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Investigation of the solar centre-to-limb variation of oxygen and lithium spectral features

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Abstract. We compare intensity spectra of the Sun observed at different limb angles in the wavelength range covering the forbidden oxygen lines and the lithium resonance feature with line formation computations performed on a CO5BOLD 3D hydrodynamical simulation of the solar atmosphere. Among the prime oxygen abundance indicators, the forbidden line at 630 nm is contaminated with a significant Ni I blend. The availability of observations at different positions on the solar disc allows us to disentangle the contributions of oxygen and nickel and to derive their individual abundances. We derived in the past, from the [OI] line, A(O) = 8.73 ± 0.05 with a nickel abundance of A(Ni) = 6.1 ± 0.04. From the observations here presented, we obtain A(O) = 8.71 and A(Ni) = 6.09, in excellent agreement with the previous result. For lithium, we investigated the Li doublet at 670.7 nm and compared synthetic spectra of the Li spectra range based on different line-lists available in the literature to the observed data. With these observations, we are still unable to conclude on which is the best line-list to be used for the blending lines.

Key words. Sun: abundances - Line: formation - Line: profiles - Radiative transfer - Hydrodynamics

1. Introduction

There are two astrophysical topics we are particularly interested in and for which hydrodynamical models can be very useful: the solar photospheric abundance of oxygen and the lithium abundance in cool stars. The first one is still a matter of debate. Since about ten years some determinations advocate a low oxygen abundance which is at variance with the value inferred by helioseismology. The lithium abundance is easily derived from the spectra of old metal-poor stars, where the Li I doublet at 670.7 nm is isolated, and the Li content of these stars is thought to reflect the primordial lithium abundance produced by standard Big Bang nucleosynthesis. In young, metal-rich stars, the Li feature is blended with other lines whose atomic data are not well known. To derive the

Li abundance in these stars, it is necessary to properly model the contributions of the blending lines to the synthetic spectrum to be compared with the observations.

We report on our recent investigations of centre-to-limb solar observations taken at the Observatoire de Paris in the site of Meudon, of the [OI] feature at 630 nm and the Li I doublet at 670.7 nm.

2. Observations

The Meudon solar tower is a 60 cm aperture solar telescope (45 m focal length) and a spectrograph with 14 m focal length is attached to it. A slit of 1 arcsec × 120 arcsec is usually chosen as the local image quality which is never better than 1 arcsec. The disperser is a 300 rules/mm diffraction grating blazed at 63°26'. The typical dispersion is 1 cm per Angström and the standard spectral resolving power is R=300 000 or about 20 mÅ.

The spectrum is focused on an interline 1370 × 1040 CCD camera with a pixel size of 6.45 microns and full well capacity of 18000 electrons. We used a 2 × 2 hardware binning in order to work with a final spectral sampling of about 10 mÅ/pixel and a spatial sampling of 0.5 arcsec/pixel along the slit of the spectrograph.

Observations of the Lithium lines were performed using this setup at several distances from disk centre. 800 spectra were taken with an integration time of 100 msec for each position on the Sun and summed in order to improve the photon signal to noise (S/N) ratio. After that, the curvature of lines was corrected and the spectra were summed over 100″along the slit which was directed North–South. Starting from an initial S/N ratio of 100 (for raw observations), this procedure allowed us to increase the photon S/N ratio to about 30 000. We finally got a single spectrum with a width of about 0.6 nm around the Li feature, for each location on the Sun with this photometric quality. We observed several positions on the solar disc, in the range $0.15 \le \mu \le 1.00$. The length of the slit is 90″, it is tangential to the limb, meaning that the centre of the slit is located at the μ values above indicated. Both ends of the slit are at a μ value slightly different from the centre of the slit, however we estimate the variation of μ along the slit to only about 1% for $\mu = 0.15$. This value is comparable to the uncertainty due to seeing fluctuations in Meudon.

3. Model atmosphere

For the investigations we compared synthetic spectra computed with the LTE radiative transfer code *Linfor3D* and based on the same 3D solar model, computed with the CO5BOLD code (Freytag et al. 2012), that we already used in Caffau et al. (2015b). The 20 representative snapshots we selected from the complete simulation cover 2.1 h; each snapshot covers a box in the solar photosphere of $5.6 \times 5.6 \times 2.25$ Mm with $140 \times 140 \times 150$ grid points.

4. Oxygen

In spite of being such an abundant element in the Universe (the most abundant after H and He), oxygen is poorly represented in the spectra of cool, late-type stars. Three infrared lines belonging to multiplet 1 (Moore 1945) at 777 nm are strong and free of blends, but are affected by departures from local thermodynamical equilibrium (LTE). By analysing the observed centre-to-limb variation of these triplet lines with 3D spectrum synthesis based on the solar CO5BOLD model, and taking departures from LTE into account, Steffen et al. (2015) derived an oxygen abundance of $A(\mathrm{O}) = 8.76 \pm 0.02$. The forbidden [OI] line at 630 nm is not affected by any telluric absorption in the solar spectrum, but is blended by a Ni I line, whose contribution to the equivalent width of the feature is about 1/3. The other atomic oxygen lines are even more problematic because they are either strongly blended (e.g. the lines at 615 nm and 844 nm) or contaminated by telluric absorption (e.g. the lines at 1130 nm and 1316 nm).

One of the reasons that recently pushes astronomers to continue investigating the solar oxygen abundance is its strongly reduced values found in recent works starting with Grevesse & Sauval (1998) and continued with

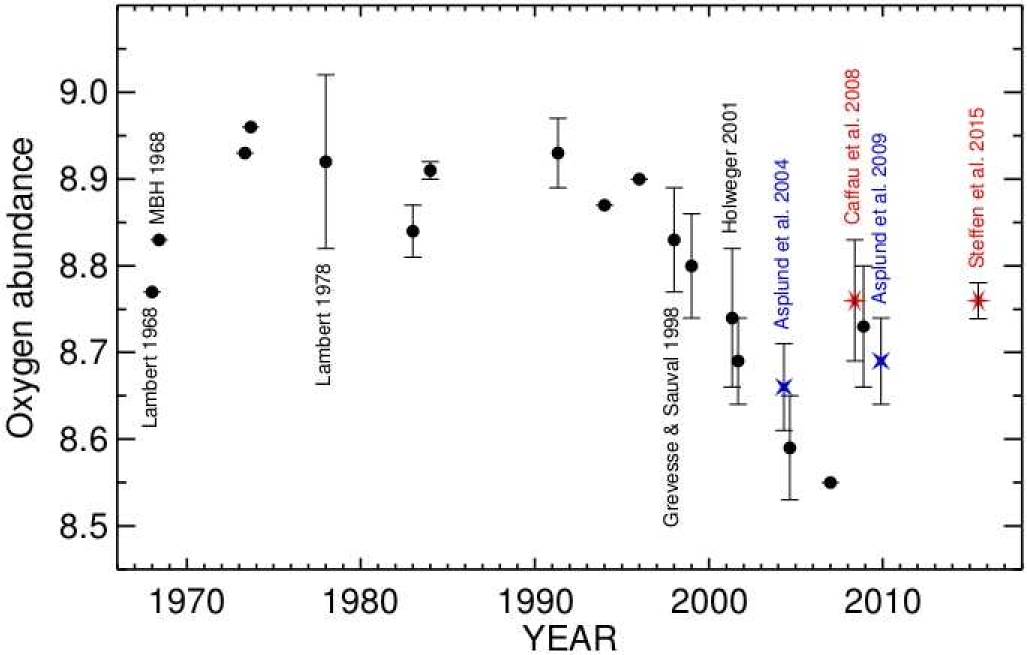

Fig. 1. The solar oxygen abundance derived by various authors over the last 50 years.

Asplund et al. (2004). The historical evolution is summarised in Fig.1. While in some cases the decrease in A(O) induced a general consensus, such as taking departures from LTE into account (e.g. Holweger 2001), there is no general consensus in the community in other cases, such as the introduction of hydrodynamical models.

We put particular effort in the analysis of the [OI] line at 630 nm. As said above, due to the combined contribution of oxygen and nickel to the equivalent width of the feature, their abundances are not independently determined. At a defined value of the equivalent width of the feature, an increase of the oxygen abundance results in a decrease of the nickel abundance and vice versa (see Fig. 2).

In Caffau et al. (2015b), we analysed centre-to-limb spectra of the [OI] feature observed with various instruments. By fitting simultaneously the observed centre-to-limb spectra at the various μ values with 3D synthetic spectra, the different sets of observations agreed with a significantly smaller Ni contribution to the [OI]+Ni blend than expected from the atomic data and from the solar nickel abundance usually adopted. In Caffau et al. (2015b) we did not present the spectra observed at the solar tower at Observatoire de Paris, because of the lower resolution and signal-to-noise ratio with respect to the observation taken with `Hinode` and VTT. We think it is a good opportunity to show these results here. Analysing eight μ positions across the solar disc observed with the spectrograph mounted at the solar tower in Meudon, we derive A(O)=8.71 and A(Ni)=6.09, in perfect agreement with the other set of observations analysed by Caffau et al. (2015b), from which we derived A(O) = 8.73 ± 0.05 and A(Ni) = 6.11 ± 0.04. In Fig. 3, the best fit is compared to the observations. Although we had only limited observing time at the solar tower in Meudon, the quality of the observations is good.

For the [OI] feature, the synthesis based on the `CO5BOLD` solar model is able to reproduce in a quite satisfactory way the observations taken at the solar tower in Meudon. The

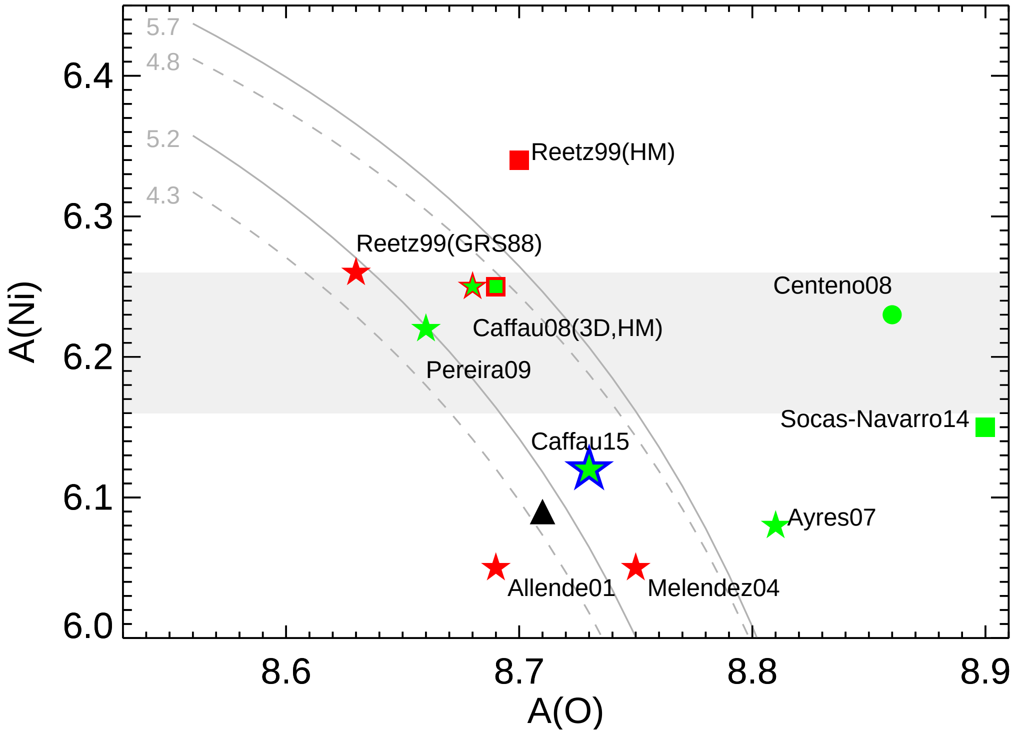

Fig. 2. Combined oxygen and nickel abundances derived by several authors from the forbidden [OI] line at 630 nm. This is a modification of Figure 3 in Caffau et al. (2015b), where we added the present results from the analysis of the observations with the solar tower in Meudon (black triangle). The dashed and solid gray lines correspond to constant EW for disc centre and disc integrated spectra, respectively.

oxygen and nickel abundances derived from these spectra are in good agreement with the values derived from other sets of observations (e.g. `Hinode` and VTT) of higher quality. The easy access we have to this solar telescope makes these observations particularly useful and interesting. Even if the resolution of the Meudon spectrograph does not reach the specifications of other instruments these observed spectra can anyway be very useful as a preparation for follow-up observations with higher spectral resolution at the VTT.

5. Lithium

Lithium is a widely studied element in metal-poor stars where the Li I resonance doublet at 670.7 nm is clean of blends. This is not the case of solar-metallicity stars where the wavelength range of the Li feature is contaminated by atomic and molecular lines. There is no general consensus on the atomic/molecular data of the features belonging to this wavelength range, and some of the lines actually lack a unique identification. We already discussed the topic in Caffau et al. (2010). After some years of work in the field, we presently consider four line-lists useful for further investigations: Reddy et al. (2002); Ghezzi et al. (2009); Meléndez et al. (2012) and Israelian (2014, priv. comm.). In Fig. 4, these four line-lists are compared. Significant differences are evident not only in line strengths but also in wavelengths. In Caffau et al. (2015a), we used the line-list from Meléndez et al. (2012) to derive the Li abundance in two young active stars.

We secured centre-to-limb observations of the Li range with the solar tower in Meudon.

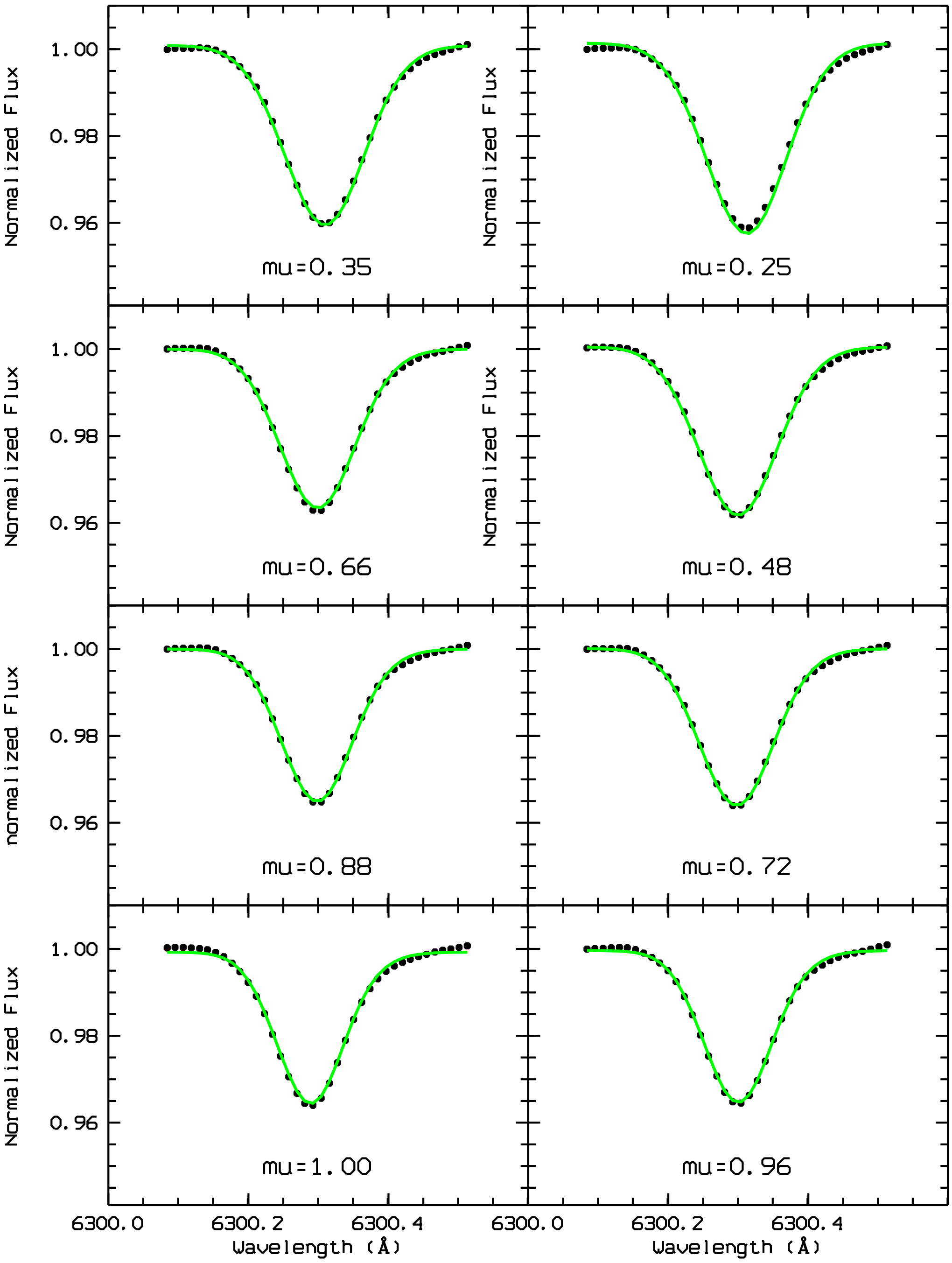

Fig. 3. The solar spectrum observed from the solar tower at the Observatoire de Paris (black dots) compared to best fit synthetic spectrum (solid green) for eight positions across the solar disc. From the fit we obtained A(O)=8.71 and A(Ni)=6.09.

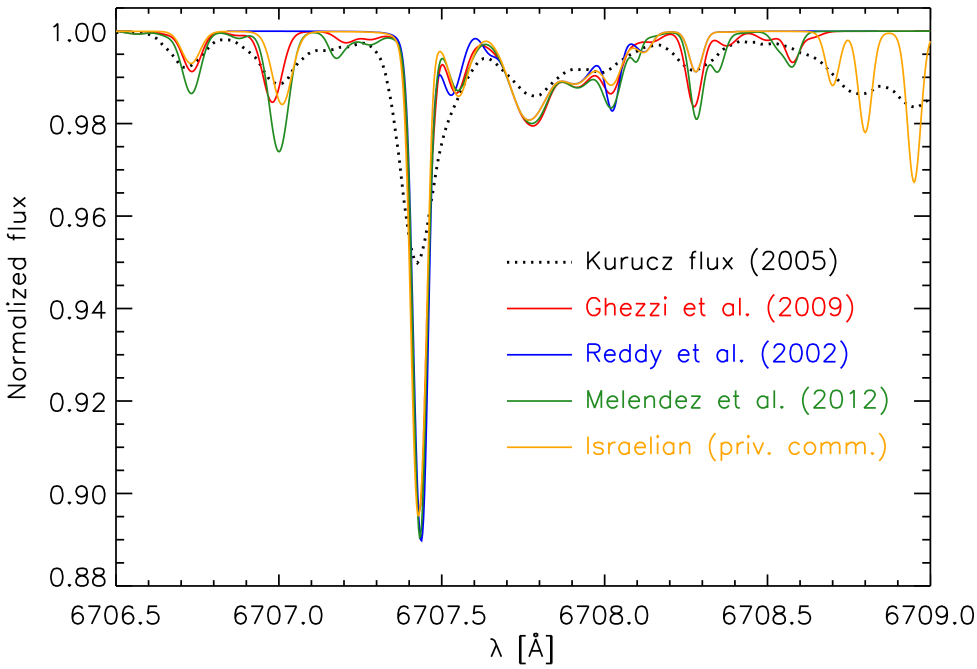

Fig. 4. The observed solar spectrum (dotted black) compared to the spectrum synthesis based on the CO5BOLD solar model with the line-lists of Ghezzi et al. (2009) (solid red), Reddy et al. (2002) (solid blue), Meléndez et al. (2012) (solid green) and Israelian (solid yellow). To improve the visibility of the individual blends, the synthetic spectra have been computed with all non-thermal velocities set to zero.

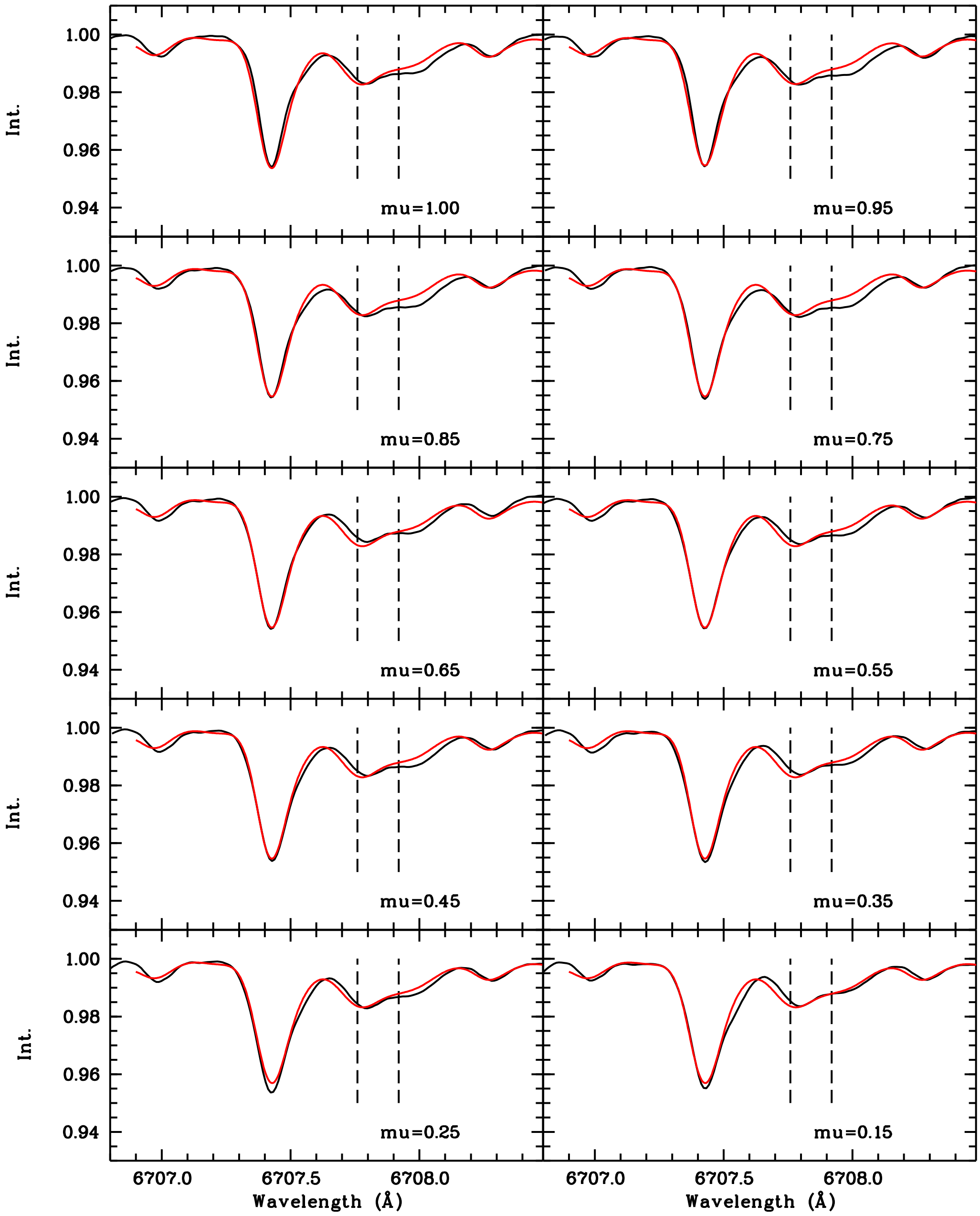

Fig. 5. The observed solar spectrum (black) compared to the spectrum synthesis based on the CO5BOLD solar model with the line-list of Ghezzi et al. (2009) (red). The dashed vertical lines mark the position of the ^{7}Li doublet.

In Fig. 5, the observations are compared to a synthetic spectrum based on the solar CO5BOLD model and the line-list of Ghezzi et al. (2009), while in Fig. 6 we compare the observed solar profile to a 3D synthesis based on the line-list

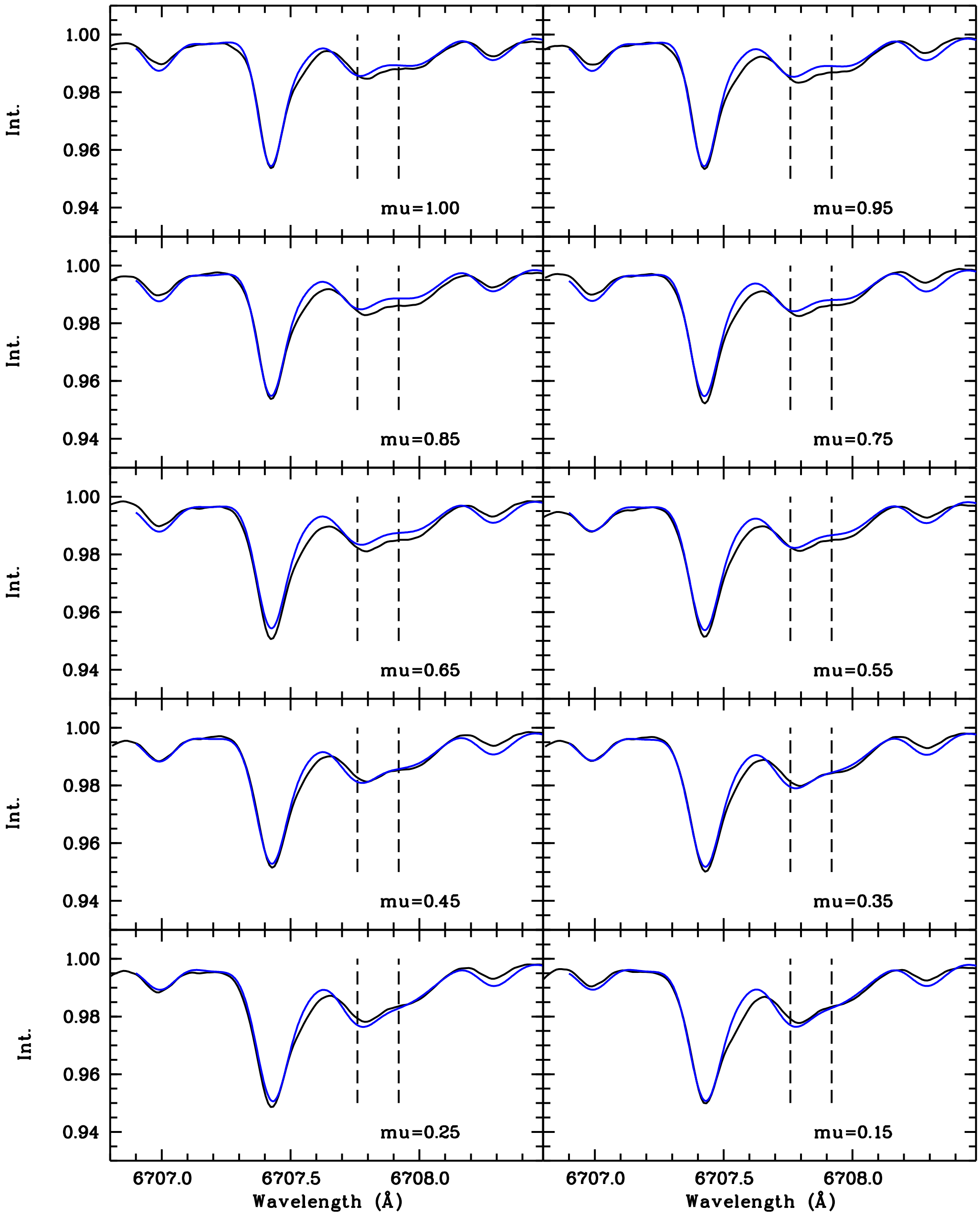

Fig. 6. The observed solar spectrum (black) compared to the spectrum synthesis based on the CO5BOLD solar model with the line-list of Meléndez et al. (2012) (red). The dashed vertical lines mark the position of the ^{7}Li doublet.

of Meléndez et al. (2012). The comparison is just an over-plot of the synthetic profile (with the abundances fixed at the solar value for all μ values) and the observations. The normalisation of the observations has been chosen to match as good as possible the synthesis. It is clear from the two figures that the agreement is not always very good for both line-lists. This could be due to problems in the observations or data reduction. Further work is needed to investigate the deviations and to identify the best line-list to be used in the case of the solar spectrum.

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