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Lithium abundance in spectroscopic surveys: application of 3D stellar model atmospheres

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Abstract. Determining chemical abundances from stellar spectra plays a fundamental role in improving our understanding of stellar, galactic and cosmic evolution. Nowadays it is possible to derive accurate chemical abundances by using realistic 3D model atmospheres, and even account for departures from LTE of selected elements. The results are in general more reliable compared to those obtained with classical 1D models, but the 3D hydrodynamical simulations and spectrum synthesis calculations are computationally rather demanding. The results of sophisticated 3D-NLTE line formation calculations based on a grid of 3D model atmospheres can be approximated by analytical fitting functions than can be used for deriving 3D-NLTE chemical abundances. The method described here provides a simple means of taking into account 3D and non-LTE effects in the analysis of a large number of observed spectra, as necessary in the context of spectroscopic surveys (e.g. Gaia-ESO), where current abundance determinations rely on classical 1D models. With the help of such tool, the use of realistic 3D model atmospheres in the framework of large surveys would become feasible.

3D model atmospheres and NLTE line formation

- The CIFIST grid (Ludwig et al. 2009, Fig. 2) comprises a grid of 3D model atmospheres computed with the radiation-hydrodynamics code ***CO^{5}BOLD*** (Freytag et al. 2012).
- NLTE departure coefficients are computed with the ***NLTE3D*** code (Steffen et al. 2015), at each geometrical position (x, y, z) in the model atmosphere, for each energy level of the model atom of Li I (Fig. 3).
- Line profiles of the lithium line are computed with the **Linfor3D** spectral synthesis code, with non-LTE departure coefficients from NLTE3D.

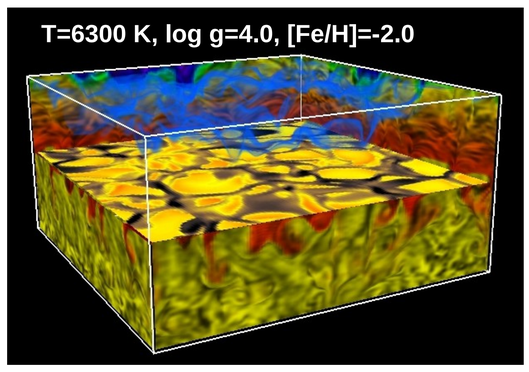

Fig 1. *Example of a 3D CO^{5}BOLD model atmosphere taken from the CIFIST grid.*

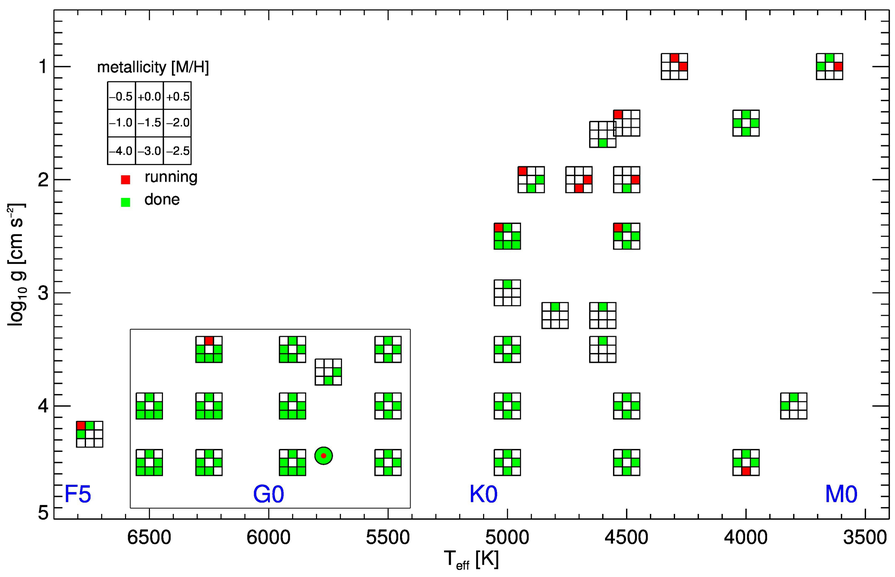

Fig 2. *Status of the model production for the CIFIST grid (updated at April 2014). Symbols mark the location of a model in the T_{eff}-log g-plane. The Sun is indicated by the round symbol. The box shows the 3D models used so far in this work.*

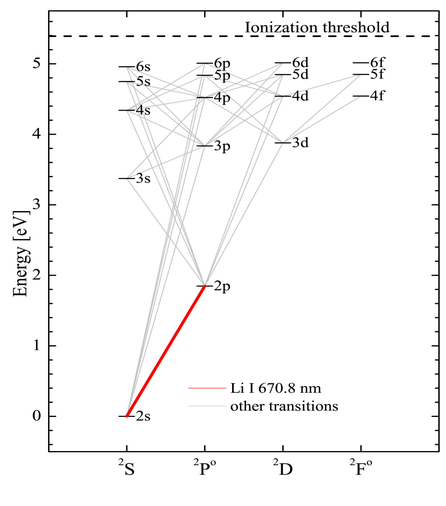

Fig 3. *Model atom of lithium used in the 3D-NLTE spectral line synthesis computations (17 atomic levels and 34 transitions). The thick red line marks the transition corresponding to the lithium 670.8 nm resonance doublet.*

Lithium

- The Li I 670.8 nm line in metal-poor halo stars is believed to reflect the primordial abundance produced in the Big Bang Nucleosynthesis.
- A precise determination of lithium abundance is necessary to put constraints on galactic, stellar and cosmic evolution and on the nucleosynthesis in stellar interiors.
- Lithium is sensitive to NLTE effects and to inhomogeneities of stellar photospheres (3D effects) that can alter the derived spectroscopic lithium abundance.
- **3D-NLTE analysis is preferable.**

Fitting function by Sbordone et al. (2010)

The derivation of chemical abundances through computation of synthetic non-LTE line profiles by using 3D hydrodynamical model atmospheres, is realistic, reliable but computationally time demanding.

T_{eff}, log g, [Fe/H] → 3D-NLTE spectral synthesis → EW[A(Li)]

An analytical fit of $A(Li)_{3D\text{-}NLTE}$ for the metal poor regime is available:

F_1{EW, Teff, logg, [Fe/H]} → $A(Li)_{3D\text{-}NLTE}$

F_2{A(Li), Teff, logg, [Fe/H]} → $EW_{3D\text{-}NLTE}$

- It can be simply hard-coded into any program, eliminating the need to access the true grid of synthetic line profiles.
- It can be easily applied in deriving precise lithium abundances in big sets of data (GAIA-ESO Survey), making use of the latest 3D model atmospheres and considering departures from LTE.

We are currently computing a set of extended ***fitting functions*** for lithium (3D-NLTE, 1D-NLTE and 1D-LTE), valid for a larger range of stellar parameters and lithium abundances. Here we present a first comparison with the existing 3D-NLTE fitting function by Sbordone et al. (2010).

3D abundance corrections

Atmospheric inhomogeneities due to stellar granulation lead to non-linear variations of line strenght, shape and Doppler shift across the stellar surface. This has an effect on the abundance determination since the 3D profile is different from the 1D profile of the mean atmosphere. The effect can be quantified by means the so called "3D abundance corrections". These corrections depend on stellar parameters, line strength and microturbulence. In the case of the lithium, the evaluation of these 3D corrections is another direct application of the fitting function. Here we define the abundance corrections as:

$$\Delta_{3D\text{-}NLTE} = A(Li)_{3D\text{-}NLTE} - A(Li)_{1D\text{-}NLTE}$$

Lithium curves of growth (CoGs)

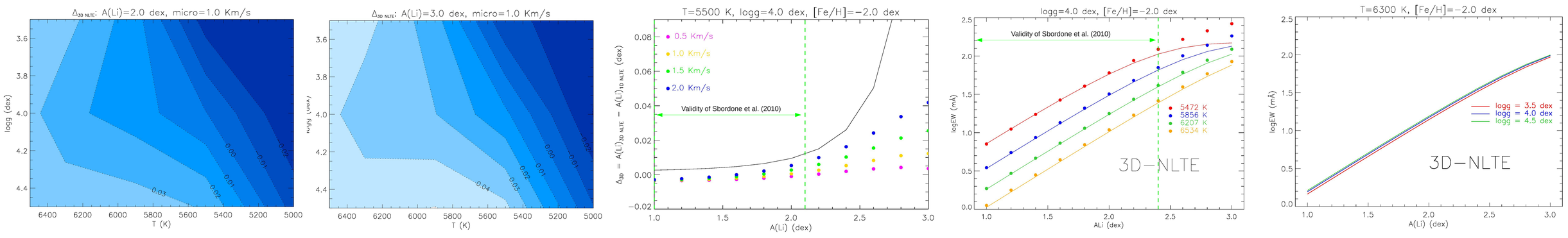

Fig 4. *Contour plots for $\Delta_{3D\text{-}NLTE}$ in the T_{eff} - log g plane for A(Li)=2.0 dex (left panel) and A(Li)=3.0 (right panel), ξ_{micro}=1.0 km/s. For A(Li)=3.0, the 3D corrections are larger compared to the ones obtained for A(Li)=2.0, becoming important in the lithium abundance determination especially at higher temperatures and gravities.*

Fig 5. *The effect of the microturbulence ξ_{micro} becomes relevant for stronger lines, leading to a larger $\Delta_{3D\text{-}NLTE}$ for higher ξ_{micro} . The continuous line was derived from the fitting function of Sbordone et al. (2010), dots are from this work.*

Fig 6. *Impact of T_{eff} and log g on the lithium CoG. Its higher sensitivity to T_{eff} is evident from the left panel. Continuous lines correspond to the fitting function by Sbordone et al. (2010). Dots correspond to the new data from this work. The saturation part of the CoG is covered by our new analysis, whereas it is almost unsampled by the fitting function of Sbordone et al. (2010). This limit is shown by the green dashed line. The effect of the surface gravity on the CoG is clearly smaller (right panel).*

Conclusions. We present a preliminary result of our extended *fitting function* for determining $A(Li)_{3D\text{-}NLTE}$ in metal-poor stars. We find 3D abundance corrections up to 0.05 dex. These are small corrections that become relevant in verifying depletion mechanisms of lithium in stars (e.g. diffusion models, extra-mixing processes) and in detecting possible signatures of extrasolar planets that might alter the chemical composition of hosts stars by small amounts. In the era of large spectroscopic surveys, these tools could provide easy access to accurate results from the latest teqniques of 3D-NLTE spectral synthesis. We are currently working on improved fitting functions covering an extended range of stellar parameters and abundances. The final product of this work will be a robust tool for chemical abundance determinations, readily usable by the scientific community. In the future it is planned to extend this approach to other chemical elements (e.g. oxygen).