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Nitrogen and sulfur abundance stratification in HD 135485

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Abstract. The observed overabundances of many chemical species relative to the expected cluster metallicity in Blue Horizontal Branch (BHB) stars appear as a result of atomic diffusion in their atmospheres. The slow rotation ($v \sin i < 10$ km s^{-1}) of hot ($T_{eff} > 11,500$ K) BHB stars is consistent with this idea. Atomic diffusion can cause accumulation or depletion of some chemical species in particular layers of the stellar atmosphere, leading to vertical stratification of their abundances. In this report, we present preliminary results of abundance stratification analysis of the atmosphere of the metal-rich B-type star HD 135485, which is located close to the horizontal branch in the Hertzsprung-Russell diagram. In particular, our numerical simulations show that nitrogen and sulfur reveal signatures of vertical abundance stratification: these elements are overabundant in layers with optical depth $\log \tau_{5000}$ <-1.0 and $\log \tau_{5000}$ <-1.5, respectively, in comparison with the deeper (depleted) layers. We present here the first results showing stratification of these elements in a BHB star.

Key words: Horizontal branch stars, chemically peculiar stars, HD 135485

1 Introduction

HD 135485 is a mid-B spectral type star and shows many prominent absorption lines of metallic species in its spectrum. From absolute and differential abundance analysis, Trundle et al. (2001) found a large (0.5-1.0 dex) enhancement of metal abundances in comparison with the solar composition. Together with general enrichment of all metals with respect to hydrogen, they obtained also a slightly enhanced helium abundance of ∼0.3 dex. Along with the anomalously high (∼1.3 dex) nitrogen abundance, the enhanced helium abundance can be interpreted as an indication that carbon-nitrogen (CN) cycle took place during the hydrogen-burning phase on the main sequence. These facts and the present position of HD 135485 on the Hertzsprung-Russell (HR) diagram argue that this star is evolved and probably belongs to the Blue Horizontal Branch (BHB) (Trundle et al., 2001). The observed low projected rotational velocity ($v \sin i < 4$ km s^{-1}) of HD 135485, the chemical peculiarities, and the effective temperature $T_{\rm eff} = 15500$ K (Trundle et al., 2001) are typical of the characteristics found for BHB stars. The enhanced helium abundance (in comparison with the observed depleted helium abundance in the other BHB stars) suggests that HD 135485 might be a very young BHB star in which helium has not yet settled.

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Surveys of BHB star properties indicate that the stars hotter than $T_{\rm eff} \simeq 11,500$ K have abundance anomalies (Grundhal et al., 1999) and show the existence of a discontinuity in the stellar rotation velocity distribution (Behr et al., 2000). All the hotter stars appear to have narrow line profiles that correspond to rotation velocities $v \sin i < 10$ km s^{-1}, while the cooler stars rotate more rapidly. The slow rotation and abundance anomalies suggest that microscopic atomic diffusion is effective in stellar atmospheres of the hot BHB stars with $T_{\rm eff} \geq 11,500$ K. Microscopic diffusion can produce vertical abundance stratification of different chemical species. Direct estimation of this stratification from line profile analysis would be a convincing argument in favour of efficient chemical diffusion in the atmospheres of hot BHB stars.

2 Observations

Spectroscopic observations of HD 135485 have been performed using the Cassegrain Echelle (CE) Spectrograph (resolving power $R \sim 60,000$) on the McDonald Observatory 2.1-meter Otto Struve Telescope (one spectrum) and the new ESPaDOnS (Echelle SpectroPolarimetric Device for Observations of Stars) spectropolarimeter ($R \sim 80,000$) at the Canada-France-Hawaii Telescope[1] (two spectra). The first spectrum covers the spectral range 4760 Å to 5570 Å, while the two ESPaDOnS spectra cover the range 3720 Å to 10290 Å.

3 Simulation of line profiles

The stellar atmosphere model was calculated with the Phoenix code assuming the local thermodynamic equilibrium (LTE), assuming the parameters $T_{\rm eff} = 15,500$ K, $\log g = 4.0$, and enhanced (+0.1 dex) metallicity adopted by Trundle et al. (2001). The line profiles are simulated using this model with zero microturbulent velocity $\xi = 0$ km s^{-1}. The line identification is performed using the VALD-2 (Ryabchikova et al., 1999) and NIST[2] (version 3.0.3) line databases. In general, we have selected for our analysis lines free of predicted or inferred blends. However, if a blend appears to be a line of the same chemical element that forms the main line profile, such a line has also been included in our simulation. To simulate the line profiles, we have employed the ZEEMAN2 spectrum synthesis code (Landstreet, 1988) with implemented automatic minimization (Khalack & Wade, 2006) using the *downhill simplex method.*

We have used two different methods to check the presence of abundance stratification. In the first method, we estimate the abundance of a chemical element from independent analysis of each line profile. Then we calculate the line optical depth τ_ℓ in the line core for each of the 50 layers of the stellar atmosphere model, taking into account the atomic data of each line. We suppose that each analyzed profile is formed mainly at τ_ℓ=1, which corresponds to a particular layer of the stellar atmosphere. Finally, for this particular layer the respective continuum optical depth τ_{5000} is specified. In this way, we have built the scale of optical depths τ_{5000} to track vertical abundance stratification.

In the first method, three free model parameters (the element's abundance, line radial velocity $V_{\rm r}$ and $v \sin i$) are derived from each line profile using the automatic minimization routine. The mean atmospheric abundances of chemical species are determined by averaging the abundance estimates from the first method and their uncertainties are calculated as a standard deviation of the abundance results around the mean value (see Table 1).

[1] The Canada-France-Hawaii Telescope (CFHT) is operated by the National Research Council (NRC) of Canada, the Institut des Sciences de l'Univers of the Centre National de la Recherche Scientifique (CNRS) and the University of Hawaii

[2] http://physics.nist.gov/PhysRefData/ASD/index.html

Table 1: Mean atmospheric abundances $\log(N/N_{\rm tot})$ of HD 135485 derived by averaging the abundances obtained from independent analysis of each line profile (see text).

	McDonald-CE		CFHT-ESPaDOnS		Sun
Ion	$\log(N/N_{\rm tot})$	n	$\log(N/N_{\rm tot})$	n	$\log(N/N_{\rm tot})$
He I	-0.54±0.15	3	-0.58±0.16	9	-1.11
C I			-2.78±0.17	10	-3.65
C II	-2.88±0.16	4	-2.69±0.14	15	-3.65
N I			-2.60±0.20	3	-4.26
N II	-3.01±0.18	9	-3.00±0.17	21	-4.26
O I	-2.74±0.19	2	-2.82±0.13	11	-3.38
O II			-3.28±0.22	9	-3.38
Ne I			-3.22±0.06	4	-4.20
Na I			-4.22±0.24	2	-5.87
Mg I			-3.62±0.20	1	-4.51
Mg II			-3.73±0.12	4	-4.51
Al II			-5.32±0.11	7	-5.67
Al III			-5.10±0.09	4	-5.67
Si II	-4.23±0.11	2	-4.28±0.23	9	-4.53
Si III			-3.96±0.22	2	-4.53
P II	-5.76±0.13	3	-5.81±0.12	8	-6.68
S II	-4.47±0.17	21	-4.48±0.18	53	-4.90
Cl II	-6.47±0.20	1	-6.35±0.20	1	-6.54
Ar II	-4.96±0.19	2	-5.03±0.05	4	-5.86
Ti II			-6.70±0.04	5	-7.14
Cr II	-5.89±0.14	2	-6.01±0.07	5	-6.40
Fe II	-4.16±0.18	31	-4.08±0.16	63	-4.59
Sr II			-8.50±0.20	1	-9.12

In the second method, we consider the two-zone stratified abundance model with a linear transition zone (Ryabchikova et al., 2003; Wade et al., 2003) to describe the abundance distribution. In this case, all the selected lines are analyzed simultaneously, and in the minimization routine we operate by 6 free model parameters: stellar radial velocity, $v \sin i$, element's abundance in the deeper layers, (standard) optical depth τ_1 of the transition zone lower (deeper) boundary (where element's abundance begins its linear increase or decrease), optical depth τ_2 of the transition zone upper boundary, and difference between the abundances at two boundaries.

4 Results of abundance analysis

The mean abundances we derive for HD 135485 are reported in Table 1. The second and third columns contain respectively the mean abundance of the chemical species and the number of analyzed line profiles in the McDonald-CE spectrum, while the fourth and fifth columns represent similar results obtained from analysis of the ESPaDOnS spectra. The last column contains the solar atmospheric abundances (Asplund et al. 2005).

The helium overabundance obtained from our LTE abundance analysis is in good agreement with the results reported by Trundle et al. (2001). Carbon is enhanced by ~0.9 dex in respect to the solar abundance. Nitrogen is strongly enhanced by ~1.7 dex for the neutral species, by ~1.3 dex

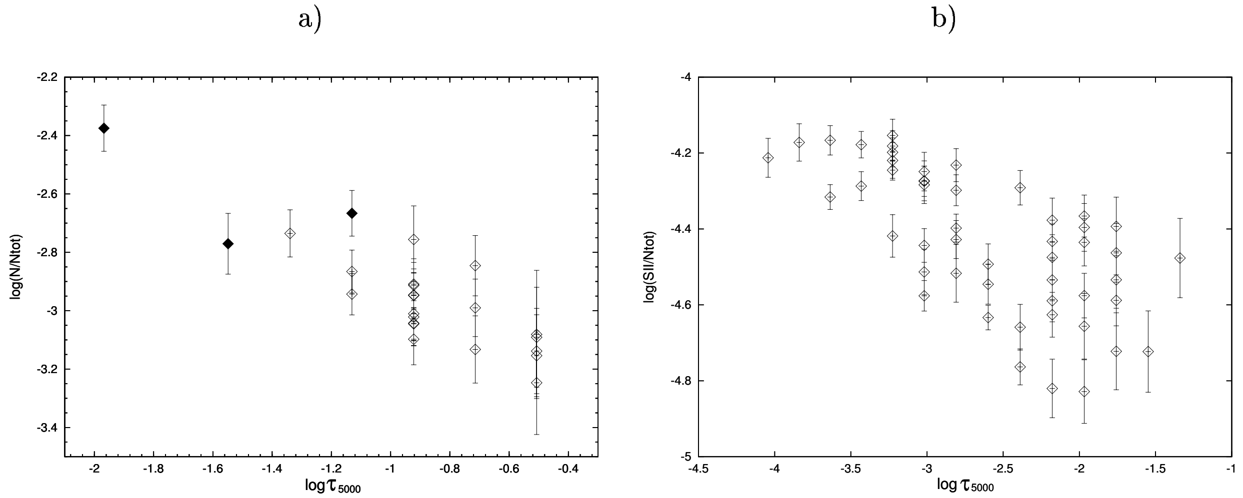

Figure 1: Abundance estimates from the analysis of a) nitrogen and b) singly ionized sulfur. Simulation of N I (filled diamonds) and N II (open diamonds) lines which are formed in layers with log τ_{5000} <-1.0 results in enhanced nitrogen abundance in comparison with lower abundance obtained from simulation of lines of the same ionization stage formed deeper in the atmosphere. A similar situation is found for S II (open diamonds) lines formed in layers with log τ_{5000} <-1.5.

for N II and appears to be vertically stratified (see Fig. 1a). The abundance obtained for singly-ionized oxygen seems to be similar to its solar abundance, while the neutral oxygen is enhanced by ~0.5 dex. Neon and argon are enhanced respectively by ~1.0 dex and ~0.8 dex in comparison with their solar abundances. The enhanced sodium abundance of ~1.6 dex is derived from the analysis of two comparatively weak Na I lines at 5688.205 Å and 8194.824 Å.

The neutral magnesium abundance of ~0.9 dex is obtained from the analysis of just one unblended Mg I line (5172.684 Å). Meanwhile, singly ionized magnesium is enhanced by ~0.8 dex. Al II and Al III are slightly enhanced by ~0.3 dex and ~0.5 dex respectively. Singly-ionized silicon is slightly enhanced by ~0.2 dex, while Si III is enhanced by ~0.6 dex in comparison with its solar abundance. Phosphorus is enhanced by ~0.9 dex. Sulfur appears to be vertically stratified like nitrogen (see Fig. 1b) and its average atmospheric abundance is enhanced by ~0.4 dex. Chlorine seems to have a solar abundance. More than 60 lines of Fe II are identified in the ESPaDOnS spectra and result in enhanced by ~0.5 dex iron abundance. Chromium and titanium appear to be enhanced by ~0.4 dex, but both elements are represented by only a few unblended lines.

5 Nitrogen and sulfur vertical abundance stratification

Applying the technique described in Sec. 3 we have tried to determine if the abundances of some chemical species are vertically stratified. The more line profiles characterized by different excitation potential and line strength we can find for a particular chemical element in the spectrum of HD 135485, the more confident results on vertical abundance stratification we can infer from the line profile simulation. According to Table 1, a reliable analysis can only be performed for carbon, nitrogen, oxygen, sulfur and iron, which are represented by a sufficient number of lines. Fig. 1 shows a systematic trend, wherein N and S lines formed higher in the atmosphere provide abundances which are significantly larger than those for lines formed lower in the atmosphere. These facts have been previously reported by Trundle et al. (2001), but interpreted in terms of microturbulence. However, such an interpretation would require a similar behaviour for the lines of C, O and Fe, which we do not observe. Our results therefore suggest that N and S are vertically stratified in the

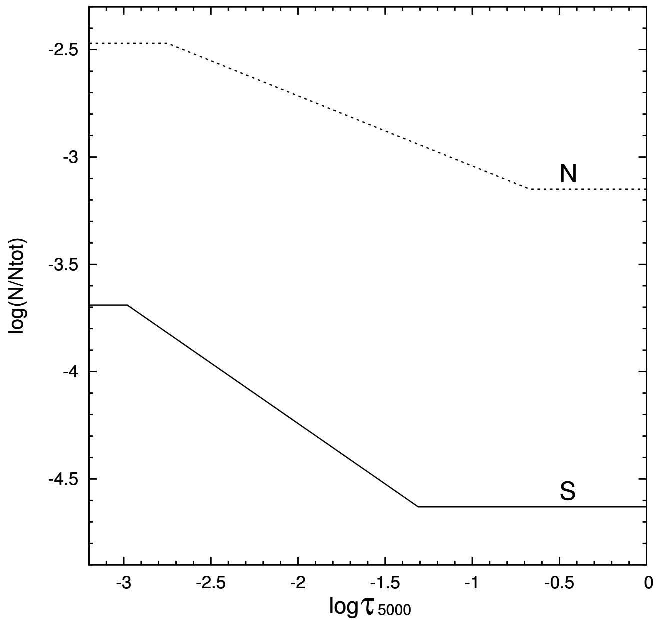

Figure 2: Model of nitrogen and sulfur abundance stratification in the atmosphere of HD 135485.

atmosphere of HD 135485.

To obtain an estimate of the abundance distribution as a function of optical depth for N and S, we have employed a two-zone empirical model with a transition zone (see Sec. 3) and analyzed simultaneously the same list of lines selected for each element. The final results for nitrogen and sulfur stratification in the atmosphere of HD 135485 are illustrated in Fig. 2. They are in good accordance with the abundance stratification data that we have obtained from the first method for N and S (see Fig. 1). Our simulation shows that the model with stratified abundance distribution results in a 30% lower χ^2-function than the model with uniform abundance, and improves significantly our fit of analyzed line profiles.

6 Summary

HD 135485 is an evolved BHB star with slow rotation, high effective temperature ($T_{\rm eff}$=15,500 K) and abundance anomalies (Trundel et al., 2001) that support the idea of an important role of microscopic atomic diffusion in stellar atmosphere of the star. Figs. 1, 2 clearly show that nitrogen and sulfur abundances are vertically stratified and increase to the upper atmospheric layers. Absence of any abundance stratification for several other elements demonstrate the impossibility to explain the observed for nitrogen and sulfur abundances trend in terms of microturbulent velocity. These facts can be considered as further arguments in support of the efficiency of atomic diffusion in the atmosphere of HD 135485, and possibly in the atmospheres of BHB stars generally.

The results for nitrogen and sulfur stratification in HD 135485 are the first report of stratification of metal species in a BHB star. Previously, just a possibility of helium stratification in the atmosphere of another BHB star Feige 86 has been reported by Bonifacio et al. (1995). An extensive search for vertical stratification for a large number of chemical species with a range of $T_{\rm eff}$ would be very useful to determine conditions in the atmospheres of BHB stars which provide the efficiency of microscopic atomic diffusion. Thereafter the respective model atmospheres, such as those of Hui-Bon-Hoa, LeBlanc & Hauschildt (2000), could be simulated, where the atmospheric structure is calculated self-consistently with the stratification predicted by diffusion.

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