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INTERPRETATION OF THE CORE-WING ANOMALY OF BALMER LINE PROFILES OF COOL Ap STARS[1]

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ABSTRACT

A number of cool magnetic chemically peculiar stars exhibit abnormal profiles of hydrogen Balmer lines. This anomaly, which is most clearly visible in Hα, consists of a sharp transition between broad Stark wings and an unusually narrow Doppler core. Although the core-wing anomaly is a clear indication of an abnormal structure of the atmospheres of cool Ap stars, it has so far eluded even qualitative interpretation. In this Letter we report results of an attempt to reproduce the core-wing anomaly of Balmer lines by empirical modification of the thermal atmospheric structure. We find that it is possible to obtain a very good fit to the inner and outer wings as well as to reproduce the abrupt core-wing transition and widths of both Hα and Hβ by increasing the temperature by 500–1000 K at intermediate atmospheric layers ($-4 \leq \log \tau_{5000} \leq -1$). Thus, detailed analysis of hydrogen lines provides a very useful method for revealing the atmospheric structure of cool Ap stars and should serve as a crucial test for future self-consistent model atmospheres of peculiar stars.

Subject headings: line: formation — line: profiles — stars: atmospheres — stars: chemically peculiar

1. INTRODUCTION

Magnetic chemically peculiar (Ap) stars comprise 10%–15% of the main-sequence B–F stars and are characterized by slow rotation, large overabundances of rare earth and some iron-peak elements as well as by the presence of strong global magnetic fields on their surfaces. Global properties of Ap stars indicate that abundance anomalies are confined to the thin outer layer of the stellar envelopes. This is also predicted by the diffusion theory (Michaud 1970), which attempts to explain Ap phenomena by the slow radial drift of the atoms of heavy elements due to a small imbalance between the gravitational force and radiative pressure. In many spectroscopic studies of Ap stars it has been implicitly assumed that diffusive separation of chemical species operates mostly in layers below the stellar photosphere and therefore the photosphere can be adequately described by homogeneous abundances and modeled with standard model atmosphere codes. However, a number of recent investigations (e.g., Bagnulo et al. 2001; Ryabchikova et al. 2002) of cool Ap stars ($T_{\rm eff} \lesssim 8000$ K) demonstrated that for many chemical elements significant radial abundance gradients are present in the photospheric line-forming regions. Thus, in general, the overall structure of the atmospheres of Ap stars can be expected to deviate from the predictions of the models, which neglect vertical abundance variations. The atmospheric structure can be further altered by the presence of magnetic fields and also, in the case of rapidly oscillating Ap (roAp) stars, by *p*-mode pulsations.

Hydrogen Balmer lines provide very useful diagnostics of the thermal structure of the atmospheres of late A, F, and G dwarfs. Balmer lines of Ap stars were widely considered normal in the past with the possible exception of Przybylski's star (HD 101065). This extreme roAp star features unusually sharp cores of Hα and other hydrogen lines (Wegner 1976). Recently, Cowley et al. (2001) showed that this core-wing anomaly (CWA) is not limited to Przybylski's star but is also visible in other cool Ap stars. Unlike hydrogen line profiles of normal A and F dwarfs, which are characterized by a smooth transition between wide Stark wings and Doppler cores (Gardiner, Kupka, & Smalley 1999), hydrogen lines of some Ap stars possess an abrupt change in slope resulting in a sharp transition from the wing to an unusually narrow core. The CWA is most clearly visible in Hα but continues to higher members of the Balmer series.

Although strange shapes of hydrogen lines hint at anomalous atmospheric structure in cool Ap stars, the exact origin of the CWA remained a mystery since Cowley et al. (2001) were unable to suggest any modification to the standard model atmospheres that would reproduce the CWA. In this Letter we give a preliminary report on our attempt to model the CWA of hydrogen lines by semiempirical modification of a standard atmospheric temperature distribution. This has enabled us to quantify atmospheric anomalies in several representative cool Ap stars.

2. OBSERVATIONAL DATA

Spectra for a sample of Ap stars were obtained with the UV-Visual Echelle Spectrograph (UVES) at the Kueyen unit of the European Southern Observatory Very Large Telescope. Using a combination of the standard UVES settings, we obtained nearly full spectral coverage between 303 and 1060 nm. With an 0".5 slit width, a spectral resolution of about 80,000 was reached. At 500 nm, the signal-to-noise ratio of the one-dimensional spectrum was typically above 300 pixel^{-1}. All observations were obtained in service mode and reduced in a standard way by the UVES pipeline. Extracted spectra were subsequently normalized in Hα and Hβ regions using low-degree polynomials. All five Ap stars selected for the study of Balmer lines are very slow rotators and are not known to exhibit spectrum variability indicative of surface abundance inhomogeneities.

3. MODELING APPROACH

Semiempirical modeling of stellar atmospheres based on metal lines to date (e.g., Holweger & Müller 1974; Allende

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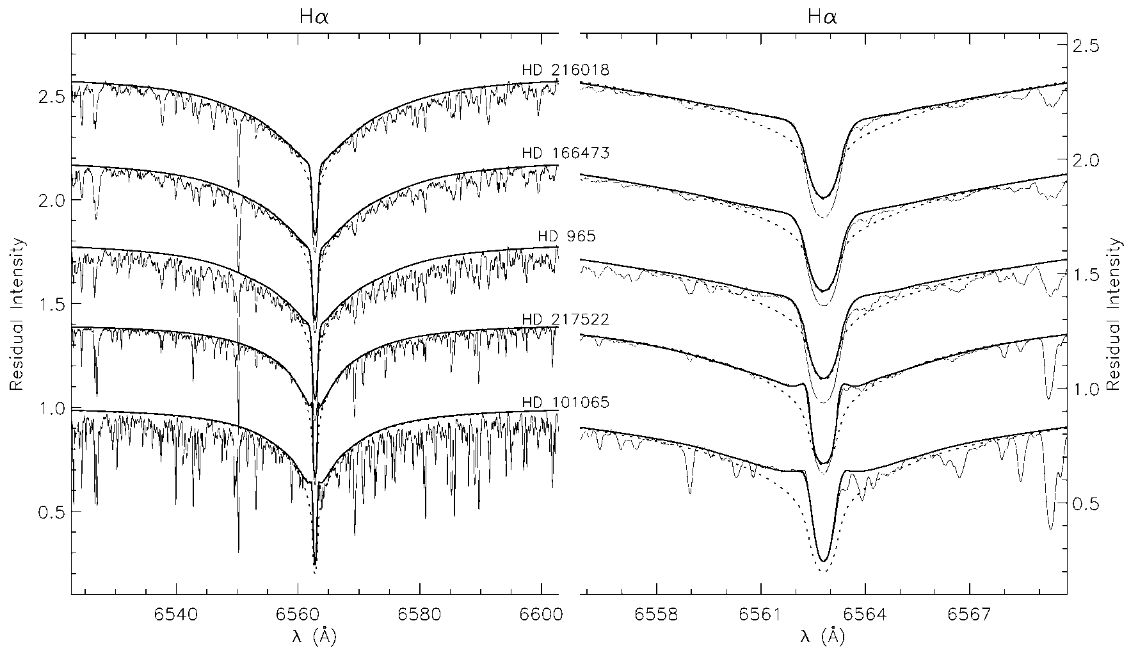

FIG. 1.—Comparison between observed (*thin solid lines*) and computed (*thick solid and dotted lines*) normalized profiles of Hα in the spectra of five cool Ap stars. *Left*: Overall fit to the shape of the hydrogen line. *Right*: Comparison of predictions of standard model atmospheres (*dotted lines*) with hydrogen lines computed with empirically modified models (*thick solid lines*) for the inner part of Hα profile. Vertical scale in both panels corresponds to Hα profiles of HD 101065. Spectra of other stars are shifted vertically with a step of 0.4.

Prieto et al. 2000) assumes chemical homogeneity throughout the atmosphere. The inhomogeneous vertical distribution of chemical elements prevents direct application of such techniques to Ap stars. In order to reconstruct the model structure from the profiles of metal lines, one has to develop a new technique that would allow dramatic effects of vertical abundance gradients to be separated from the sensitivity of spectral line shapes and strengths to the temperature and pressure in stellar atmosphere. Nevertheless, absorption lines of neutral hydrogen are highly sensitive to the atmospheric structure but weakly affected by the chemical inhomogeneity of Ap atmospheres. Therefore, one can hope to use hydrogen lines, in particular those from the readily observable Balmer series, to probe atmospheres of Ap stars and to quantify their difference from the atmospheres of normal stars of similar spectral types by interpreting characteristic anomalous features, such as the CWA pointed out by Cowley et al. (2001).

We based our analysis of Balmer line profiles of cool Ap stars on calculations using the LTE spectrum synthesis code SYNTH (Piskunov 1992). In this code, Stark broadening of hydrogen lines is described by the model-microfield method calculations of Stehlé & Hutcheon (1999), and broadening by collisions with neutral hydrogen (self-broadening) is implemented following Barklem, Piskunov, & O'Mara (2000). Radiative broadening is included, as is an estimate of the helium collisional broadening. This modern implementation of hydrogen line broadening theory was recently thoroughly tested by Barklem et al. (2002) in the analysis of Balmer lines in cool dwarf stars.

Although Balmer lines provide crucial diagnostics of stellar atmospheres, they are still sensitive to atmospheric conditions in only a limited range of optical depths. Therefore, we do not attempt to derive the complete model atmosphere structure of Ap stars independently but start from the normal atmosphere and then modify it in order to reproduce the anomalous shapes of Balmer lines. This approach is justified by the fact that the CWA affects only the inner part of hydrogen line profiles ($\Delta\lambda \leq 4$ Å) but does not have a perceptible effect on the intermediate and far wings of Hα and Hβ. We used the model atmosphere code ATLAS9 (Kurucz 1993a) to compute initial model atmospheres for five program Ap stars. Convection was taken into account under mixing-length theory, with the mixing-length parameter $\alpha = 1.25$ and no convective overshooting. For the extreme roAp star HD 101065 we used opacity distribution functions (ODF) from the study of Piskunov & Kupka (2001), who computed ODFs with individual stellar abundance tables. For other program stars, which show moderate abundance anomalies, we assumed a scaled solar abundance pattern and employed ODFs computed by Kurucz (1993b). For HD 965, HD 216018, and HD 217522 metallicity, surface gravity and an initial guess for the effective temperature were derived from Strömgren photometric colors using the calibration of Moon & Dworestky (1985), while estimates of stellar parameters of HD 101065 and HD 166473 were adopted from Cowley et al. (2000) and Gelbmann et al. (2000), respectively. Effective temperatures were refined by fitting wings of Hα as illustrated in Figure 1. Typically, $T_{\rm eff}$ derived from Hα provided a reasonable fit to Hβ wings, although direct comparison between observations and spectrum synthesis is hampered by severe blending of Hβ by metal lines. The final set of stellar parameters is summarized in Table 1.

After deriving an initial approximation to the model atmospheres we iteratively adjusted the thermal atmospheric structure until a good fit to the observed shape of the inner Hα wings was achieved and the sharp break between the wings and the Doppler core was reproduced. At each iteration, after changing the temperature stratification, we recomputed all other gas parameters required as an input for the spectrum synthesis code by assuming homogeneous abundances, constancy of the total gas pressure, and ideal gas laws and by using computer

TABLE 1
Model Atmosphere Parameters of Program Stars

HD Number	T_{eff} (K)	log g	[Fe/H][a]
HD 965	7450	4.5	+0.5
HD 101065	6300	4.2	...
HD 166473	7700	4.2	+0.5
HD 216018	7750	4.2	+0.5
HD 217522	6850	4.3	+0.0

[a] Overall metallicity (relative to solar) of ODFs used for model atmosphere calculations. For HD 101065 we employed ODFs computed with a realistic abundance table.

routines from the equation-of-state solver described by Valenti, Piskunov, & Johns-Krull (1998). Figure 1 shows our final fit to the Hα profiles. Reasonable agreement between the theory and observations was also evident when the same empirical model atmosphere was used to compute Hβ profiles, as illustrated in Figure 2. Empirical model atmospheres derived from fitting the CWA of Hα are compared with initial (standard) models in Figure 3.

4. RESULTS AND DISCUSSION

We found that the unusual profiles of Balmer lines of cool Ap stars can be explained by the presence of an anomalously hot layer in their atmospheres. Within our scenario, the hot layer gives rise to emission, which reduces the width of the Doppler core of Hα and fills the inner part of Balmer line wings producing characteristic sharp transition between the wings and the core. In the three hotter stars ($T_{\mathrm{eff}} > 7000$ K) from the small sample studied here it was necessary to increase the temperature by about 500 K or less in the range of optical depths $-2.5 \leq \log \tau_{5000} \leq -1.5$ in order to fit Hα profiles. On the other hand, Hα profiles of the two cooler stars, HD 101065 and HD 217522 ($T_{\mathrm{eff}} < 7000$ K), call for a larger thermal anomaly extending to $\log \tau_{5000} \approx -3.5$ and a temperature increase of up to 1000 K relative to the standard model atmospheres.

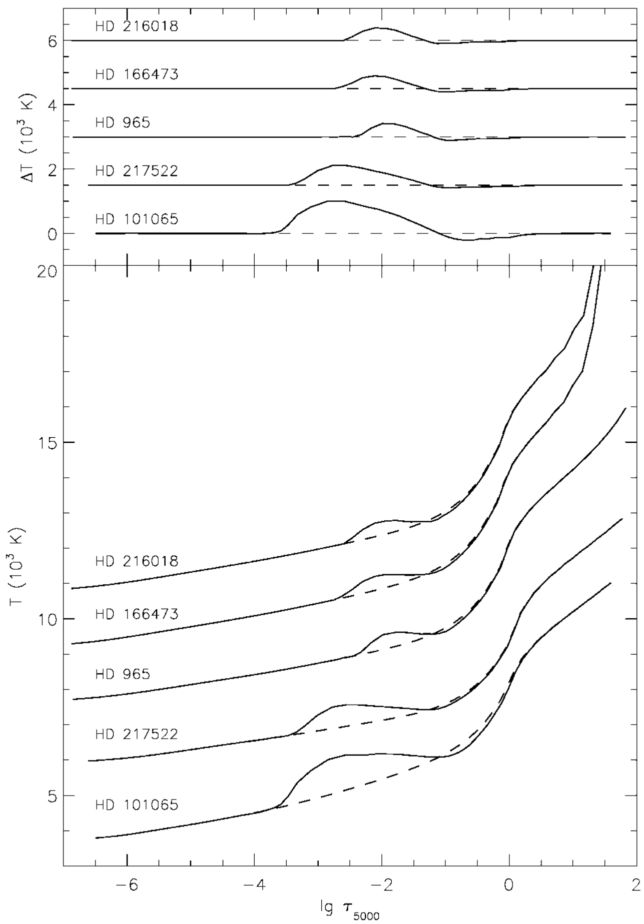

Fig. 3.—*Bottom*: Comparison of the thermal structure of standard Kurucz model atmospheres (*dashed lines*) with the empirical temperature stratification derived from Hα profiles. *Top*: Difference between each pair of models. In both panels the vertical scale corresponds to HD 101065. Data for other stars are shifted vertically with a step of 1500 K.

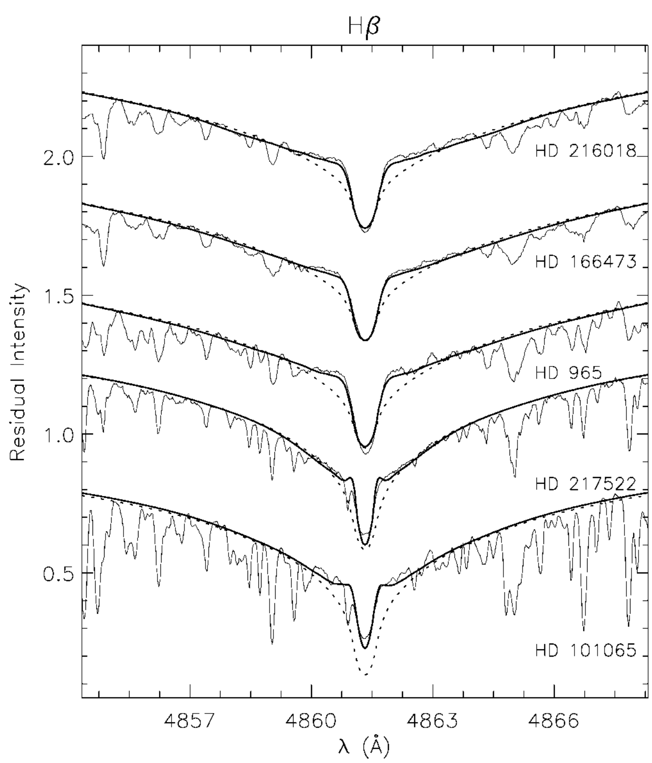

Fig. 2.—Same as Fig. 1, but for the inner part of the Hβ profile

The presence of vertical abundance gradients in the atmospheres of Ap stars is probably the most important effect neglected in our empirical models. Vertical abundance inhomogeneities will lead to different ion and electron number densities compared with those employed in our models, and this will have an effect on hydrogen lines via Stark broadening. We investigated the extent of this problem by introducing arbitrary modifications in electron number densities but found that such distortions can lead to only moderate changes in the overall width of Hα and Hβ wings. In none of the studied examples were we able to produce sharp localized anomalies, similar to the CWA, in hydrogen line profiles. This suggests that the CWA is primarily a *temperature effect*, and hence assumption of chemical homogeneity does not introduce large error in our results.

We also note that deviations from LTE, which are also neglected in our spectrum synthesis, are important only in the highest atmospheric layers and typically change the depth of the Doppler core by increasing it by a few percent (Cowley et al. 2001). This effect is clearly seen in observed profiles in Figure 1, which have somewhat deeper cores than predicted by both the standard and empirical models. Nevertheless, departures from LTE do not affect the *width* of the Doppler core and cannot be responsible for the break of the slope in the Hα profile at the transition between the core and the wings. Therefore, we believe that the LTE assumption is not particularly restrictive in our modeling. It may, however, lead to some underestimate of the upper boundary of the anomalous region in the atmosphere of HD 101065. The Hα profile of this star shows the strongest CWA and requires one to extend modification of the thermal atmospheric structure to very small optical depths where the LTE approximation may not be valid.

What is the origin of the hot layer in the atmospheres of Ap stars? This question can ultimately be answered by detailed self-consistent model atmosphere calculations. Such models should take into account chemical inhomogeneities and properly include the effects due to the strong magnetic field, which plays a crucial role in stabilizing atmospheres of Ap stars against convective and turbulent mixing and thus maintains large chemical and temperature gradients. However, before self-consistent models become available, we may speculate that the anomalous atmospheric structure is somehow related to the strong vertical abundance gradients. For example, both observations (Ryabchikova et al. 2002) and theory (Babel 1992) indicate that the concentration of many iron-peak and light elements is high deep in the atmospheres of Ap stars, but decreases sharply to solar or even less than solar abundance between $\log \tau_{5000} \approx -1$ and -2. It may be a dramatic change in the back-warming effect, related to this abundance profile, that we observe as a strong temperature gradient at the upper boundary of the hot layer.

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