3D and NLTE Effects on Spectroscopic Parameters of Late-Type Stars

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Abstract. We investigate the impact on spectroscopic effective temperatures (\(T_{\text{eff}}\)), surface gravities (\(\log(g)\)), and metallicites ([Fe/H]) of metal-poor stars, when departures from LTE are taken into account and the atmospheric model is constructed from realistic 3D, hydrodynamical simulations. We demonstrate that traditional 1D, LTE analysis underestimates the values for all three parameters in the metal-poor subgiant HD140283.

1. Introduction

The fundamental stellar parameters, \(T_{\text{eff}}\), \(\log(g)\), and [Fe/H], constitute the basis of all spectroscopic abundance analysis. The iron content is commonly adopted as single proxy for the entire content of metals in the stellar atmosphere. With the knowledge of the three stellar parameters, we can acquire further information about the evolution of the star itself, i.e. determine its mass and age, and the evolution of the stellar population it resides in.

A common approach is to determine stellar parameters spectroscopically, using the wealth of Fe lines present in late-type star spectra. In particular, a spectroscopic temperature is determined by selecting the \(T_{\text{eff}}\) of the atmospheric model such that the abundances inferred from Fe I lines exhibit no significant slope with the excitation potential of the lower level of the line transition. This method exploits the different temperature-sensitivity of the level populations of different excitation potential, the lowest excited lines being most sensitive. Further, a spectroscopic surface gravity, is determined by adjusting the model gravity such that Fe I and Fe II lines give consistent abundances. When the stellar parameters are constrained in this fashion, along with the microturbulence, one may derive a highly precise value of the metallicity.

However, the success of the method hinges on the realism of the atmospheric structure. Even if high precision may be obtained with a very simplistic model, the answer may be inaccurate. Traditional methods rely on model atmospheres calculated under the assumptions of hydrostatic equilibrium and a one-dimensional (1D) geometry. The most critical approximation is the mixing-length description of the convective energy
transport. The development of 3D, radiation-hydrodynamical simulations has uncovered systematic uncertainties introduced by these simplifying assumptions. In particular, metal-poor stars have been demonstrated to have much cooler line-forming layers than previously thought (see Collet et al. 2011, and references therein).

A second critical assumption is that spectral line formation can be well modelled in local thermodynamic equilibrium (LTE). The atomic level populations of minority species, such as Fe I, may react very sensitively on the super-thermal ultra-violet (UV) radiation field, in the shortage of thermalizing collisional processes. For these species, statistical equilibrium (NLTE) is a more realistic assumption (e.g. Mashonkina et al. 2011). We have tested the influence of NLTE and 3D models on stellar parameters derived for a sample of benchmark metal-poor stars. For this purpose we adopt atmospheric models determined with MARCS (Gustafsson et al. 2008), a state-of-the-art 1D code, and STAGGER, a 3D radiation-hydrodynamical code (e.g. Nordlund et al. 2009). The convection simulations are averaged temporally and spatially on surfaces of equal optical depth, so that spectrum synthesis can be carried out in one dimension. For this study we thus neglect the potential impact of existing temperature and density inhomogeneities. Line formation calculations for 1D and <3D> models are performed in LTE and NLTE with the radiative transfer code MULTI2.3 (Carlsson 1986).

2. Results

Figure 1 illustrates schematically how the Fe abundances derived for a famous metal-poor subgiant, HD140283, are affected by the assumptions of LTE and 1D atmospheres. The adopted stellar parameters \( T_{\text{eff}} = 5777 \pm 55 \, \text{K} \) and \( \log(g) = 3.70 \pm 0.08 \) have been determined by the infra-red flux method (Casagrande et al. 2010) and measurement of the parallax (van Leeuwen 2007). 1D modelling produces a negative slope of Fe I line abundances with excitation potential that corresponds to approximately 300 K, in LTE as well as NLTE. The <3D> model exhibits an equally strong but positive slope in LTE, while the combination of NLTE and <3D> successfully establishes the excitation balance at this effective temperature. The inferred metallicity is \([\text{Fe}/\text{H}] = -2.35\).

Also evident from the figure is that ionization balance between Fe I and Fe II lines is achieved simultaneously. In the 1D, LTE case, the surface gravity would have to be lowered by 0.42 dex to achieve ionization balance at the spectroscopic temperature. The star would thus be moved from its location in the HR diagram close to a point further along the same isochrone \( T_{\text{eff}} = 5450 \, \text{K}, \log(g) = 3.25 \) and \([\text{Fe}/\text{H}] = -2.70\), turning HD140283 into a red giant at the base of the branch. More details about this star and the rest of the benchmark star sample will be presented in Bergemann et al. and Lind et al. (in prep.). The latter paper will present an extensive 1D, NLTE grid for late-type stars.

Discussion

Q.: The disparity of Fe abundances with excitation potential can be reduced for 1D models in two ways: 1) Models with convective overshoot reduce the temperature gradient in line forming regions. 2) Transition probabilities for high-excitation lines may have large errors and choices can be made that essentially eliminate these trends over all wavelengths from UV to NIR.
Figure 1. The figure illustrates the excitation equilibrium for 1D and <3D> models of HD140283. Solid: Linear regression to LTE abundances inferred from Fe I lines. Dotted: Same as solid, but in the NLTE case. Dashed: Mean abundances inferred from Fe II lines.

**Lind:** For our benchmark star sample, models with convective over-shoot (Kurucz 1992) bear no greater resemblance to the temperature structure recovered from hydrodynamical simulations than models without overshoot. Like the mixing-length description in itself, the implementation of overshoot is not based on first principles but governed by free parameters that require calibration. It is also important to realise that all 1D models in radiative equilibrium, including those with overshoot, will inevitably overestimate the temperatures in shallow optical layers of metal-poor stars.

As shown in Figure 1 the modelling technique may have very dramatic impact on the excitation equilibrium irrespectively of which transition probabilities are adopted. We have made a critical selection of lines for this analysis, and estimate that the uncertainty in atomic data propagates into no more than \(\approx 50\) K in the case of HD140283, which is small compared to the differences between 1D and <3D> models (Bergemann et al. in prep).

**Q.:** When spectroscopic stellar parameters are unreliable they can be replaced by parameters derived from photometric colours.

**Lind:** Our analysis demonstrates that 1D LTE spectroscopic stellar parameters are not accurate for metal-poor stars. Low excitation lines in particular require a combined 3D and NLTE treatment to be modelled correctly. With those caveats in mind, spectroscopy is an excellent tool to extract information about fundamental stellar parameters, with
the considerable advantage of being insensitive to foreground extinction. Depending on the latitude of the stars, reddening uncertainties may well amount to hundreds of Kelvin, especially for optical colours. One should also bear in mind that synthetic color-temperature calibrations are similarly model dependent (e.g. Önehag et al. 2009). The infra-red flux method (González Hernández & Bonifacio 2009; Casagrande et al. 2010) offers a low sensitivity to the atmospheric model, but is dependent on the reddening and the photometric zero-point. With a tight constraint on the reddening, the uncertainty on temperatures derived with this method is small.

Q.: Your results show that spectroscopic 1D LTE stellar parameters are too cool compared to interferometric measurements, which contradicts e.g. Baines et al. (2010), who argue that the reverse is true.

Lind: Baines et al. report angular diameter measurements and inferred effective temperatures for a sample of solar-metallicity K giants. At these low temperatures ($T_{\text{eff}} < 4800\text{K}$) and high metallicities, NLTE and 3D effects for Fe I lines are small. These are probably not the reason for the discrepancy between 1D LTE spectroscopic temperatures and the interferometric results. More likely to blame is missing opacity, as suggested by the authors, or the presence of unresolved blends in the line-rich spectra, possibly skewing the results. Another possibility is that the interferometric measurements are subjected to systematic errors in the adopted limb-darkening coefficients (Chiavassa et al. 2010).

References

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