTO star can be altered by such mixing processes. However, as thermohaline mixing could be disrupted by gravitational settling (Thompson et al. 2008), or stellar rotation could hinder the effectiveness of thermohaline mixing (Denissenkov & Pinsonneault 2008), the net surface abundance changes could still be very small, due to interactions among those processes. Unfortunately, the current stellar-evolution models do not provide good understanding on how efficient these processes are, and how they interact with each other, at least in a quantitative manner. For these reasons, as well as the difficulty of including such processes within the population-synthesis framework, in this study we assume that the CEMP frequencies of turnoff populations would be closer to the original values than those based on giants, and that one could obtain a more valid estimate of the frequencies of CEMP stars in a given population by making use of MSTO stars.

However, additional complications exist. The stars located near the MSTO are relatively warmer than the red giants, and as a result, for a given carbon abundance, the molecular CH G-band feature becomes significantly weaker. To make matters more difficult, at low metallicity (assuming carbon is not enriched) a star’s CH G band will be weaker still. Even with high-resolution spectroscopy Aoki et al. (2013) noted that, although they were able to detect the CH G band for a star with [C/Fe] $\geq +1.5$ and [Fe/H] $\sim -3.0$ at $T_{\text{eff}}$ $\sim 6000$ K, they failed to measure the CH G band for [C/Fe] $< +1.5$ in their sample of VMP stars. These effects become even more prevalent for medium-resolution spectra, hence the calculated CEMP frequencies obtained from the turnoff stars may also be lower than the actual values.

In order to address this difficulty, and to provide a check on just how many CEMP halo stars may have been misclassified as C-normal objects ([C/Fe] $< +0.7$) for stars around the turnoff region, we have performed the following experiment. Following the prescription by Lee et al. (2013), we inject artificial noise (with characteristics similar to that for a typical SDSS/SEGUE spectrum) into the grid of synthetic spectra that are used to estimate [C/Fe]. The noise-added synthetic spectra have $S/N = 40$, 45, and 50, which are typical of the quality of the SDSS/SEGUE spectra in our study with $|Z| < 5$ kpc (justification for this choice is provided below). For the purpose of this exercise, we define giants as models with parameters in the ranges $4500 \text{ K} \leq T_{\text{eff}} \leq 5500$ K and $1.0 \leq \log g \leq 3.0$, turnoff stars for $5750 \text{ K} \leq T_{\text{eff}} \leq 6500$ K and $3.5 \leq \log g \leq 4.0$, and dwarfs for $4500 \text{ K} \leq T_{\text{eff}} \leq 5500$ K and $4.5 \leq \log g \leq 5.0$. At each $S/N$, there are 25 different realizations, and we consider the discrete values of [C/Fe] $= +0.75$, $+1.0$, and $+1.25$. At each node of $T_{\text{eff}}$, $\log g$, and [Fe/H], there are 225 model spectra ($3 \times 3 \times 25$). The step for $T_{\text{eff}}$ and $\log g$ is 250 K and 0.5 dex,
respectively, corresponding to $5 \times 5 = 25$ grid points for the giants. Similarly, there are eight realizations for the turnoff stars, and 10 for the dwarf stars. Therefore, at each $[\text{Fe}/\text{H}]$ bin in Figure 3, there are 5625 ($225 \times 25$) spectra for the giants, 1800 ($225 \times 8$) for the turnoff stars, and 2250 ($225 \times 10$) for the dwarf stars considered. These spectra are processed through the SSPP to determine estimates of $[\text{C}/\text{Fe}]$. With the measured $[\text{C}/\text{Fe}]$ in hand, we then derive the CEMP frequencies of the spectra, as a function of $[\text{Fe}/\text{H}]$, which have an estimated $[\text{C}/\text{Fe}]$ less than $+0.7$ among the spectra with $+0.75 \leq [\text{C}/\text{Fe}] \leq +1.25$ for giants, turnoff stars, and dwarf stars.

Figure 3 shows the results of this experiment. The plus signs represent the actual frequencies of CEMP stars, which are set to 1.0. The green squares indicate giants, the red circles the turnoff stars, and the blue triangles the dwarfs. Inspection of this figure reveals that some of the C-rich dwarfs and giants start to be classified as C-normal ($[\text{C}/\text{Fe}] < +0.7$) from around $[\text{Fe}/\text{H}] < -2.0$; the number of the misclassified stars slowly increases with decreasing metallicity. By way of comparison, the C-rich turnoff stars begin to be misclassified as C-normal stars as metallicity drops below $[\text{Fe}/\text{H}] < -1.0$; this misclassification rapidly increases with declining metallicity, as expected.

Under the assumption that our observed sample is uniformly distributed throughout the stellar parameter and $[\text{C}/\text{Fe}]$ space, as in the grid of synthetic spectra, we now derive a correction function to capture the “true” CEMP frequency, as a function of $[\text{Fe}/\text{H}]$, for the SDSS/SEGUE turnoff stars, based on the results of the test carried out above. We then use this correction function to adjust the frequency calculation, among the stars with $+0.7 \leq [\text{C}/\text{Fe}] < +1.5$, taking the “missing” C-rich stars into account.

3.5. Comparison of the Frequencies of C-rich Turnoff Stars with Model Predictions

Because giants are more luminous than turnoff stars, they can probe to greater distances in the Galaxy. This increases the likelihood of introducing a greater number of giants than turnoff stars into a magnitude-limited sample (the frequency of giants can also be influenced by the luminosity function of the halo field stars, as well as by shifts in the mix of stellar populations between the nearby and more distant halo stars). This possible population transition has already been noted in Figure 2, and discussed in detail in the previous section. Thus, in order to make sure we are sampling the giants and turnoff stars in similar regions of the Galaxy, we restrict our consideration to the stars with $|Z| < 5$ kpc for the calculation of the CEMP frequencies of the turnoff stars.

Figure 4 shows the differential frequencies of CEMP stars for MSTO stars, as a function of $[\text{Fe}/\text{H}]$, as red open triangles; the adjusted frequencies by the correction function derived in the previous section are indicated as green filled triangles. The corrected CEMP frequencies are, on average, higher than the uncorrected ones by about 5% below $[\text{Fe}/\text{H}] = -2.0$. The blue open circles represent the predicted turnoff CEMP frequencies from an AGB binary-synthesis model with an IMF peaked at 10 $M_\odot$, while the magenta open squares indicates the prediction obtained using a Salpeter IMF. As for the giant case, we have adopted the AGB binary-synthesis model from Suda et al. (2013). This model assumes the homogeneous mixing in the surface convective zone of 3.5 $\times$ 10$^{-3}$ $M_\odot$, taken from the model of 0.8 $M_\odot$ with $[\text{Fe}/\text{H}] = -3.0$ at the turnoff point by Suda & Fujimoto (2010). For comparison, the filled black circles are the frequencies from the giants with $|Z| < 5$ kpc given in Figure 2.

The behavior seen in Figure 4 is generally consistent with our expectations over most of the metallicity range, in that the CEMP frequencies for the giants are lower than those for the turnoff sample, except at $[\text{Fe}/\text{H}] \sim -2.6$, in which the giant sample displays a slightly higher CEMP fraction than the turnoff stars (although the Poisson error bars almost overlap). This could be caused by a bias in the distance-restricted sample, as there are more turnoff stars than giant stars closer to the Galactic plane, which can affect the calculated CEMP fraction (given the trend of increasing fractions of CEMP stars with increasing $|Z|$). However, in this metallicity bin, we have 99 C-rich stars out of 733 turnoff stars, while there are only 14 C-enhanced stars among the 52 giants, a much smaller number. Thus, it is necessary to increase the number of the giant stars in this metallicity bin to confirm whether the CEMP giant frequency is unduly influenced by the small sample size. The small number statistics limitation applies to the CEMP frequency below $[\text{Fe}/\text{H}] = -3.0$ as well. Furthermore, related to the issue of the definition of C-rich stars addressed for the giant CEMP fraction, when adopting the C-rich definition of $[\text{C}/\text{Fe}] > +1.0$, we obtain not only a CEMP fraction of 6% for the giants in the same metallicity bin as above, which is lower than for the turnoff stars by $\sim 3\%$, but the CEMP frequencies of the turnoff stars in all metallicity bins are consistently higher than those of the giants. Therefore, we have a relatively larger number of stars just above $[\text{C}/\text{Fe}] > +0.7$ in between $[\text{Fe}/\text{H}] = -3.0$ and $-2.5$ than is the case for the other metallicity bins.

Note that, as mentioned in the previous section, we consider the turnoff sample to reflect more realistic CEMP-star frequencies than the giant sample, assuming that the internal mixing processes during their main-sequence lifetimes do not
impact the calculated CEMP fraction (due to the difficulty of modeling those processes), and that both the turnoff and giant stars experience the same internal mixing processes during their main-sequence lifetimes. However, let us consider once again the possible effect of thermohaline mixing on the surface carbon abundance. According to Stancliffe et al. (2007), when they explored model stars with accreted material of rather high carbonicity, [C/Fe] = +3.26, their stellar-evolution model indicated that the carbon abundance was only changed through the FDU by \( \sim 0.8 \) dex, without taking thermohaline mixing into account, while they reported that [C/Fe] could be reduced by \( \sim 0.8 \) dex by thermohaline mixing prior to the star reaching the turnoff position, and the FDU event subsequently changed it very little (\( \sim 0.1 \) dex). This may explain why the turnoff and giant stars exhibit a similar fraction of C-rich stars for [Fe/H] \( \sim -2.2 \) in Figure 4, provided that both experienced substantial thermohaline mixing of the accreted material (to deeper levels than are reached by the convective envelope during the FDU).

Inspection of Figure 4 also reveals that the fraction of C-rich turnoff stars below [Fe/H] \( = -3.0 \) appears much higher than that of the giant sample. In this extremely metal-poor regime, the CEMP stars are dominated by stars of the CEMP-no class (which observations suggest do not require a binary companion to account for their production). This may raise the overall carbon-rich fraction, due to the additional source(s) of carbon at low metallicity. Moreover, stars that are C-rich at birth do not lose this status by the FDU or extra mixing episodes for the giants, because the surface carbon abundance is little changed by these events, as mentioned in Section 3.2. Therefore, assuming all the stars with [Fe/H] \( < -3.0 \) do not contain any accreted material from a binary companion, it is quite uncertain why the turnoff stars exhibit a much larger CEMP fraction than the giants, instead of a small difference in the frequency, as in the case of [Fe/H] \( > -2.5 \) in Figure 4. For there to be more C-rich turnoff stars than C-rich giants in the low-metallicity regime, we require that the giants experience substantial reduction of their carbon-rich material during giant-branch evolution. However, note that because our sample at [Fe/H] \( < -3.0 \) has substantially fewer extremely low-metallicity stars (less than 10 stars below [Fe/H] \( = -3.5 \)) than metal-rich stars ([Fe/H] \( > -2.5 \)), we need to confirm this apparently larger frequency of C-rich turnoff objects by enlarging the number of the giant and turnoff stars.

Figure 4 also shows that the models produce higher CEMP frequencies for the turnoff stars than for the giants in the case of either IMF (compared with Figure 2), which at least qualitatively agrees with the observations. The small difference in the model-predicted CEMP frequencies between the giants and turnoff stars (Figures 2 and 4) arise from the difference in the mass of the convective envelope; a star that evolves to the giant stage has a much deeper convective zone, and hence more effective dilution, resulting in lower CEMP frequencies derived for the giants.

Our derived CEMP frequencies from the distance-restricted turnoff sample appear to be in good agreement with the model prediction based on a Salpeter IMF (magenta open squares), down to metallicity [Fe/H] \( = -2.5 \), which is a bit lower than for the giants. This reaffirms that the AGB model works well for progenitor stars in the low-mass range. However, the model estimate of the CEMP frequency does not reproduce the observed frequencies for [Fe/H] \( < -2.5 \). Moreover, unlike the case for the giants (Figure 2), the observed CEMP frequencies from our turnoff sample do not agree with the model estimation from the top-heavy IMF for [Fe/H] \( < -2.5 \) at all, as these remain roughly flat instead of growing dramatically with decreasing metallicity in the observational data. Nonetheless, as the model prediction overlaps with our derived CEMP frequency at [Fe/H] \( \sim -3.4 \), one may speculate that the shift of the IMF took place between [Fe/H] \( = -3.5 \) and [Fe/H] \( = -2.5 \), earlier than inferred from the giants.

### 3.6. Model Uncertainties

One reason for the large discrepancy between the observed frequencies of CEMP stars and the model predictions may be
 uncertainties of the model parameters adopted for producing carbon in the AGB star, and in the subsequent processes that enrich (or deplete) the envelope with carbon. Below, we discuss known sources of uncertainty associated with the AGB binary-synthesis model, which may result in changes of the predicted carbon abundance of the secondary star.

Most AGB stars in the mass range of $\sim 1$–$8 M_\odot$ can produce carbon, but whether or not they develop carbon-enriched envelopes depends on the efficiency of the third dredge-up (TDU), and helium-flash driven deep mixing (He-FDDM; Fujimoto et al. 1990, 2000)\(^9\) events for $[\text{Fe}/\text{H}] < -2.5$. At present, it is not fully understood how such episodes depend on the mass and metallicity of an AGB star.

For example, in a study of the evolution of AGB stars with metallicity between $Z = 10^{-5}$ and $10^{-4}$, Lau et al. (2009) found that the He-FDDM did not take place for $Z > 10^{-5}$, independent of the mass of a star, and that this event did not occur for a star with $M > 2 M_\odot$, regardless of its metallicity. However, Suda & Fujimoto (2010) found that the He-FDDM event occurred for a star with $M < 3 M_\odot$ for zero metallicity, while it occurred for a star with $M < 2 M_\odot$ for $-5 \leq [\text{Fe}/\text{H}] \leq -3$. They also found that the TDU episode was restricted to a mass range of $M \sim 1.5$–$5 M_\odot$ for $[\text{Fe}/\text{H}] = -3.0$, and that this mass range became smaller as the metallicity decreased. Campbell & Lattanzio (2008) claimed yet another pattern, with He-FDDM events occurring in stars up to $3 M_\odot$ below $[\text{Fe}/\text{H}] = -5$. Clearly, there is still a great deal of uncertainty in the modeling of these events. This uncertainty is further exacerbated by the physics employed in the one-dimensional stellar-evolution codes used to model these events. Typically, these events are modeled using a diffusive treatment for the mixing of chemical species. However, recent three-dimensional hydrodynamical modeling of these episodes suggests that the process is, in fact, not diffusive (e.g., Herwig et al. 2011; Stancliffe et al. 2011). Such simulations will hopefully lead to a better treatment of the physics of He-FDDM in stellar-evolution codes.

In the adopted models from Suda et al. (2013), the increasing fractions of CEMP stars comes from the He-FDDM, which can enhance the surface carbon abundance by a factor of 10, from $[\text{C}/\text{H}] \sim -1$ to $+0$, regardless of the initial metallicity of the models, for stars with masses of 0.8–3 $M_\odot$. In this view, the value of $[\text{C}/\text{Fe}]$ for the secondary component (the presently observed CEMP star) of a given binary increases with decreasing $[\text{Fe}/\text{H}]$, so that a larger fraction of CEMP stars can be achieved at lower metallicity. It is also assumed that the efficiency of the binary mass transfer and the mass-loss rates do not depend on metallicity.

In addition, among these AGB stars, the intermediate-mass ($\sim 3$–$8 M_\odot$) objects can be enriched with nitrogen by operation of the hot-bottom burning (HBB) process, which converts carbon into nitrogen by CN processing, and predicts the production of NEMP stars (Johnson et al. 2007). However, the dependency of the HBB on the mass and metallicity of an AGB star is yet not well-established.

Furthermore, the adopted population models assume that even the CEMP-no stars form from the AGB binary mass-transfer scenario, rather than including additional sources that have been argued are likely to be present in the early universe. According to the AGB models (see also Komiyama et al. 2007), low-mass ($M < 3.5 M_\odot$) AGB stars efficiently create s-process elements by generating extra neutrons via the $^{13}\text{C}(\alpha, \, n)^{16}\text{O}$ reaction, while a weak s-process (for light s-process elements) operates by $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ for the intermediate-mass stars (see, e.g., Lugaro et al. 2012). CEMP-no stars could form in the AGB mass-transfer scenario by suppressing the formation of the $^{13}\text{C}$ pocket for intermediate-mass stars ($M > 3.5 M_\odot$; Suda et al. 2013).

Thus, in order to preferentially produce CEMP-no stars at low metallicity and maintain the observed ratio of CEMP-no/ (CEMP-s + CEMP-no), which is close to 0.5 at $[\text{Fe}/\text{H}] \sim -3.0$ (from Table 1 of Suda et al. 2013), the models have to assume that the $^{13}\text{C}$ pocket does not form in stars with metallicity below $[\text{Fe}/\text{H}] = -2.5$. The absence of the $^{13}\text{C}$ pocket at low metallicities is also required to explain the observed decreasing trend of $[\text{Pb}/\text{Ba}]$ for CEMP stars with $[\text{Fe}/\text{H}] < -2.5$ (Aoki et al. 2002, 2008; Suda et al. 2004; Barbuy et al. 2005; Cohen et al. 2006). Regardless of the detailed physics of the processes involved, it has been claimed (most recently by Cohen et al. 2013) that the lack of Fe-peak seed nuclei for CEMP stars with $[\text{Fe}/\text{H}] < -3.0$ would inevitably drive neutron-capture processes to the formation of Pb, rather than, e.g., Ba. It is thus of significance that Ito et al. (2013) obtained a rather low upper limit on the abundance of lead ($\log \epsilon(\text{Pb}) < -0.10$) for a CEMP-no star BD +44°493 with $[\text{Fe}/\text{H}] = -3.8$, while previous predictions called for $\log \epsilon(\text{Pb}) + 1.5$ at these low metallicities if the lead were produced by the s-process (Cohen et al. 2006).\(^{10}\)

Even taking into account the uncertainties in the parameters of the AGB models, a more plausible interpretation of our results may be the existence of additional (non-AGB) carbon-production mechanisms, as discussed in the Introduction, which result in large frequencies of CEMP stars in the metallicity regime $[\text{Fe}/\text{H}] < -3.0$. The current observations certainly favor this interpretation, since most CEMP-no stars in the Galaxy appear at $[\text{Fe}/\text{H}] < -3.0$, and these stars do not commonly exhibit the radial velocity variations that would be expected if membership in a binary system were required (as in the AGB mass-transfer scenario).

Chemical abundance pattern of CEMP-no stars observed with high-resolution spectroscopy (e.g., Ito et al. 2009, 2013; Norris et al. 2013) are similar to the predictions from massive, rapidly rotating, MMP stars (Meynet et al. 2006, 2010) or faint SNe that experience mixing and fallback (Umeda & Nomoto 2003, 2005; Tominaga et al. 2007, Kobayashi et al. 2011; Ito et al. 2013; Nomoto et al. 2013). If such mechanisms are the dominant sources of the large amounts of carbon produced at low metallicity, these scenarios also favor an IMF that preferentially produces massive stars, because the abundance patterns of most CEMP-no stars can be reproduced by faint SNe of population III stars having masses of 25–40 $M_\odot$ (Tominaga et al. 2014; Ishigaki et al. 2014). In fact, one might also expect a rather abrupt “break” in the CEMP frequencies when the primary carbon sources change in nature—such a sudden change can be seen for the turnoff stars in Figure 4 below $[\text{Fe}/\text{H}] = -3.0$. Although we are not able to distinguish CEMP-no stars from CEMP-s stars in our sample, given that the majority of the CEMP-no stars are found with $[\text{Fe}/\text{H}] < -3.0$, our derived frequencies imply that non-AGB related phenomenon may be the dominant mechanisms for producing large carbon abundances at extremely low $[\text{Fe}/\text{H}]$.

\(^{10}\) Recent analysis of near-UV high-resolution spectroscopy of BD +44°493 obtained with Hubble Space Telescope/STIS has produced an even lower limit on the Pb abundance for this star, $\log \epsilon(\text{Pb}) < -0.23$ (Placco et al. 2014).
4. CONCLUSIONS

We have compared our derived CEMP frequencies from the SDSS/SEGUE giant sample with those predicted by AGB binary-synthesis models using two different IMFs—a Salpeter IMF, and an IMF with a characteristic mass of $10 \ M_\odot$. Good agreement between the observed CEMP frequencies for stars with $[\text{Fe}/\text{H}] > -1.5$ with those predicted by binary-synthesis models employing a Salpeter IMF indicates that the adopted AGB model works well for low-mass progenitor stars. Qualitatively, a good agreement with an IMF biased to higher-mass progenitors is also found for $[\text{Fe}/\text{H}] < -2.5$, suggesting that the nature of the IMF shifted, from one that is high-mass dominated in the early history of the Milky Way, to one that is now low-mass dominated. This transition appears to have occurred, in “chemical time,” between $[\text{Fe}/\text{H}] = -2.5$ and $[\text{Fe}/\text{H}] = -1.5$, as other recent studies have argued (e.g., Suda et al. 2011, 2013; Yamada et al. 2013).

As noted by previous work, the more distant halo giants (those with $|Z| > 5$ kpc) exhibit higher frequencies of CEMP stars compared to those closer to the Galactic plane. A plausible explanation for this difference is the expected change of the dominant stellar populations from the inner-halo to the outer-halo population, coupled with the assumption that the outer-halo stars are associated with progenitors capable of producing large amounts of carbon without the accompanying production of heavy metals (producing CEMP-no stars). Thus, one might expect that the inner-halo population harbors a higher ratio of CEMP-s/CEMP-no stars, while the opposite may apply to the outer-halo population. Recent tests of this prediction provide tentative supporting evidence, although larger samples are required (Carollo et al. 2014).

The weak CH G bands for moderately carbon-enhanced stars ($+0.7 < [\text{C}/\text{Fe}] < +1.5$) among warm, metal-poor MSTO stars gives rise to an apparent lowering of the fraction of C-rich stars. We have derived a correction function to compensate for this, making use of noise-added synthetic spectra. The corrected CEMP frequencies for turnoff stars are higher, on average, by $\sim 5\%$ compared with the uncorrected frequencies. Both the corrected and uncorrected CEMP frequencies derived from the turnoff sample exceed those of the giants for $[\text{Fe}/\text{H}] < -3.0$.

We have made use of MSTO stars with $|Z| < 5$ kpc to compute more realistic CEMP frequencies than obtained using giants (or the combination of giants with other classes), corrected as mentioned above. The underlying assumption is that internal mixing processes, such as thermohaline mixing, rotational mixing, and atomic diffusion, do not much affect the calculated CEMP fraction of the turnoff stars, even though there exists some observational evidence to the contrary. There is also the possibility that some of these mixing processes counteract each other, so that their combined effect on the surface abundances may be smaller than that of each individual process. Unfortunately, current stellar-evolution models do not (at least in a quantitative way) provide insight as to how much they can alter the chemical abundances, and how they interact with each other on the surface of a turnoff star.

For $[\text{Fe}/\text{H}] > -2.5$, our corrected CEMP frequencies from the turnoff stars agree with the model predictions based on a Salpeter IMF, indicating that the AGB model used in this study is probably not far from reality, at least as applied to low-mass stellar progenitors. However, unlike the case for the giant sample, the top-heavy IMF model does not reproduce the observed trend of the CEMP frequencies for the turnoff stars at all. Even so, taking into account the overlap between the model prediction and our derived CEMP frequency at $[\text{Fe}/\text{H}] \sim -3.4$, one may speculate that the shift of the IMF occurred between $[\text{Fe}/\text{H}] = -3.5$ and $[\text{Fe}/\text{H}] = -2.5$, earlier in chemical time than inferred from the giants.

Because the AGB binary-synthesis model (using a Salpeter IMF or a top-heavy IMF) predicts far too low frequencies of CEMP stars for our turnoff sample, it appears that there likely exists one or more additional mechanisms, such as faint Type II SNe and/or rapidly rotating massive stars capable of producing carbon-rich stars below $[\text{Fe}/\text{H}] = -3.0$, the metallicity regime where the CEMP-no stars dominate over the subclass of CEMP-s stars. However, the CEMP frequencies of the giants agree relatively well with the predictions from the binary-synthesis model with a top-heavy IMF in the extremely low-metallicity regime ($[\text{Fe}/\text{H}] < -3.0$), even without taking into account other sources of carbon production. As current observational data indicates that CEMP-no stars dominate below $[\text{Fe}/\text{H}] = -3.0$, this might suggest that the current AGB binary-synthesis model produces too high a carbon abundance below $[\text{Fe}/\text{H}] = -3.0$ for intermediate- to high-mass stars ($3-8 \ M_\odot$).

Even if AGB binary-mass transfer is not the source for the additional carbon production for $[\text{Fe}/\text{H}] < -3.0$, it does require an IMF that preferentially produces massive stars to produce CEMP-no stars.

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