Contrib. Astron. Obs. Skalnaté Pleso **38**, 267 – 272, (2008)

Model atmospheres of magnetic and chemically peculiar stars

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Received: November 30, 2007; Accepted: December 10, 2007

Abstract. The recent results of the theoretical analysis of the model atmospheres of magnetic and chemically peculiar stars are presented. All the calculations are based on the direct opacity sampling technique, and account for the anomalous Zeeman effect and polarized radiation transfer (i.e. full Zeeman treatment). The study includes analyses on the model atmosphere structure, energy distribution, photometric colors, etc., and investigates the role of the magnetic field (its strength and inclination) as well as different chemical compositions (abundance patterns) on the stellar model atmospheres.

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

1. Introduction

A fraction of at least 25% (Schneider, 1993) of the upper main sequence stars is known as spectroscopically peculiar stars. Their spectra show anomalously strong (or weak) absorption lines of some chemical elements in comparison to those of normal stars with the same fundamental parameters. These stars are often called chemically peculiar (CP) stars, implying that unusual chemical composition (element abundances) rather than other causes is responsible for the spectrum anomalies. Consequently, this means that abundances in the atmospheres of CP stars are substantially different (enhanced or depleted) compared to the solar ones.

Moreover, for magnetic CP stars, the magnetic field influences the formation of spectral lines in their atmospheres due to the anomalous Zeeman effect. Spectral lines split into a number of components, increasing the line absorption and the line equivalent width, which is known as the magnetic intensification effect. Hundreds of thousands of lines modify the line opacity, and then change the model atmosphere structure (due to the backwarming effect), as well as modifying the outgoing radiation. The magnetic line blanketing in stellar atmospheres is supposed to be responsible for observable characteristic features of magnetic CP stars, for instance flux depressions (Kodaira, 1969) in the visual spectrum, and flux redistribution from UV region to the visual (Leckrone, 1973).

The development of improved model atmospheres for CP stars is an extremely important task for understanding the nature of features of CP stars. Model atmospheres are used for a variety of stellar astrophysics problems in application to CP stars: fundamental parameters determination, abundance analysis, stellar magnetic field geometry research, detailed line profile study (including the full treatment of the Zeeman effect), and stellar surface properties reconstruction. An enormous part of this work is currently being performed using classic model atmospheres.

In the following sections we briefly summarize main results of the recent papers Khan and Shulyak (2006 a), Khan and Shulyak (2006 b) and Khan and Shulyak (2007).

2. Magnetic line blanketing

We calculated a grid of model atmospheres of magnetic A and B stars for different effective temperatures, metallicities, strengths of the magnetic field and different angles of its inclination to the atmosphere plane. We have used this grid to analyze the behaviour of the model atmosphere structure and the observables for variety of fundamental modelling parameters. The LLModels code (Shulyak *et al.*, 2004) was used throughout the studies.

We found that the model atmospheres with magnetic line blanketing produce fluxes that are deficient in the UV region, and the presence of the magnetic field leads to the flux redistribution from the UV to visual region. This property of the theoretical models is in agreement with observations of CP stars.

We also investigated the most prominent feature of CP stars in the visual region, the flux depression centered at 5200 Å. Our numerical results show that the magnitude of the feature near 5200 Å depends strongly on magnetic field strength, $T_{\rm eff}$ and metallicity. The depression grows with increasing magnetic field strength and metallicity. However, for higher effective temperatures the magnitude of the depression for overabundant models becomes smaller, while the sensitivity to the magnetic field strength appears almost negligible.

In order to study the flux depression around 5200 Å more carefully we examined the influence of the magnetic field on the photometry observables, in particular, photometric peculiarity parameters Δa, Z and $\Delta(V_1 - G)$, that are sensitive in this spectral region. The changes of peculiar parameters due to the influence of the magnetic field are noticeable for low effective temperatures, whereas for hotter stars sensitivity to the magnetic field is reduced considerably, and the relation between B and the peculiarity index depends on metallicity.

The relation between values of peculiar parameters and the magnetic field strength is not linear due to the saturation effects for stronger fields ($B > 10\,{\rm kG}$), except Δa which appears to have approximately linear dependance on magnetic field strength from 5 to 40 kG for $T_{\rm eff} = 8000\,{\rm K}$.

We have not found any significant changes in model atmosphere structure, photometric indices, the energy distribution and profiles of hydrogen Balmer lines that depend on the magnetic field inclination angle Ω. It appears that the magnetic field strength is the main factor to affect the line blanketing, and the variation of the scaled abundances clearly has a more pronounced effect on model atmospheres than variation of the field inclination angle.

Also we note that in general, the magnetic fields of Ap stars are considered to be dipoles to first order. The field intensity for a dipolar field is twice as strong at the poles as at the equator. Essentially all studies using longitudinal field and surface field measurements have found that the fields deviate from a dipole – that one pole is stronger than the other (that a quadrupolar component is required) and often that the pole-to-equator variation of the field strength is not as strong as that of a dipole (an octupolar component is required) (e.g. Landstreet, Mathys 2000). Consequently, a typical range of field intensity variation over the surface of Ap stars is probably about 30–40%. Thus, we suppose that a single model atmosphere calculated using the observable mean surface magnetic field strength B_s as an input model parameter seems to be reliable (say, for routine abundance analysis of magnetic Ap stars).

3. Individual abundance patterns

We have computed and analyzed a grid of model atmospheres of chemically peculiar stars. The main purpose was to perform a systematic homogeneous analysis of the effects of the individual abundance patterns on the model atmosphere structure, energy distribution, photometric indices (in the $uvby\beta$ and Δa systems), hydrogen line profiles, and on an abundance determination procedure.

The grid of model atmospheres consists of more than 300 models and represents the following types of stars: CP1 (Am stars), CP2 (Si, Cr-Sr-Eu A and B stars), CP3 (Hg-Mn, B-type stars) and CP4 (He-weak, B-type stars). All models were calculated with the LLModels code (version 8.4) assuming no magnetic field and no convection to highlight abundance effects only. Consequently, we considered model atmospheres with different chemical composition and compare them to the reference models with solar abundances.

The majority of the tested chemical elements (within the limits of abundance values considered) produce less than 1% variations in the model atmosphere temperature profile and fall into the small changes group. These elements are He, C, N, O, Mg (deficient), Ca, Sr, Eu, Hg. According to the results, a 1% limit was adopted as the error bar threshold.

Several elements were assigned to the moderate changes group in accordance with the effects they produce on the model atmosphere structure (1–3%) and the energy distribution. These elements are Mn, Ni, Mg (enhanced).

The group of elements which produce large changes in the model atmosphere structure (more than 3%) and energy distribution consists of Si, Cr, Fe and scaled abundance patterns.

If we consider changes in the temperature structure produced by the elements Si, Cr and Fe in the main line forming region then we find that the sequence of Fe-Si-Cr represents these elements from the most to the least influential.

Model atmospheres peculiar in Cr, Mn and Fe demonstrate a very similar, highly organized, temperature behaviour. There are two distinct cooling and heating regions in the upper and the lower (i.e. the main line forming region) atmosphere, respectively. As the abundance value grows, the temperature drops in the upper atmosphere and increases in the lower atmosphere. The inflection point which separates these two regions moves outwards with growing $T_{\rm eff}$. The magnitude of the heating region steadily grows with increasing $T_{\rm eff}$ excluding the lowest value of 8000 K. The same effects, except for the cooling region feature, apply to models with scaled abundances as well.

The reason why Cr, Mn and Fe demonstrate such behaviour is likely the similarity of their energy level configurations (and the corresponding spectral line distribution patterns), and their relatively high content in the atmosphere.

We concluded that the elements Si and Fe are the main providers of two different types of the temperature changes to produce the same distinctive temperature structure that model atmospheres with scaled abundances do. In other words, the temperature structure of a model atmospheres peculiar only in Si and Fe may be close to the temperature profile of a models with scaled abundances. The agreement is quite good for low effective temperatures, while for high effective temperatures ($T_{\rm eff} > 11\,000$ K) the cumulative effect of all other chemical elements is required. We suspect that overabundant C, Mg and Ca are of the most significance.

We confirm that model atmospheres with scaled abundance patterns can not be used to simulate accurately effects of the individual abundance patterns.

We found that Fe is the principal contributor into the 5200 Å depression for the whole range of effective temperatures, while Cr and Si are important primarily for low effective temperatures.

The analysis of the diagram of the peculiarity index a vs. $b-y$ for the model atmospheres peculiar in Si, Cr and Fe revealed regular patterns in the locus of points representing those models. In fact, there are three separate directions (axes) associated with the growing content of each element on the diagram. The inclination of the Fe-axis to the normality line a_0 and the fact that it does not depend on the effective temperature clearly demonstrate that Fe is indeed the key element to the fundamental property of the Δa system to recognize CP stars with overabundant ($\Delta a > 0$) and underabundant ($\Delta a < 0$, i.e. for λ Bootis stars) Fe-peak elements in their atmospheres.

We investigated an abundance analysis procedure based on theoretical atmospheres with individual abundance pattern using models with scaled solar composition and spectral lines in the visual region. We find that the error bar of the analysis, which occurs in the context of the ideal conditions of a theoretical study, is of order 0.25 dex, and that the particular error value depends on the model atmosphere being used for such analysis, and varies for different effective temperatures.

Considering the results of our numerical experiments as they apply to the stratification analysis using homogeneous model atmospheres, we conclude that uncertainty of the value of the vertical abundance gradient is within an 0.4 dex error bar. That, of course, does not eliminate the phenomena of the abundance stratification in the atmospheres of CP stars, however it can effectively increase or decrease the gradient value deduced from the observations.

4. Conclusions

Model atmospheres with individual abundance patterns including magnetic field effects can be routinely calculated. Such models should be used in order to match the actual anomalies of CP stars and minimize analysis errors. See for example Shulyak *et al.* (2008).

Acknowledgements. This work was supported by a Postdoctoral Fellowship to S.K. at UWO funded by a Natural Science and Engineering Council of Canada Discovery Grant and by FWF Lisa Meitner grant Nr. M998-N16 to D.S.

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