CARBON ABUNDANCES OF THREE CARBON-ENHANCED METAL-POOR STARS FROM HIGH-RESOLUTION GEMINI-S/bHROS SPECTRA OF THE $\lambda 8727$ [C i] LINE

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ABSTRACT

We present the results from an analysis of the $\lambda 8727$ forbidden [C i] line in high-resolution Gemini-S/bHROS spectra of three Carbon-Enhanced Metal-Poor (CEMP) stars. Previous derivations of C abundances in CEMP stars have primarily used the blue bands of CH and the C$_2$ Swan system, features which are suspected to be sensitive to photospheric temperature inhomogeneities (the so-called three-dimensional effects). We find the [C/Fe] ratios based on the [C i] abundances of the two most Fe-rich stars in our sample (HE 0507-1653: [Fe/H] $= -1.42$ and HE 0054-2542: [Fe/H] $= -2.66$) to be in good agreement with previously determined values. For the most Fe-deficient star in our sample (HE 1005-1439: [Fe/H] $= -3.08$), however, the [C/Fe] ratio is found to be 0.34 dex lower than the published molecular-based value. We have carried out three-dimensional local thermodynamic equilibrium (LTE) calculations for [C i], and the resulting corrections are found to be modest for all three stars, suggesting that the discrepancy between the [C i] and molecular-based C abundances of HE 1005-1439 is due to more severe three-dimensional effects on the molecular lines. Carbon abundances are also derived from C i high-excitation lines and are found to be 0.45–0.64 dex higher than the [C i]-based abundances. Previously published non-LTE (NLTE) C i abundance corrections bring the [C i] and C i abundances into better agreement; however, targeted NLTE calculations for CEMP stars are clearly needed. We have also derived the abundances of nitrogen, potassium, and iron for each star. The Fe abundances agree well with previously derived values, and the K abundances are similar to those of C-normal metal-poor stars. Nitrogen abundances have been derived from resolved lines of the CN red system assuming the C abundances derived from the [C i] feature. The abundances are found to be approximately 0.44 dex larger than literature values, which have been derived from CN blue bands near 3880 and 4215 Å. We discuss evidence that suggests that analyses of the CN blue system bands underestimate the N abundances of metal-poor giants.

Key words: stars: abundances – stars: atmospheres – stars: carbon – stars: individual (HE 0054-2542, HE 0507-1653, HE 1005-1439) – stars: Population II

1. INTRODUCTION

The discovery that a significant fraction of very metal-poor (VMP; [Fe/H]$\leq -2.0$) stars have highly enhanced abundances of carbon ([C/Fe] $\geq +1.0$) has spurred vigorous research efforts focused on delineating the nucleosynthetic histories of these objects and their role in the chemical evolution of the Galaxy. The actual fraction of VMP stars that are carbon enhanced has yet to be precisely determined, but current estimates range from $\sim 10\%$ to $\sim 25\%$ (Cohen et al. 2005; Marsteller et al. 2005; Frebel et al. 2006; Lucatello et al. 2006). This fraction rises at lower metallicities, reaching $\sim 40\%$ of stars with [Fe/H] $\leq -3.5$, and stars with [Fe/H] $< -4.0$, only three of which are currently known, are all carbon enhanced. The increasing incidence of carbon enhancement at lower metallicities implies that the nucleosynthetic pathway(s) leading to these Carbon-Enhanced Metal-Poor (CEMP) stars is highly efficient at low metallicities and that it played an important role in the nucleosynthetic history of the early Galaxy. Indeed, the fraction of CEMP stars as a function of metallicity may have critical implications for the initial mass function (IMF) in the early universe (Tumlinson 2007).

The manner in which the majority of VMP stars are discovered, and how CEMP stars are subsequently identified, follows a well-established procedure. Stars are first tagged as VMP candidates based on the strength of the Ca ii K line in low-resolution spectra from objective-prism surveys, in particular the HK survey (Beers et al. 1985, 1992; Beers 1999) and the Hamburg/ESO survey (HES; Wisotzki et al. 2000; Christlieb 2003). Medium-resolution spectra of the VMP candidates are then obtained and used to identify bona fide VMP stars within the sample. The medium-resolution spectrum of a given VMP star is used to estimate its metallicity ([Fe/H]) by analyzing the strength of the Ca ii K line as a function of the broadband colors of the star, and inspection of the CH G-band found at 4300 Å reveals whether or not the star is enhanced in C (e.g., Rossi et al. 2005). Estimates of a star’s C abundance can be obtained from the CH G-band; however, in the spectra of many CEMP stars, the G-band feature is sufficiently strong to be saturated, rendering

8 Here we describe the identification of metal-poor stars based on the low-resolution spectra of objective-prism surveys, the most prolific sources of VMP stars. For a description of other methods used to find metal-poor stars, please see Beers & Christlieb (2005).

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it incapable of providing accurate abundance determinations. In these cases, C\textsubscript{2} lines of the Swan system can be used instead to estimate C abundances. Once identified, VMP stars are often slated for high-resolution spectroscopic follow-up studies, with which more accurate abundances of Fe, C, and numerous other elements, as well as important ratios such as $^{12}$C/$^{13}$C, can be derived.

Analyses of C abundances in high-resolution spectroscopic follow-up studies of CEMP stars focus on the same molecular features as those analyzed in medium-resolution spectra, namely the blue bands of the CH and C\textsubscript{2} Swan systems, because it is the molecular features that stay strong and are most easily measurable in the spectra of VMP giants. Another reason is that atomic C\textsubscript{i} lines result from high-excitation transitions, and if measurable, these lines are not believed to be accurate abundance indicators because of their sensitivity to non-local thermodynamic equilibrium (NLTE) effects (Asplund 2005; Fabbian et al. 2006). However, the abundances derived from the CH and C\textsubscript{2} features in the spectra of VMP stars using standard one-dimensional local thermodynamic equilibrium (LTE) analyses may not be accurate either. Abundances derived from molecular features are generally very sensitive to the temperature structure of stellar atmosphere models, and studies of time-dependent three-dimensional hydrodynamical models have shown that the molecular lines are susceptible to temperature inhomogeneities due to photospheric granulation, the so-called three-dimensional effects (Asplund 2005). The effects on molecular lines are such that abundances based on three-dimensional models are lower than those derived using one-dimensional models, with differences as large as $\sim$1.0 dex at [Fe/H] = −3 (Asplund & Garcés Pérez 2001; Collet et al. 2007).

The derivation of accurate C abundances of CEMP stars is essential to their proper characterization and subsequently to the correct interpretation of their role in the chemical evolution of the Galaxy. Here we present the results of our investigation into the accuracy of published C abundances as derived from CH and C\textsubscript{2} features by analyzing the forbidden [C\textsubscript{i}] line at 8727.13 Å in high-resolution Gemini-S/bHROS spectra of three CEMP stars: HE 0054-2542 (CS 22942-019), HE 0507-1653, and HE 1005-1439. The λ8727 [C\textsubscript{i}] line is expected to be a highly accurate abundance indicator and not susceptible to NLTE effects (e.g., Gustafsson et al. 1999), and it has been used to derive the C abundance of the Sun (e.g., Lambert 1978; Allende Prieto et al. 2002; Asplund et al. 2005b), field dwarfs (e.g., Gustafsson et al. 1999; Bensby & Feltzing 2006), R Coronae Borealis stars (e.g., Pandey et al. 2004), and Cepheid variables (e.g., Luck & Lambert 1981). For CEMP stars, it provides an excellent benchmark for C abundances derived from molecular features.

2. ASTROPHYSICAL SPECTROSCOPY OF CARBON

Carbon abundances can be derived from both atomic and molecular features in the spectra of late-type stars. The available atomic lines include numerous high-excitation ($\chi \geq 7.48$ eV) C\textsubscript{i} lines found throughout the optical and near-IR (NIR) spectral regions and a single [C\textsubscript{i}] forbidden feature at 8727.13 Å. Suitable molecular features include electronic and rotational–vibrational transitions of CH and C\textsubscript{2}, which are also found throughout the optical and NIR spectral regions. Deriving C abundances from CO and CN transitions is also possible, but prior knowledge of the stellar O and N abundances is needed. For CEMP stars, it is more often the case that the C abundance of a star is known from an analysis of CH or C\textsubscript{2} features, and the CO and CN lines are used for the derivation of O and N abundances. However, for cool environments such as those found in the atmospheres of red giants, a significant fraction of C is tied up in CO, so C abundances derived from C\textsubscript{1}, [C\textsubscript{i}], CH, and C\textsubscript{2} lines can also be sensitive to the adopted O abundance. Below we discuss the two sets of atomic and molecular C features in the context of using them to derive accurate stellar abundances, particularly of CEMP stars.

2.1. C\textsubscript{i}

The permitted neutral C lines in the spectra of late-type stars all originate from high-excitation transitions, and they all are sensitive to NLTE effects. The NLTE effects are such that C abundances are overestimated by LTE analyses (lines are weaker in LTE compared to NLTE), and thus NLTE corrections are negative. Detailed accounts of modeling the C atom and the nature of NLTE effects are given by Asplund (2005) and Fabbian et al. (2006).

The stellar parameter space for which NLTE effects and the high-excitation C\textsubscript{i} lines have been investigated is rather limited, but in general the published studies agree quite well. For solar-like stars (stars with similar $T_{\text{eff}}$, log g, and metallicity as the Sun), NLTE corrections are typically $\sim$0.05 to $-$0.1 dex (Stürenburg & Holweger 1990; Asplund 2005; Takeda & Honda 2005; Fabbian et al. 2006). These corrections are predicted to increase in magnitude, i.e., become more negative, with increasing $T_{\text{eff}}$ and decreasing log g, as well as with increasing line strength. Metallicity apparently has a minor effect on predicted NLTE corrections, with the peak correction occurring near [Fe/H] = −1.0 and then tapering off slightly by no more than 0.10 dex at [Fe/H] = −3.0. Interestingly, Fabbian et al. (2006) note that the assumed [C/Fe] ratio also affects the predicted NLTE corrections such that the magnitude of the corrections become larger for increasing [C/Fe] ratios since the line-formation region is shifted outward in the atmospheres where the departures from LTE are more pronounced. One would thus expect this effect to be significant in the analysis of CEMP stars.

2.2. [C\textsubscript{i}]

The [C\textsubscript{i}] forbidden line results from a low-excitation ($\chi = 1.26$ eV) electric quadrupole ($D_{2}^{1} - S_{0}^{1}$) transition in carbon’s ground-state configuration ($2s^{2}2p^{2}$). The ground state of C\textsubscript{i} is populated according to Boltzmann statistics, and thus transitions from this state are formed in LTE. The next three energy levels, of which the [C\textsubscript{i}] transition arises from the first, are strongly coupled through collisions to the ground state, assuring that they too are in LTE (Stürenburg & Holweger 1990). For this reason, the [C\textsubscript{i}] line is expected to be a highly accurate abundance indicator and not susceptible to NLTE effects (e.g., Gustafsson et al. 1999). Deriving accurate C abundances from the [C\textsubscript{i}] line is not without its challenges, however. Lambert & Swing (1967) preliminarily identified a possible blending Fe\textsubscript{i} line at 8727.10 Å, but along with subsequent authors (e.g. Gustafsson et al. 1999; Allende Prieto et al. 2002; Asplund et al. 2005b), they determined that the blending Fe\textsubscript{i} feature contributes negligibly to the [C\textsubscript{i}] line strength in the solar spectrum. However, for completeness, the blending feature should be included in the λ8727 line list, particularly for stars with [C/Fe] $<$ 0. Also, in the solar spectrum there is a strong ($\sim$100 mÅ) Si\textsubscript{i} line at 8728.01 Å, just
0.88 Å to the red of the [C I] feature. The Si I line can affect the continuum in the λ8727 region, making high-resolution spectroscopy essential to the accurate measurement of the [C I] line. Neither of these concerns is applicable to metal-poor stars, for which the blending Fe I and neighboring Si I features become increasingly weak at subsolar metallicities. Unfortunately, the [C I] line also becomes weak at low metallicities, vanishingly at [Fe/H] < −1.0 (Akerman et al. 2004), except for CEMP stars. As we demonstrate below, the [C I] line can remain strong enough for reliable measurements in the spectra of CEMP stars down to at least [Fe/H] ~ −3.0.

As a final note, we point out that temperature inhomogeneities due to photospheric granulation, the so-called three-dimensional effects, do not greatly affect abundances derived from neutral atomic C lines (Asplund 2005). The difference in the solar C abundance as derived from the [C I] line using three-dimensional hydrodynamical LTE models and conventional one-dimensional LTE models amounts to ~0.05 dex (Asplund et al. 2005b). While the susceptibility of the [C I] line to LTE three-dimensional effects as a function of metallicity has not been investigated, the high-excitation C I lines are expected to remain relatively impervious to them at all metallicities due to their large depths of formation (Asplund 2005).

2.3. CH and C2

These molecular features are likely to be relatively immune to NLTE effects, although little computational work has been done in this area (Asplund 2005). What is clear is that the molecular lines are highly sensitive to temperature inhomogeneities and by extension, three-dimensional effects. For the Sun, three-dimensional corrections for abundances derived from CH and C2 lines have been estimated to range from 0.00 to −0.15 dex (one-dimensional abundances are higher), depending on the lines being analyzed (Asplund et al. 2005b). The divergence between C abundances derived from these molecular lines using one-dimensional and three-dimensional models grows with decreasing metallicity, reaching differences ranging from −0.5 to −0.8 dex for giants and subgiants at [Fe/H] = −3 (Asplund 2005; Collet et al. 2007).

The susceptibility of the CH and C2 features to three-dimensional effects is unfortunate, because these lines are the ones that generally remain strong at low metallicities. Indeed, the CH band near 4300 Å and lines of the C2 Swan system at 4730, 5170, and 5635 Å are the features most often used to derive C abundances of CEMP stars. Many authors have noted that the C abundances derived from these molecular features may be in error by as much as 0.60 dex or more (e.g., Aoki et al. 2007; Frebel et al. 2007), but because three-dimensional hydrodynamical models tailored for CEMP stars have not been constructed, accurate corrections to one-dimensional abundances cannot be made. This is the source of the motivation for the research presented in this paper. By deriving abundances from an accurate abundance indicator, the [C I] forbidden line, we can provide some insight into the relative accuracy of the C abundances derived from molecular lines in the spectra of CEMP stars.

3. OBSERVATIONS AND DATA REDUCTION

3.1. Observations

Multiple spectra of three CEMP stars were taken on UT 2006 December 26 and 27 at the Gemini-S telescope with the bench-mounted High-Resolution Optical Spectrograph (bHROS). The spectrograph is located within a thermal enclosure in the pier lab of the Gemini-S telescope and is fiber-fed from the telescope’s Cassegrain focus via a fiber cassette inserted into the Gemini Multi-Object Spectrograph (GMOS-South). The object-only mode of operation was used for our observations; this mode utilizes a single 0′9 fiber that feeds a dedicated image slicer to produce a “slit” that is 0′14 wide and ~6′5 long, projected to the camera focal plane. A slicer rotation mechanism is used to ensure a “vertical” slit at the observed spectral wavelength. The spectrograph is cross dispersed using a set of fused silica prisms to ensure the echelle orders are well separated on the detector, a single 2048 × 4608 E2V CCD with 13.5 μm pixels. The wavelength range over which bHROS is operational spans from 4000 to 10000 Å.

For our observations, 4 × 2 (spatial direction × dispersion direction) binning was used to reduce the spectrograph’s working resolution of R = λ/δλ = 150,000 to an effective resolution of R = 75,000 in order to increase the signal-to-noise (S/N) ratio of the spectra and to lessen the impact of read noise, which can be significant given the detector’s intrinsically high read noise of 5.3 e− and wide spectral orders (200 unbinned pixels). The grating was configured to produce a central wavelength on the detector of 8352 Å. In this configuration, incomplete coverage from 7135 Å to 9170 Å was obtained over seven echelle orders. The continuous coverage available within a single order is about 88 Å, depending on the order.

The spectra were obtained in queue operations during photometric conditions with optical seeing varying between 0.35 and 0.8, with the majority of the delivered image quality better than 0.5. The total exposure time was 9880 s for HE 0054-2542 (three exposures), 6280 s for HE 0507-1653 (two exposures), and 15,900 s for HE 1005-1439 (five exposures); the S/Ns of the combined spectra at 8727 Å are 114 for HE 0054-2542, 149 for HE 0507-1653, and 65 for HE 1005-1439. A detailed observing log is presented in Table 1. In addition to our target spectra, we also obtained a calibration set of daily biases, flats, and ThAr arc spectra.

3.2. Reductions

Processing of the spectra was completed following normal echelle reduction practices with standard IRAF packages, with careful adaptations to suit the bHROS data. The raw spectra were bias corrected by overscan and bias-image subtraction. The inter-order scattered light is typically ~5 ADU and varies by only a few tenths of an ADU over 50 pixels, which is the

| Table 1 |
|---|
| **Observing Log** |
| Star | UT Date | Exposures | Integration Time (s) |
| HE 0054-2542 | 2006 Dec 25 | 1 | 3140 |
| HE 0507-1653 | 2006 Dec 25 | 1 | 3600 |
| HE 0054-2542 | 2006 Dec 26 | 1 | 3140 |
| HE 0507-1653 | 2006 Dec 25 | 2 | 3140 |
| HE 1005-1439 | 2006 Dec 26 | 3 | 3400 |
| HE 1005-1439 | 2006 Dec 25 | 1 | 2400 |
| HE 1005-1439 | 2006 Dec 26 | 1 | 3300 |

9 IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
width of our binned orders and much larger than the spectral features we are observing. Since the uncertainty in the smoothed fit to the scattered light is larger than the gradient in the scattered light, no scattered light correction was performed. Cosmic rays were removed using L. A. Cosmic (van Dokkum 2001). The images were then flat fielded to remove both the pixel-to-pixel variations and fringe from our spectra. The E2V CCD used in bHROS suffers from severe fringing in the red. However, as the light path for the flat observations is identical to our target observations, the illumination pattern on the detector is constant, and the fringe pattern is consistent in all spectra. Thus, the fringe patterns in our spectra are very well removed in the flat-fielding process.

The use of a prism cross disperser combined with a long “slit length” causes the spectral orders to be tilted severely away from the central order, potentially resulting in the loss of “slit length” causing the spectral orders to be tilted severely away from the central order, potentially resulting in the loss of slanting effects of the strong molecular C bands in the B- and V-filter passbands, of their stellar sample to obtain initial values of $T_{\text{eff}}$ and $\log g$. They then proceeded to refine the stellar parameters, including the microturbulent velocity, spectroscopically by requiring the abundances of Fe i, Fe ii, and Ti ii derived using high-resolution spectra of their sample to be independent on a line-by-line basis of line strength, excitation potential, and ionization state. This process was hampered by the modest S/N and resolution of their spectra (typically S/N $\gtrsim$ 30, $R$ $\sim$ 20,000), and any adjustments to the initial parameter values were constrained to fall within the estimated parameter uncertainties. The final parameters adopted by them for HE 0054-2542 are $T_{\text{eff}} = 4900$ K, $\log g = 1.8$ (cgs), $\xi = 2.0$ km s$^{-1}$, and [Fe/H] $= -2.67$.

Aoki et al. (2002c) used broadband photometry and a temperature scale based on dereddened $(B - V)_{0}$ colors devised for carbon-rich metal-poor stars by Aoki et al. (2002a) to estimate $T_{\text{eff}}$ for their stellar sample. Surface gravities and microturbulent velocities were then derived spectroscopically using high-resolution spectra by forcing ionization balance between the abundances of Fe i and Fe ii, and demanding that line-by-line Fe i abundances were independent of the equivalent width (EW). The resulting parameters found by Aoki et al. (2002c) for HE 0054-2542 are $T_{\text{eff}} = 5000$ K, $\log g = 2.4$ (cgs), $\xi = 2.1$ km s$^{-1}$, and [Fe/H] $= -2.64$.

The agreement in the stellar parameters between the Preston & Sneden (2001) and Aoki et al. (2002c) studies is quite good, with the possible exception of the surface gravity. Both groups derived $\log g$ for this star spectroscopically, that is to say by forcing ionization balance; however, it is likely that the low signal-to-noise ratio and moderate resolution spectra of Preston & Sneden adversely affected their parameter derivations. Indeed, the authors point out that the line-to-line scatter in the individual abundances are typically 0.2 – 0.3 dex, which prevented them from doing a detailed assessment of their stellar parameters. Thus, we have adopted the $\log g$ value for HE 0054-2542 derived by Aoki et al. (2002c), who used higher quality spectra in their analysis ($R = 50,000$ and S/N $\sim 60$). Likewise, we have adopted the $T_{\text{eff}}$ and [Fe/H] abundance of Aoki et al. (2002c), along with $\xi = 2.0$ km s$^{-1}$, for this star.

### Table 2

| Star       | $T_{\text{eff}}$ | $\log g$ | $\xi$ | [Fe/H] | [C/Fe] | [N/Fe] | $V_{\text{r}}$ | $\sigma_{\text{mean}}$ |
|------------|------------------|----------|-------|--------|--------|--------|----------------|------------------------|
| HE 0054-2542 | 5000             | 2.40     | 2.00  | -2.64  | +2.00  | +0.80  | -230.84       | 0.44                   |
| HE 0507-1653 | 5000             | 2.40     | 2.00  | -1.38  | +1.30  | +0.80  | 358.94        | 0.25                   |

**Notes.** $B$ and $V$ magnitudes for HE 0054-2542 are from Aoki et al. (2002c); $B$, $V$, $R$, and $I$ magnitudes for HE 0507-1653 and HE 1005-1439 are from Beers et al. (2007). $J$ and $K$ magnitudes for all three stars are from the 2MASS Point Source Catalog (Skrutskie et al. 2006).
the best-photometric $T_{\text{eff}}$ estimate for CEMP stars (Cohen et al. 2002). The $T_{\text{eff}}$ were then refined, and log $g$, $\xi$, and the Fe abundances were derived spectroscopically. For HE 0507-1653, however, too few weak Fe i lines were present in its spectrum to allow for an accurate microturbulent velocity to be determined, so $\xi = 2.0$ km s$^{-1}$, a value close to the average for the remaining stars in their sample, was assumed. The final stellar parameters for HE 0507-1653 from Aoki et al. (2007) and those adopted here are $T_{\text{eff}} = 5000$ K, log $g = 2.4$, $\xi = 2.0$ km s$^{-1}$, and [Fe/H] = $-1.38$.

HE 1005-1439. Aoki et al. (2007) is also the source for the stellar parameters adopted for this star. The $(V - K)$-based $T_{\text{eff}}$ for HE 1005-1439, though, was found to be $\sim 650$ K higher than the average $T_{\text{eff}}$ calculated using the $(V - R)$. $(V - I)$, and $(R - I)$ colors, and the authors adopted the lower $T_{\text{eff}}$, suspecting the $(V - K)$-based $T_{\text{eff}}$ was in error. We too adopt this lower temperature, $T_{\text{eff}} = 5000$ K, as well as the other parameters from the Aoki et al. study: log $g = 1.9$, $\xi = 2.0$ km s$^{-1}$, and [Fe/H] = $-3.17$.

4.2. Model Atmospheres

The structure of a stellar photosphere is dependent in part on the star’s chemical composition due to the contribution of metals to the continuous opacity. As the concentration of metals increases, the electron pressure increases as a result of a greater number of free electrons, which in turn affects the temperature and pressure stratification of the photosphere. Metals such as C, Si, Al, Mg, and Fe contribute the most to the continuous opacity, and so the photospheres of CEMP stars, with their enhanced C abundances, are expected to have temperature and pressure profiles that differ from those of “C-normal” metal-poor stars. In light of this, using model stellar atmospheres constructed with scaled solar abundances for a chemical abundance analysis of CEMP stars is less than optimal, as the change in the temperature and pressure structure in the line-forming regions due to the enhanced C, if not properly modeled, could result in inaccurate abundance derivations.

Unfortunately, C-enhanced models are not as readily available as models with scaled solar abundances, so it is not surprising that the majority of CEMP star abundance studies found in the literature have made use of the latter. Nonetheless, a handful of these studies have addressed the use of C-enhanced models versus solar-scaled models (e.g., Lucatello et al. 2003; Aoki et al. 2007), and one study, that of Hill et al. (2000), has provided results from a more comprehensive investigation. Hill et al. compared the profiles of the temperature and the molecular partial pressures of three C-bearing molecules with the gas pressure of a C-enhanced model atmosphere based on the revised MARCS code (Plez et al. 1992) and two solar-scaled models, one from the grids of Kurucz (Kurucz 1992) and the other from the MARCS code (Gustafsson et al. 1975), with parameters $T_{\text{eff}} = 4500$ K, log $g = 1$, and [Fe/H] = $-3$. They found that the temperature gradient in the C-enhanced model differed significantly from those of the solar-scaled models. The differences in the abundances derived using the different models are not quantified by the authors, but they do show that the upper layers of the C-enhanced atmosphere, where strong lines generally form, are cooler than those in the C-normal atmospheres. Conversely, in the deeper layers where intermediate and weaker lines form, they showed that the C-enhanced models are hotter. These differences in the temperature structure can affect abundance derivations, especially those based on molecular features which are highly sensitive to temperature.

While a more rigorous study of metal-poor stellar-atmosphere models enriched with C, as well as N and O, and their effect on stellar abundance derivations is needed, we have taken a more empirical approach to addressing the issue. We have generated both solar-scaled and C-enhanced models using the adopted stellar parameters (Table 2) for each star in our sample and have used both models in our abundance analysis. The solar-scaled models have been interpolated from the ATLAS9 grids of Kurucz.10 These models assume LTE and use the convective overshoot approximation. The C-enhanced models have been generated using the LTE stellar atmosphere code ATLAS12 (Kurucz 1996). These models also include enhancements in N and O. The C and N abundances, which are given in Table 2, are from the literature: Aoki et al. (2002c) for HE 0054-2542 and HE 1005-1439. Oxygen abundances are not available for these stars, so we adopted an abundance of [O/Fe] = +0.40, which is typical for Galactic halo stars.

4.3. Abundance Derivations

The abundance analysis of the three stars in our sample has been carried out using the stellar line analysis code MOOG (Sneden 1973). Spectral synthesis was used to fit the [C i] line, with the C abundance being the only free parameter. The oscillator strength for this transition, log $gf = -8.136$, is taken from Allende Prieto et al. (2002), who averaged the values given by Galavis et al. (1997) and Hibbert et al. (1993). This value is in agreement with that provided by the NIST database11 (log $gf = -8.14$), and it is in reasonable agreement with the value (log $gf = -8.21$) found in the Vienna Atomic Line Database (VALD; Piskunov et al. 1995; Kupka et al. 1999; Ryabchikova et al. 1999). The atomic line list for the region surrounding the [C i] feature is from VALD, and it includes the blending Fe i line at 8727.10 Å (log $gf = -3.93$). Although we expect this Fe i line to be of no consequence in the spectra of our metal-poor stars, Bensby & Feltzing (2006) determined that the line can be important for stars with $T_{\text{eff}} < 5700$ K, so for completeness we include it in our line list. Transition data for the three CN lines in the immediate vicinity of the [C i] line are also included in the line list and are taken from Gustafsson et al. (1999). The fits to the observed spectra are shown in Figure 1.

In addition to the A8727 [C i] feature, we have scoured the bHROS spectra for additional spectral lines and have identified for each star 2–8 Fe i lines, 2–3 high-excitation C i permitted lines, 5–9 resolved CN lines of the CN red system, and the K i resonance line at 7698.96 Å. The Fe i lines provide a measurement of the overall stellar non-CNO metallicity, and our analysis provides an additional independent determination of the Fe abundances of the stars in our sample. NLTE effects are expected to influence the formation of high-excitation C i lines, so the comparison of the C i-based abundances to those based on the [C i] feature provide an empirically determined estimate of the magnitude of the effect in these CEMP stars. The CN lines have been analyzed for N abundances, assuming the C abundance derived from the [C i] feature. Nitrogen abundances for CEMP stars have been largely derived from CN molecular bands at 3885 and 4215 Å via synthetic synthesis (e.g., Cohen et al. 2006; Aoki et al. 2007), so our analysis of individual CN lines of the red system provides an independent measurement of the N abundances of our sample. We note that many additional CN lines of the red system are found

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10 See http://kurucz.harvard.edu/grids.html
11 See http://physics.nist.gov/PhysRefData/ASD/index.html
in our spectra, but we have concentrated on a handful of the cleanest lines that could be securely identified. Finally, potassium is predominately produced in the oxygen-burning zones of Type II supernovae (Woosley & Weaver 1995), so determining its abundance may provide some insight into the chemical history of the prenatal gas from which the stars formed. A sample of Fe i and CN features in our bHROS spectra is shown in Figure 2.

EWs of the Fe i, C i, and K i lines were measured using the one-dimensional spectrum analysis software SPECTRE (Fitzpatrick & Sneden 1987) and were then used to derive abundances with the abfind driver in the MOOG package. The atomic parameters for the Fe i, C i, and K i lines were obtained from VALD. We made use of the extensive list of Davis & Phillips (1963) in the identification of measurable CN lines and have adopted the wavelengths therein; transition probabilities for the CN lines are from a proprietary list (A. McWilliam 2001, private communication). The adopted atomic parameters and the measured EWs for each star are listed in Table 3. In addition to EWs, SPECTRE was used to measure the observed wavelengths of five lines for each star in our line list in order to calculate radial velocities (V_r). The heliocentric-corrected mean values, along with the uncertainties in the means (σ_{mean} = σ/\sqrt{N-1}, where σ is the standard deviation and N is the number of lines measured), are provided in Table 2.

5. RESULTS AND DISCUSSION

The results of the abundance derivations and error analysis are tabulated in Table 4. The [Fe/H] abundances, as are all relative abundances appearing herein, are given relative to the solar abundances provided by Asplund et al. (2005a): A_⊙(Fe) = log N_⊙(Fe) = 7.45, A_⊙(C) = 8.39, and A_⊙(N) = 7.78. Before the derived abundances are discussed, the results of the error analysis and the comparison of the abundances derived using the C-enhanced and solar-scaled models are presented.

5.1. Abundance Uncertainties

The abundance uncertainties provided in Table 4 are based on abundance sensitivities of each individual element to changes in the input stellar parameters; they do not include any systematic errors, which may be considerable, resulting from assumptions made in the analysis (including the neglect of possible three-dimensional and NLTE effects) or other potential sources. For the analysis including the solar-scaled ATLAS9 models (hereafter simply referred to as ATLAS9), the parameters are T_{eff}, log g, ξ, and [m/H], the overall stellar metallicity. For the analysis including the C-enhanced ATLAS12 models (hereafter simply referred to as ATLAS12), in addition to the parameters previously listed, sensitivities to the model C and N abundances were also calculated. Following Aoki et al. (2007), from which we adopted the stellar parameters for HE 0507-1653 and HE 1005-1439, we assume uncertainties of ±100 K, ±0.30 dex, and ±0.25 km s^{-1} for T_{eff}, log g, and ξ, respectively. We point out, however, that Aoki et al. (2007) adopted an uncertainty of ±0.30 km s^{-1} for ξ. Uncertainties of ±0.15 dex for [m/H], ±0.20 dex for C, and ±0.20 dex for N were adopted for the ATLAS12 analysis. The
Figure 2. High-resolution bHROS spectra of our stellar sample. The lines that have been measured and that have been utilized in the abundance analysis are marked. All of the marked lines have been measured for each star except the CN line at 8398.48 Å, which was measurable only in the spectrum of HE 0054-2542.

Table 3
Equivalent Width Measurements

| Species | $\lambda_{\text{rest}}$ (Å) | $\chi$ (eV) | log gf | EWs (mÅ) |
|---------|---------------------|-----------|--------|----------|
|         |                     |           |        | HE 0054-2542 | HE 0507-1653 | HE 1005-1439 |
| Fe i... | 7181.19             | 4.22      | -0.884 | ...       | ...         | 24.5 |
|         | 7445.76             | 4.26      | -0.237 | 9.6       | 74.5        | ... |
|         | 7723.21             | 2.28      | -3.617 | ...       | ...         | 19.3 |
|         | 7998.94             | 4.37      | 0.048  | ...       | ...         | 79.9 |
|         | 8046.05             | 4.42      | -0.082 | 10.1      | 73.8        | ... |
|         | 8327.06             | 2.20      | -1.525 | ...       | 147.3       | ... |
|         | 8387.78             | 2.18      | -1.493 | 59.4      | 126.1       | 38.2 |
|         | 8688.64             | 2.18      | -1.212 | ...       | ...         | 49.8 |
|         | 8699.45             | 4.96      | -0.380 | ...       | ...         | 25.6 |
|         | 8705.20             | 8.77      | -1.519 | ...       | ...         | 18.3 |
|         | 8335.15             | 7.69      | -0.420 | ...       | ...         | 138.8 |
|         | 9088.51             | 7.48      | -0.429 | 130.0     | ...         | 115.4 |
| C i...  | 9094.83             | 7.49      | 0.150  | 185.2     | 216.8       | 147.4 |
| CN...   | 7185.15             | 0.42      | -1.604 | 9.1       | ...         | 12.1 |
|         | 8010.09             | 0.19      | -1.480 | 20.9      | 107.0       | 24.9 |
|         | 8017.01             | 0.22      | -1.463 | 21.7      | 106.4       | 25.7 |
|         | 8053.09             | 0.26      | -1.406 | 18.7      | 107.5       | 22.0 |
|         | 8054.09             | 0.28      | -1.406 | 21.5      | 107.6       | 18.6 |
|         | 8064.11             | 0.29      | -1.393 | 20.7      | ...         | 20.3 |
|         | 8074.43             | 0.31      | -1.380 | 21.2      | ...         | ... |
|         | 8345.73             | 0.65      | -1.139 | 13.8      | 87.9        | 23.0 |
|         | 8398.48             | 0.73      | -1.100 | 14.0      | ...         | ... |
| K i...  | 7698.96             | 0.00      | -0.170 | 35.9      | 131.8       | 13.7 |
Such a large uncertainty is not entirely surprising given that only the mean abundance, which has a standard deviation of 0.32 dex.

0507-1653 is more than a factor of 1.5 larger than those of the other two stars. This is entirely due to the large uncertainty in the abundance uncertainties arising from the ATLAS9 and ATLAS12 analyses do not differ greatly. While one might assume this suggests that the derived abundances are not sensitive to changes in the enhanced C abundances of the ATLAS12 models, this is not the case for the N abundances, for which a change in C abundance of ±0.50 dex can lead to an N abundance change of ±0.13 dex. However, because the uncertainty in the N abundances derived from the CN lines is dominated by the sensitivities to $T_{\text{eff}}$ and $\log g$, the sensitivity to C does not greatly affect $\sigma_{\text{Total}}$(N). Second, the $\sigma_{\text{Total}}$(N) is significantly larger than for the other elements analyzed because of the acute sensitivity of the N abundance to $T_{\text{eff}}$ and $\log g$. Its sensitivity to model [m/H] and C abundances also contributes a small amount to $\sigma_{\text{Total}}$(N). Third, none of the other abundances derived for the three stars are sensitive to the adopted N abundance, suggesting that the N abundances do not affect significantly the structure of the ATLAS12 model atmospheres. Last, the $\sigma_{\text{Total}}$ for the C abundances of HE 0054-2542, HE 0507-1653, and HE 1005-1439, respectively, in each figure, the optical depths\(^{12}\) at reference wavelength 5000 Å (\(\tau_{5000}\)) that bracket the line-forming regions of the spectral features included in our analysis are marked; the inset included with each figure highlights the temperature–log \(P_{\text{gas}}\) relations of these regions. As can be seen in the figures, the ATLAS12 model is hotter than the ATLAS9 model.

\(^{12}\) The \(\tau_{5000}\) values have been taken from the output files of the MOOG package and represent the optical depths of the mean depth of formation for each spectral line.

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**Table 4**

| Species | ATLAS12: C-Enhanced Models | ATLAS9: Solar-Scaled Models |
|---------|---------------------------|--------------------------|
|         | HE 0054-2542 | HE 0507-1653 | HE 1005-1439 | HE 0054-2542 | HE 0507-1653 | HE 1005-1439 |
| Fe/H\(^{a}\) | −2.66 | −1.42 | −3.08 | −2.63 | −1.42 | −3.09 |
| $\sigma_{\ldots}$ | 0.08 | 0.15 | 0.13 | 0.10 | 0.16 | 0.14 |
| A(C\(i\)) | 7.85 | 8.30 | 7.45 | 7.85 | 8.26 | 7.45 |
| $\sigma_{\ldots}$ | 0.12 | 0.14 | 0.11 | 0.11 | 0.13 | 0.12 |
| A(C\(i\)) | 8.34 | 8.94 | 7.90 | 8.43 | 9.08 | 7.99 |
| $\sigma_{\ldots}$ | 0.08 | 0.34 | 0.15 | 0.12 | 0.42 | 0.17 |
| A(N) | 6.36 | 7.56 | 6.97 | 6.21 | 7.41 | 6.82 |
| $\sigma_{\ldots}$ | 0.34 | 0.31 | 0.33 | 0.36 | 0.32 | 0.37 |
| A(K) | 3.03 | 4.40 | 2.50 | 3.05 | 4.45 | 2.53 |
| $\sigma_{\ldots}$ | 0.08 | 0.19 | 0.07 | 0.09 | 0.21 | 0.08 |

**Note.**\(^{a}\) Calculated using the solar Fe abundance of Asplund et al. (2005a).

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**Table 5**

| Species | $\Delta T$ (±150 K) | $\Delta \log g$ (±0.50 dex) | $\Delta \Delta$ (±0.25 km s\(^{-1}\)) | $\Delta$ [m/H] (±0.50 dex) | $\Delta$ A(C) (±0.50 dex) | $\Delta$ A(N) (±0.50 dex) | $\sigma_{\text{Total}}$\(^{b}\) |
|---------|------------------|----------------------|-----------------|-----------------|-----------------|-----------------|------------------|
| Fe\(\ldots\) | ±0.11 | 0.00 | ±0.02 | ±0.04 | ±0.06 | 0.00 | ±0.08 |
| [C\(i\)] \(\ldots\) | ±0.07 | ±0.18 | 0.00 | +0.0 | ±0.04 | 0.00 | ±0.12 |
| C\(\ldots\) | ±0.08 | ±0.10 | ±0.05 | 0.00 | ±0.02 | 0.00 | ±0.08 |
| N\(\ldots\) | ±0.38 | ±0.33 | 0.00 | +0.15 | ±0.13 | 0.00 | ±0.34 |
| K\(\ldots\) | ±0.11 | 0.00 | ±0.02 | ±0.04 | ±0.05 | 0.00 | ±0.08 |

**Notes.**\(^{a}\) Abundance sensitivities are given for HE 0054-2542.\(^{b}\) The total abundance uncertainty, given by the quadratic sum of the individual parameter sensitivities and the uncertainty in the mean abundance, for abundances based on more than a single spectral line.

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The abundance sensitivities to changes in the stellar parameters of the ATLAS12 models are given for HE 0054-2542 in Table 5. The sensitivities for HE 0054-2542 are representative of those for all three stars, although some resulting uncertainties warrant special comment. First, as is evident in Table 4, the abundance uncertainties arising from the ATLAS9 and ATLAS12 analyses do not differ greatly. While one might assume this suggests that the derived abundances are not sensitive to changes in the enhanced C abundances of the ATLAS12 models, this is not the case for the N abundances, for which a change in C abundance of ±0.50 dex can lead to an N abundance change of ±0.13 dex. However, because the uncertainty in the N abundances derived from the CN lines is dominated by the sensitivities to $T_{\text{eff}}$ and $\log g$, the sensitivity to C does not greatly affect $\sigma_{\text{Total}}$(N). Second, the $\sigma_{\text{Total}}$(N) is significantly larger than for the other elements analyzed because of the acute sensitivity of the N abundance to $T_{\text{eff}}$ and $\log g$. Its sensitivity to model [m/H] and C abundances also contributes a small amount to $\sigma_{\text{Total}}$(N). Third, none of the other abundances derived for the three stars are sensitive to the adopted N abundance, suggesting that the N abundances do not affect significantly the structure of the ATLAS12 model atmospheres. Last, the $\sigma_{\text{Total}}$ for the C abundances of HE 0507-1653 is more than a factor of 1.5 larger than those of the other two stars. This is entirely due to the large uncertainty in the mean abundance, which has a standard deviation of 0.32 dex. Such a large uncertainty is not entirely surprising given that only two C\(i\) lines with vastly different line strengths (18 and 217 mÅ were measurable for this star; the sensitivity of its C\(i\) abundance to the other parameters is comparable to those of the other stars.

**5.2. C-Enhanced Versus Solar-Scaled Models**

In Table 4, the results of both the ATLAS12 and ATLAS9 analyses are given. The Fe, [C\(i\)], and K abundances of the three stars are consistent between the two analyses, with abundance differences being ≤ 0.05 dex. There are greater discordances, however, between the ATLAS12 and ATLAS9 abundances for C\(i\) and N. The differences are such that the ATLAS12 C\(i\) abundances are 0.09–0.14 dex lower than the ATLAS9 abundances, whereas the ATLAS12 N abundances are consistently higher than those from the ATLAS9 analysis by 0.15 dex.

The differences in the C\(i\) and N abundances, as well as the minor discrepancies in the Fe, [C\(i\)], and K abundances, are entirely attributable to the divergences in the temperature and pressure structures of the ATLAS12 and ATLAS9 model atmospheres. In Figures 3–5, temperature is plotted versus the logarithm of the pressure from the ATLAS12 and ATLAS9 models of HE 0054-2542, HE 0507-1653, and HE 1005-1439, respectively. In each figure, the optical depths\(^{12}\) at reference wavelength 5000 Å (\(\tau_{5000}\)) that bracket the line-forming regions of the spectral features included in our analysis are marked; the inset included with each figure highlights the temperature–log \(P_{\text{gas}}\) relations of these regions. As can be seen in the figures, the ATLAS12 model is hotter than the ATLAS9 model.

\(^{12}\) The \(\tau_{5000}\) values have been taken from the output files of the MOOG package and represent the optical depths of the mean depth of formation for each spectral line.
Figure 3. Temperature vs. the logarithm of the gas pressure of the one-dimensional LTE C-enhanced ATLAS12 (red) and solar-scaled ATLAS9 (black) models for HE 0054-2542. The inset shows the relations in the line-forming region of the spectral features considered in our analysis, as marked by the upper and lower optical depths (log $\tau_{5000}$) in the main panel.

Figure 4. The same as Figure 3 but for HE 0507-1653.

Figure 5. The same as Figure 3 but for HE 1005-1439.

in the line-forming region of each star except at the deepest boundaries for HE 0054-2542 and HE 1005-1439 (the two most Fe-deficient stars), where the ATLAS12 model dips below the ATLAS9 model. Accurately quantifying the effect of the model differences on the abundances derived from each spectral line is difficult due to the convolution of the effects of the temperature and pressure differences at a given $\tau_{5000}$, but the differences of the models at the mean depths of formation for each line are such that they qualitatively account for the abundance discrepancies that are seen. For example, the mean depths of formation of the C\textsc{i} lines differ between the models in such a way that the ATLAS9 temperature at this layer is less than the ATLAS12 temperature and conversely, the ATLAS9 pressure is greater than the ATLAS12 pressure. Both of these differences conspire to result in an ATLAS9 abundance that is greater than that of ATLAS12, which is seen for all three stars.

The differences in the ATLAS12 and ATLAS9 abundances of C\textsc{i} and N demonstrate that model atmospheres characterized by metal abundances scaled from the solar composition are not ideally suited for chemical abundance analyses of CEMP stars. This result corroborates the conclusion of Hill et al. (2000). The comparison of their C-enhanced and solar-scaled models is similar to those seen here for the two most Fe-deficient stars HE 0054-2542 and HE 1005-1439: the C-enhanced model is hotter at a given pressure than the solar-scaled model in the deepest atmospheric layers, and it is cooler in the outer layers. Hill et al. point out that very strong lines, such as the molecular band heads, would be stronger in the C-enhanced model because of the lower temperature in the outer regions in which these lines are expected to form, and that the intermediate and weak lines that form deeper in the atmospheres, near log $\tau_{5000} = -1$, will be weaker in the C-enhanced models due to their higher temperatures in these layers. Because of these structural differences, Hill et al. conclude that C-enhanced models should be used in analyses of CEMP stars if possible.

As stated above, accurately quantifying the effect of using solar-scaled as opposed to C-enhanced model atmospheres in abundance analyses of CEMP stars is challenging. The differences in the derived abundance for any given element are dependent on both the structural differences in the temperature and pressure profiles of the model atmospheres and the depth of formation of each individual spectral line. This is evident by the differing results for Fe, [C\textsc{i}], and K, which show no or only minor differences in the ATLAS12 and ATLAS9 abundances, and for C\textsc{i} and N, which show more significant discrepancies. The magnitude of the effect is expected to be even more severe for the molecular band heads, which are highly sensitive to temperature and pressure, that are often used in the derivation of C, N, and O abundances of CEMP stars. Any inaccuracies in the derived abundances of CEMP stars will negatively affect the interpretation of the nucleosynthetic history of these stars and
their role in the chemical evolution of the Galaxy. Under the assumption that C-enhanced models more accurately represent the real atmospheres of CEMP stars, it is clear that C-enhanced models should be used in their abundance analyses. Moreover, we hope our analysis will provide sufficient motivation for a more rigorous examination of C-enhanced model atmospheres and their effect on the derived abundances of CEMP stars.

Unless explicitly stated to the contrary, the remaining discussion will refer to the abundances derived using the C-enhanced ATLAS12 models.

5.3. Abundances

5.3.1. Iron Abundances

The limited wavelength coverage of the bHROS spectra and the Fe deficiency of the stars in our sample combine to restrict the number of lines (N ≤ 8) from which Fe abundances can be derived for each star. For the two most Fe-deficient stars, HE 0054-2542 and HE 1005-1439, only three and two Fe lines, respectively, were measurable. Regardless, the derived Fe abundances of all three stars (Table 4) are in very good agreement with previously determined values. Preston & Sneden (2001) and Aoki et al. (2002c) have both analyzed HE 0054-2542 and have found [Fe/H] = −2.67 and [Fe/H] = −2.64, respectively; our value of [Fe/H] = −2.66±0.08 falls between their results. Our abundances of [Fe/H] = −1.42±0.15 for HE 0507-1653 and [Fe/H] = −3.08±0.13 for HE 1005-1439 are in good agreement with those of Aoki et al. (2007), who derived [Fe/H] = −1.38 for the former and [Fe/H] = −3.17 for the latter. Thus, despite utilizing different spectral lines and different model atmospheres, our results confirm the subsolar Fe abundances of HE 0054-2542, HE 0507-1653, and HE 1005-1439.

5.3.2. C Abundances from the [C i] Line

As shown in Figure 1, the synthetic spectra of the λ8727 region fit well the observed spectra of each star. The resulting abundances from the best fits of the [C i] features are given in Table 4. Adopting our derived [Fe/H] abundances and A_C(λ8727) = 8.39, the C abundances relative to Fe, listed in Table 6, are [C/Fe] = +2.12±0.14 for HE 0054-2542, [C/Fe] = +1.33±0.21 for HE 0507-1653, and [C/Fe] = +2.14±0.17 for HE 1005-1439, where the stated uncertainty is the quadratic sum of the C and Fe uncertainties given in Table 4. We discuss the abundances for each star in turn.

**HE 0054-2542.** Similar to the [Fe/H] abundance, our [C/Fe] ratio from the one-dimensional LTE analysis for this star is bracketed by the abundances derived by Preston & Sneden (2001) and Aoki et al. (2002c), and it is in good agreement with both of their values. Preston & Sneden found an abundance of [C/Fe] = +2.2 by analyzing the CH bands at wavelengths 4228–4241 Å and 4358–4374 Å. Their derived abundance is labeled as uncertain, although the uncertainty is not quantified. The abundance from Aoki et al. (2002c), [C/Fe] = +2.0, is derived from the (1-0) band of the C2 Swan system at 4735 Å, and the result is also given without an uncertainty estimate. Typical errors in [C/Fe] abundances derived from high-resolution spectra range from about 0.15–0.25 dex (e.g., Cohen et al. 2006; Sivarani et al. 2006), and if this typical uncertainty is adopted for the Preston & Sneden and Aoki et al. (2002c) studies, their C abundances are in agreement. Both of the previously derived abundances are within the uncertainty associated with our value derived from the [C i] feature, and we thus conclude that the three measurements are consistent.

**HE 0507-1653.** The [C i]-based one-dimensional LTE abundance for this star is in excellent agreement with the value found by Aoki et al. (2007), the difference between the two results being only 0.04 dex. Aoki et al. (2007) derived an abundance of [C/Fe] = +1.29±0.19 based on an analysis of the C2 Swan (0-1) band at 5635 Å. The (0-1) band was chosen for measurement because, according to the authors, the CH G-band and the C2 Swan (0-0) band at 5170 Å were saturated and not suitable for the purpose.

**HE 1005-1439.** Unlike for the two more Fe-abundant stars in our sample, the one-dimensional LTE-based C abundance derived from the [C i] feature for HE 1005-1439 differs from the previously determined measurement. This star was analyzed by Aoki et al. (2007) as part of the same study that included HE 0507-1653, although the abundance for HE 1005-1439 is based on the C2 Swan (0-0) band at 5170 Å instead of the (0-1) band at 5635 Å. Aoki et al. (2007) derived an abundance of [C/Fe] = +2.48±0.20, which is 0.34 dex, or about a 2σ deviation, larger than our [C i]-based abundance. Aoki et al. (2007) suggest that C abundances derived from C2 bands may be systematically higher by 0.2 dex than those derived from CH bands based on the results of Aoki et al. (2002d), who derived consistent C abundances for the CEMP star LP 625-44 from the (1-0), (0-0), and (0-1) bands of the Swan system but found the abundance derived using the CH band at 4323 Å to be about 0.20 dex lower. However, the abundances derived for HE 0054-2542 do not support the existence of such a systematic offset; indeed, the C2-based abundance derived for this star by Aoki et al. (2002c) is 0.2 dex lower than the CH-based abundance derived by Preston & Sneden (2001), in direct contrast to the suggested systematic offset. Furthermore, a similar offset has not been suggested to exist between individual lines of the C2 Swan system. In contrast, Aoki et al. (2002d) find consistent results from three different C2-band heads using the same line list as Aoki et al. (2007). Thus, there is no reason to believe that any one of the C2 Swan lines is superior to any of the others for abundance analyses and that the 0.34 dex difference in the C2 and [C i]-based abundances derived for HE 1005-1439 is due to the particular C2 Swan line used.

Because the [C i] and C2-based abundances for HE 1005-1439 differ at about the 2σ level of the internal uncertainty, the difference cannot be ascribed with statistical confidence to the inability of the C2 Swan lines to reproduce reliable LTE abundances. Instead, the abundance difference may be a result of other inadequacies in either of the abundance analyses, although the exact component of the analyses that could be responsible for such a large discrepancy is not readily identifiable. As discussed above, the adopted line lists and the modeling of the lines do not seem to be at fault. The stellar parameters used by Aoki et al. (2007) are the same as those used in our analysis, so while the sensitivity of the abundance derived from the λ5170 C2 line to changes in stellar parameters may differ from that of the [C i]-based abundance, it is unlikely the adopted stellar parameters can account for the 0.34 dex difference in

### Table 6

| Star          | Δ(C) | [C/Fe] | Δ(N) | [N/Fe] |
|---------------|------|--------|------|--------|
| HE 0054-2542  | 7.85 | +2.12  | 6.36 | +1.24  |
| HE 0507-1653  | 8.30 | +1.33  | 7.56 | +1.20  |
| HE 1005-1439  | 7.45 | +2.14  | 6.97 | +2.27  |
the derived C abundance. Despite the moderate S/N = 65 of the coadded spectrum for HE 1005-1439, the [C\textsc{i}] line is well shaped and easily identifiable (Figure 1), and an excellent fit with the synthetic spectrum from both the continuum and the [C\textsc{i}] feature is obtained. Furthermore, reproduction of the [C\textsc{I}/Fe\textsc{II}] abundance of HE 1005-1439 derived by Aoki et al. (2007) would require an EW that is approximately a factor of 2 larger than the one measured in our bHROS spectrum (Figure 6). Thus, while the spectrum of HE 1005-1439 is of slightly lower quality than those of the other two stars in our sample, there is no conspicuous evidence to suggest that it is a source of significant error in the derived C abundance.

Having largely ruled out other possibilities, in Section 5.4 we discuss whether three-dimensional effects could explain the different abundance results from the [C\textsc{i}] and C\textsc{2} lines.

5.3.3. The High-Excitation C\textsc{i} Lines

Carbon abundances have been derived from high-excitation (7.48–8.77 eV) C\textsc{i} lines in the spectra of our CEMP star sample for comparison to the [C\textsc{i}] results. The C\textsc{i} lines are known to form out of LTE, and the measurements presented here should provide an empirical estimate of the associated NLTE effects in these stars. The comparison of the one-dimensional LTE abundances derived from the [C\textsc{i}] and C\textsc{i} lines is made in Table 7, and as expected from existing NLTE calculations (Fabbian et al. 2006), the abundances based on the C\textsc{i} lines are greater than those derived from the forbidden line. Similarly, Aoki et al. (2002d) derived the C abundance of the CEMP star LP 625-44 from five high-excitation C\textsc{i} lines and found the abundance to be 0.45 dex greater than that derived from CH and C\textsc{2} molecular features. The stellar parameters of LP 625-44 ([Fe/H] = −2.7, [C/Fe] = +2.25, \(T_{\text{eff}}\) = 5500 K, and log g = 2.5; Aoki et al. 2002d) are similar to those of HE 0054-2542, and the C\textsc{i} over-abundances are nearly identical for the two stars. In Section 5.4, we present predicted NLTE abundances for C\textsc{i} and the corresponding three-dimensional effects for [C\textsc{i}].

5.3.4. Nitrogen Abundances

Numerous lines of the CN red system are present in our bHIROS spectra, and we have identified 5–9 clean, resolved lines for each star (Table 3) suitable for abundance analysis. The mean abundances derived from these lines are provided in Table 4 and correspond to relative abundances of \([\text{N}/\text{Fe}] = +1.24\pm0.35\) (0.03) for HE 0054-2542, \([\text{N}/\text{Fe}] = +1.20\pm0.34\) (0.02) for HE 0507-1653, and \([\text{N}/\text{Fe}] = +2.27\pm0.35\) (0.09) for HE 1005-1439 (Table 6). The number given in the parentheses following each uncertainty is the standard deviation in the mean abundance for each star and is indicative of the excellent agreement in the line-by-line abundances derived from the CN red system features. As mentioned above in Section 5.1, the large uncertainties in the N abundances arise from the severe sensitivity of these molecular features to changes in the \(T_{\text{eff}}\) and log g parameters and are typical compared to those from other studies (Cohen et al. 2006; Aoki et al. 2007).

Previous N abundance determinations for the three stars in our sample have all been based on features of the CN blue system near 3880 and 4215 Å and are all at least 0.40 dex lower than the abundances presented here. Preston & Sneden (2001) and Aoki et al. (2002b) determined the \([\text{N}/\text{Fe}] = +0.7, +0.3\) and +0.1 dex, respectively. Aoki et al. (2002b) revisited the analysis of Aoki et al. (2002c) and determined the \(λ3880\) CN band in their spectrum was too strong to provide an accurate abundance estimate. Using the \(λ4215\) CN band, Aoki et al. (2002b) derived an abundance of \([\text{N}/\text{Fe}] = +0.8\), a value that is in better agreement with that of Preston & Sneden but lower than our derived abundance by 0.44 dex. The N abundances for HE 0507-1653 and HE 1005-1439 have been determined by Aoki et al. (2007) from an analysis of the \(λ4215\) CN band for each star. Their reported abundances are \([\text{N}/\text{Fe}] = +0.80\) for the former and \([\text{N}/\text{Fe}] = +1.79\) for that latter; these values are 0.40 and 0.48 dex, respectively, lower than our abundances.

Given the large uncertainties in the N abundances, the differences between our values and those previously published cannot be said to be statistically significant. Nonetheless, the disagreement is striking. About 50% of the difference for each star is attributable to our use of the ATLAS12 model
atmospheres, from which the abundances are a consistent 0.15 dex higher than those derived from the ATLAS9 analysis. The N abundances from our ATLAS9 analysis are ~0.3 dex higher than the literature values, and the source of this remaining difference is not so obvious. The adoption of different molecular dissociation energies by different studies can lead to diverging abundances, but this is not the case here. Following Spite et al. (2005) and Norris et al. (2007), we have adopted a dissociation energy of $D_0 = 7.76$ eV for the CN molecule, which is essentially the same as the value of $D_0 = 7.75$ eV adopted by Aoki et al. (2002b) and Aoki et al. (2007).\footnote{The CN dissociation energy does not appear in the published papers of Aoki et al. (2002b, 2007) and has been provided by W. Aoki (2008, private communication).} Spite et al. (2005) derived the N abundances of ten metal-poor giants from both the CN blue band near 3880 Å and the NH band at 3360 Å, and the CN-based abundances were found to be systematically lower than the NH-based abundances by ~0.40 dex. The reason for the discrepancy was not apparent to the authors, but we find it to be similar to the ~0.30 dex difference between the CN blue bands and CN red system abundances from the ATLAS9 analysis seen here. Taken together, the results of Spite et al. (2005) and of our study suggest that analyses of the CN blue system bands underestimate the N abundances of metal-poor giants. Because the CN band is used often for the derivation of N abundances is such stars, further investigation into the ability of this feature to provide accurate abundances is needed.

Accurately determined N abundances are critical in understanding the nucleosynthetic history of CEMP stars and to placing constraints on stellar evolution models. Mass-transfer from a primary companion during its asymptotic giant branch (AGB) phase is thought to be the source of the enhanced C and the enhancements of other elements in the photospheres of metal-poor AGB giants. Because the CN band is used often for the derivation of N abundances is such stars, further investigation into the ability of this feature to provide accurate abundances is needed.

5.3.5. Potassium Abundances

Potassium abundances have been determined for large samples of metal-poor stars by a handful groups, starting with Gratton & Sneden (1987) and then more recently by Cayrel et al. (2004), Zhang & Zhao (2005), and Zhang et al. (2006). The consensus among these studies is that the LTE [K/Fe] ratios for metal-poor stars, irrespective of evolutionary stage, are supersolar, and they evince substantial scatter, particularly at metallicities of [Fe/H] $\leq -1.0$. The K I resonance line at 7699 Å, generally the only line available in the spectra of late-type stars with which K abundances can be derived, is highly sensitive to NLTE effects; large negative corrections (~0.2 to ~0.8 dex) for LTE abundances derived from this line have been predicted (Takeda et al. 2002). The magnitude of the corrections has been shown to be dependent on $T_{\text{eff}}$ and log g but not [Fe/H], and after applying the corrections to the LTE abundances, the supersolar [K/Fe] ratios and the large scatter remain (e.g., Takeda et al. 2002; Zhang & Zhao 2005).

The LTE K abundances derived for the three stars in our sample are given in Table 4 and correspond to [K/Fe] relative abundances of +0.61, +0.74, and +0.50 for HE 0054-2542, HE 0507-1653, and HE 1005-1439, respectively. The K abundance has been derived for only one other CEMP star, HE 1410-0004 (Cohen et al. 2006), a subgiant with [Fe/H] $= -3.02$; the K abundance for this star has been determined to be [K/Fe] $= +0.71$. The LTE abundances of these CEMP stars fall squarely among the scatter in the LTE [K/Fe] abundances seen for C-normal metal-poor stars (e.g., Cayrel et al. 2004; Zhang & Zhao 2005). The consistent abundances derived using the ATLAS12 and ATLAS9 models and the lack of a metallicity dependence on the calculated NLTE corrections both suggest that the NLTE effects associated with K abundances in CEMP stars do not differ significantly from those in C-normal stars. While targeted K NLTE calculations for CEMP stars are needed, the existing NLTE corrections to K abundances should, to first approximation, be adequate.

5.4. Three-Dimensional and NLTE Effects

The elemental abundances presented in Section 5 were estimated based on one-dimensional model atmospheres and LTE spectral line formation. Since these may be questionable assumptions, especially in the low-density regimes of metal-poor red giant atmospheres (Asplund 2005), it is important to investigate the possible systematic errors introduced in the analysis by these simplifications. Indeed, the difference in the HE 1005-1439 C abundances derived from [C I] and molecular lines, and the systematically lower abundances derived from [C I] compared with C I for the one-dimensional LTE analysis may exactly signal such three-dimensional and/or NLTE effects.

Three-dimensional time-dependent hydrodynamical model atmospheres have relatively recently started to be employed for abundance analysis of metal-poor stars (e.g. Asplund et al. 1999; Asplund & García Pérez 2001; Asplund 2005; Asplund et al. 2006; Collet et al. 2006; Collet et al. 2007; González Hernández et al. 2008). The main difference in the atmospheric structure is the much lower temperatures in the line-forming region of the three-dimensional model compared with classical one-dimensional model atmospheres; these temperature differences affect in particular the abundances derived from molecular lines, neutral species, and low-excitation lines (Asplund et al. 1999). C I is a majority species and hence is less affected by temperature variations than, for example, Li I or Fe I, but because the 8727 Å [C I] line originates from a relatively low-excitation level (1.26 eV), one would expect the one-dimensional abundances to be slightly overestimated at the lowest metallicities (Asplund 2005).

We have carried out three-dimensional LTE line-formation calculations for the [C I] 8727 Å transition using the same three-dimensional hydrodynamical model atmospheres as described in Collet et al. (2007), which have stellar parameters similar to our three stars in terms of $T_{\text{eff}}$, xlog g, and [Fe/H]. The three-dimensional models were constructed assuming scaled-solar abundances and are thus not directly applicable to CEMP stars. For an exploratory study like this we never-
theless consider this a justifiable approach. Because the three-dimensional effects are estimated from a differential comparison with one-dimensional MARCS models (Asplund et al. 1997) that were computed assuming identical stellar parameters (including the chemical composition), to first order the effects of a C-enriched atmosphere discussed in Section 5.2 will cancel out. Specifically constructed three-dimensional models appropriate for CEMP stars would be valuable, however, for more accurate estimates of the various three-dimensional effects. We also note that a comparison with MARCS models is more relevant than with Kurucz models, because the three-dimensional and MARCS models are built on the same microphysics in terms of opacities and equation of state.

The $\lambda8727$ [C$\text{i}$] three-dimensional line-formation calculations have been computed for metallicities of [Fe/H] = +0, −1, −2, and −3, and the three-dimensional abundance effects appropriate for our three stars have been estimated and applied to the one-dimensional LTE results described in Section 5.3. The three-dimensional-based abundances are given in Table 6. As expected, the three-dimensional effects remain modest for the [C$\text{i}$] line: slightly positive for HE 0507-1653 and $\sim$ −0.1 dex for HE 0054-2542 and HE 1005-1439, the two most metal-poor stars. In this respect, [C$\text{i}$] behaves like lines from other majority species such as O$\text{i}$ (Asplund 2005; Collet al. 2007), but the three-dimensional effects are less severe than, for example, for the [O$\text{i}$] 6300 Å line for a given line strength, because of its higher excitation potential. It should be noted that the exact value of the three-dimensional corrections remains somewhat uncertain since the O abundances are not yet known in these stars; if [O$\text{i}$]/[Fe$\text{II}$] is significantly larger than the +0.4 assumed here, a greater fraction of C will be tied up in CO. Thus, notwithstanding, it is clear that the three-dimensional effects on the $\lambda8727$ [C$\text{i}$] line will remain relatively small.

Fabbian et al. (2006) have investigated the line formation of neutral C atoms in late-type stars and have provided predicted NLTE abundance corrections for the high-excitation C$\text{i}$ lines employed here for stars characterized by a range of $T_{\text{eff}}$, log $g$, and metallicities. The NLTE abundance corrections for HE 0054-2542, HE 0507-1653, and HE 1005-1439 are $\sim$−0.30, −0.45, and $\sim$−0.30 dex, respectively, when assuming a C abundance enhancement of [C/Fe] = +0.4 and neglecting the highly uncertain inelastic H collisions (Asplund 2005). Thus, NLTE effects on the C$\text{i}$ lines can explain most of the differences between the abundances derived from the C$\text{i}$ and [C$\text{i}$] lines. We note that Fabbian et al. indeed predict that the magnitude of the C$\text{i}$ NLTE corrections should become larger with increasing [C/Fe], because the line-formation is then shifted outward in the atmosphere, where the departures from LTE are more pronounced. This effect has not been investigated computationally for C enhancements of [C/Fe] > 0.4, and our result, combined with that of Aoki et al. (2002d), suggests that such a study is very much needed. Additionally, the three-dimensional NLTE line formation for C$\text{i}$ has not yet been studied due to computational challenges arising from the large number of atomic levels that need to be considered, but given the very substantial one-dimensional NLTE effects uncovered here, such calculations would also be very welcome.

As is clear from Table 6, taking three-dimensional and NLTE effects into account for [C$\text{i}$] and C$\text{i}$, respectively, have brought the two abundance indicators into better agreement, from a difference of $\sim$0.5 dex to $\sim$0.25 dex. The remaining difference can be plausibly attributed to underestimated three-dimensional and NLTE effects, erroneous $T_{\text{eff}}$, or simply observational uncertainties. Of the two abundance indicators, we consider the [C$\text{i}$]-based abundances to be the most reliable.

As discussed in Section 5.3, the abundances of HE 0054-2542 and HE 0507-1653 derived from the [C$\text{i}$] line are in good agreement with those derived from CH and C$\text{II}$ features. Collet et al. (2007) have shown that, assuming scaled-solar abundances, the three-dimensional corrections for CH are relatively constant, at $\sim$−0.1 to $\sim$−0.2 dex, down to [Fe/H] = −2 for giants; C$\text{II}$ lines were not investigated. These three-dimensional effects would therefore not be expected to ruin the overall agreement for the two CEMP stars. More noteworthy, the C$\text{II}$-based abundance for HE 1005-1439 from Aoki et al. (2007) is 0.34 dex larger than our one-dimensional result for [C$\text{i}$] and 0.49 dex larger than the corresponding three-dimensional value. While no three-dimensional calculations for C$\text{II}$ have been performed to date, at least qualitatively this is in line with our expectations that the three-dimensional corrections for molecular lines become more severe toward lower metallicities (Asplund & García Pérez 2001; Asplund 2005; Collet et al. 2007). Unfortunately, here we are unable to carry out such a study without a better knowledge of the stellar O abundances; the cool outer atmospheric layers of the low-metallicity three-dimensional models that give rise to the C$\text{II}$ lines are particularly conducive to CO molecule formation, which locks up a significant fraction of C and thereby limits the amount available for C$\text{II}$ (the [C$\text{i}$] lines will be less affected by the CO formation since they form in deeper atmospheric layers where the temperatures are significantly higher).

6. CONCLUSIONS

An investigation into the accuracy of published C abundances as derived from the traditionally used CH and C$\text{II}$ Swan bands of CEMP stars has been presented. We have analyzed the $\lambda8727$ [C$\text{i}$] line, a normally reliable C-abundance indicator that is impervious to NLTE effects, in high-quality Gemini-S/bHIROS spectra of three CEMP stars and have compared the C abundances derived from this line to previously published values. The one-dimensional LTE abundances derived from the [C$\text{i}$] feature are found to confirm the abundances derived from both CH and C$\text{II}$ molecular features in the two most Fe-abundant stars, HE 0054-2542 and HE 0507-1653 ([Fe/H] = −2.66 and $\sim$−1.42, respectively), but the [C$\text{i}$]-based abundance of the most Fe-deficient star, HE 1005-1439 ([Fe/H] = −3.08), is 0.34 dex, or about a 2σ deviation, lower than the abundance derived from the C$\text{II}$ Swan (0-0) band at 5170 Å.

As described in Section 5.3.2, the specific C$\text{II}$ Swan band used to derive C abundances does not appear to be a factor in the difference seen for HE 1005-1439. Also, no particular component of the two abundance analyses could be identified as the most likely source of the discordance, although internal errors may yet be the underlying cause. Unidentified systematic errors in the analyses also cannot be ruled out as the source of the difference, but the agreement in the abundances of HE 0507-1653 derived by us and Aoki et al. (2007)—the study that also derived the discordant abundance of HE 1005-1439,—suggests that no such systematic errors are to be expected. Thus, the difference in the C abundance seen between the two studies may indeed be the result of three-dimensional effects in the analysis of the C$\text{II}$ Swan band. Collet et al. (2007) investigated the impact of three-dimensional effects on CNO abundances of red giants derived from weak CH, NH, and OH
lines and found the three-dimensional C abundances to be 0.5–0.8 dex lower (for stars with [Fe/H] = −3.0) than those derived using traditional one-dimensional analyses. While these corrections are larger than the difference between the C$_{2}$ and [C$_{1}$]-based abundances for HE 1005-1439, it must be pointed out that Collet et al. (2007) considered stars with scaled-solar metallicities, and the corrections may not be applicable to CEMP stars. Also, the three-dimensional corrections for CH lines are not necessarily similar to those for C$_{2}$ lines (e.g., Asplund et al. 2005b; Collet et al. 2006).

To investigate the potential three-dimensional effects on [C$_{1}$]-based abundances of low-metallicity stars, we have carried out three-dimensional LTE line-formation calculations for [C$_{1}$] using the same three-dimensional hydrodynamical-model atmospheres as described by Collet et al. (2007). The three-dimensional correction for HE 0507-1653 is estimated to be slightly positive (+0.03 dex), while the corrections for HE 0054-2542 and HE 1005-1439 are negative (−0.07 and −0.15 dex, respectively). Thus, the corrections are quite modest but do increase in magnitude at lower metallicities, similar to what is seen for the [O$_{1}$] line (Asplund 2005; Collet et al. 2007). While more accurate [C$_{1}$] three-dimensional corrections for these CEMP stars await C-enhanced three-dimensional models and more certain O abundances, the observations and calculations presented here are qualitatively in line with expectations that the three-dimensional corrections for molecular line-based C abundances become more severe toward lower metallicities.

We have also determined abundances from high-excitation C$_{1}$ lines and found them to be systematically higher than the [C$_{1}$]-based abundances by ∼0.5 dex when assuming LTE. One-dimensional abundance corrections have been taken from Fabbian et al. (2006), who performed NLTE calculations for a range of stellar parameters assuming a C abundance enhancement of [C/Fe] = +0.4, and the NLTE-corrected C$_{1}$ abundances are in significantly better agreement with the three-dimensional [C$_{1}$]-based values. However, there remains a ∼0.25 dex difference in the two C abundances which can be tentatively attributed to underestimated NLTE effects on the C$_{1}$ line (because calculations for [C/Fe] > +0.4, which are appropriate for our sample, have not been investigated) or possibly attributed to erroneous T$_{eff}$ values.

At this time, the complicated three-dimensional and NLTE effects that may impact [C$_{1}$], C$_{1}$, CH, and C$_{2}$ features in the spectra of CEMP stars have not yet been fully established. Analyses of the [C$_{1}$] line in high-resolution spectra of additional CEMP stars, particularly those at the lowest metallicities, for which CH and/or C$_{2}$-based abundances exist (or are forthcoming) are needed to determine if abundances derived from the forbidden line diverge in a systematic way from those derived from the molecular features. Additionally, three-dimensional models and NLTE line-formation calculations with chemical compositions appropriate for CEMP stars are clearly needed to complement the observations. These measures are necessary so that the most accurate C abundances possible can be derived for CEMP stars.

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