

# C I non-LTE spectral line formation in late-type stars

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**Abstract.** We present non-Local Thermodynamic Equilibrium (non-LTE) calculations for neutral carbon spectral line formation, carried out for a grid of model atmospheres covering the range of late-type stars. The results of our detailed calculations suggest that the carbon non-LTE corrections in these stars are higher than usually adopted, remaining substantial even at low metallicity. For the most metal-poor stars in the sample of Akerman *et al.* (2004), the effects are of the order of  $\Delta \log \epsilon_{\text{C}} \simeq -0.35... - 0.45$  (when neglecting H collisions). Applying our results to those observations, the apparent [C/O] upturn seen in their LTE analysis is no longer present, thus revealing no need to invoke contributions from Pop. III stars to the carbon nucleosynthesis.

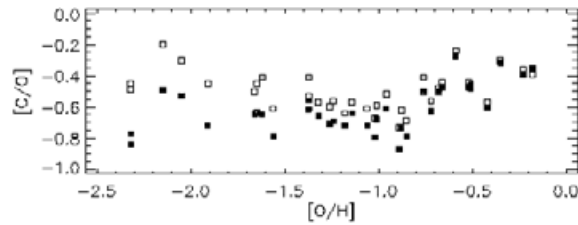
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The lack of detailed investigations on the non-LTE formation of spectral lines for a variety of chemical elements is unfortunately a major obstacle in pushing current stellar abundance studies to the 0.1 dex precision limit or less. It is fundamental to have a clear understanding of the trends with for example metallicity, for various elements, as a way to shed light on the chemical evolution of our Galaxy and of the Universe in general.

We have carried out non-LTE spectral line formation calculations for C I using the code *Multi* (Carlsson 1986). A grid of MARCS model atmospheres with stellar parameters in the range  $4500 \leq T_{\text{eff}} \leq 7000$ ,  $2.0 \leq \log g \leq 5.0$  and  $-3 \leq [\text{Fe}/\text{H}] \leq 0$  has been employed. The carbon atomic model used in this study contains 217 energy levels and 650 radiative transitions (*f*-values and photo-ionization cross-sections from the OP database TOPbase, Cunto *et al.* 1993) and collisions with electrons and hydrogen are also included.

The magnitude of the non-LTE effects affecting the formation of carbon spectral lines in these late-type stars and their trend with effective temperature, gravity, metallicity and carbon content have been investigated: spectral lines were found to be generally stronger in non-LTE across our parameter grid. Thus, with respect to the LTE approximation, we obtain negative abundance corrections, which become particularly severe at high temperature (6000–7000 K) and low gravity (2.0–3.0), where they can reach  $\sim -1.0$  dex and more, while for the most metal-poor halo turn-off stars  $\Delta \log \epsilon_{\text{C}} \simeq -0.35... - 0.45$ . The driving non-LTE effects are found to be the source function dropping below the local Planck function (at solar metallicity), while increased line opacity is responsible for the non-LTE line strengthening at low metallicity. The most pronounced corrections are seen at  $[\text{Fe}/\text{H}] = -1$  dex, where these two effects work in the same sense. However, corrections are shown to be generally large across the whole grid.



**Figure 1.** Trend of the  $[C/O]$  ratio vs. oxygen abundance, in Milky Way halo and disk stars, in logarithmic abundances relative to solar. The empty symbols represent literature data (see Akerman *et al.* 2004). Filled symbols represent the abundance values we obtain with oxygen non-LTE corrections as adopted by those authors, but accounting for our larger non-LTE corrections for carbon. Both carbon and oxygen abundance corrections used in this plot are calculated neglecting inelastic collisions with hydrogen.

In particular, to better constrain the evolution of the C/O ratio, we have focussed our attention on the non-LTE processes affecting the lines still visible in the metal-poor regime. The influence of changing the efficiency of H collisions (which probably remain the major source of uncertainty in our study and in similar ones), has also been investigated in the present work, showing little sensitivity of the overall resulting non-LTE abundance corrections for the metal-poor halo stars of interest, where they become less dramatic but still remain important (of the order of  $\Delta \log \epsilon_C \simeq -0.25 \dots -0.35$ ) when setting efficient hydrogen collisions. Very recently, statistical equilibrium calculations for carbon across a grid of stellar parameters similar to the one adopted here, have been carried out by Takeda & Honda (2005). These authors find similar significantly large non-LTE corrections. A detailed comparison with their results is of interest and, together with full details of our study, will be shortly available in a subsequent paper (Fabbian *et al.* 2005).

These findings have important consequences on studies of Galactic chemical evolution, in particular on the derivation of carbon abundance at low metallicity. Figure 1 shows results of Akerman *et al.* (2004), where those authors have assumed that the carbon non-LTE corrections are of the same order as those calculated for oxygen. An apparent upturn in the  $[C/O]$  ratio at low metallicity is then visible when an LTE analysis is performed. However, after applying the here calculated non-LTE corrections, such a trend is no longer present, which suggests it is probably due to errors intrinsic in the use of the LTE approximation. Instead, an almost flat “plateau” is recovered, with  $[C/O] \sim -0.7$  at  $[O/H] = -1$  and remaining approximately constant down to  $[O/H] \sim -2.5$ . Thus, there is apparently no need to invoke C production in Pop. III stars, as advocated by Akerman *et al.* (2004) and Spite *et al.* (2005). More high-quality spectroscopic data for these metal-poor turn-off stars is highly desirable to better constrain the trends at low metallicity.

## References

- Akerman, C.J., Carigi, L., Nissen, P.E., Pettini, M., & Asplund, M. 2004, *A&A* 414, 931  
 Carlsson, M. 1986, 'A Computer Program for Solving Multi-Level Non-LTE Radiative Transfer Problems in Moving or Static Atmospheres', in *Uppsala Astronomical Report No. 33*  
 Cunto, W., Mendoza, C., Ochsenein, F., & Zeippen, C. J. 1993, *A&A* 275, L5  
 Fabbian, D., Asplund, M., Carlsson, M., & Kiselman, D. 2005, *to be submitted to A&A*  
 Gustafsson, B., Karlsson, T., Olsson, E., Edvardsson, B., & Ryde, N. 1999, *A&A* 342, 426  
 Takeda, Y. & Honda, S. 2005, *PASJ* 57, 65