C II ABUNDANCES IN EARLY-TYPE STARS: SOLUTION TO A NOTORIOUS NON-LTE PROBLEM

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ABSTRACT

We address a long-standing discrepancy between non-LTE analyses of the prominent C II 4267 and 6578/82 Å multiplets in early-type stars. A comprehensive non-LTE model atom of C II is constructed based on critically selected atomic data. This model atom is used for an abundance study of six apparently slow-rotating main-sequence and giant early B-type stars. High-resolution and high S/N spectra allow us to derive highly consistent abundances not only from the classical features but also from up to 18 additional C II lines in the visual—including two so far unreported emission features equally well reproduced in non-LTE. These results require the stellar atmospheric parameters to be determined with care. A homogeneous (slightly) subsolar present-day carbon abundance from young stars in the solar vicinity (in associations and in the field) of log (C/H) + 12 = 8.29 ± 0.03 is indicated.

Subject headings: line: formation — radiative transfer — stars: abundances — stars: early-type

Online material: color figures

1.INTRODUCTION

One of the most abundant metals in the universe is carbon, the central building block of all organic chemistry. Abundances derived from luminous early B-type and late O-type stars provide important constraints on stellar and galactochemical evolution. In extragalactic applications (e.g., analyses of dwarf stars in the Magellanic Clouds; see Hunter et al. 2005 and Korn et al. 2005), one desires to study the strongest features in the metal line spectra, as these are the only ones measurable at low signal-to-noise ratio (S/N) and/or high projected rotational velocities. In the case of ionized carbon, these are the prominent lines of the two multiplets C II λλ4267.02/4267.27 and λ6578.03/6582.85. These lines are unfortunately highly sensitive to non-LTE effects as well as to the choice of stellar atmospheric parameters. So far, all studies from the literature failed to derive consistent abundances from these lines.

The problem was addressed by Lennon (1983), Eber & Butler (1988), and Sigut (1996, hereafter S96) using C II model atoms of increasing complexity. A spectrum synthesis based on the latter two non-LTE model atoms obtained better—a but apparently still not good—agreement with observation when compared to earlier work or LTE results. Non-LTE abundance analyses in Galactic OB stars, e.g., by Gies & Lambert (1992) and Kilian (1992) employing the Eber & Butler (1988) model derived a metal deficiency (including C) in these young stars with respect to the Sun, in accordance with studies of H II regions.

The present work aims at providing a solution to the classical non-LTE problem of carbon abundance determinations in OB stars. A reliable C II model atom is developed, and first applications on high-quality spectra are presented. Besides taking great care in the selection of atomic data, we also place special emphasis on an accurate atmospheric parameter determination, in order to minimize systematic uncertainties. The measurable C II spectrum in the visual is investigated, the two prominent line multiplets as well as numerous weaker lines.

2.MODEL CALCULATIONS

A hybrid approach is used for the non-LTE line formation computations. These are based on line-blanketed LTE model atmospheres calculated with ATLAS9 (Kurucz 1993). Synthetic spectra are computed with recent versions of DETAIL and SURFACE (Giddings 1981; Butler & Giddings 1985), solving the restricted non-LTE problem (see Przybilla et al. 2001 for details).

Hydrogen and He i/ii populations are computed using recent model atoms by Przybilla & Butler (2004) and Przybilla (2005), respectively. We have compared our synthetic H and He i/ii lines with predictions from Lanz & Hubeny (2003) in the effective temperature range of 27,500 K ≤ Teff ≤ 32,500 K for dwarf as well as giant stars. Overall good agreement is found. Exceptions are the He i singlet lines, which are predicted to be (significantly) stronger in our approach, in accordance with observation.

The C II model atom considers LS terms up to principal quantum number n = 10 and angular momentum l = 9 explicitly in non-LTE, with all fine-structure sublevels combined into one. The doublet and quartet spin systems are treated simultaneously. Level energies are adopted from Moore (1993), S96, and Quinet (1998).

Oscillator strengths from three sources are considered: fine-structure data from ab initio computations using the multiconfiguration Hartree-Fock method in the Breit-Pauli approximation (Froese Fischer & Tachiev 2004, hereafter FFT04), data from an application of the Breit-Pauli R-matrix method (Nahar 2002a), and results obtained in the Opacity Project (OP) from a close-coupling method in the LS approximation (Yan et al. 1987). Our primary source of gf-values is FFT04, followed by OP and Nahar for the remaining transitions. Note that data for several important transitions from Nahar disagree with those from FFT04 and OP, which show consistency among each other. Intercombinations are neglected because of the very small gf-values and high densities.

Photoionization cross sections are taken from the OP (Yan & Seaton 1987) where available. For the remainder, data from Nahar (2002b) are adopted. The choice is empirically motivated, giving preference to the OP data in order to reproduce observation over the entire parameter range simultaneously.
from all indicators. The two data sets show differences in the resonance structures.

Effective collision strengths for electron impact excitation among the lowest 16 $^1S$ states are adopted from the $R$-matrix computations of Wilson et al. (2005). Collisional excitation for transitions without reliable data are treated using the Van Regemorter (1962) approximation in the optically allowed case and via the semiempirical Allen (1973) formula otherwise. Collision strengths varying between 0.01 ($\Delta n \geq 4$) and 100 ($\Delta n = 0$) are employed, as suggested by evaluation of the detailed data of Wilson et al. (2005).

Collisional ionization rates are evaluated according to the Seaton (1962) approximation, with threshold photoionization cross sections from OP and Nahar (2002b), allowing for an empirical correction of 1 order of magnitude higher for the $6^2P$ and $6^2F$ terms—corresponding to the upper levels of the C II 6151 and 6462 Å transitions. For completeness, a C III model atom is also accounted for in the computations, but its details are of no further importance to the present study.

Voigt profiles are adopted in the formal solution using SURFACE. Wavelengths and $gf$-values are taken from Wiese et al. (1996). Radiative damping parameters are calculated from OP lifetimes, and coefficients for collisional broadening by electron impact are adopted from Griem (1974) for the doublet C II $\lambda$4267, while the approximation of Cowley (1971) is used for the other lines.

3. ANALYSIS

Six apparently slow-rotating stars are considered for the model atom calibration and first applications. The observations consist of high-resolution, high S/N spectra with wide wavelength coverage, obtained with the Fiber-fed Extended Range Optical Spectrograph (FEROS) at the 2.2 m telescope at ESO (La Silla, Chile).

Effective temperatures $T_{\text{eff}}$ are derived spectrophotometrically from $IUE$ fluxes and Johnson and 2MASS magnitudes for all the stars except HR 2928, where $T_{\text{eff}}$ is in agreement with Kilian (1992). Further constraints can be derived from the He I $\lambda\lambda$ 5876, 5893 ionization equilibrium for $\tau$ Sco and HR 3055. Figure 1 displays best fits to the spectrophotometry. Gravities ($\log g$) are derived from line profile fits to H$\delta$, H$\gamma$, H$\beta$, and H$\alpha$. Examples for some H and He I/II lines in $\tau$ Sco and HR 5285 are given in Figure 2.

After constraining $T_{\text{eff}}$ and $\log g$, we compute small grids of synthetic spectra for different carbon abundances $\epsilon(C) = \log (N_C/N_H) + 12$ and several values of microturbulence $\xi$. These grids are used for C abundance determinations from observation via a $\chi^2$-minimization technique. The free-fitting parameters are $\epsilon(C)$, $v \sin i$, and macroturbulence $\zeta$. The macroturbulent velocities in the sample stars remain smaller than twice the sound speed. The microturbulent velocity is fixed in the usual approach, by demanding $\epsilon(C)$ to be independent of the equivalent width $W_e$ of the C II $\lambda$4267 line ensemble (see Fig. 5 below).

An excellent match between theory and observation is achieved, as shown in Figure 3 exemplarily for the hottest ($\tau$ Sco) and coolest (HR 5285) stars in our sample. The complete line list includes the C II $\lambda\lambda$ 3919.0/20.6, 4267.0/2, 5133.3/37.3/39.2/43.4/45.2/51.1, 5648.1/62.5, 6151.5, 6461.9, 6578.0/82.9, 6779.9/80.6/83.1/87.2/6791.5, and 6800.7 Å transitions. Fits to C II $\lambda6462$ for all the stars are shown in Figure 4. This line and C II $\lambda6151$ are subject to marked non-LTE effects, turning from absorption at spectral type B2 into emission at earlier spectral types, a behavior never reported before. The emission

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**Fig. 1.**—Best fits of theoretical energy distributions to measurements by $IUE$ (dotted lines) and Johnson and near-IR 2MASS photometry (diamonds). The observed fluxes are dereddened by the values indicated using a standard reddening law and assuming as typical for the local interstellar medium. They were degraded to the resolution of the ATLAS9 fluxes. The models are normalized to the observed $V$ magnitudes and shifted for clarity relative to each other. See Fig. 5 for atmospheric parameters. [See the electronic edition of the Journal for a color version of this figure.]

**Fig. 2.**—Comparison of synthetic H and He I/II lines (smooth lines) with observation of a B0 V ($\tau$ Sco) and a B2 V (HR 5285) star. Atmospheric parameters as summarized in Fig. 5 are employed. [See the electronic edition of the Journal for a color version of this figure.]
results from a non-LTE overpopulation of the upper levels of these transitions relative to the lower levels, facilitated by close collisional coupling of the former to the C III ground state, which is close to LTE in all the sample stars. For HR 3055 and HR 2928, C II 6462 and 6151 Å are not considered when deriving the average \( \epsilon(C) \). See S96 for a discussion of the nature of the non-LTE effects of C II 4267 and 6578/82 Å.

Non-LTE and LTE abundances for all individual lines are displayed as a function of \( W_\lambda \) in Figure 5, showing excellent consistency in non-LTE. A slight degradation of the overall consistency is indicated for \( \tau \) Sco (see below). Atmospheric parameters and averaged \( \epsilon(C) \) are also given.

4. DISCUSSION AND RESULTS

We have investigated the sensitivity of the transitions to modifications of atmospheric parameters and several atomic parameters qualitatively. The individual lines show a different behavior: C II 6151 and 6462 are very sensitive to changes of \( \log g \), \( \xi \), and collisional and photoionization cross sections; C II \( \lambda 4267 \) is sensitive to photoionization; and all C II line
strengths react sensitively to changes in $T_{\text{eff}}$. As an example, exchanging our current photoionization data with the homogeneous set of Nahar (2002a) would result in considerably reduced uncertainties in the mean $\epsilon(C)$ of $\tau$ Sco and HR 3055. However, for the same model configuration, abundances from C ii $\lambda$4267 in the other stars are reduced by up to 0.5 dex, approximately reproducing the LTE results in Figure 5, while the remaining lines behave similarly to the final model. Further analyses have to be made to quantify these dependencies.

LTE analyses may produce abundances from the prominent C ii $\lambda$4267 transition that are in error by $\sim$0.3–0.8 dex, from C ii 6578/82 Å that are in error by up to $\sim$0.4 dex (note that approximately near-zero corrections may also occur), and from the weak C ii 6151 and 6462 Å lines in the cooler stars that are in error by $\sim$0.6–0.8 dex. In the hotter stars, the last two lines turn into emission and cannot be reproduced at all by assuming LTE. All other transitions are subject to non-LTE corrections on the order of $\sim$0.2 dex.

Noteworthy (small) discrepancies to the overall excellent agreement arise only for the C ii $\lambda$4267 and 6578/82 Å transitions in $\tau$ Sco. Among the sample stars, $\tau$ Sco is the only object showing a considerable (clumped) stellar wind and hard X-ray emission (see Howk et al. 2000). The problems may be related to these complications, as wind emission affects the H$\alpha$ profile and as the X-ray emission modifies the photoionization rates (these both have to be modeled correctly in order to reproduce these strongly non-LTE–affected C ii lines accurately).

Our non-LTE computations reproduce the C ii $\lambda$4267 theoretical equivalent widths of S96 (his Fig. 1). For C ii 6578/82 Å, we reproduce the S96 values at 15 kK; however, at 20 kK our $W_0$ are $\sim$10% lower, and at 30 kK they are up to 50% higher (see S96, Figs. 5 and 6). The difference arises because we use non-LTE populations when computing the H$\alpha$ line opacities that define the continuum against which these lines are measured (S96 assumes LTE). Note also that the $T_{\text{eff}}$-scale employed by S96 for his comparison with observation appears to produce values of $T_{\text{eff}}$ that are lower by 700–3000 K than our derivations.

A highly consistent mean $\epsilon(C) = 8.29 \pm 0.03$ is derived from the sample stars, which provides a tight estimate to the present-day C abundance from young stars in the solar vicinity. The atmospheric composition appears to be unaffected by chemical mixing in the course of stellar evolution; i.e., we find no trend of $\epsilon(C)$ with evolutionary age. For comparison, by adopting Kilian’s (1992) results, one derives a mean $\epsilon(C) = 8.19 \pm 0.12$ from the same six stars, implying a systematic shift and a significantly increased statistical scatter. More objects need to be further analyzed in order to verify the claim of such homogeneous present-day (slightly) subsolar—considering as references $\epsilon(C)_\odot = 8.39 \pm 0.05$ (Asplund et al. 2005) or $\epsilon(C)_\odot = 8.52 \pm 0.06$ (Grevesse & Sauval 1998)—C abundances in nearby associations (HR 1861: Ori OB1; $\tau$ Sco, HR 5285: Sco-Cen) and in the field (the other stars).

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