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# High-resolution spectroscopy of M subdwarfs

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**Abstract.** We present a UVES/VLT high-resolution spectroscopic analysis of M subdwarfs (sdM), which have opacities different from those of normal dwarfs. Our atlas covers the optical region from 6400 Åup to the near infrared at 9000 Å. We present spectral details of cool atmospheres at very high-resolution (R∼ 40 000) and compare the spectra with the recent BT-Settl model atmosphere. We derived metallicities based on the best fit of synthetic spectra to the observed spectra. Thanks to the high resolution of our spectra, we perform a detailed comparison of lines profile of individual elements such as Fe I, Ca II, Ti I, Na I, K I and are able to determine accurate metallicities of these stars which can be later linked to their kinematical properties. Our comparison shows that molecular features like TiO, VO and CaH, and atomic features like Fe I,Ti I, Na I, are very well reproduced by the model.

**Key words.** Stars: abundances – Stars: atmospheres – Stars: Population II

## 1. Introduction

Subdwarfs are among the faintest and coolest stellar objects. Due to their lower metallicity, the subdwarfs lie below their solar-metallicity counterpart in the H-R diagram. The effective temperature ($T_{\rm eff}$ < 4000 K) and pressures in subdwarf atmospheres allow for the widespread formation of the molecules. With decreasing temperature, sdM spectra show an increase in abundances of diatomic and triatomic molecules in the optical and in the near infrared (such as SiH, CaH, CaOH, TiO, VO, CrH, FeH, OH, $H_2O$, CO). Oxides such as TiO and VO and hydrides such as CaH, FeH, MgH dominate the opacity sources in the optical and the $H_2O$ bands in the near infrared. However with decreasing metallicity, the TiO bands are less strong, and the pseudo-continuum brightens as a result. But this enhances the contrast to the other opacities such as hydride bands and atomic lines which probe the higher pressures of the deeper layers where they emerge from. We see therefore these molecular bands in more details than for M dwarfs and under more extreme gas pressure conditions. This of-

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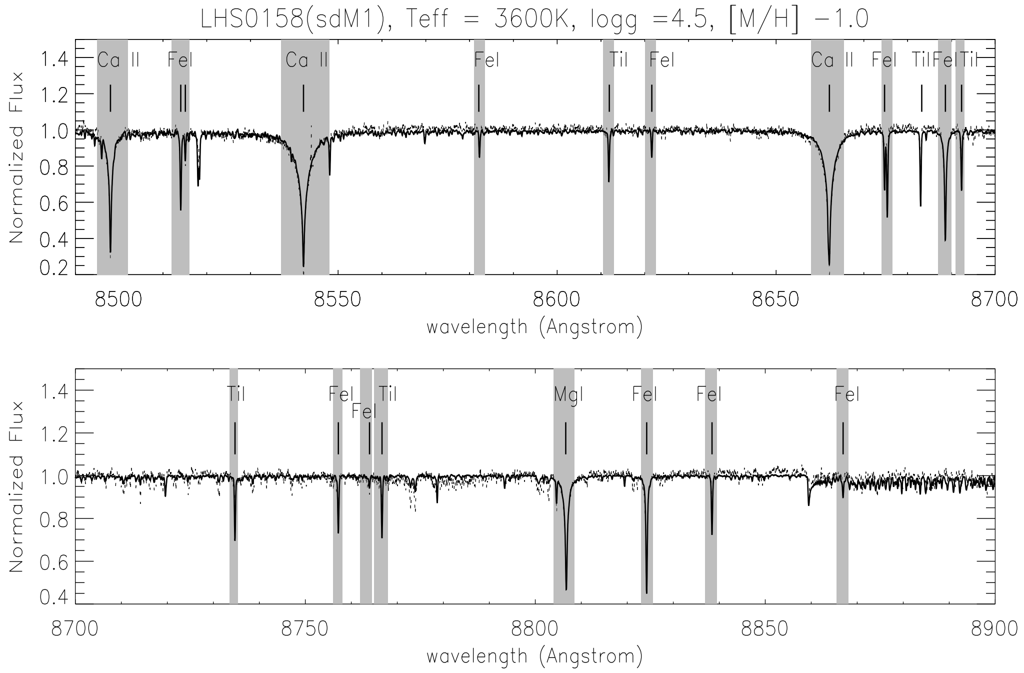


**Fig. 1.** Comparison of LHS 158 (sdM1, dot) with the best fit BT-Settl model (solid) to various atomic lines such as Fe I, Ca II and Ti I.

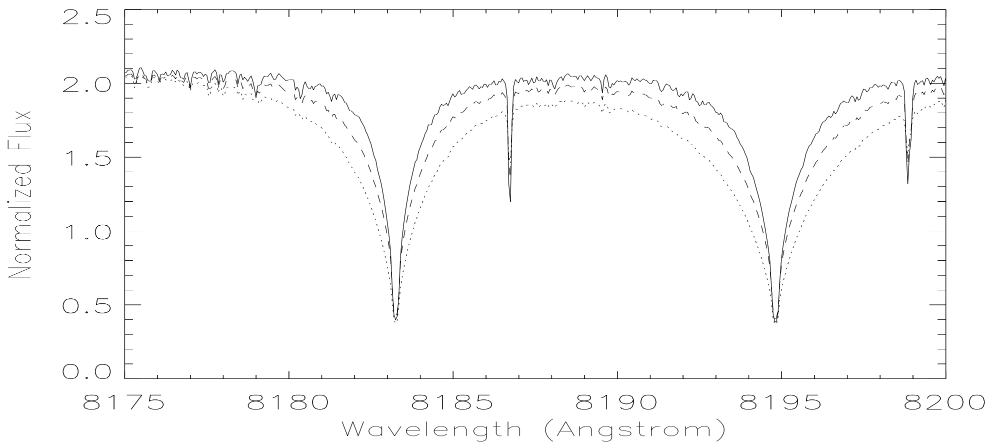


**Fig. 2.** BT-Settl models for an effective temperature of 3500 K and varying $\log g$ = 4.5 (solid), 5.0 (dash), 5.5 (dot). The effect of gravity and the pressure broadening of the Na I doublet is clearly visible.

ten reveals the inaccuracy or incompleteness of the opacities used in the model.

Thus the presence of these molecular bands reduces the strength of atomic lines and the spectral contrast. This makes the complexity of stellar atmosphere of subdwarfs to increase significantly with decreasing effective temperature.

## 2. Observation and data reduction

Data were obtained with the UVES spectrograph at ESO/VLT in service mode during April and September, 2011. UVES was operated in dicrohic mode using the red arm with non-standard central wavelength centered at 830 nm. This mode covers the wavelength range 6400 – 9000 Å with a gap between the two CCDs of the red arm from 8200 to 8370 Å. The spectra were taken with a slit width of 1.″0, yielding a resolving power of $R \sim 40\,000$. Data were reduced using the ESO pipeline REFLEX for UVES data.

The large wavelength coverage of the UVES spectra covers many atomic and molecular features like Fe I, Ti I, K I, Na I, Ca II, and TiO, VO, CaH which are very useful for the spectral analysis of these subdwarfs.

## 3. Model atmosphere

For the current study we use the most recent BT-Settl model described in Allard et al. (2012) and Rajpurohit et al. (2012). The revised BT-Settl model is based on the Caffau et al. (2011) solar abundances and uses slightly revised atomic and molecular opacities as well as cloud physics. The formation of dust is not accounted for in the models, as the sample contains no sdM cooler than 2500 K when dust formation begins (Rajpurohit et al. 2012). The synthetic colors and spectra are distributed with a spectral resolution of nearly R=100 000 via the `PHOENIX` web simulator[1].

[1] `http://phoenix.ens-lyon.fr/simulator`

## 4. Results

The stellar parameters ($T_{\rm eff}$, $\log g$, [M/H]) have been calculated using a chi-square minimization technique in an automatic interactive way in IDL program by both looking at overall fit and fit to the individual atomic lines. We let the metallicity, $T_{\rm eff}$, $\log g$ parameters vary simultaneously. To ensure that we end up in a global minimum when converging to a solution for the best-fit, a 3-D $\chi^2$ map has been obtained. The majority of the lines included in the analysis are weak, although some stronger lines are present. We also compared the line wings and strength and found that the strong and weak lines contributed equally to the final $\chi^2$ solution. Fig. 1 shows such the comparison of a sdM1 (LHS 158) spectrum with BT-Settl model atmosphere to atomic line profiles such as Fe I, Ca II, and Ti lines. Fig. 2 show the effect of gravity and the pressure broadening of the Na I doublet.

## 5. Conclusions

Thanks to a careful spectroscopic analysis of optical high-resolution spectra (R ∼ 40 000), we have derived for the first time metallicities for a sample of stars covering the entire spectral sdM sequence. This study is also very useful to constrain and improve the atmosphere models. While the comparison shows that the majority of molecular bands and atomic features are very well reproduced by the models, a number of unknown features are still present and need to be incorporated in the model. Improving the completeness of molecular line lists will improve the accuracy of the precise metallicity determinations.

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