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Behaviour of the HeI 587.6, 667.8, 706.5 and 728.1 nm lines in B-type stars*

On the helium stratification in the atmosphere of magnetic helium peculiar stars

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Abstract. High resolution spectra of the HeI587.6, 667.8 706.5 and 728.1 nm lines have been obtained to test the prediction (notably by Vauclair et al. 1991) that helium abundance should decrease with depth in helium rich stars and increase in helium weak stars. A sample of B-type main sequence stars, with expected solar abundances and non stratified atmospheres, have also been observed in order to compare the behaviour of the selected lines with the chemically peculiar case and with theory.

We found significant discrepancies with theory for the lines HeI706.5. and 728.1 nm, and, in order to outline differences between 'normal' and 'peculiar' stars, we have adopted an empirical correction to the Lorentz broadening parameter in the Voigt profile, under the assumption of LTE. This parameter is derived from the imposition of a satisfactory fit with observations for the relation equivalent width vs. effective temperature for normal B stars.

For helium rich stars we confirm Vauclair et al. (1991) predictions that helium abundance decreases with depth. However, we found that helium abundance decreases with depth in helium weak stars too, which contradicts Vauclair et al. (1991) predictions.

For some peculiar stars, the inferred helium abundance is in disagreement with the peculiarity class reported in the *General Catalogue of Ap and Am stars* (Renson et al. 1991).

Key words: diffusion – line: formation – stars: abundances – stars: chemically peculiar – stars: early-type

1. Introduction

Magnetic chemically peculiar stars usually show helium lines whose strength is not consistent with their spectral type. In such stars, helium lines are also variable with the same period of light and magnetic field variations. In the framework of the Oblique Rotator Model, suggested by Babcock (1949) and Stibbs (1950), such variability is explained by a non homogeneous distribution of helium on the stellar surface and the spectral periodic variations are attributed to the combination with stellar rotation. Abundance anomalies, on the other hand, are explained with radiation driven diffusion processes (Michaud 1970).

For helium peculiar stars (CP4 stars according to the nomenclature of Preston, 1974), the computations of Vauclair et al. (1991) indicate that, for mass-loss rates of the order of $10^{-13} M_\odot\, yr^{-1}$, helium should accumulate at the magnetic poles and, for higher mass rates, helium should accumulate in rings at intermediate latitude. Vauclair et al. (1991) have indeed studied the helium diffusion process in presence of a dipolar magnetic field and mass loss. They concluded that helium abundance increases with optical depth, reaches a maximum value and than decreases to the original value. Helium abundance in the outer layers and its maximum depends on the effective temperature and mass loss rate. According to Vauclair et al. (1991) calculations, a $2M_\odot$ star is helium weak since helium accumulates below the photosphere and a $5M_\odot$ star should appear helium rich if the mass loss rate is between $10^{-13} - 10^{-15} M_\odot\ yr^{-1}$. For lower mass loss rates helium should fall down and for larger values helium abundance should remain constant. Therefore, according to these calculations, helium should not only been non homogeneously distributed on the stellar surface but also stratified in the atmosphere.

In order to test the hypothesis of helium stratification, we have performed high resolution spectroscopy of the HeI587.6, 667.8, 706.5 and 728.1 nm lines, which are formed at different atmospheric layers (see Fig. 1). It is expected that a helium abundance analysis based on spectrum synthesis with model atmospheres having constant abundance with depth would show systematic discrepancies for these lines. In principle, stars with a stratified chemical element show line profiles which are differ-

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* Based on observations collected at the European Southern Observatory, LaSilla, Chile

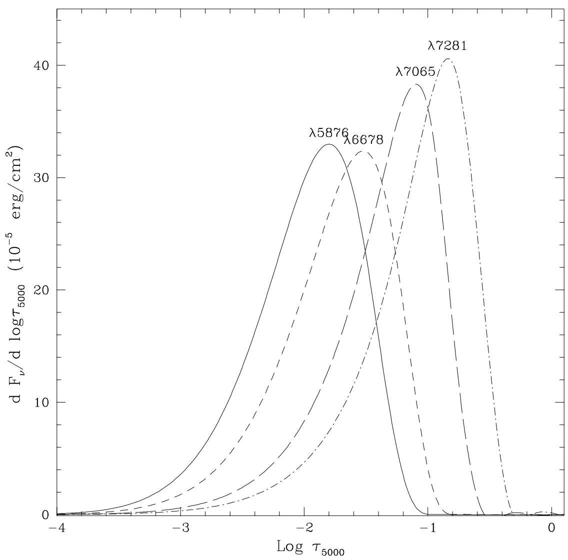

Fig. 1. Contribution functions for residual flux in the center of the HeI587.6, 667.8, 706.5 and 728.1 nm lines for a solar composition star with T_{eff} = 15000 K and log g = 4.0.

ent with respect to stars with non stratified atmosphere (Farthmann et al. 1994). Unfortunately, the line profiles of chemically peculiar stars are also modified by the non homogeneous distribution on the stellar surface. The Doppler imaging technique to infer the stellar surface distribution of abundance from time resolved line profiles assumes non stratified atmospheres and, even in this case, does not have unique solutions. The most general case, where each atmospheric layer is characterized by its own abundance distribution, presents a large number of free parameters and makes the inferred stratification doubtful. Therefore, in this work, we prefer to investigate helium stratification using the equivalent width. Such a method can be viewed as a study on the stratification averaged on the horizontal direction.

A set of main sequence stars, which are expected to have non stratified solar helium abundance, with effective temperature covering the range of the peculiar stars in our sample have been observed in order to establish the dependence of the selected lines on the effective temperature and to perform a comparison with theory. This step is particularly important for the HeI728.1 nm line, which to our knowledge has never been observed before.

2. Observations and data analysis

Spectra of the HeI587.6, 667.8, 706.5 and 728.1 nm lines for the main sequence and peculiar stars listed in Table 1 have been obtained on March 10 and 11, 1995 at the Coudé Auxiliary Telescope of the European Southern Observatory equipped with the long camera. The spectral resolution was R = 50000. Lines of the ThAr wavelength calibration lamp show that the instrumental broadening can be reproduced on average with a Gaussian profile with a FWHM = $7kms^{-1}$. Data have been reduced using IRAF package. The achieved S/N was between 150 and 250.

To investigate the presence and importance of line blending, we have used SYNTHE code with atmosphere models and the atomic line list provided by Kurucz (1993). None of the considered helium lines appears to be significantly affected by blends with metal lines for 10000 K $<$ T_{eff} $<$ 30000 K and 3.5 $<$ log g $<$ 4.5.

Table 1 reports the measured equivalent widths for each observed star, together with the spectral type (ST) given by the *Bright Star Catalogue* (Hoffleit & Jaschek 1982), peculiarity class (PC) given by the *General Catalogue of Ap and Am stars* (Renson et al. 1991) and $v_e \sin i$ values retrieved from the SIMBAD database.

3. The behaviour of helium lines in main sequence stars: observations and theory

In order to compare the observed and theoretical line strengths for main sequence stars, we have reported the measured equivalent widths as a function of the effective temperature (Fig. 2). To better define these relations, we have added the observations by Heasley et al. (1982) of the HeI587.6 and 667.8 nm lines and by Jaschek et al. (1994) of the HeI667.8 an 706.5 nm lines. The adopted effective temperatures (T_{eff}) are reported in Table 1 and are obtained using the Moon (1985) algorithm. The source of the strömgren photometric data was SIMBAD.

The most extensive NLTE calculations for helium lines to-date have been performed by Auer & Mihalas (1973). Dufton & McKeith (1980) have subsequently carried out new NLTE calculations using up-dated photoionization and collisional excitation rates. Their calculations include HeI587.6 and 706.5 nm. Fig. 2 shows that, for main sequence stars, the NLTE calculations do not adequately reproduce the observations with the exception of the HeI587.6 nm line.

We have also solved the radiative transfer in LTE by using XLINOP9 (Kurucz priv. comm.). We have adopted LTE atmosphere models computed using ATLAS9 (Kurucz 1993). These models represent, at present, the most realistic description for the atmospheric structure through the inclusion of about 5.8×10^7 lines for the computation of the line-blanketing effects. Both HeI587.6 and 706.5 nm multiplets have been treated as a whole, without resolving their fine structure transitions. Absorption profiles have been represented by Voigt functions in which the Lorentz component includes the effects of radiative, Stark and Van der Waals broadening. log gf are from Wiese et al. (1966), Van der Waals damping constant have been computed as described by Castelli & Bonifacio (1990), Stark broadening (γ_s) constants are from Dimitrijević & Sahal-Bréchot (1990). Fig. 2 shows that LTE calculations do not reproduce adequately the observations neither.

The contribution functions for the residual flux in the center of the selected lines (see, e.g., Gray 1992 for definition) have been computed in the LTE approximation by using XLINOP9, Kurucz (1993) atomic data and solar composition atmosphere model with T_{eff} = 15000 K and log g = 4.0. These are plotted in Fig. 1.

Table 1. Measured equivalent widths

Star *HD*	$ST+PC$	$T_{\rm eff}$ K	$\log g$	$v_e \sin i$ $km\,s^{-1}$	$W(5876)$ mÅ	$W(6678)$ mÅ	$W(7065)$ mÅ	$W(7281)$ mÅ
				Normal stars				
56456	$B8/9V$	11830	3.92	–	120	50	0	0
61831	$B2.5V$	17490	3.69	138	630	–	–	–
67797	$B5V$	15980	3.80	190	540	390	280	110
108767	$B9.5V$	10460	3.99	148	95	0	0	0
113703	$B5V$	15790	4.26	189	470	–	–	–
121790	$B2IV-V$	19230	3.57	122	730	650	420	240
129116	$B2.5V$	18580	4.04	187	720	–	–	–
136664	$B4V$	17230	4.03	210	590	430	290	180
144470	$B1V$	24530	3.99	140	710	610	420	240
149438	$B0V$	27310	3.92	24	750	620	450	270
				Peculiar stars				
57219	$B3He$	18100	3.81	124	670	490	350	150
64740	$B2He$	23620	3.80	274	1030	860	480	280
65575	$B3Si$	17220	3.54	100	620	480	320	170
68450	$B0He$	29660	3.65	97	1130	800	740	350
81188	$B3Hew$	18920	3.41	49	580	–	–	–
106625	$B8HgMn$	12120	3.36	41	100	40	25	0
110073	$B8Mn$	13000	3.71	28	120	60	30	5
120709	$B5HewP$	16860	4.26	12	390	280	160	60
125823	$B5Hew$	19470	4.06	10	400	320	200	65
131120	$B7Hew$	18940	4.08	–	390	–	–	–
142096	$B3Hew$	18060	4.44	207	610	–	–	–
142301	$B8HewSi$	17670	4.22	–	170	–	–	–
142990	$B6Hew$	18720	4.22	200	425	–	–	–
143669	$B6Hew$	16120	4.15	170	240	140	80	–
144334	$B8Hew$	16440	4.37	44	95	–	–	–
146001	$B8Hew$	14210	4.32	200	220	–	–	–

4. Determination of the helium abundance

Given the difficulties of the theory to reproduce adequately the observations of normal stars, a helium abundance analysis based on spectrum synthesis with model atmospheres could not be applied with confidence. We have therefore resorted to the following semi-empirical strategy in order to draw some conclusions on the stratification of helium in chemically peculiar stars. Firstly, we adopt the LTE approach, preferring the completeness of the atmospheric structure through the inclusion of a realistic line blanketing to the NLTE solution. Secondly, we note that the equivalent width of a line in LTE depends on the function $\beta(v) = \beta_0 H(a, v)$ where H is the Voigt line profile and β_0 is proportional to the abundance (see, e.g., Mihalas 1978). In such approximation, matching the observed dependence of the equivalent width on the effective temperature by modifying the line profile should preserve the correct dependence of the equivalent width on the abundance. This process can be applied effectively to the stars considered here through a correction to the density-dependent component of the Lorentz profile (i.e. Stark-like). We have therefore applied an empirical correction factor to the Stark width by imposing that the theoretical equivalent width in the LTE approximation reproduce the observed dependence on the effective temperature for main sequence stars (Fig. 2 and Table 2).

Table 2. Stark broadening parameter for unity density at 10^4 K from Dimitrijević & Sahal-Bréchot (1990) (D&S) and density-dependent Lorentz broadening parameter used in the analysis. See text for details.

Line(nm)	$\log(\gamma_s)$ D&S	
587.57	−4.48	−4.55
667.8152	−4.23	−4.10
706.53	−4.59	−3.86
728.1349	−4.38	−3.70

We have checked the consistency of the abundance derived against the NLTE calculations of Dufton & McKeith (1980) for HeI587.6 nm, which do reproduce satisfactorily the observations (Table 3). As an example, for the helium weak star HD 120709 ($T_{\rm eff}$ = 16860 K, log g = 4.26) we observed an equivalent width of 390 mÅ for the HeI 587.6 nm line from which we derive He/H = 0.047. Note that, according to Dufton & MacK-

Table 3. Equivalent widths in mÅ for the HeI587.6 nm line computed by Dufton & McKeith (1980) (D&M) and in this paper for zero microturbulence velocity and log g = 4.0.

T_{eff} =	15000		17500		20000	
He/H	D&M		D&M		D&M	
0.05	235	238	411	397	512	474
0.10	308	320	522	512	646	611
0.20	396	487	650	717	808	820

eith, the equivalent width of this line is 411 mÅ for a star with $T_{\rm eff}$ = 17500 K, log g = 4.20 and He/H = 0.05.

Within the limits of the approximations adopted, this procedure effectively bypasses the limitations of the theory in reproducing the observed relation equivalent width vs. effective temperature, still maintaining the basic features of abundance analysis based on spectrum synthesis with model atmospheres. It is *de facto* equivalent to factorizing the dependence of the equivalent width on the line profile and abundance, and constraining empirically the former by means of the observed relation equivalent width vs. effective temperature for normal stars.

5. Helium stratification in CP4 stars

Helium peculiar stars are light variables with the same period of helium equivalent width variations. They are brighter when helium is less abundant. According to the Oblique Rotator model, the observed helium line variations are due to the stellar rotation because of a non homogeneous distribution of helium on the stellar surface. Catalano & Leone (1996) have computed the expected surface flux for solar and zero helium abundance with ATLAS9 for the effective temperature range of chemically peculiar stars and found that helium abundance does not affect the emergent flux and the temperature dependence on the optical depth, confirming Molnar's (1974) conclusion that the non homogeneous distribution of helium on stellar surface is not responsible for the observed light variations. Consistently with the above considerations, Hauck & North (1993) have shown that the effective temperature of helium peculiar stars can be well estimated using the classical methods adopted for main sequence stars. Thus, we have used Moon (1985) algorithm to infer the effective temperature and gravity of the observed helium peculiar stars (Table 1).

If, as suggested by Vauclair et al. (1981), helium is stratified in the atmosphere of chemically peculiar stars, inferring the helium abundance from the observed line, which are mainly formed at different atmospheric layers, we should not obtain an unique value of helium abundance.

Note that because of the non linear relation between the equivalent width (EW) and abundance, errors in the equivalent width measure give different positive and negative abundance errors. We have therefore preferred to use EW$-\Delta$EW and EW+ΔEW to determine from each helium line an abundance range. The error in the equivalent width measure has

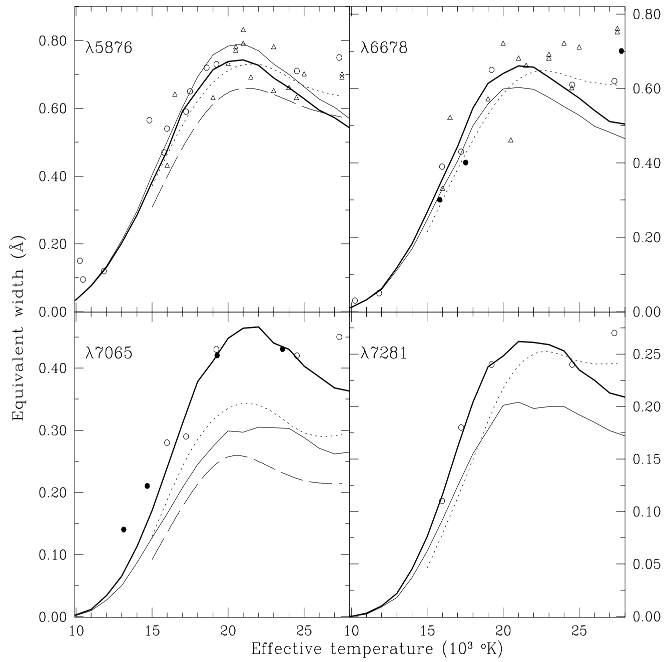

Fig. 2. Equivalent widths of 587.6, 667.8, 706.5 and 728.1 nm helium lines as a function of $T_{\rm eff}$ for main sequence stars. Open circles represent our observations, filled circles the Jaschek et al. (1994) observations and triangles those of Heasley et al. (1982). For log g = 4.0 and zero turbulence velocity, NLTE calculations by Auer & Mihalas (1973) are indicated by a dotted line, NLTE calculations by Dufton & McKeith (1984) by a dashed line and our LTE calculations, adopting Dimitrijeviĉ & Saha-Brèchot (1984) Stark broadening, by a solid line. The empirical LTE relation constrained by the observations, obtained according to the procedure described in the text, is represented by a bold solid line.

Table 5. Abundances of CP stars inferred from the HeI587.6 nm line

Star	*ST + PC*	*Ab*(5876) N_{He}/N_{Tot}
81188	*B3Hew*	0.090 − 0.095
131120	*B7Hew*	0.020
142096	*B3Hew*	0.065 − 0.075
142301	*B8HewSi*	< 0.005
142990	*B6Hew*	0.025 − 0.035
144334	*B8Hew*	< 0.005
146001	*B8Hew*	0.050 − 0.070

been evaluated using the relation given by Leone et al. (1995): $\Delta EW = \frac{1}{2}(2\frac{v_e \sin i}{c}\lambda)\frac{1}{S/N}$. Such an approch does not consider the variation in S/N from wing to core, and therefore may not be appropriate for deep lines. However, because of the high rotational velocities, most lines in our samples are shallow. Furthermore, our formula obviously overestimates the error in EW and, even for the deepest lines, the error introduced by such a S/N variation is expected to be within our estimate. Helium can be considered stratified in the atmosphere of a star if the

Table 4. Derived abundances from each lines according to the measured equivalent widths and the relative error. See text for error definition.

Star *HD*	*ST + PC*	*Ab*(5876)	*Ab*(6678)	*Ab*(7065)	*Ab*(7281)
			N_{He}/N_{Tot}		
57219	*B3He*	0.100 – 0.105	0.075	0.070 – 0.080	0.040 – 0.060
64740	*B2He*	0.250 – 0.280	0.200 – 0.220	0.135 – 0.150	0.110 – 0.150
65575	*B3Si*	0.105 – 0.115	0.095	0.085 – 0.095	0.075 – 0.090
106625	*B8HgMn*	0.030 – 0.050	0.025 – 0.035	0.030 – 0.045	< 0.030
110073	*B8Mn*	0.030 – 0.035	0.025 – 0.035	0.025 – 0.050	< 0.050
120709	*B5HewP*	0.045 – 0.050	0.040 – 0.045	0.030 – 0.035	0.020 – 0.030
125823	*B5Hew*	0.025	0.020	0.015 – 0.020	0.005 – 0.010
143669	*B6Hew*	0.020 – 0.025	0.015 – 0.020	0.010 – 0.015	

abundance ranges, obtained from different lines, do not substantially overlap. Table 4 reports the found helium abundance ranges. According to Table 3, the helium abundance of helium rich stars – especially for the cooler ones – is underestimated.

For some chemically peculiar stars in our sample, the helium abundance inferred from different lines can certainly be considered different and indicative of a decreasing abundance with the optical depth. HD 57219, which is classified as helium strong in the *General Catalogue of Ap and Am stars* (Renson et al. 1991), presents solar helium abundance from the HeI587.6 nm line and should be classified as helium weak according to the other helium lines. Therefore the derived abundance of helium for this star is lower in the inner layers. Helium abundance of the helium strong star HD 64740 decreases in the inner atmospheric layers as well. The silicon star HD 65575 shows no evidence of helium stratification. The two HgMn stars HD 106625 and HD 110073 are helium weak stars and with a non stratified abundance of helium. Helium appears to be also stratified in the atmosphere of the helium weak stars HD 120709, HD 125823 and HD 143699.

Helium abundances for a sample of helium weak stars determined only from the HeI587.6 nm line are reported in Table 5. For the sample stars which are classified helium weak in the *General Catalogue of Ap and Am stars* and whose helium abundance has been inferred only from the HeI587.6 nm line, we confirm their peculiarity class with the exception of HD 81188, which we have found having solar abundance.

6. Conclusion

We have performed spectroscopy of the HeI587.6, 667.8 706.5 and 728.1 nm lines for a sample of main sequence and helium peculiar stars in order to test the hypothesis that helium is stratified in the atmosphere of these latter.

Given the difficulties of the theory in reproducing the observed dependence of the equivalent width on the effective temperature, main sequence stars have been used to define the relation between the equivalent width and the effective temperature. In fact, amongst the lines in our sample, the available NLTE calculations give a satisfactory fit with the observations only for the HeI587.6 nm line. We have also performed LTE calculations with updated values for the Stark broadening. These calculations assume solar helium abundance for main sequence star and give a good description of the line blanketing, but cannot reproduce the observed behaviour neither.

We have therefore resorted to an empirical correction to the Lorentzian broadening parameter in our LTE computations, which is constrained by the observations of main sequence stars. This is equivalent to a factorization of the dependence of the equivalent width on the Voigt profile and on the abundance and to a subsequent correction on the Voigt profile based on the observations of main sequence stars. This procedure has been tested for consistency with the NLTE calculations of Dufton & MacKeith (1980). We have used this procedure to estimate helium abundance of the observed peculiar stars from each of the observed lines, which sample different layers in the atmosphere. We have found that helium abundance decreases in the inner atmospheric layers in helium rich stars, confirming Vauclair et al. (1991) predictions, but it does not increase in helium weak stars, for which an increasing helium abundance is predicted by the Vauclair et al. (1991) model. Silicon and HgMn stars show no evidence of helium stratification.

The derived helium abundance for the the stars HD 57219 and HD 81188 disagree with the peculiarity class reported in the *General Catalogue of Ap and Am stars* (Renson et al. 1991).

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