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Stellar atmospheres with full Zeeman treatment

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Abstract. A new model atmosphere program for magnetic chemically peculiar stars with non-homogeneous vertical distributions of the various chemical elements is presented. This code is based on the line synthesis code Cossam and uses Atlas12 continuous opacities. The findings are compared with the results of other groups.

Key words: stars: chemically peculiar – stars: atmospheres – stars: magnetic fields – methods: numerical – polarisation

1. Introduction

Modelling CP2 stars harbouring magnetic fields with standard Atlas-like codes (Kurucz, 1970) is problematic since such models cannot account for magnetic fields and stratification. Among the requirements for a model atmosphere program for CP2 stars are that it has to work well in the temperature range of interest ($T_{\rm eff}$ ranging from 7000 to 15 000 K) and that it should take into account peculiar and stratified abundances as well as magnetic fields with an arbitrary strength and inclination. The formal solution to the RTE must deal with all 4 Stokes parameters and the hydrostatic equilibrium should allow for magnetic pressure. To counteract the missing opacity problem a comprehensive and recent line list has to be used.

2. Code details

Camas[1] is a newly developed thread-parallel, modularised, object oriented Ada95 code for CP2 stars that uses the Atlas12 continua (Kurucz, 1996) for comparability with standard models. Camas is written in Ada, like M. J. Stift's polarised spectral synthesis code Cossam (Stift, 2000) and M. J. Stift's radiative diffusion code Carat (Alecian, Stift 2002). One of the aims of Camas is to provide a model atmosphere program that is consistent with the existing codes and that allows verbatim software reuse on a large scale. Apart from this consistency issue, Ada95's strong typing, exception handling, easy implementation of parallel processing, modularity mechanisms, generic programming and object orientation proved to be very useful in the context of the development of this model atmosphere program.

[1] Camas is an acronym for "codice per le atmosfere magnetiche stellari".

To make the models feasible, some simplifications had to be made: the models are plane parallel and no dynamic phenomena are considered. Up to now only an interface for a magnetic pressure routine has been included but a model for the magnetic pressure is still missing.

The input models were taken from the Castelli and Kurucz ODFnew grid (Castelli, Kurucz 2004) and the line list is a full extract from the VALD database (Kupka *et al.*, 2000) and includes the computed as well as the measured lines. While it is crucial for spectral synthesis to select high quality lines, it is preferable to include all available data for atmosphere models since in this case the total opacity matters most.

2.1. Polarised radiation transfer

The vector transfer equation for polarised light can be written as

$$\frac{d}{dz}\mathbf{I} = -\mathbf{K}\,\mathbf{I} + \mathbf{K}\,(S,0,0,0)^{\dagger}. \tag{1}$$

The parameter z is the vertical position in the stellar atmosphere, $\mathbf{I}$ is the Stokes vector. The absorption matrix $\mathbf{K}$ contains line and continuum opacities: $\mathbf{K} = \kappa_c\,\mathbf{1} + \kappa_{\rm o}\,\Phi$. The expression $\kappa_c\mathbf{1}$ stands for the continuum opacity times the unit 4x4 matrix, $\kappa_{\rm o}$ denotes the line centre opacity for zero damping and zero magnetic field and Φ is the line absorption matrix.

In the presence of magnetic fields, the opacity is enhanced due to the Zeeman effect. To compute this enhancement, not only the magnetic field strength but also the geometry of the magnetic field has to be considered. The orientation of the magnetic field enters Eq. 1 via the line absorption matrix (Φ), which depends on the azimuth and the inclination of the magnetic field vector relative to the pencil of light. Details of the angle dependence of the line absorption matrix can be found in Alecian and Stift (2004).

Camas models can handle magnetic fields of arbitrary direction. Fields perpendicular to the plane parallel layers of the model need less computation time than fields with components in this plane. In the former case, the opacities are constant in the horizontal plane due to the symmetry around the z-axis, which makes an integration in azimuth unnecessary. If the field is not perpendicular to the plane parallel layers, six different azimuths are used for the integration.

The models presented here have four angle quadrature points in $\mu = \cos\theta$ because Alecian and Stift (2002) and later Khan and Shulyak (2006 b) showed that this number of angle quadrature points is sufficient.

2.2. Zeeman Feautrier solver

As shown in Alecian and Stift (2004), it is possible to generalise the Feautrier equation to the magnetic case in the presence of blends. The polarised Feautrier equation can be derived from

$$\frac{d\boldsymbol{J}}{d\tau_{5000}} = \mathbf{X}\boldsymbol{H} \text{ and } \frac{d\boldsymbol{H}}{d\tau_{5000}} = \mathbf{X}(\boldsymbol{J}-\boldsymbol{S}) \text{ with } \mathbf{X} := \frac{\mathbf{K}}{\kappa_{5000}\mu}. \tag{2}$$

It can be written as

$$\frac{d}{d\tau_{5000}}(\mathbf{X}^{-1}\frac{d\boldsymbol{J}}{d\tau_{5000}}) = \mathbf{X}(\boldsymbol{J}-\boldsymbol{S}). \tag{3}$$

The boundary conditions (BC) are similar to the nonmagnetic case. It turned out that the best solution is a surface BC taken from the textbooks of Mihalas and a lower BC taken from the Multi code (Carlsson, 1995).

The Feautrier scheme's system of N equations with N unknowns can be solved in a standard way, however, the method of Rybicki and Hummer (1991) is useful to improve the numerics.

2.3. Temperature correction

The temperature correction scheme of Camas is an adaption of Dreizler's Unsöld-Lucy scheme (Dreizler, 2003) for polarised radiation. Both schemes use two flux criteria: the local balance of emitted versus absorbed energy

$$\frac{d(H_I)_z}{d\tau_{5000}} = 0 \text{ (energy conservation)}, \tag{4}$$

and the nonlocal condition of constant flux

$$\int_0^\infty \oint H_I \mathrm{d}\Omega \mathrm{d}\nu - \frac{\sigma}{4\pi}T_{\text{eff}}^4 = 0 \text{ (given value for the total flux)}. \tag{5}$$

The correction based on the local energy conservation cannot be used in deep layers where the atmosphere becomes diffusive, whereas the correction based on the surface flux and the global energy conservation are inefficient in regions with small opacities. derived from the local energy conservation has an impact on the surface layers whereas the corrections from the global energy conservation and the surface flux are also effective in deeper layers. The generalised temperature corrections are:

$$\begin{aligned}\Delta T \;=\; & \frac{\pi}{4\sigma T^3}\Bigg(\underbrace{d_1\Bigg(\frac{S\int_0^\infty[\mathbf{K}_\nu \boldsymbol{J}_\nu]_I \mathrm{d}\nu}{\int_0^\infty[\mathbf{K}_\nu]_{I,I} S_\nu \mathrm{d}\nu} - S\Bigg)}_{\text{local energy conservation}} + \underbrace{d_2\frac{S\int_0^\infty[\mathbf{K}_\nu \boldsymbol{J}_\nu]_I \mathrm{d}\nu}{J_I\int_0^\infty[\mathbf{K}_\nu]_{I,I} S_\nu \mathrm{d}\nu}\frac{f_0\Delta H_I(0)}{fg}}_{\text{surface flux}} \\ & + \; d_3\frac{S\int_0^\infty[\mathbf{K}_\nu \boldsymbol{J}_\nu]_I \mathrm{d}\nu}{J_I\int_0^\infty[\mathbf{K}_\nu]_{I,I} S_\nu \mathrm{d}\nu}\frac{1}{f}\underbrace{\int_0^\tau \frac{\int_0^\infty[\mathbf{K}_\nu \boldsymbol{H}_\nu]_I \mathrm{d}\nu}{H_I\kappa_{5000}}\Delta H_I \mathrm{d}\tau_{5000}}_{\text{global energy conservation}}\Bigg).\end{aligned} \tag{6}$$

Here the differences between the equilibrium flux and the flux in the model are denoted as $\Delta H = H_{\text{Equilibrium}} - H_{\text{Model}}$. The subscript I stands for the Stokes I component and d_1 to d_3 are damping constants.

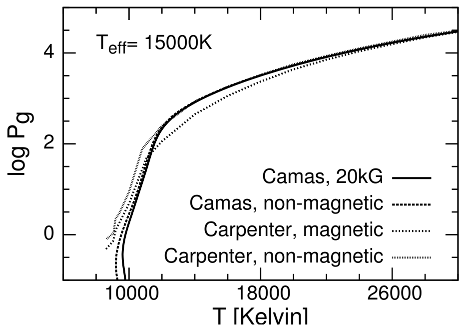

Figure 1. Carpenter's magnetic model and models without magnetic pressure.

3. Results and comparisons

Comparing the CAMAS models to models taken from literature can help to shed light on the impact of the enhanced line blanketing and the magnetic pressure.

3.1. Comparison with Carpenter's results

Carpenter's program (Carpenter, 1983; 1985) is based on ATLAS6 and deploys ODFs instead of dOS. It makes a phenomenological approach to the magnetic pressure. The differences near the "knee" in Fig. 1 are interpreted as a manifestation of lower gas pressure due to the inclusion of magnetic pressure in the hydrostatic equilibrium. This result shows the importance of the magnetic pressure. Moreover Shulyak *et al.* (2007) showed that modelling this pressure leads to a better fit of the observed hydrogen line profiles.

Carpenter's magnetic model displayed in Fig. 1 is a model near the magnetic equator of the star whereas the models without magnetic pressure correspond to models near the poles. The Camas models without magnetic pressure have gas pressures similar to the nonmagnetic models of Carpenter.

3.2. Comparisons with LLMODELS

The versions of LLMODELS with published models (see Kochukhov *et al.*, 2005; Khan, Shulyak 2006 a, b) did not include the magnetic pressure, therefore they are expected to be similar to the pole-models of Carpenter as well as the CAMAS models. As a comparison of the CAMAS results to the results of Kochukhov *et al.* (2005), the differences between the fieldless and the "isotropic" model are shown on the left side in Fig. 2. The so called "isotropic" model does not include the geometry of the field. It assumes that the magnetic field is always perpendicular to the pencil of radiation instead of carrying out the correct 2D angle integration.

The counter-intuitive result of a decrease of pressure combined with an increase of the temperature in the $\tau_{\rm ross}$ plots in Fig. 2 is caused by the depth scale

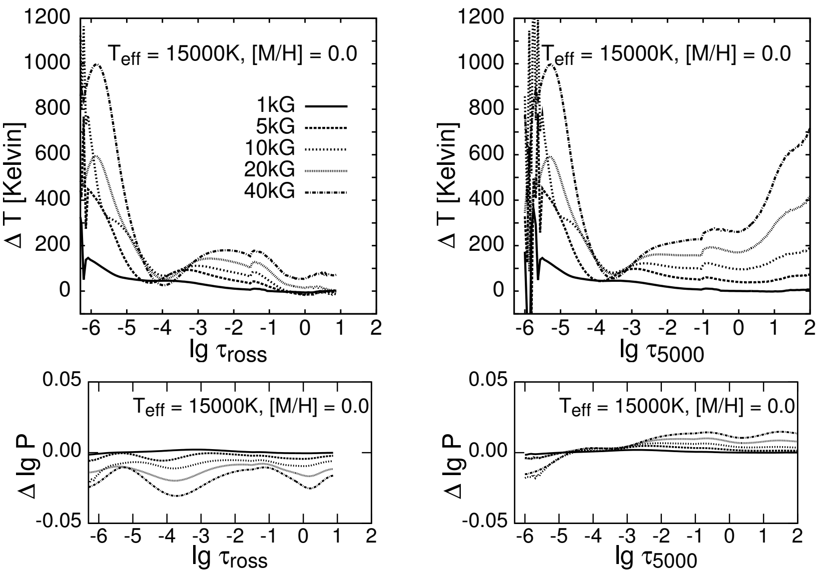

Figure 2. The $\tau_{\rm ross}$ plots confirm the results shown in Fig. 1 and Fig. 2 in Kochukhov *et al.* (2005). On the right hand side a monochromatic depth scale is used.

which also depends on the opacity. This becomes obvious if τ_{5000}, which is not directly affected by (magnetic) line blanketing, is used instead of the directly affected $\tau_{\rm ross}$. On the τ_{5000} scale the pressure behaves as expected.

Recent LLmodels results allow for the full geometry of the problem. At high field strengths, the differences between the anisotropic and the "isotropic" model presented in Khan and Shulyak (2006 b) behave differently from what is found for the models shown in Fig. 3. Here the same trend is found for weak and strong fields, whereas the sign of the trend in the LLmodels results changes.

4. Conclusions

The results of all three codes show clearly that the enhanced opacity due to the Zeeman splitting has an effect on the model's temperature structure, as presented in Fig. 2 and Fig. 3. Camas essentially confirms the results of LLmodels. The isotropic models are quite similar. A detailed investigation of the differences in the anisotropic case is ongoing.

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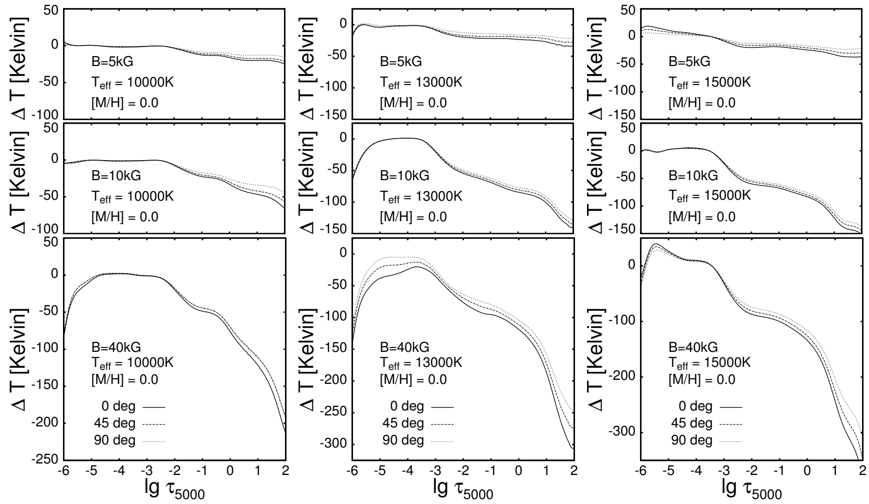

Figure 3. The differences between the anisotropic and the "isotropic" CAMAS models show the same trend for all magnetic field strengths.

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