Carbon abundances of the reference late-type stars from
1D analysis of atomic C I and molecular CH lines

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ABSTRACT

A comprehensive model atom was constructed for C I using the most up-to-date atomic data. We evaluated non-local thermodynamical equilibrium (NLTE) line formation for neutral carbon in classical 1D models representing atmospheres of late-type stars, where carbon abundance varies from solar value down to [C/ H] = −3. NLTE leads to stronger C I lines compared with their LTE strength and negative NLTE abundance corrections, ∆NLTE. The deviations from LTE are large for the strong lines in the infrared (IR), with |∆NLTE| ≤ −0.03 dex. The NLTE abundance corrections were found to be dependent of the carbon abundance in the model. As the first application of the treated model atom, carbon NLTE abundances were determined for the Sun and eight late-type stars with well-determined stellar parameters that cover the −2.56 ≤ [Fe/H] ≤ −1.02 metallicity range. Consistent abundances from the visible and IR lines were found for the Sun and the most metal-rich star of our sample, when applying a scaling factor of $S_H = 0.3$ to the Drawinian rates of C+H collisions. Carbon abundances were also derived from the molecular CH lines and, for each star, they agree with that from the atomic C I lines. We present the NLTE abundance corrections for lines of C I in the grid of model atmospheres applicable to the carbon-enhanced (CEMP) stars.

Key words: line: formation, Sun: abundances, stars: abundances, stars: late-type

1 INTRODUCTION

Carbon abundance studies are of high importance in various fields of astrophysics and astrochemistry. Carbon is an essential element for the beginnings of life on the Earth. It acts as a primary catalyst for H-burning via the CNO cycle, and it contributes significantly to the stellar interior and atmosphere opacity. Carbon plays an important role in dust formation processes in the interstellar medium.

Carbon is one of the representatives of the ‘heavy’ ($Z \geq 6$) elements, which are of stellar nucleosynthesis origin. Accurate stellar carbon abundances may improve our understanding the chemical evolution history of our Galaxy and other galaxies. In the course of normal stellar evolution, carbon is essentially all produced by He burning through the 3α nuclear reaction: $3^{4}$He → $^{12}$C + γ (Burbidge et al. 1957). In the modern galacto-chemical evolution models the major sources of carbon are supernovae of type II (SNeII), supernovae (HNe), supernovae of type Ia (SNeIa), and asymptotic giant branch (AGB) stars (see, for example Kobayashi et al. 2011). A relative contribution of different sources to the galactic carbon varied with time.

In the early Galaxy, the carbon production was dominated by SNeII and HNe. Indeed, progenitors of SNeII and HNe are massive stars, with a mass of larger than 8 and 20 solar mass ($M_\odot$), respectively, and a short lifetime of few $10^6–10^7$ years. One also considers the scenarios with rotating massive stars. The delay time for nucleosynthesis in SNeIa ranges between 0.3 Gyr and 3 Gyr, for a wide variety of hypothesis on the progenitors (Greggio 2005). According to Kobayashi et al. (2011), an onset of the carbon production by the AGB stars refers to the time, when the galactic iron abundance grew to [Fe/H] ≃ −1.5.

With the SNeII + HNe model, Kobayashi et al. (2011) predicted the close-to-solar C/Fe abundance ratio at low metallicities, $−4 \leq [\text{Fe/H}] \leq −3$, but the [C/Fe] ratio becomes as large as 0.9, when including the yields of rotating massive stars. At [Fe/H] ≃ −1, [C/Fe] reaches 0.13, if all the sources, AGB + SNeIa + SNeII + HNe, are included, and
[C/Fe] decreases down to −0.19, when excluding the AGB yields.

A role of different carbon sources at different metallicities can be investigated from confronting the observations with the chemical evolution models. Studies in the literature demonstrate a variety of the observed trends of [C/Fe] versus [Fe/H]. For the sample of the −3.2 < [Fe/H] < −0.7 dwarfs Akerman et al. (2004) obtained enhanced C abundance relative to Fe, with [C/Fe] reducing towards higher metallicity from 0.45 to 0.25. They analysed the near-infrared (IR) C I lines under the local thermodynamic equilibrium (LTE) assumption. Fabbian et al. (2006) revised the C abundances of that stellar sample based on the non-local thermodynamic equilibrium (NLTE) line formation for C I and obtained the [C/Fe] ratio to be, on average, close to the solar one. Reddy et al. (2006) studied the C I lines in the visible spectral range in the sample of the thick disk and thin disk F-G dwarfs in the −1.2 < [Fe/H] < +0.2 range. From the LTE analysis they obtained a supersolar [C/Fe] ratio of about 0.4 for the most metal-poor ([Fe/H] < −0.4) thick disk stars and a decline down to the subsolar values at higher metallicity. In the overlapping metallicity range, the thick disk stars reveal, on average, lower [C/Fe] ratios than the thick disk stars. In contrast, the study by Bensby & Feltzing (2006) based on the [C I] line at 8727 Å shows that [C/Fe] versus [Fe/H] trends for the thin and thick discs are totally merged and flat, with [C/Fe] ≃ 0.1, for the subsolar metallicities, down to [Fe/H] = −0.8.

From observations of the CH bands in 83 subdwarfs Carbon et al. (1987) found [C/Fe] to be essentially constant and close to the solar value over the range −2.5 < [Fe/H] < −0.7. However, they noted an upturn in the [C/Fe] values at [Fe/H] < −2. A remarkably flat [C/Fe] versus [Fe/H] relation, with [C/Fe] = +0.18, was found by Spite et al. (2003) from observations of the CH bands for the sample of ‘unmixed’ giant stars in the range −4 < [Fe/H] < −2.5.

The situation with understanding sources of the carbon production in the early Galaxy is complicated by a discovery of the Carbon-Enhanced Metal-Poor (CEMP) stars that show very high enhancements in carbon, with [C/Fe] up to 3 dex (see recent papers of Behara et al. 2010, Spite et al. 2013, Itö et al. 2013, Lee et al. 2013, Cohen et al. 2013, Otsuka & Tajitsu 2013, Placco et al. 2014, Kennedy et al. 2014, Abate et al. 2014, Ramirez-Ruiz et al. 2013, Aoki et al. 2013, Shuder et al. 2014). It is still debated whether their carbon enhancements are inborn, or their atmospheres were polluted, most likely by accretion from an AGB binary companion. Recent study of Starkenburg et al. (2014) confirmed a binarity of the CEMP-s stars that are additionally enhanced in barium. But new radial velocity data for the 15 CEMP-no stars, not enhanced in barium, were found to be inconsistent with the binary properties of the CEMP-s class, thereby strongly indicating a different physical origin of their carbon enhancements.

Stellar carbon abundance determinations rely on various spectroscopic indicators. These are allowed and forbidden lines of C I and lines of the molecular species CH, C2, and CO. Suitable lines of C I are located in the visible (4300 − 7900 Å) and near-IR (7900 − 20000 Å) spectral regions. All the allowed lines have close together excitation energies of the lower level, E_{exc}, but different oscillator strengths, with smaller values for the visible than the near-IR lines. As a result, the visible C I lines are much weaker than the near-IR ones.

The [C I] forbidden line at 8727 Å can reliably be measured for the close-to-solar metallicity stars. For stars, not enhanced in carbon, the C I visible lines can be used down to [Fe/H] = −1.5 and the IR lines down to [Fe/H] = −2.5. At the lower metallicity, [Fe/H] < −2.5, stellar carbon abundances are determined presumably from the CH molecular lines.

An use of different abundance indicators with classical 1D model atmospheres can produce systematic shifts and false metallicity trends. This is exactly the case in the Tomkin et al. (1992) study. They obtained, on average, 0.4 dex higher abundance from the atomic C I compared with the molecular CH lines for the sample of metal-poor halo dwarfs. When dealing with a wide metallicity range, it is impossible to apply a common carbon abundance indicator. One needs, therefore, to investigate the possible sources of abundance discrepancy between the atomic and molecular lines. These can be (i) employing the homogeneous and plane-parallel (1D) model atmospheres, (ii) inadequate line-formation treatment based on the LTE assumption, (iii) and the uncertainties in stellar parameters.

First determinations of the carbon abundance based on a three-dimensional (3D), time-dependent and hydrodynamical model atmosphere were made by Asplund et al. (2003) for the Sun. For the atomic lines, it was shown that the abundance differences between the 3D and 1D MARCS (Gustafsson et al. 1977) models are small and amount to +0.01 dex, +0.01 dex, and −0.02 dex, on average, for the atomic C I, molecular CH electronic and C2 electronic lines, respectively. Asplund et al. (2003) updated the calculations and obtained consistent abundances from the different species, with the mean log C/C = 8.43 ± 0.05 for the 3D model and log C/C = 8.42 ± 0.05 for the 1D MARCS model. Caffau et al. (2010) computed positive 3D-1D abundance corrections for the solar C I lines, up to 0.1 dex for the stronger near-IR lines and ≤0.03 dex for the fainter visible lines.

For the stellar atmosphere parameters beyond the solar ones the 3D calculations were only performed for the C I fictitious lines (Dobrovolskas et al. 2013). For the E_{exc} = 6 eV lines at λ = 8500 Å in the T_{eff}/log g/[M/H] = 5930/4.0/0, 5850/4.0/−1, and 5860/4.0/−2 models the 3D-1D abundance corrections do not exceed few 100-th in a logarithmic scale (Dobrovolskas et al. 2013, Fig. 2.19).

An influence of the 3D effects on abundance determination from the molecular CH lines was evaluated by Collet et al. (2007) and Hayek et al. (2011) for cool giants of various metallicity. Collet et al. (2007) showed that the 3D-1D abundance corrections for the CH lines at λ ≃ 4300 Å are overall negative and they amount to −0.15 dex at solar metallicity and −0.8 dex at [M/H] = −3 in the models with T_{eff} = 5050 K and log g = 2.2. Hayek et al. (2011) updated the Collet et al. (2007) calculations and obtained smaller 3D effects, namely 3D−1D = 0.0, −0.18 dex, and −0.35 dex in the giant (log g = 2.2) models with [M/H] = 0 (T_{eff} = 5060 K), [M/H] = −2 (5050 K), and [M/H] = −3 (5100 K), respectively.

Thus, the discrepancy between the C I and CH-based
2 NLTE LINE FORMATION FOR C I

2.1 Model atom and atomic data

Energy levels. Model atom includes 208 energy levels of C I up to \( n = 10, l = 4 \), nine lowest levels of C II, and the ground state of C III. Most energy levels were taken from the NIST database \(^1\) (Rachenco et al. 2008). They belong to singlet and triplet terms of the \( 2s^22p \) \( nl \) \( (n = 2-10, l = 0-2) \), \( 2s^22p \) \( nf \) \( (n = 4-8) \), and \( 2s2p^3 \) electronic configurations and the \( 2s2p^3 \) quintet term. In addition, the \( 2s^22p \) \( nl \) \( (nl = 5g, 6g, 6h) \) levels were taken from the Kurucz’s database. \(^2\) To provide close collisional coupling of C I to the continuum electron reservoir, the energy separation of the highest C I levels from the ionization limit must be smaller than the mean kinetic energy of electrons, i.e., \( 0.5 \) eV for atmospheres of solar temperature. In our model atom the energy gap between the uppermost levels of C I and ionization limit is equal to \( 0.13 \) eV. Fine structure splitting was included everywhere, up to \( n = 8 \). All the states with \( n = 9 \) and \( n = 10 \) have close energies, and their populations must be in equilibrium to each other. Therefore, the levels of common parity were combined into the single superlevel. The Grotrian term diagram for our model atom is shown in Fig. [1].

Radiative data. Our model atom includes 1524 allowed bound-bound \((b – b) \) transitions. Their transition probabilities were taken from the NIST and VALD databases, where available, and the Opacity Project database TOPbase \(^3\), as implemented by Steenbock & Holweger (1984). The efficiency of C+H collisions is treated as a free parameter in our attempt to achieve consistent element abundances derived from the visible and near-IR lines in the Sun and selected stars. For each object, the calculations were performed with a scaling factor of \( S_H = 0, 0.1, 0.3, \) and \( 1 \). Hydrogen collisions for the forbidden transitions were ignored. Ionisation by electronic collisions was everywhere treated through the Steenbock & Holweger (1984) classical path approximation. The formula, with \( S_H \) applied to calculate the C+H ionisation rates.

Our model atom is similar to that of Fabbian et al. (2006) except applying in this study detailed electron-impact excitation cross-sections from Reid (1994).

Collisional data. All levels in our model atom are coupled via collisional excitation and ionisation by electrons and by neutral hydrogen atoms. Detailed electron-impact excitation cross-sections calculated in the close-coupling approximation using the R-matrix method are available for more than 400 transitions from Reid (1994). For the remaining transitions we use the impact parameter method (IPM, Seaton 1962b) for the allowed transitions and assume that the effective collision strength \( \Omega_{ij} \) = 1 for the forbidden transitions. Accurate data on inelastic collisions of carbon with neutral hydrogen atoms remain still undefined. We employed, therefore, the Drawin’s formula \(^4\) as implemented by Steenbock & Holweger (1984). The efficiency of C+H collisions is treated as a free parameter in our attempt to achieve consistent element abundances derived from the visible and near-IR lines in the Sun and selected stars. For each object, the calculations were performed with a scaling factor of \( S_H = 0, 0.1, 0.3, \) and \( 1 \). Hydrogen collisions for the forbidden transitions were ignored. Ionisation by electronic collisions was everywhere treated through the Steenbock & Holweger (1984) classical path approximation. The formula, with \( S_H \) applied to calculate the C+H ionisation rates.

2.2 Method of calculations

To solve the radiative transfer and statistical equilibrium equations, we used the code DETAIL \(^5\) based on the accelerated A-iteration method \(^6\). The opacity package was improved as described in Mashonkina et al. (2011). The departure coefficients, \( b_i = n_{\text{NLTE}} / n_{\text{LTE}} \), were then used to com-

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1 http://physics.nist.gov/PhysRefData/
2 http://cfaku5.cfa.harvard.edu/atoms.html
3 http://legacy.gsfc.nasa.gov/topbase
4 Drawin’s formula
5 DETAIL
6 Rybicki & Hummer (1991)
2.3 Departures from LTE depending on carbon abundance and surface gravity

Figure 2 shows the departure coefficients for the selected lines in the solar 5777/4.44/0 model atmosphere. Neutral carbon C I dominates the element number density over all atmospheric depths. Thus, no process seems to affect the C I ground-state and low-excitation level populations significantly, and they keep their thermodynamic equilibrium values. The levels 3s\(^1\)P\(^o\) and 3s\(^3\)P\(^o\) are overpopulated outward log\(\tau\) = −0.2 due to the ultraviolet radiative pumping in the transitions 2p\(^2\) 3S − 3s\(^1\)P\(^o\) (2479 Å), 2p\(^2\) 1D − 3s\(^1\)P\(^o\) (1931 Å), and 2p\(^2\) 3P − 3s\(^3\)P\(^o\) (1657 Å). Levels with \(E_{\text{exc}}\) > 8 eV are underpopulated outward log\(\tau\) = −0.2 due to spontaneous transitions to the lower levels.

The NLTE effects for a given spectral line can be understood from analysis of the departure coefficients at the line formation depths. The C I lines used in abundance analysis are listed in Table 1 Here, we consider two lines with similar \(E_{\text{exc}}\), but different \(gf\)-values. The C I 5380 Å (3s\(^1\)P\(^o\) − 4p\(^1\)P\(^o\)) line is weak, and it forms in the deep layers, around log\(\tau_{5000}\) = 0, where the departures from LTE are small. In contrast, C I 9111 Å (3s\(^3\)P\(^o\) − 3p\(^3\)P\(^o\)) is strong, and its core forms around log\(\tau_{5000}\) = −1, where the departure coefficient of the lower level, \(b(3s\(^3\)P\(^o\))\) is larger than unity and \(b(3s\(^3\)P\(^o\))\) > \(b(3p\(^3\)P\(^o\))\). NLTE leads to strengthened lines of C I and negative abundance corrections, Δ\(\text{NLTE}\) = log\(\text{NLTE}\) - log\(\text{LTE}\), with the stronger NLTE effects for the stronger lines.

To evaluate the NLTE effects depending on the carbon abundance, we calculated the NLTE abundance corrections with the four model atmospheres having common \(T_{\text{eff}}\) = 6000 K and log\(g\) = 4.0, but different metallicities, with [M/H] = 0, −1, −2, and −3. For each model the NLTE calculations were performed with the two different carbon abundances, [C/Fe] = 0 and [C/Fe] = 1. The \(S_{\text{H}}\) = 0.3 and a microturbulence velocity of \(\xi_{\text{T}}\) = 1 km s\(^{-1}\) were employed. The obtained results are displayed in Fig. 3 for C I 9405 Å and 9111 Å.

Figure 1. Grotrian term diagram for neutral carbon. The solid lines indicate the seven transitions, where the investigated spectral lines arise. The \(nf\), \(ng\), \(nh\) energy levels, where the Russell-Saunders coupling is broken, are shown on the right column.
The NLTE effects for C I depend on the element abundance. For [C/Fe] = 0 the NLTE abundance corrections reduce, in absolute value, towards lower equivalent width (element abundance) throughout the metallicity range from [M/H] = 0 to −3. To understand this, we consider the departure coefficients in Fig. 4. On the one hand, the total number of free electrons, acting as the source of thermalisation, decreases with decreasing metallicity and the departures from LTE are amplified. Indeed, at a common optical depth the departure coefficients deviate from unity larger in the low than in the solar metallicity model. On the other hand, with metallicity (carbon abundance) decreasing, the line formation region moves to deeper layers, where the NLTE effects wane. Of the two competing effects the latter prevails, and the NLTE effects reduce toward lower metallicity.

A different behavior was found in the [C/Fe] = 1 case, namely the NLTE effects grow, when moving from [M/H] = 0 to −1, and then reduce towards lower EW. The C I 9405 Å and 9111 Å lines are very strong in the [M/H] = 0 model, with EW ≃ 500 mÅ and 330 mÅ, respectively, which are mostly contributed from the broad line wings. The line wings form in deep atmospheric layers, where the departures from LTE are small. When moving to [M/H] = −1, a contribution of the line wings decreases, and the NLTE effects grow. In the [M/H] = −2 and −3 models the NLTE effects decrease due to shifting the line formation regions in the deeper layers.

We compared our calculations with the NLTE results of Takeda & Honda (2005) and Fabbian et al. (2006). To be as close as possible to the NLTE method of Fabbian et al. (2006), we employed the same collisional recipe as Fabbian et al. (2006) and $S_H = 1$. Figure 4 shows the NLTE abundance corrections depending on metallicity for the representative line at 9094 Å in the model atmospheres with common $T_{\text{eff}} = 6000$ K, log $g = 4.0$, [C/Fe] = 0.4, and $\xi_t = 1$ km s$^{-1}$. All the three studies give consistent results for the [M/H] = 0 and −1 models, where the NLTE effects are the strongest. At [M/H] = −2 our data agree well with Takeda & Honda (2005), while a discrepancy of 0.08 dex in $\Delta_{\text{NLTE}}$ was obtained with Fabbian et al. (2006). The NLTE correction computed by Fabbian et al. (2006) for the [M/H] = −3 model is as large as that for [M/H] = −2, although the C I 9094 Å line is much weaker in the [M/H] = −3 (EW = 8 mÅ) than [M/H] = −2 (EW = 50.2 mÅ) model. In our calculations $\Delta_{\text{NLTE}} = -0.07$ dex. It is worth noting that spectral lines of EW = 8 mÅ are too weak for accurate measurements, and, thus, the theoretical predictions cannot be checked with the observations.

3 SOLAR CARBON ABUNDANCE

3.1 Atomic C I lines

As a first application of the treated model atom, we derived the solar carbon abundance from lines of C I. For comparison, the element abundance was also determined from the molecular CH lines. The solar flux observations were taken from the Kitt Peak Solar Atlas (Kurucz et al. 1984). We used the MARCS model atmosphere 5777/4.44/0 and a depth-independent microturbulence of 0.9 km s$^{-1}$. The element abundance was determined from line profile fitting. As
Figure 4. Departure coefficients, $b$, for the C I levels and the ground state of C II as a function of log $\tau_{5000}$ in the four model atmospheres with different metal abundance: [M/H] = 0, −1, −2, and −3. Everywhere, $T_{\text{eff}} = 6000$ K, log $g = 4.0$, [C/Fe] = 1, $\xi_t = 1$ km s$^{-1}$. In each panel the two vertical lines indicate the formation region for C I 9405 Å.

Figure 5. NLTE abundance corrections depending on metallicity for C I 9094 Å from this study (circles), Fabbian et al. (2006, squares), and Takeda & Honda (2005, rhombi). Everywhere, $T_{\text{eff}} = 6000$ K, log $g = 4.0$, [C/Fe] = 0.4, $\xi_t = 1$ km s$^{-1}$.

A rule, the uncertainty in fitting the observed profile is less than 0.02 dex for weak lines and 0.03 dex for strong lines. Our synthetic flux profiles were convolved with a profile that combines a rotational broadening of 1.8 km s$^{-1}$ and broadening by macroturbulence with a radial-tangential profile. The most probable macroturbulence velocity $V_{\text{mac}}$ was varied between 2 km s$^{-1}$ and 4 km s$^{-1}$ for different lines of C I and CH. Quality of the fits is illustrated in Fig. 4 for two lines of C I. The C I 5380 Å profile beyond 5380.45 Å is contributed from an unknown blend. Weak telluric line at 9111.95 Å affects C I 9111 Å, however, the difference between observed and calculated NLTE spectra, (O - C), does not exceed 0.4 % for the remaining profile.

For lines listed in Table I we determined the element abundance under various line-formation assumptions. In LTE, the abundance difference between the visible and near-IR lines of C I, $\Delta \log \epsilon(\text{vis} - \text{IR})$, amounts to $-0.21$ dex. In line with the previous studies, we find that the [C I] 8727 Å forbidden line does not suffer from the NLTE effects, because it arises in the transition between the metastable levels that keep the LTE populations. The NLTE corrections are small for the visible lines, independent of the applied collisional recipes, with $|\Delta_{\text{NLTE}}| \leq 0.03$ dex. For the IR lines, the departures from LTE are sensitive to a variation in collisional rates. For example, for different lines $\Delta_{\text{NLTE}}$ ranges between $-0.14$ dex and $-0.45$ dex, when $S_H = 0$, and between $-0.08$ dex and $-0.32$ dex, when $S_H = 1$. Consistent within 0.03 dex and 0.02 dex NLTE abundances from the
visible and near-IR lines were obtained for $S_H = 0.3$ and 1, respectively. We derived from the atomic lines a solar carbon abundance of $\log \epsilon_C = 8.43 \pm 0.03$ ($S_H = 0.3$).

### 3.2 Molecular C$_2$ and CH lines

**C$_2$ electronic lines.** We selected the 12 least blended lines from the C$_2$ Swan band in the 4992–5150 Å range. They are listed in Table 2 along with the lower level excitation potentials and the transition probabilities taken from Brooke et al. (2013).

**CH electronic lines.** We used a dissociation energy of $D_0(C_2) = 6.297$ eV from Urbach et al. (1991). Our analysis is based on the lines from the (0, 0) and (1, 1) bands of CH A–X around 4300 Å. They are listed in Table 3. The lower level excitation potentials and the transition probabilities were taken from Masseron et al. (2014). The dissociation energy is $D_0(CH) = 3.465$ eV (Huber & Herzberg 1979). Our test calculations showed that using the molecular parameters from Jorgensen et al. (1994) results in higher abundances, by 0.00 to 0.04 dex for different CH lines, compared with the corresponding values based on the Masseron et al. (2014) data.

Abundances from the individual molecular C$_2$ and CH lines are presented in Tables 2 and 3. It can be seen that lines of C$_2$ give consistent within 0.04 dex abundances, and the mean abundance, log $\epsilon_C = 8.46 \pm 0.02$, agrees well with the NLTE($S_H = 0.3$) abundance from the atomic C I lines. Abundances from different lines of CH are consistent within 0.05 dex, and the mean abundance, log $\epsilon_C = 8.39 \pm 0.02$, agrees with that from the atomic lines.

### 3.3 Comparison with previous studies

When applying a common $S_H$ of 0, we find the obtained solar mean abundance from lines of C I (8.41±0.05) to be consistent within the error bars with the 1D and 3D results of Asplund et al. (2009, hereafter, AGSS09), namely log $\epsilon_C = 8.39\pm0.04$ (1D) and 8.42±0.05 (3D), and the 3D abundance log $\epsilon_C = 8.446\pm0.121$ calculated by Caffau et al. (2010, hereafter, CLB10). Abundance from the forbidden [C I] 8727 Å line, log $\epsilon_C = 8.45$, is 0.07 dex and 0.10 dex higher compared with the corresponding values from AGSS09 and CLB10. In part, this is due to employing in this study a 0.03 dex lower $gf$-value. Indeed, we relied on log $gf = -8.165$ from Froese Fischer (2006), while AGSS09 and CLB10 adopted log $gf = -8.136$ by Hibbert et al. (1993). Another source of the discrepancy is a different treatment of faint blending lines. According to the Kurucz (2007) data, two lines of Fe I contribute to the 8727 Å blend. These are Fe I 8727.10 Å ($E_{\text{exc}} = 5.587$ eV, log $gf = -5.924$) and Fe I 8727.13 Å ($E_{\text{exc}} = 4.186$ eV, log $gf = -4.262$). Caffau et al. (2010) treated Fe I 8727.13 Å, using the higher log $gf = -3.93$ from the older Kurucz (1993) calculations. A difference of −0.33 dex in $gf$-value of the blending Fe I line makes a +0.02 dex difference in the carbon abundance derived from [C I] 8277 Å. To understand a source of the remaining discrepancy, we inspected the forbidden line in the solar flux Kurucz et al. (1984) and disk-center intensity Brautl & Testerman (1972) spectra and obtained fully consistent abundances, with log $\epsilon_C = 8.45$. It is worth noting, we measured EW([C I] 8277) = 5.5 mÅ in the disk-center intensity spectrum, while AGSS09 and CLB10 reported lower values of 5.3 mÅ and 5.1 mÅ, respectively.

Our 1D results for the molecular lines agree well with...
Table 2. Carbon abundances derived from solar lines of C$_2$

| $\lambda$, Å | log($gf$) | $E_{exc}$ [eV] | log(eC) |
|-------------|-----------|----------------|---------|
| 4992.2750   | 0.288     | 0.802          | 8.44    |
| 4992.3035   | 0.281     | 0.802          |         |
| 5033.7792   | 0.191     | 0.584          | 8.47    |
| 5143.3240   | $-0.411$  | 0.102          | 8.44    |
| 5144.9149   | $-0.447$  | 0.097          | 8.46    |
| 5145.2255   | $-0.485$  | 0.098          | 8.46    |
| 5145.3240   | 0.038     | 0.328          |         |
| 5145.3711   | 0.638     | 0.084          |         |
| 5052.6161   | 0.153     | 0.489          | 8.45    |
| 5052.6254   | 0.162     | 0.489          |         |
| 5086.3897   | 0.031     | 0.328          | 8.48    |
| 5103.7231   | $-0.023$  | 0.250          | 8.47    |
| 5103.7710   | $-0.038$  | 0.250          |         |
| 5109.0921   | $-0.053$  | 0.227          |         |
| 5109.1490   | $-0.068$  | 0.228          | 8.47    |
| 5109.3030   | $-0.084$  | 0.228          |         |
| 5135.5590   | 0.137     | 0.471          |         |
| 5135.5818   | 0.127     | 0.472          | 8.45    |
| 5135.6825   | 0.117     | 0.472          |         |
| 5073.4490   | 0.090     | 0.388          |         |
| 5073.4513   | 0.101     | 0.388          | 8.45    |
| 5073.5815   | 0.080     | 0.388          |         |
| Mean        |           |                | 8.46±0.02|

Table 3. Carbon abundances derived from solar lines of CH

| $\lambda$, Å | log($gf$) | $E_{exc}$ [eV] | log(eC) |
|-------------|-----------|----------------|---------|
| 4218.710    | $-1.315$  | 0.413          |         |
| 4218.734    | $-1.337$  | 0.413          | 8.37    |
| 4248.729    | $-1.467$  | 0.191          |         |
| 4248.937    | $-1.431$  | 0.191          | 8.38    |
| 4248.952    | $-3.256$  | 0.191          |         |
| 4253.000    | $-1.506$  | 0.523          | 8.41    |
| 4253.206    | $-1.471$  | 0.523          |         |
| 4255.248    | $-1.461$  | 0.157          | 8.41    |
| 4255.248    | $-3.210$  | 0.157          |         |
| 4263.969    | $-1.575$  | 0.459          | 8.36    |
| 4274.133    | $-3.025$  | 0.074          | 8.38    |
| 4274.186    | $-1.563$  | 0.074          |         |
| 4356.355    | $-1.846$  | 0.157          | 8.40    |
| 4356.371    | $-1.455$  | 1.109          |         |
| 4356.594    | $-1.793$  | 0.157          | 8.39    |
| Mean        |           |                | 8.39±0.02|

Figure 6. Best NLTE fits (continuous curve) of the solar C I 5380 Å and 9111 Å lines (asterisk). For each line, the LTE profile (dashed curve) was computed with the carbon abundance obtained from the NLTE analysis. The differences between observed and calculated NLTE spectra, (O - C), are shown in the upper parts of the panels.

the 1D and 3D data of AGSS09, log eC = 8.40±0.03 (CH) and 8.46±0.03 (C$_2$) in 1D and log eC = 8.43±0.03 (CH) and 8.46±0.03 (C$_2$) in 3D.

4 DETERMINATION OF CARBON ABUNDANCES OF THE SELECTED STARS

4.1 Stellar sample, observations, and stellar parameters

We selected nine metal-poor stars in the $-2.56 \leq [\text{Fe/H}] \leq -1.02$ metallicity range, for which the high-quality observed spectra and the well determined stellar parameters are available in the literature (Table 4). We describe briefly the sources of stellar effective temperatures and surface gravities.

Effective temperatures. For HD 122563 we adopted $T_{\text{eff}} = 4600$ K from [Mashonkina et al. 2011], and it is consistent with the recent value based on the interferometric observations of [Creeve et al. 2012]. The infrared flux method (IRFM) temperatures were adopted for HD 84937 as recommended by [Mashonkina et al. 2011], HD 59374, HD 94028, HD 103095, HD 140283, BD$-4^\circ$3208, and BD$+66^\circ$268, as
Table 4. Atmospheric parameters of the selected stars and sources of the data.

| Star  | $T_{\text{eff}}$ | log $g$ | [Fe/H] | $\xi_t$ | Ref. |
|-------|-----------------|--------|--------|--------|------|
| HD 29907 | 5500            | 4.64   | -1.55  | 0.6    | 1    |
| HD 59374 | 5850            | 4.38   | -1.02  | 1.0    | 2    |
| HD 84937 | 6350            | 4.09   | -2.08  | 1.7    | 2    |
| HD 94028 | 5970            | 4.33   | -1.50  | 1.4    | 3    |
| HD 103095 | 5130           | 4.66   | -1.26  | 0.9    | 3    |
| HD 122563 | 4600            | 1.60   | -2.56  | 2.0    | 2    |
| HD 140283 | 5780            | 3.70   | -2.38  | 1.6    | 3    |
| BD+4°3208 | 6390            | 4.08   | -2.20  | 1.3    | 3    |
| BD+66°268 | 5300            | 4.72   | -2.06  | 0.7    | 3    |

Notes: References: (1) Mashonkina et al. (2003); (2) Mashonkina et al. (2011); (3) Sitnova et al. (2015).

4.2 Analysis of carbon atomic and molecular lines

In this section we derive the carbon abundances of the selected stars from the atomic C I and molecular CH lines using the same approach as for Sun (Sect. 4.1) and the same set of atomic and molecular data.

The Shane/Hamilton observed spectra are affected by fringes in the IR spectral range. For the three stars, HD 59374, BD+4°3208, and BD+66°268, we applied the local continuum normalisation procedure and this made possible to analyse the IR lines of C I. For C I 9094 Å and 9111 Å in HD 103095 and HD 94028 we adopted equivalent widths from Tomkin et al. (1992).

The NLTE calculations for C I were performed using the C I-based abundances determined with the Balmer line wing fits (Mashonkina et al. 2003). For HD 29907 its effective temperature was determined from the Balmer line wing fits (Mashonkina et al. 2011; Sitnova et al. 2015). For HD 29907, HD 84937, HD 94028 we analysed the single line in the visible region, C I 5052 Å, and the two IR lines, with equivalent widths from Tomkin et al. (1992).

For two IR lines of C I in HD 103095 we relied on equivalent widths from Tomkin et al. (1992) and obtained an abundance difference of more than 0.2 dex between the lines, independent of the line-formation scenario.

For two stars we cannot inspect the difference in abundances between the atomic C I and molecular CH lines. In BD+4°3208 the molecular CH lines are too weak to be measured reliably, and only upper limit was estimated for the abundance from few individual lines (Table 7). In contrast, in HD 122563 the atomic C I lines cannot be measured, but stellar carbon abundance is reliably obtained from the molecular CH lines, with a standard deviation of 0.04 dex.

Figure 8 displays the abundance differences between the atomic C I and molecular CH lines for the Sun and seven metal-poor stars of our sample. Nowhere, $\Delta$ log $\epsilon$(C I - CH) exceeds 0.07 dex and reveals any metallicity dependence. This suggests a minor influence of the 3D effects on abundance determinations from the molecular CH lines for metal-poor stars of our sample. Nowhere, $\Delta$ log $\epsilon$(C I - CH) exceeds 0.07 dex and reveals any metallicity dependence. This suggests a minor influence of the 3D effects on abundance determinations from the molecular CH lines for metal-poor stars of our sample.
Table 5. Characteristics of observed spectra.

| Object   | V^1 (mag) | Telescope/ Observing run | Spectral range | R  | S/N |
|----------|-----------|--------------------------|----------------|----|-----|
| HD 29907 | 9.91      | 8m VLT2/UVES Apr.2001    | 3300−7000      | 80000 | 150 |
| HD 59374 | 8.50      | 3m Shane/Hamilton Jan.2011, Mar.2012 | 3700−9300 | 60000 | 100 |
| HD 84937 | 8.28      | 8m VLT2/UVES ESO UVESPOP | 3300−9900      | 80000 | 200 |
| HD 94028 | 8.22      | 3m Shane/Hamilton Jan.2011, Mar.2012 | 3700−9300 | 60000 | 100 |
| HD 103095 | 8.28     | 3m Shane/Hamilton Jan.2011, Mar.2012 | 3700−9300 | 60000 | 100 |
| HD 122567 | 8.22     | 8m VLT2/UVES ESO UVESPOP | 3300−9900      | 80000 | 200 |
| HD 140283 | 7.99      | 3m Shane/Hamilton Jan.2011, Mar.2012 | 3700−9300 | 60000 | 100 |
| BD−4°3208 | 9.99     | 3m Shane/Hamilton Jan.2011, Mar.2012 | 3700−9300 | 60000 | 100 |
| BD+66°268  | 9.91     | 3m Shane/Hamilton Jan.2011, Mar.2012 | 3700−9300 | 60000 | 100 |

^1 V is a visual magnitude from the SIMBAD database.

Figure 7. Best fits (continuum curves) of the selected atomic and molecular lines in HD 59374 (top row) and HD 84937 (bottom row). The observed spectra are shown by bold dots. The dashed curve in the right bottom panel shows the theoretical spectrum with no carbon in the atmosphere.

4.3 Carbon-enhanced stars

Studies of the CEMP stars are important for better understanding the Galaxy chemical evolution. High carbon abundance makes possible to measure lines of C I in the visible spectral range even for very metal-poor (VMP) CEMP stars. Behara et al. (2010, hereafter, BBL10) and Spite et al. (2012, hereafter, SCB13) used C I 4932 Å, 5052 Å, and 5380 Å and the molecular CH lines to derive the carbon abundances of the four turn-off stars in the −3.3 ≤ [Fe/H] ≤ −2.5 metallicity range from the 1D and 3D calculations with applying the NLTE abundance corrections for lines of C I. They found large abundance discrepancies between lines of C I and CH in both 1D and 3D analysis, with (C I − CH) of −0.35 dex to −0.79 dex in 1D and −0.23 dex to +0.42 dex in 3D.

We noticed that the NLTE carbon abundance correction, Δ_{NLTE} = −0.45 dex, applied by BBL10 and SCB13 is rather large and performed the NLTE calculations using our model atom of C I and atmospheric parameters from BBL10 and SCB13. The obtained NLTE effects turned out much smaller, with Δ_{NLTE} = −0.04 dex. Using the 1D-LTE abundances from BBL10 and SCB13 and our Δ_{NLTE}, we found consistent abundances from the two chemical species for three of four investigated stars, with (C I − CH) = 0.02 dex (BBL10’s star) and −0.03 dex and 0.07 dex (SCB13’s stars). For one of the BBL10’s stars (C I − CH) = −0.46 dex. In
Table 7. Carbon abundances of the program stars from the CH A-X electronic lines.

| HD/BD   | 29907 | 59374 | 84937 | 94028 | 103095 | 122563 | 140283 | −4°3208 | +66°268 |
|---------|-------|-------|-------|-------|--------|--------|--------|---------|---------|
| λ, Å    |       |       |       |       |        |        |        |         |         |
| 4362.4 - 4364.6 | 6.77  | −     | 6.58  | 7.12  | 7.07   | −      | 6.35   | −       | 6.34    |
| 4366.0 - 4367.0 | 6.78  | −     | 6.58  | 7.12  | 7.10   | −      | 6.32   | −       | 6.39    |
| 4310.0 - 4312.5 | 6.73  | −     | 6.60  | 6.99  | −      | 5.13   | 6.35   | −       | 6.34    |
| 4313.4 - 4313.8 | −     | −     | 6.64  | 7.00  | −      | 5.13   | 6.30   | −       | 6.39    |
| 4218.710     | 6.71  | 7.48  | 6.62  | 7.08  | −      | 5.09   | 6.35   | −       | 6.34    |
| 4218.734     | 6.71  | 7.48  | 6.62  | 7.08  | −      | 5.09   | 6.35   | −       | 6.34    |
| 4253.000     | 6.79  | 7.55  | −     | 7.05  | 6.93   | 5.12   | 6.38   | −       | 6.39    |
| 4253.206     | 6.79  | 7.55  | −     | 7.05  | 6.93   | 5.12   | 6.38   | −       | 6.39    |
| 4255.248     | 6.74  | 7.60  | 6.67  | 7.06  | 6.93   | 5.15   | 6.40   | < 6.33  | 6.34    |
| 4255.248     | 6.74  | 7.60  | 6.67  | 7.06  | 6.93   | 5.15   | 6.40   | < 6.33  | 6.34    |
| 4263.969     | 6.79  | 7.57  | −     | 7.05  | −      | 5.01   | 6.37   | −       | 6.36    |
| 4274.133     | 6.75  | 7.63  | −     | 7.07  | −      | 5.09   | 6.42   | −       | 6.36    |
| 4274.186     | 6.75  | 7.63  | −     | 7.07  | −      | 5.09   | 6.42   | −       | 6.36    |
| 4356.355     | 6.78  | 7.64  | 6.63  | −     | 7.08   | −      | 6.46   | −       | 6.37    |
| 4356.371     | 6.78  | 7.64  | 6.63  | −     | 7.08   | −      | 6.46   | −       | 6.37    |
| 4356.594     | 6.76  | 7.63  | −     | 7.05  | −      | −      | −      | −       | −       |
| Mean         | 6.76  | 7.57  | 6.60  | 7.06  | 7.02   | 5.10   | 6.37   | < 6.33  | 6.36    |
| σ           | 0.03  | 0.06  | 0.05  | 0.04  | 0.07   | 0.04   | 0.04   | 0.02    |         |

C I+CH          6.78  7.60  6.60  7.06  7.01  5.10  6.40  6.27  6.45
[C/Fe]         −0.10  0.19  0.25  0.13 −0.16 −0.71 0.35  0.04  0.08

3D the difference (C I − CH) is positive everywhere, up to +0.7 dex.

This motivated us to compute the NLTE abundance corrections for lines of C I in the small grid of model atmospheres appropriate for the CEMP stars. We adopted $S_H = 0.3$ and $\xi_t = 1.5 \text{ km s}^{-1}$. The results are presented in Table 9.

For the visible lines, C I 4932 Å, 5052 Å, 5380 Å, and 6587 Å, $\Delta_{NLTE}$ nowhere exceeds 0.13 dex in absolute value. The NLTE corrections are more negative, up to $-0.70$ dex, for the IR lines at 9061 Å, 9078 Å, and 9111 Å. The SE calculations were performed with [C/Fe] = 1, 2, and 3, although the employed MARCS model atmospheres (Gustafsson et al. 2008) were computed with [C/Fe] = 0. To check how $\Delta_{NLTE}$ depends on the carbon abundance used in the model atmosphere construction, we asked Frank Grupp to calculate the two MAFAGS-OS (Grupp 2001, Grupp et al. 2009) models with common atmospheric parameters, 6250/4.0/−3, but different [C/Fe] = 0 and [C/Fe] = 3. When employing a common carbon abundance of [C/Fe] = 3 in the SE calculations, we found very similar NLTE effects for C I in these two models.

4.4 Comparison with previous studies

Tomkin et al. (1992) determined carbon abundances of 34 metal-poor halo dwarfs from the atomic C I and molecular
Table 6. LTE and NLTE abundances of the program stars.

| HD, BD | λ, Å  | LTE  | NLTE |
|--------|-------|------|------|
|        |       | S_{H}=0.1 | S_{H}=0.3 |
| 29907  | 5052.144 | 6.82 | 6.79 | 6.79 |
| 59374  | 4932.049 | 7.63 | 7.59 | 7.59 |
| 5052.167 | 7.75 | 7.70 | 7.71 |
| 5380.337 | 7.74 | 7.70 | 7.70 |
| Mean(vis) | 7.71 | 7.66 | 7.67 |
| σ       | 0.07  | 0.06  | 0.07 |
| 9062.492 | 7.73 | 7.51 | 7.52 |
| 9078.288 | 7.80 | 7.60 | 7.62 |
| 9088.515 | 7.79 | 7.59 | 7.61 |
| 9094.834 | 7.88 | 7.51 | 7.54 |
| 9111.809 | 7.97 | 7.68 | 7.71 |
| Mean(IR) | 7.83 | 7.58 | 7.60 |
| σ       | 0.09  | 0.07  | 0.08 |
| Mean(C I) | 7.79 | 7.61 | 7.63 |
| σ       | 0.10  | 0.08  | 0.08 |
| 84397  | 8335.148 | 6.69 | 6.60 | 6.62 |
| 9062.492 | 6.68 | 6.59 | 6.61 |
| 9078.288 | 6.68 | 6.58 | 6.60 |
| 9111.809 | 6.67 | 6.55 | 6.57 |
| Mean | 6.68 | 6.58 | 6.60 |
| σ | 0.01  | 0.02  | 0.02 |
| 94028  | 5052.167 | 7.19 | 7.14 | 7.16 |
| 9094.834  | 7.18 | 6.90 | 6.94 |
| 9111.809  | 7.19 | 7.01 | 7.04 |
| Mean | 7.19 | 7.02 | 7.05 |
| σ | 0.01  | 0.12  | 0.11 |
| 103095  | 9094.834  | 6.92 | 6.85 | 6.88 |
| 9111.809  | 7.14 | 7.07 | 7.10 |
| Mean | 7.03 | 6.96 | 6.99 |
| σ | 0.16  | 0.16  | 0.16 |
| 140283  | 8335.148 | 6.43 | 6.34 | 6.35 |
| 9061.433 | 6.57 | 6.47 | 6.48 |
| 9062.492 | 6.52 | 6.44 | 6.45 |
| 9078.288 | 6.51 | 6.41 | 6.42 |
| 9088.515 | 6.55 | 6.44 | 6.45 |
| Mean | 6.52 | 6.42 | 6.43 |
| σ | 0.05  | 0.05  | 0.05 |
| -4°3208 | 9061.433 | 6.34 | 6.21 | 6.22 |
| 9062.492 | 6.39 | 6.29 | 6.30 |
| 9111.809 | 6.44 | 6.29 | 6.30 |
| Mean | 6.39 | 6.26 | 6.27 |
| σ | 0.05  | 0.05  | 0.05 |
| +66°268 | 9061.433 | 6.64 | 6.56 | 6.58 |
| 9062.492 | 6.54 | 6.47 | 6.48 |
| Mean | 6.59 | 6.52 | 6.53 |
| σ | 0.07  | 0.06  | 0.07 |

1 Equivalent widths from Tomkin et al. (1992).

CH lines and found that the atomic lines lead to systematically higher abundances compared with those from the CH lines, with the average difference, [C/Fe]_{CI} - [C/Fe]_{CH} = +0.4 dex. The C I lines were analysed based on the NLTE line formation. For four stars in common with that study we obtained [C/Fe]_{CI} - [C/Fe]_{CH} = -0.02 dex from our calculations and +0.25 dex from the data of Tomkin et al. (1992). The discrepancy between the two studies can be due to using a 130 K, on average, lower effective temperature in Tomkin et al. (1992) compared with our work. For the common stars we employed the IRFM effective temperatures, while Tomkin et al. (1992) the temperatures based on the b − y, R − I, R − IK, and V − K colors. It can be seen from Table 9 that using the lower temperature leads to the higher C I-based and the lower CH-based abundance.

Table 9. NLTE abundance corrections for C I lines in the carbon-enhanced model atmospheres.

| λ, Å | 4932 | 5052 | 5380 | 6587 | 9061 | 9078 | 9111 |
|------|------|------|------|------|------|------|------|
| log g |      |      |      |      |      |      |      |
| T_{eff} = 4500 K, [M/H] = −3, [C/Fe] = 2 |
| 0.5  | -0.10 | -0.12 | +0.01 | -0.26 | -0.21 | -0.26 |
| 1.0  | -0.08 | -0.10 | 0.00  | -0.21 | -0.17 | -0.21 |
| 2.0  | -0.06 | -0.07 | -0.02 | -0.13 | -0.10 | -0.13 |
| T_{eff} = 5000 K, [M/H] = −2, [C/Fe] = 2 |
| 1.5  | -0.08 | -0.12 | -0.06 | -0.55 | -0.50 | -0.59 |
| 2.0  | -0.06 | -0.09 | -0.07 | -0.48 | -0.41 | -0.50 |
| 2.5  | -0.04 | -0.07 | -0.05 | -0.37 | -0.32 | -0.39 |
| T_{eff} = 5500 K, [M/H] = −2, [C/Fe] = 2 |
| 3.0  | -0.08 | -0.13 | -0.09 | -0.66 | -0.59 | -0.70 |
| 3.5  | -0.04 | -0.06 | -0.05 | -0.54 | -0.45 | -0.56 |
| 4.0  | -0.03 | -0.05 | -0.03 | -0.44 | -0.34 | -0.39 |
| 4.5  | -0.02 | -0.03 | -0.02 | -0.29 | -0.24 | -0.29 |
| 5.0  | -0.01 | -0.02 | -0.01 | -0.19 | -0.14 | -0.19 |

5 CONCLUSIONS

We constructed a comprehensive model atom for C I using the most up-to-date atomic data and evaluated the NLTE line formation for C I in classical 1D models representing the atmospheres of late-type stars, where carbon abundance varies from solar value down to [C/H] = −3.

In line with the previous studies we found that NLTE leads to stronger C I lines compared with their LTE strengths and negative NLTE abundance corrections. The deviations from LTE are large for the strong lines, C I 9061-9111 Å (multiplet 3), 9405 Å, and 9658 Å, that form in the uppermost atmospheric layers, where collisions are inefficient. For these lines \( \Delta_{\text{NLTE}} \) range between −0.10 dex and −0.45 dex depending on stellar parameters. The NLTE corrections do not exceed 0.03 dex in absolute value for the weaker visible lines C I 4932 Å, 5052 Å, 5380 Å, and 6587 Å. The NLTE effects depend strongly on the carbon abundance in the atmosphere. Therefore, the NLTE abundances of
individual stars should be determined using an appropriate carbon abundance in the SE calculations.

In the $-1 \leq [M/H] \leq 0$ range our results agree well with that of Takeda & Honda (2003) and Fabbian et al. (2006). At $[M/H] = -2$ our $\Delta_{\text{NLTE}}$ are consistent with that of Takeda & Honda (2003), but they are 0.08 dex smaller in absolute value compared with that of Fabbian et al. (2006). We computed smaller NLTE abundance corrections for the $[M/H] = -3$ model atmospheres than the corresponding values in Takeda & Honda (2003) and Fabbian et al. (2006). This is not due to applying the Reid (1994) data. We did not find any observational data in the literature to check, what is correct.

The treated model atom was applied to analyse lines of C I in the Sun and reference late-type stars covering the $-2.56 \leq [\text{Fe/H}] \leq -1.02$ range. The solar and stellar carbon abundances were also determined from the molecular CH lines, using recent molecular data from Masseron et al. (2014). We aimed to check, whether different abundance indicators lead to consistent results for each star.

The solar abundances derived from lines of C I, CH, and C$_2$ are consistent within the error bars, when applying $S_H = 0.3$ to 1 in the SE calculations for C I. Our results are in line with the 1D and 3D solar abundances of Asplund et al. (2009) and Caffau et al. (2010). For each program star the difference between the NLTE ($S_H = 0.3$) abundance from the atomic C I lines and the molecular CH lines does not exceed 0.07 dex. An exception is a cool VMP dwarf BD +66$^\circ$268, where the atomic IR lines are rather weak resulting in $(\text{C I} - \text{CH}) = 0.17$ dex. The obtained results suggest that the molecular CH lines can safely be used for stellar carbon abundance determinations with classical 1D model atmospheres in a broad metallicity range, at least, down to $[\text{Fe/H}] \approx -2.4$.

We show that the NLTE abundance corrections for C I 4932 Å, 5052 Å, and 5380 Å in the carbon-enhanced 6200/4.0/−3 models do not exceed 0.04 dex in absolute value. Applying our $\Delta_{\text{NLTE}}$ to the carbon 1D-LTE abundances of the four CEMP stars as determined by Behara et al. (2010) and Spite et al. (2013) leads to $(\text{C I} - \text{CH})$ of smaller than 0.07 dex for three of them. In 3D the difference $(\text{C I} - \text{CH})$ is positive everywhere, up to $+0.7$ dex. For the 4th star neither 1D nor 3D helps to make abundances from the different chemical species consistent. We present the NLTE abundance corrections for lines of C I in the carbon-enhanced models of different $T_{\text{eff}}$, log g, and [M/H]. They will be useful for accurate determinations of the carbon abundances of the CEMP stars.

The NLTE method treated in this study for C I will be used in our further studies for accurate determinations of not only stellar carbon abundances, but also effective temperatures. The abundance difference between lines of C I and CH can serve as an efficient $T_{\text{eff}}$ indicator.

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