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Atmospheres of CP stars: magnetic field effects

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Abstract. We present the resent calculations of magnetic field effects in atmospheres of CP stars. The calculations are based on LLModels stellar model atmosphere code which implements direct treatment of the opacities due to the bound-bound transitions and ensures an accurate and detailed description of the line absorption. In these studies we focus on two general problems: the calculations of anomalous Zeeman splitting and the effects of Lorentz force in stellar atmospheres. First, we investigate the influence of the enhanced line blanketing due to the Zeeman effect on model structure, energy distribution, photometric colors, metallic line spectra and the hydrogen Balmer line profiles. The results are discussed with respect to those of non-magnetic models. As a next step we modelled the Lorentz force results from the interaction between the stellar magnetic field and the electric currents induced by time evolution of global dipolar-like field. This additional force may modify the pressure-temperature structure influences on the formation of absorption spectral features, especially the Balmer line profiles. The results of this study are investigated using recent observations of A0p star θ Aur obtained with BOES echelle spectrograpth of the 1.8 m telescope of the Korean Astronomy Observatory.

Key words. stars: chemically peculiar – stars: magnetic fields – stars: atmospheres

1. Introduction

Magnetic chemically peculiar (CP) stars are upper and middle main sequence (B-F) stars characterized by anomalous abundances and energy distribution in their spectra. The effective temperature of these stars ranges from 6500 K to about 25 000 K and the magnetic field strength reaches up to $\sim$ 30 kG. Several characteristic features in the energy distribution of magnetic CP stars are suspected to be a result of the enhanced line blanketing due to the magnetic intensification of spectral lines. For instance, Kodaira (1969) found several flux depressions in the visual spectrum of CP stars, and Leckrone (1973) showed that the

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UV flux of CP stars is depressed compared to that of normal stars. These possible manifestations of the magnetic line blanketing emphasize a necessity to consider a magnetic field in the model atmosphere calculation of CP stars.

Generally, the magnetic field influences the energy transport, hydrostatic equilibrium, diffusion processes and the formation of spectral lines. In previous studies (Stępień 1978; Muthsam 1979; Carpenter 1985; LeBlanc et al. 1994; Valyavin et al. 2004) attempts were made to model some of these factors. In the present study we pointed on the two of these effects: Zeeman splitting (which leads to the additional line opacity of Zeeman components) and effects of Lorentz forces (which reexamines hydrostatic equilibrium of stellar atmospheres). The Zeeman splitting has been introduced in the model calculation assuming horizontal magnetic field configuration. In this case the effects produced by the polarized radiative transfer on the Stokes I are minimal and we can use the transfer equation for the non-polarized radiation. The Lorentz force is considered as a result from the interaction between a magnetic field and induced electric currents caused by slow evolution of global magnetic field. In order to study such an effect we began a systematic survey of Balmer lines variability of brightest CP stars.

In calculations described in the present paper we employed the stellar model atmosphere code LLModels developed by Shulyak et al. (2004). This code uses a direct method, the so-called line-by-line technique, for the line opacity calculation. Such an approach allowed us to account for the anomalous Zeeman splitting of spectral lines in the line blanketing calculation and, hence, to achieve a qualitatively new level of accuracy in modelling the influence of magnetic field on the stellar atmospheric structure.

2. Zeeman effect

In the early calculations of model stellar atmospheres magnetic splitting was implemented very approximately either by introducing a pseudo-microturbulent velocity which affects all spectral lines in the same way (Muthsam 1979) or by adopting a normal Zeeman triplet pattern with the same effective Landé factors (Carpenter 1985) for all lines. Recent investigation by Stift & Leone (2003) demonstrated that the magnetic intensification of spectral lines depends mostly 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 by using a simple triplet pattern are insufficient.

The main goal of the presented in this section work is to introduce a realistic calculation of the anomalous Zeeman effect in the classical 1-D models of stellar atmospheres and to investigate the resulting effects on the model structure, energy distribution and other common observables. For detailed description of this work we refer the reader to the already published paper of Kochukhov et al. (2005). Here we briefly summarize most important results.

2.1. Models grid and the line list

The model atmosphere grid investigated covers a substantial part of the stellar parameter space occupied by the magnetic CP stars. The following model parameters have been used: $T_{\rm eff}$=8000 K, 11 000 K, 15 000 K, surface gravity $\log g$ = 4.0, metallicity $[M/H]$ = 0.0, +0.5, +1.0 and magnetic field strength 0, 1, 5, 10, 20 and 40 kG.

The initial line lists were extracted from VALD (Kupka et al. 1999). The total number of spectral lines was more than 21.6 millions between 50 and 100 000 Å. This line list was used for the preselection procedure in the LLModels code using the selection threshold ε = 1% (where ε is the relation of the line and continuum absorption coefficients). It allowed to decrease the number of spectral lines involved in the line blanketing calculation to about 300 000–800 000 (depending on the model atmosphere parameters). Unfortunately, the VALD database does not provide Landé factors for all lines. Roughly 4–10% of the preselected spectral lines lack information about the Landé factors. For the light elements (He-Sc) we employed the LS coupling approximation using the term designation provided for each line in the VALD. It reduced the number of lines with missing Landé factors to 1–4%. For these remaining lines we assumed a classical Zeeman triplet splitting pattern with the effective Landé factor $g_{\rm eff} = 1.2$ (which is the average value for the spectral lines with computed or experimental Landé factors). After the splitting procedure the total number of lines became 5 000 000 – 14 000 000.

2.2. Numerical results

Fig.1 illustrates the difference between the temperature structure of magnetic and non-magnetic models as a function of the optical depth. As it was expected the Zeeman splitting leads to the temperature increase in the line forming region ($\log \tau_{Ross} \approx 1$). At the same time, models computed for $T_{\rm eff}$=15 000 K display a significant increase of temperature throughout the atmosphere. This behavior is explained by the shift from visual to UV of the wavelength interval which plays the most important role for the atmospheric energy balance.

The comparisons of the energy distributions are shown in Fig.2. Three important features can be seen. The flux deficiency in the UV region and the respective flux excess in the visual which increases with the magnetic field strength and metallicity. The presence of a magnetic field changes the stellar flux distribution in opposite direction in the visual and UV regions. At short wavelengths and in the visual magnetic star appears to be cooler and hotter respectively in comparison with a non-magnetic object with the same fundamental parameters. Finally, we find that some of the theoretical flux distributions of magnetic stars show depression in the 5200 Å region. This spectral feature has a well-known counterpart frequently observed in the spectra of peculiar stars (Kupka et al. 2003). In our theoretical calculations the 5200 Å depression is prominent at lower $T_{\rm eff}$ but becomes rather small for hotter models.

We studied the influence of the magnetic line blanketing on the photometric colors in the Strömgren $uvbyH\beta$, Geneva and Δa systems. We showed that the behavior of the photometric indices is closely related to the flux redistribution between the visual and UV regions and the presence of several flux depressions (such as one at 5200 Å). For low $T_{\rm eff}$ photometric changes are very pronounced, whereas for hotter magnetic stars modification of the $uvbyH\beta$ photometric observables is fairly small (except c_1). We also showed that none of the photometric indicators of magnetic stars proposed in the literature shows a linear trend over the whole range of the considered magnetic field strength.

Fig.3 illustrates H_β profiles computed for models with different $T_{\rm eff}$ and magnetic field module using the Synth program (Piskunov 1992). It is clearly seen that the changes in the atmospheric structure due to the magnetic line blanketing do not have a strong influence on the hydrogen line profiles. For H_β the maximum change relative to the non-magnetic model amounts to about 3% of the continuum level for B = 40 kG, but it does not exceed 1% for $B \leq 10$ kG, which is a more typical surface field strength for the majority of magnetic CP stars. The metal lines spectra do not show any significant changes too. The strongest effect is found for $T_{\rm eff}$=8000 K, where in the presence of the 10 kG field many medium strength and weak lines become systematically shallower by 4–6% of the continuum level relative to the calculation with the zero field model. This is reduced to less than 2–3% for the $T_{\rm eff}$=11 000 and 15 000 K models. For many lines the main discrepancy is concentrated in the line wings, with the magnetic models predicting slightly narrower line profiles.

We also investigated the effect of Zeeman splitting on main model parameters determination ($T_{\rm eff}$ and $\log g$). It is found that the magnetic line blanketting does not introduce noticeable errors in such routines. The derived effective temperature values increase systematically with the field strength for all three considered $T_{\rm eff}$ values. The bias introduced by magnetic field reaches 100–200 K for $T_{\rm eff}$=8000–11 000 K and 900 K for $T_{\rm eff}$=15 000 K. The surface gravity is modified by up to 0.2 dex. These changes are rather small and are within the allowed error bar for stars with respective parameters.

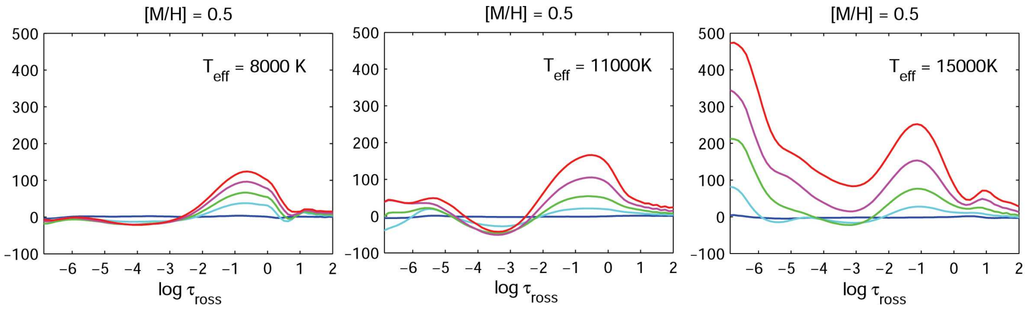

Fig. 1. Difference of temperature between magnetic and non-magnetic model atmospheres for the effective temperatures $T_{\rm eff}$=8000 K, 11 000 K, 15 000 K and metallicities [M/H]=+0.5

Finally, having introduced a more realistic calculation of magnetic intensification, we investigated the question of to what extent models with enhanced microturbulent velocities are able to match the properties of magnetic models. Until the present work the most common approach to account for the magnetic line blanketing was to use an increased value of the microturbulent velocity (Muthsam 1979; Kupka et al. 2004). For the magnetic field B (e.g., Kupka et al. (1996)):

$$\xi_{\rm mag} = 4.66\times10^{-13} c\,\lambda g_{\rm eff} B, \quad (1)$$

where c is the speed of light in kms^{-1}, the field strength B is measured in gauss, λ is the wavelength in Å and $g_{\rm eff}$ is the effective Landé factor. In previous model atmosphere studies $\lambda\approx 5000$ Å and $g_{\rm eff} = 1.0$–1.2 were typically adopted, which gives $\xi_{\rm mag}\approx 4$ and 8 kms^{-1} for the magnetic field strength of 5 and 10 kG respectively. We found that enhanced microturbulence is able to mimic the behavior of magnetic models (energy and temperature distributions). At the same time, an exact quantitative match requires adopting a different $\xi_{\rm mag}$ parameter for each considered quantity. For example, to reproduce the temperature structure and energy distribution of the $T_{\rm eff}$=8000 K models one has to use (depending on metallicity) $\xi_{\rm mag} = 2.1$–2.6 kms^{-1} and 3.7–4.1 kms^{-1} for $B = 5$ and 10 kG respectively, which is roughly a factor of two smaller microturbulence than predicted by Eq. (1). At the same time, matching the anomalous absorption in the 5200 Å region requires a 2–3 kms^{-1} higher value of $\xi_{\rm mag}$. We conclude that enhanced microturbulence can only be used as a rough guess of the effects due to the Zeeman splitting and does not properly reflect the behavior of magnetic models.

3. Lorentz force

In this section we present preliminary results of modelling Lorentz force effects in magnetized atmospheres of CP stars. The importance of such effects had been noted by a number of authors (see the papers of Stępień (1978), Peterson & Theys (1981), Hubbard & Dearborn (1982), LeBlanc et al. (1994), etc.). Different physical processes had been considered to induce electric currents and thus Lorentz force, but all investigators noted significant changes in hydrostatic structure of atmospheric layers to be observed as a variations of strongest spectral features like Balmer lines. In our study we base on the work of Landstreet (1987) who considered the effects of time-evolution of global dipolar-like magnetic field. The physical explanation of such a model comes from the suggestion that the magnetic field of convective-free CP star are fossil remnants of the galaxy magnetic field. If so then this field should be slowly decaying with the characteristic time of about 10^{10} years (Moss 1984). In this case the fields are nearly force-free and do not affect hydrostatic structure of the stellar atmosphere. However, such long time scale of the field evolution had been obtained under very simplified assumptions. The life-time of main-sequence A-B stars is of the order of 10^8 years and it suggests that

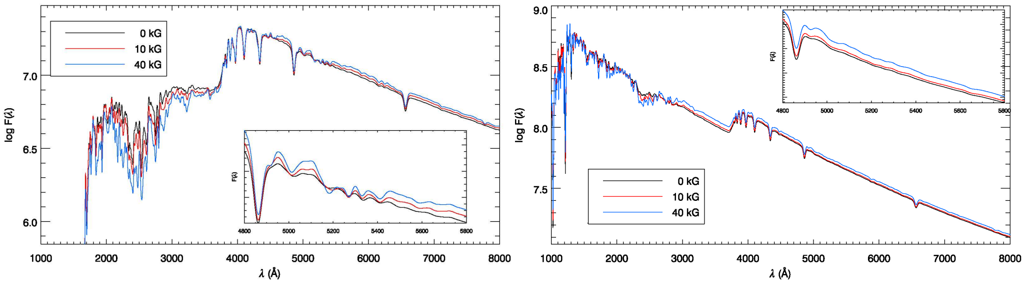

Fig. 2. Convolved LLModels energy distributions (FWHM=15 Å) from UV to near IR region for effective temperature $T_{\rm eff}$=8000 K (left figure) and $T_{\rm eff}$=15 000 (right figure) and metallicity [M/H]=+0.5. The insets show energy distributions in the 5200 Å region.

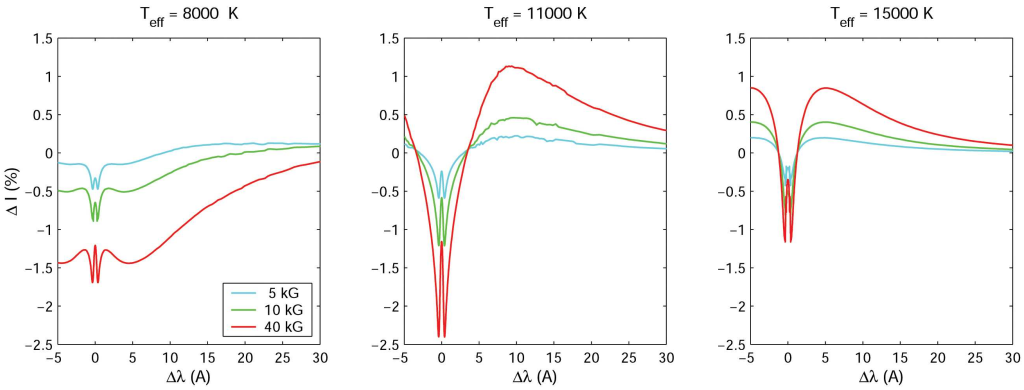

Fig. 3. Comparison between the synthetic H_β profiles computed for [M/H]=+1.0 and different values of the magnetic field strength and $T_{\rm eff}$.

the significant transformation of a star during evolution across the HR diagram reduces the field evolution rate to the shorter times. In this case the quick evolution of the field may act the atmosphere through the respective magnetic force term. Later Valyavin et al. (2004) have implemented this theory in *ATLAS9* stellar model atmosphere code (Kurucz 1993). Using direct numerical calculations they noted significant modifications of hydrostatic structure and thus variations of hydrogen line profiles. Using the resent high-resolution observations of some of magnetic CP stars and based on LLModels code we have started a systematical searching for Lorentz force effects.

3.1. Approximations of the model

The basic approximation made in the model calculation are as follows:

- the magnetized atmospheric layers are assumed to be static;
- the stellar surface magnetic field is dominated by the dipolar or quadrupolar force-free component in all atmospheric layers;
- distortion of the dipolar magnetic field is created by the field evolution and can be presented through the induced azimuthal electric current;
- due to the axial symmetry of the surface field its evolution creates an electric current with only azimuthal component;
- stellar rotation, Hall's current and other dynamical effects are neglected;

3.2. Basic equations

The equation of pressure balance in the presence of magnetic force has the form:

$$\nabla \boldsymbol{P}_{tot} = \rho \boldsymbol{g} + \frac{1}{c} \boldsymbol{j} \times \boldsymbol{B}, \quad (2)$$

where $\boldsymbol{P}_{tot}$ is the total atmospheric pressure, ρ is the gas density, $\boldsymbol{g}$ is the surface gravity, $\boldsymbol{j}$ is the induced electric current and $\boldsymbol{B}$ is the magnetic field. From the model assumptions the electric current can be expressed with Legendre polynomials $j_\phi \approx P_n^1(\cos\theta)$ (Wrubel 1952). The scalar radial component from Eq.2 is

$$\frac{\partial P_{tot}}{\partial r} = -\rho g \pm \frac{j_{\rm eq}}{c} B_\theta \sin\theta. \quad (3)$$

Here positive sign refers to the case of an outward directed Lorentz force and the negative sign is for an inward directed force. Ohm's law is written as:

$$\boldsymbol{j} = \sigma \boldsymbol{E}_\parallel + \sigma_1 \boldsymbol{E}_\perp - \frac{\sigma_2}{B} \boldsymbol{E}_\perp \times \boldsymbol{B}, \quad (4)$$

where $\boldsymbol{E}_\parallel$ and $\boldsymbol{E}_\perp$ are electric field components directed along and across magnetic field lines, σ is the electrical conductivity in the absence of magnetic field, σ_1 is the conductivity across the magnetic field lines and σ_2 is the Hall's conductivity. Note that the first and the third term in Eq. 4 are set to zero following the model assumptions.

The calculation of electrical conductivity are from Pikelner (1966). It also includes calculations of Spitzer conductivity of electrons as well as evaluation of Chandrassekhar function. The additional changes have been made in the block which solves hydrostatic equation making it possible to compute magnetic force during the solution of hydrostatic equation (thus implementing self-consistent solution).

The critical issue is the determination of induced $E_{\rm eq}$. It is to note that this is a free parameter of the model we are considering and there is no way to derive its exact value. However, it is still possible to determine the magnitude of $E_{\rm eq}$. From the Maxwellian equation

$$\nabla \times \boldsymbol{E} = -\frac{1}{c} \frac{\partial \boldsymbol{B}}{\partial t} \quad (5)$$

one can obtain the following approximated expression:

$$E_{\rm eq} \sim \frac{R\, B_{\rm eq}}{ct}, \quad (6)$$

where R is the stellar radius, $B_{\rm eq}$ is the magnetic field strength at the magnetic equator and t is the characteristic decay time of the magnetic field. Introducing typical A0 star parameters and surface field of 10 kG one has $E_{\rm eq} \approx 10^{-13} - 10^{-10} cm^{-1/2} g^{1/2} s^{-1}$ depending upon life-time at the main sequence, as it was already noted.

3.3. HD 40312

HD 40312 (θ Aur) is a broad-lined A0p star with a comparably weak dipolar magnetic field (Wade et al. 2000). This star shows equatorial regions of its magnetosphere (phases 0.2 and 0.85, see Wade et al. (2000)) such as polar areas (phases 0.0 and 0.5). Also, the magnetic field strength is about 1 kG that is of great importance for our study for it was shown (see Valyavin et al. (2004)) that the maximum of the magnetic field effect on Balmer lines is expected to be for smaller magnetic fields which mostly affect the surface atmospheric layers ($\tau_{\rm Ross} < 1$).

The observations have been carried out with *BOES* echelle spectrograph of the 1.8 *m* telescope of the Korean Astronomy Observatory (*KAO*) in a course of nine observing nights in a period from 10.01.2004 to 10.02.2004. The spectral resolution is R=45 000. The reduction procedures were carried out using the image processing program DECH (Galazutdinov 1992) and MIDAS package. The expected accuracy of the reduction of Balmer line profiles is about 0.2 – 0.3%.

The parameters of the θ Aur atmosphere are: $T_{\rm eff}$=10 400 K, $\log g$=3.6, $\upsilon \sin i$=55 kms^{-1}. First, we investigated the influence of individual abundances on line shape of hydrogen lines. For this purpose we took the phase-dependent abundances from the work of Kuschnig et al. (2004) which were derived using Doppler Imaging technique. A set of model atmospheres with the abundances

Table 1. Phase-dependent abundances of θ Aur

phase	He	Mn	Si	Cr	Fe
0.00	-2.32	-5.28	-3.35	-5.12	-3.86
0.25	-2.32	-5.27	-3.27	-5.35	-3.86
0.50	-2.40	-5.35	-3.09	-4.99	-3.63
0.75	-2.32	-5.50	-3.22	-4.75	-3.69

listed in Table1 has then been calculated. To make sure that the abundances do not significantly affect hydrogen line shapes, we have also calculated the same set of models but with the scaled abundances by a factor of 0.5 dex (including helium). We found that the maximum effect which can be introduced by phase-dependent abundances does not exceed 1% even when the scaled abundances are used. This thus allowed us to use averaged (over all four phases) abundances in the model atmosphere calculations.

Next, we computed new set of model atmospheres calculating the Lorentz force for each phase. The calculations were carried out implementing both dipole and dipole+qudrupole configurations. Since LLModels implements 1-D plane-parallel configuration, all the calculations were carried out at the center of the star disk. It is to say that such an approach is far from the realistic account of the magnetic force, but at this stage of our investigation we are only trying to answer the question of does such effect take place in real magnetic stars and if so how strong could be the currents distributed over the stellar surface.

The preliminary results of our modelling are presented in Fig.4 where both H_α and H_β line profile variations are shown. As one can see, neither dipole nor dipole+quadrupole magnetic field configurations are able to explain the shape of the effect observed. The possible explanations can be addressed to the limitations of 1-D models and the need to provide a precise disc integration over the stellar surface. Also, it should be noted that the surface magnetic field could not be explained by any axisymmetrical configuration at all. In this case (and still ignoring stellar rotation, meridional circulations and other dynamical effects) the field is no longer force-free and then there would be a combination of the other processes which are able to produce noticeables magnetic forces and thus requires, as an extreme case, self-consistent 3-D MHD calculations. Another possibility is to implement Magnetic Doppler Imaging routines in order to reproduce the surface magnetic field configuration with the high resolution. The later one requires high-resolution observation in all four Stokes parameters and has been implemented only for a few stars.

4. Conclusions

In this work we have studied the influence of Zeeman splitting on model structure and other characteristics of magnetic CP stars. We have achieved a new level of accuracy of the calculation of magnetic stellar model atmospheres. The open question is still the precise calculation of radiative transfer equation for all four Stokes parameters taking into account individual magnetic field configurations and thus refusing from the horizontal magnetic field approximation. This work is almost finished in the new version of LLModels code.

The effects of the Lorentz force in the stellar atmospheres was investigated using the suggestion of Landstreet (1987) and theoretical calculations of Valyavin et al. (2004). The first results clearly show variation of H-lines profiles while the numerical modelling is not able to explain this variation by neither dipole nor dipole+quadrupole configurations of the magnetic field. The possible reasons can be associated with some dynamical effects (rotation, diffusion in the presence of magnetic field, etc.) as well as with the significant role of the Hall's current which is expected to be important in the atmosphere of θ Aur (see Fig.1 in Valyavin et al. (2004) and explanation in the text).

Finally, we hope that this work will stimulate 3-D self-consistent MHD calculations of magnetic Ap and Bp stars and development of such software.

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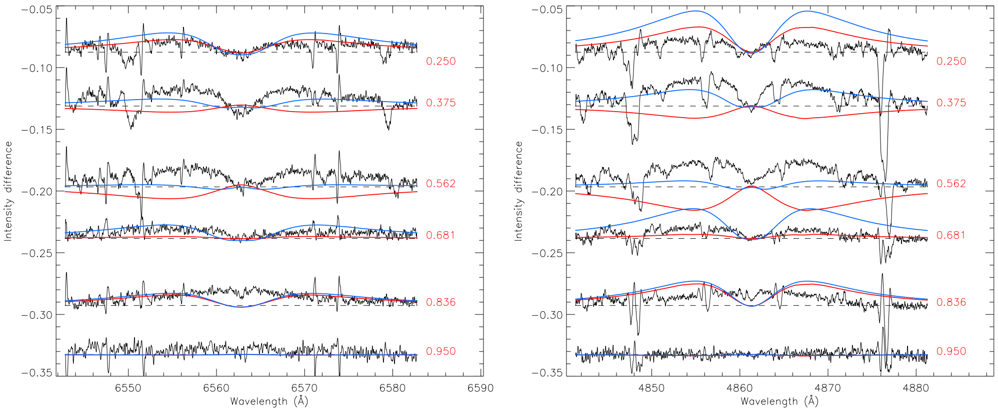

Fig. 4. H_α (left figure) and H_β (right figure) profile variations during the rotational period. Black curve – observations (difference between line profile at the given phase and phase 0.05), red curve – synthetic spectra for model with dipolar configuration and $E_{\rm eq} = 5 \times 10^{-11}$ CGS, blue curve – dipole+quadrupole configuration and $E_{\rm eq} = 4 \times 10^{-11}$ CGS.

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