The A-Star Puzzle
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Stellar model atmospheres with magnetic line blanketing

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Abstract. Model atmospheres of A and B stars are computed taking into account magnetic line blanketing. These calculations are based on the new stellar model atmosphere code LLModels which implements a direct treatment of the line opacities and ensures an accurate and detailed description of the line absorption. The anomalous Zeeman effect was calculated for field strengths between 1 and 40 kG and a field vector perpendicular to the line of sight. The magnetically enhanced line blanketing changes the atmospheric structure and leads to a redistribution of energy in the stellar spectrum. The most noticeable feature in the optical region is the appearance of the λ5200 broad, continuum feature. However, this effect is prominent only in cool A stars and disappears for higher effective temperatures. The presence of a magnetic field produces an opposite variation of the flux distribution in the optical and the UV regions. A deficiency of the UV flux is found for the whole range of considered effective temperatures, whereas the "null wavelength region" where the flux remains unchanged shifts towards the bluer wavelengths for higher temperatures.

Keywords. Stars: chemically peculiar, stars: magnetic fields, stars: atmospheres

1. Introduction

Magnetic chemically peculiar (CP) stars are upper and middle main sequence stars characterized by anomalous chemical abundances and unusual distribution of energy in their spectra. A strong magnetic field is expected to have important effects on atmospheres and spectra of CP stars. Several characteristic features of the energy distribution of magnetic CP stars, such as the broad, continuum features in the visual (Kodaira 1969) and the UV flux deficiency (Leckrone 1973), are suspected to be a result of the enhanced line blanketing due to the magnetic intensification of spectral lines. This emphasizes the necessity to consider magnetic line blanketing in the atmospheres of CP stars.

In general, a magnetic field influences the energy transport, hydrostatic equilibrium, the diffusion processes, and the formation of spectral lines. Previous studies (Stępień 1978, Muthsam 1979, Carpenter 1985, Leblanc *et al.* 1994, Valyavin *et al.* 2004) have attempted to model some of these factors. However, due to a limitation of computer resources, it was impossible to fully account for the Zeeman effect on the line absorption. In early model atmospheres calculations magnetic splitting was treated very approximately by introducing a pseudo-microturbulent velocity (Muthsam 1979) or by adopting an identical Zeeman triplet pattern for all lines (Carpenter 1985). Recent investigation by Stift & Leone (2003) demonstrated that the magnetic intensification of spectral lines depends primarily on the parameters of anomalous Zeeman splitting pattern, in particular on the number of Zeeman components. In the light of these results it becomes clear that previous attempts to simulate magnetic line blanketing by an enhanced microturbulence or using a simple triplet pattern are insufficient.

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2. Calculation of magnetic model atmospheres

2.1. *Stellar model atmosphere code LLModels*

The stellar model atmosphere code LLModels developed by Shulyak *et al.* (2004) uses a direct method, the so-called line-by-line or LL technique, for the line opacities calculation. This approach allowed us to account for the individual anomalous Zeeman splittings of spectral lines.

In all calculations presented here we employed two criteria to achieve the convergence of the models: the constancy of the total flux *and* the conservation of the radiative equilibrium. The LLModels uses either atomic line lists compiled by Kurucz (1993) or the VALD (Kupka *et al.* 1999) line list. The code relies on a preselection procedure to choose spectral lines contributing significantly to the total absorption coefficient at each of $(3–5)\times10^5$ frequency points considered in the flux calculation. The code selects spectral lines for which $\ell_\nu/\alpha_\nu \geqslant \varepsilon$, where ε is the adopted selection threshold and ℓ_ν and α_ν are line and continuous opacities.

2.2. *Line list*

Magnetic line blanketing was accounted for all spectral lines except those of hydrogen according to the individual anomalous Zeeman patterns. The initial line lists were extracted from VALD using the preselection threshold $\varepsilon = 1\%$.

Landé factors of the lower and upper atomic levels necessary for the calculation of the Zeeman splitting of lines are provided for majority of lines in VALD. For 4–10% of the preselected spectral lines which lack information on Landé g factors the LS coupling approximation was employed for light elements (He to Sc) and a classical Zeeman triplet with $g_{\rm eff} = 1.2$ was assumed for other lines.

2.3. *Zeeman effect in the line opacity*

In general, to calculate a stellar spectrum in the presence of a magnetic field one has to consider the polarized radiative transfer equation for the Stokes $IQUV$ parameters. Solution of this problem requires special numerical techniques and is rather computationally expensive (e.g., Piskunov & Kochukhov 2002) and, hence, cannot be easily included in the routine model atmosphere calculation of magnetic stars. Nevertheless, the problem of the magnetic line blanketing can be simplified considerably by assuming that the magnetic field vector is oriented perpendicular to the line of sight. In this case we can neglect effects produced by the polarized radiative transfer and use the transfer equation for non-polarized radiation treating individual Zeeman components as independent lines. The method is fully justified for weak lines (Stenflo 1994) and produces reasonable results for moderate and strong spectral features. Thus, we modified the original line list by inserting additional spectral lines which correspond to individual Zeeman components of the anomalous splitting patterns. This procedure resulted in $(5–14)\times10^6$ (depending on the metallicity) individual transitions included in evaluation of opacity during the model atmosphere calculations.

3. Numerical results

We have calculated a set of model atmospheres with $T_{\rm eff} = 8000\,$K, $11000\,$K, and $15000\,$K, and $\log g = 4.0$, and magnetic field moduli 0, 1, 5, 10, 20 and 40 kG. This model atmosphere grid covers the range of stellar parameters typical of Ap stars. In this first exploratory investigation we assumed scaled solar abundances with [M/H]= 0.0, +0.5 and +1.0, although accounting for individual stellar abundances is straightforward

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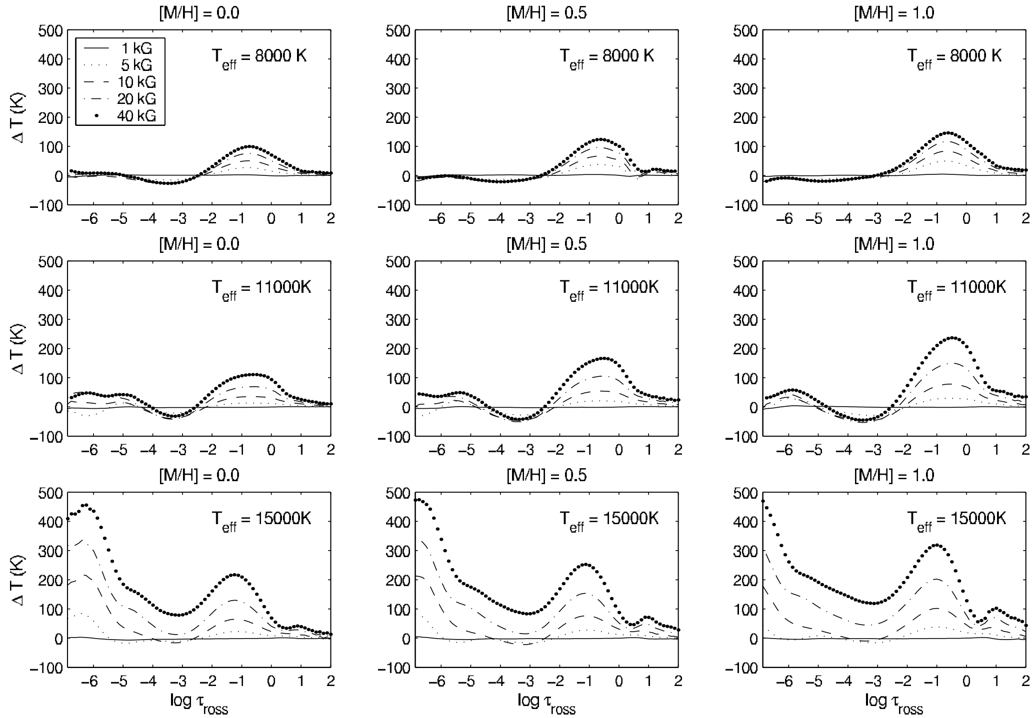

Figure 1. Temperature differences between magnetic and non-magnetic model atmospheres for effective temperatures $T_{\rm eff} = 8000\,{\rm K}$, $11000\,{\rm K}$, and $15000\,{\rm K}$ and [M/H]$= 0.0, +0.5, +1.0$.

with our code. Convection was neglected because the strong magnetic field is expected to prevent turbulent motions of plasma in the stellar atmosphere.

3.1. *Model structure*

The temperature difference between magnetic and nonmagnetic model atmospheres is presented in Fig. 1 as a function of Rosseland optical depth. The temperature anomaly due to the magnetically enhanced line opacity increases with magnetic field strength and metallicity. Pronounced temperature anomalies occur at the optical depth $\log \tau_{\rm ross} \approx -2$ and in the uppermost atmospheric layers. Additional magnetic line blanketing leads to a redistribution of the absorbed energy back to the underlying atmospheric layers and, thus, results in the heating of the main line forming region (near $\log \tau_{\rm ross} \approx -2$) by 100–300 K.

3.2. *Energy distribution*

The energy distributions for [M/H]$= +0.5$ and different $T_{\rm eff}$ are presented in Fig. 2. Flux distributions for other metallicity values show similar behaviour. We note three interesting features in theoretical energy distributions. The first one is a flux deficit in the UV region. Its magnitude depends on $T_{\rm eff}$ and increases with the magnetic field strength. Second, the magnitude of the well-known broad, continuum feature (flux depression) at $\lambda5200$ increases with magnetic field intensity and metallicity. However, appreciable $\lambda5200$ features are visible only for low $T_{\rm eff}$ but become negligibly small for higher temperatures. Finally, the presence of the magnetic field changes the flux distribution in the visual and the UV regions in opposite directions. Magnetic stars appears to be cooler in the UV and hotter in the visual than non-magnetic stars of similar $T_{\rm eff}$. The "null wavelength" where flux remains unchanged shifts to the shorter wavelengths with increasing $T_{\rm eff}$.

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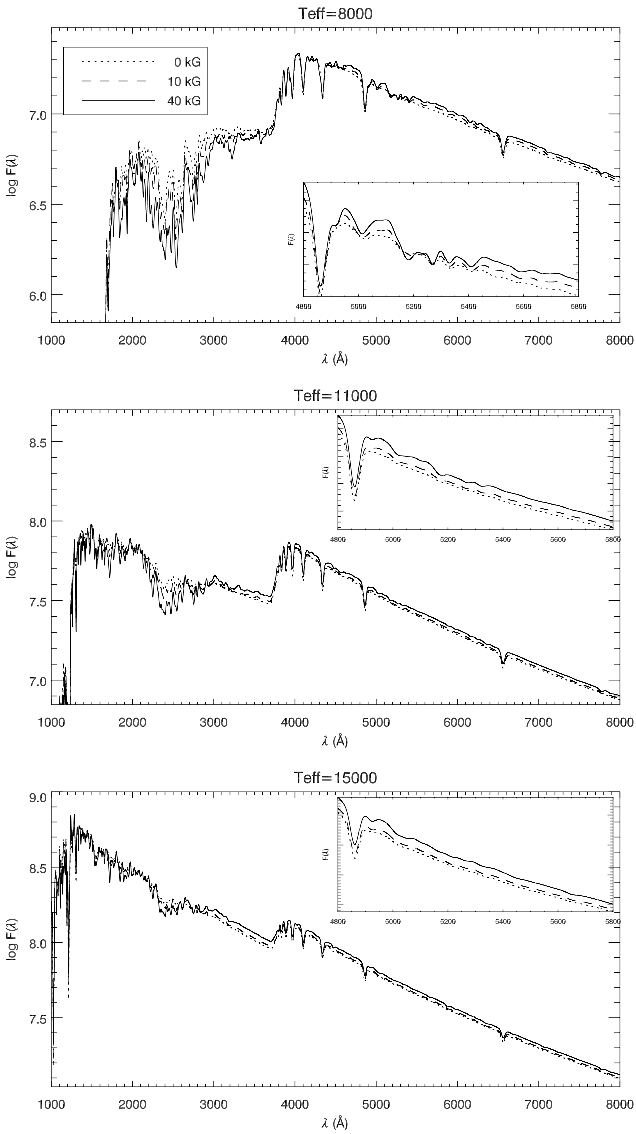

Figure 2. Energy distributions from near UV to near IR regions for the effective temperatures $T_{\rm eff} = 8000\,$K, $11000\,$K, and $15000\,$K and [M/H]= +0.5. The inset shows flux near the $\lambda 5200$ region. For display purposes energy distributions have been smoothed with a Gaussian profile corresponding to the resolving power $R = 150$.

3.3. *Colors*

We studied the influence of magnetic line blanketing on the photometric colors in the $uvby\beta$, UBV, Geneva and Δa systems. Relations between the anomalies of all photometric indices except for c_1 and the intensity of magnetic field are strong functions of the effective temperature. For low $T_{\rm eff}$ a change relative to a non-magnetic case is clearly present, whereas for high $T_{\rm eff}$ this anomaly disappears. Enhanced metal abundances increase the anomalies of all photometric indices. In general, we find that saturation effects become important in all photometric indices for field strengths above $\geqslant$ 10 kG and, hence, there is no linear dependence of any photometric index with the magnetic field intensity.

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3.4. *Hydrogen line profiles*

We calculated the profiles of Hα, Hβ and Hγ hydrogen lines using the SYNTH code (Piskunov 1992) and recent Stark broadening computations by Stehlé (1994).The changes in the atmospheric structure of magnetic stars do not influence the Balmer line profiles. The maximum deviation is only about 3% of the continuum level for the greatest considered field strength.

4. Discussion

Our study shows that magnetically modified line blanketing heats the atmospheres of magnetic stars for certain range of optical depths, an effect which increases with effective temperature and metallicity. We found that magnetic model atmospheres have flux deficits in the UV. The presence of a magnetic field leads to the flux redistribution from the UV to the visual region. This property of our theoretical models is in agreement with observations of Ap stars (Leckrone 1974, Molnar 1973, Jamar 1977).

Theoretical energy distributions show that an increase of $T_{\rm eff}$ is accompanied by the blueward shift of the null wavelength. This agrees with the observational results and numerical experiments presented by Leckrone *et al.* (1974).

Unlike normal stars, magnetic CP stars show several broad, continuum features in the visual and ultraviolet regions. The most prominent feature in the visual is the one centered on λ5200. Our numerical results reproduce this feature for cool Ap stars and show that the magnitude of the depression increases with magnetic field strength and metallicity.

Historically, photometric data were widely used to distinguish peculiar star from normal counterparts and to determine atmospheric parameters. We found that the magnetically induced anomalies of photometric indices are noticeable for lower effective temperatures and negligible for higher $T_{\rm eff}$. This is in compliance with the properties of flux distribution and the study of Cramer & Maeder (1980), who noted that energy distribution becomes less sensitive to magnetic field effects for hotter stars.

The peculiarity indices Δa, Z and $\Delta(V_1 - G)$ are used for identification and determination of the properties of magnetic CP stars. It is interesting to examine the influence of magnetic field on their values. We found a relatively small effect (the change in Δa is as large as $+0.075$ mag for a 40 kG field). In generally the relations between the indices and the magnetic field strength, which saturates for strong fields, is nonlinear. In any case, Δa appears to be more sensitive to the magnetic field modulus, in compared with Z. We note, that Cramer & Maeder (1980) emphasized that a saturation of the photometric effects with strong fields is an observational fact and needs to be explained in terms of model atmospheres. Our numerical results provide a theoretical explanation of this effect.

Finally, we investigated how magnetic opacity affects the determination of the atmospheric parameters of Ap stars from their photometric indices. We found that the deviation of $T_{\rm eff}$ and $\log g$ derived with standard photometric calibrations are within usual error bars (100–300 K and 0.1 dex respectively). In other words, magnetic opacity are not expected to produce significant errors of photometric estimates of stellar parameters.

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Discussion

WADE: For the field strengths >10 kG, one would expect Zeeman components of most lines to be fully split and resolved, and so that the influence of very large fields on the flux should be not so much more than intermediate fields. Can you explain then why the effect of a 40 kG field is so much greater than for a 10 kG field?

KOCHUKHOV: The major contribution to the influence of the magnetic line blanketing on the model atmosphere structure and flux distribution comes from many strong UV spectral lines. In that spectral region magnetic splitting is factor 2-3 smaller than in the optical due to the λ^2 dependence of the Zeeman effect. Furthermore, real spectral lines often exhibit complex *anomalous* Zeeman patterns. Even in the visual region the magnetic intensification of such a line does not reach maximum until $\approx$ 50–100 kG (see Stift & Leone, 2003, A&A, 398, 411). Thus, a 40 kG field is not sufficient to resolve all metal lines (especially in the UV) and result in a saturation of the magnetic effect in our model atmosphere calculations.

DWORETSKY: It is good to see a theoretical explanation in detail of the λ5200 feature. I recall that H. Maitzen using photographic spectra to look for spectroscopic clues (absorption lines) to its origin many years ago. Your work clearly provides a neat explanation.

KOCHUKHOV: Indeed, our modelling suggests that the λ5200 depression in cool A stars appears due to the magnetic line blanketing. However, we do not find depressions in the theoretical flux distributions computed for hot magnetic stars. It seems that some other effects (vertical chemical stratification being the best candidate) are responsible for the λ5200 feature at these higher temperatures.

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