Magnetic field effects in atmospheres of CP stars: models and results

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### General Signatures of CP Stars

<table>
<thead>
<tr>
<th>Anomalous Abundances</th>
<th>Surface and vertical stratification of chemical elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide Range of Effective Temperatures</td>
<td>$T_{\text{eff}} = 6500 , \text{K} - 25000 , \text{K}$</td>
</tr>
<tr>
<td>Strong Magnetic Fields</td>
<td>$\sim 100 , \text{G up to } \sim 30 , \text{kG}$</td>
</tr>
<tr>
<td>Flux Depressions</td>
<td>Flux depressions in the visual [ UV \text{ flux deficiency} ]</td>
</tr>
</tbody>
</table>
Photometry

Photometric calibrations do not work for CP stars due to unusual energy distribution (stratification + magnetic fields)

Model Atmosphere

Line blanketing effect has to be calculated in detail to ensure accurate model structure \(\Rightarrow\) ODF and “classical” OS methods do not work properly for CP stars

Solution

A new code was needed to fight with peculiar stars and to improve our understanding about the structure of their atmospheres
Part I

LLmodels
Shulyak et al. (2004)

More or less accurate line profiles representation of ALL lines
$N(\nu) = 500\,000 \div 700\,000$
sampling window $= 5\,\text{Å}$
Basic Structure

- **Base:** ATLAS9 (Kurucz, 1993), ATLAS12 (Kurucz, 1994), STARSP (Tsymbal, 1996)
- Fortran 90/95 module structured programming including OOP simulation
- Dynamical memory allocation/deallocation
- **Platforms supported:** Linux, Windows, Mac OSX
Basic Assumptions

- Plane-parallel geometry
- LTE level populations
- Hydrostatic and radiative equilibria
- No large-scale dynamical flows along stellar surface
- No molecular opacity
**Lines Atomic Data**

- R.L. Kurucz (CDROM-1,1993)
  - lowlines.dat (~ 31 mln. of lines, ions I-V)
  - hilines.dat (~ 10 mln. of lines, ions VI-IX)
  - nltelines.dat (39572 lines, H, He, C, Na, Mg, Al, Si, etc.)
- VALD
  - Experimental + predicted atomic data (~ 22 mln. of lines)

**Line Preselection Procedure**

Preselection criterion: \( \frac{\alpha_{0}^{\text{line}}}{\kappa_{\text{cont}}} \geq x \), usually \( x = 1\% \)

Dynamic preselection method (different regimes are possible)
General Methods: Hydrostatic Equation

\[
\frac{d \ln P_{\text{total}}}{d \ln \tau_{\text{ref}}} = \frac{g \tau_{\text{ref}}}{\kappa_{\text{ref}} P_{\text{total}}}, \quad P_{\text{total}} = P_{\text{gas}} + P_{\text{rad}} + P_{\text{turb}} + P_{\text{mag}}
\]

\(\tau_{\text{ref}}, \kappa_{\text{ref}}\): either Rosseland opacity scaling or monochromatic scaling (usually at \(\lambda = 5000 \text{ Å}\))

Standard Hamming’s predictor-corrector scheme
General Methods: Convection

Mixing-Length Theory (MLT)

Based on local pressure scale height:

\[ H_p = \frac{P_{total}}{\rho g} = \frac{1}{\alpha} \]

\( \alpha \) has to be tuned for different stars

Application: cool stars atmosphere with strong convection regime

CM convection

Canuto & Mazzitelli (1991, 1992) – further improvement of convection model: no need for such free parameter as \( \alpha \) any more

Application: atmospheres of A–F stars with weak convection regime
General Methods: Radiative Transfer

Matrix Operator Method (Kurucz, 1970)

\[
[J, H, K]_\nu^{(1,2,3)} = \frac{1}{2} \int_0^{\tau_\nu} S_\nu E_{1,2,3}(\tau_\nu - t) dt + \frac{1}{2} \int_{\tau_\nu}^{\infty} S_\nu E_{1,2,3}(t - \tau_\nu) dt
\]

Standard Feautrier Scheme (Mihalas, 1982)

\[
\mu^2 \frac{\partial^2 u_{\mu,\nu}}{\partial \tau_\nu^2} = u_{\mu,\nu} - S_\nu
\]

Quadratic DELO (Rees et al., 1989)

\[
\mu \frac{dI}{dm} = K I - j, \quad I = (I, Q, U, V)^\dagger, \quad K = \kappa_c 1 + \sum_{\text{lines}} \kappa_0^{\text{line}} F_{\text{line}}
\]
General Methods: Convergence

- Optically thick layers
  
  \[(H_{\text{rad}} + H_{\text{conv}}) - \sigma T_{\text{eff}}^4 = 0\]

- Optically thin layers
  
  \[\int \kappa_\nu J_\nu d\nu - \int \kappa_\nu S_\nu d\nu = 0\]

Convergence criteria:

1. \(\varepsilon(\text{flux}) \leq 1\%\)
2. \(\varepsilon(\text{rad. equilibrium}) \leq 1\%\)
3. \(\Delta T_i \leq 1\, \text{K at each layer}\)
LLmodels run on iMac

Magnetic field effects in atmospheres of CP stars
Advantages of LL Method

- Provides more realistic description of model structure
- High dynamical range in opacity
- No precalculated opacity tables are used
- Models with individual and stratified abundances
- Models with magnetic fields effects included
- Fast computational speed without parallel computing
Stratification Modeling

**Self-Consistent Diffusion Models**
Solution of diffusion equations taking into account microscopic properties of plasma to determine particles net flux

**Empirical Models**
Deriving stratification profiles directly from observed line profiles to be compared with diffusion models
Stratification Modeling

**Empirical Models**
Deriving stratification profiles directly from observed line profiles to be compared with diffusion models

**Role of LLmodels**
So far, stratification is considered as input parameter in LLmodels
Stratification from observations ⇒ LLmodels calculation ⇒ re-deriving stratification from observations + adjusting model parameters ⇒ LLmodels calculation ...
Methods of Empirical Analysis

Step Function Approximation (after J. Babel 1992)
Code DDAFIT written by O. Kochuchov (Ryabchikova et al. 2005)
Least-square fit of observed line profiles adjusting amplitude and position of abundance jump

Solution of Vertical Inverse Problem (VIP) (Kochukhov et al. 2006)
Modified Levenberg-Marquardt minimization algorithm with Tikhonov regularization
Theoretical Fit

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Examples of Fe and Cr stratifications

![Graphs showing Fe and Cr stratifications with various lines and labels for different stars.](image)
Element Distributions in HD 24712
Importance of REE Stratification

![Graph showing temperature vs. logarithm of optical depth for homogeneous and stratified models.](image)

- **t2750g4.3 homogeneous**
- **t2750g4.3 stratified**

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Connection with Observations (Kochukhov et al, 2002)

**Hβ**

- Residual intensity versus wavelength (Å) for different stars:
  - HD 216018
  - HD 166473
  - HD 965
  - HD 217522
  - HD 101065

**T vs. log τ_{5000}**

- Temperature (T) versus log of the optical depth (τ_{5000}) for different stars:
  - HD 216018
  - HD 166473
  - HD 965
  - HD 217522
  - HD 101065

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Part II

Magnetic Models
Magnetic Field Effects

Anomalous Zeeman Splitting
Additional opacity produced by Zeeman components

Polarization of Electromagnetic Radiation
Differences in total flux in each direction and depth

Magnetic Pressure
Reexamines hydrostatic equilibrium of stellar plasma

Drift of Charged Particles
The result of the presence of different forces in the atmosphere
Magnetic Field Effects

- Anomalous Zeeman Splitting
  Additional opacity produced by Zeeman components

- Polarization of Electromagnetic Radiation
  Differences in total flux in each direction and depth

- Magnetic Pressure
  Reexamines hydrostatic equilibrium of stellar plasma
Parameters of the Models

Models Grid
- $T_{\text{eff}} = 8000\, \text{K}, 11000\, \text{K}, 15000\, \text{K}$
- $\log g = 4.0$
- $[M/H] = 0.0, +0.5, +1.0$
- $B = 0, 1, 5, 10, 20, 40\, \text{kG}$
- $\Omega = 0^\circ, 45^\circ, 90^\circ$

Calculation Settings
- $\log \tau_{\text{Ross}}$ between $+2$ and $-6.875$ using 72 layers
- Spectral region from $100 - 500\, \text{Å}$ to $30000 - 50000\, \text{Å}$
- Without convection and microturbulence
Temperature Structure

Legend

- 1 kG
- 5 kG
- 10 kG
- 20 kG
- 40 kG

\[ \Delta T \text{ vs. } \log \tau_{\text{Ross}} \]

- [M/H] = 0.0
  - \( T_{\text{eff}} = 8000\text{K} \)
  - \( T_{\text{eff}} = 11000\text{K} \)
  - \( T_{\text{eff}} = 15000\text{K} \)

- [M/H] = 0.5
  - \( T_{\text{eff}} = 8000\text{K} \)
  - \( T_{\text{eff}} = 11000\text{K} \)
  - \( T_{\text{eff}} = 15000\text{K} \)

- [M/H] = 1.0
  - \( T_{\text{eff}} = 8000\text{K} \)
  - \( T_{\text{eff}} = 11000\text{K} \)
  - \( T_{\text{eff}} = 15000\text{K} \)
Energy Distribution

Legend
- 0 kG
- 10 kG
- 40 kG

$T_{\text{eff}} = 8\,000$ K, $[\text{M/H}] = +0.5$

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Energy Distribution and Numerical Results

HD 137509

Zeeman Splitting and Polarized RT
Lorentz Force
Energy Distribution

**Legend**
- 0 kG
- 10 kG
- 40 kG

\[ T_{\text{eff}} = 15\ 000\ \text{K},\ \lbrack M/H\rbrack = +0.5 \]
Synthetic Colors

Legend

- $[M/H]=+0.0$
- $[M/H]=+0.5$
- $[M/H]=+1.0$
- $[M/H]=+1.0$
- $[Cr]=+2.0$

Synthetic Colors

- $T_{\text{eff}} = 8000K$
- $T_{\text{eff}} = 11000K$
- $T_{\text{eff}} = 15000K$

Magnetic field effects in atmospheres of CP stars
Hydrogen Lines

Legend

- 5 kG
- 10 kG
- 40 kG

$H_\beta$ Profiles for $[\text{M/H}]=+0.5$

- $T_{\text{eff}} = 8000$ K
- $T_{\text{eff}} = 11000$ K
- $T_{\text{eff}} = 15000$ K

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Magnetic field effects in atmospheres of CP stars
Pseudo-Microturbulent Models

General Expression

Muthsam 1979, Kupka et al. 2004:
\[ \xi_{\text{mag}} = 4.66 \times 10^{-13} c \lambda g_{\text{eff}} B \]
\[ g_{\text{eff}} = 1.0 - 1.2, \lambda = 5000 \text{Å} \]

Suggested Consistency

\[ \xi_{\text{mag}} = 4 \text{ km s}^{-1}, B \approx 5 \text{ kG} \]
\[ \xi_{\text{mag}} = 8 \text{ km s}^{-1}, B \approx 10 \text{ kG} \]

The Effect

- The exact match requires different \( \xi_{\text{mag}} \) for each quantity
  
  \[ T_{\text{eff}} = 8\,000K \]
  \[ B = 5 \text{ kG} \]
  \[ B = 10 \text{ kG} \]

  T-structure: \[ 2.1 - 2.6 \text{ km s}^{-1} \] and \[ 3.7 - 4.1 \text{ km s}^{-1} \]

  \[ \Delta a (5200\text{Å feature}): 4.1 - 4.6 \text{ km s}^{-1} \] and \[ 6.7 - 7.1 \text{ km s}^{-1} \]

- Models sensitivity to the magnetic line blanketing decreases with \( T_{\text{eff}} \) faster than the influence of microturbulence

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Effect of $\vec{B}$ Inclination: Temperature Distribution

- $T_{\text{eff}} = 8000\,\text{K}$
  - $[M/H] = 1.0$
  - $B = 5\,\text{kG}$
  - Inclination: $0^\circ$, $15^\circ$, $30^\circ$, $45^\circ$, $60^\circ$, $75^\circ$, $90^\circ$

- $T_{\text{eff}} = 11000\,\text{K}$
  - $[M/H] = 1.0$
  - $B = 10\,\text{kG}$

- $T_{\text{eff}} = 15000\,\text{K}$
  - $[M/H] = 1.0$
  - $B = 10\,\text{kG}$

- $T_{\text{eff}} = 8000\,\text{K}$
  - $[M/H] = 1.0$
  - $B = 40\,\text{kG}$

- $T_{\text{eff}} = 11000\,\text{K}$
  - $[M/H] = 1.0$
  - $B = 40\,\text{kG}$

- $T_{\text{eff}} = 15000\,\text{K}$
  - $[M/H] = 1.0$
  - $B = 40\,\text{kG}$
Model Parameters of HD 137509 (Kochukhov 2006)

Main Parameters

ATLAS9 model with \([M/H] = +1\)

\[ T_{\text{eff}} = 12750 \pm 500 \text{ K}, \quad \log g = 3.8 \pm 0.1, \quad < B > = 29 \text{ kG} \]

Preliminary Abundances

<table>
<thead>
<tr>
<th></th>
<th>He</th>
<th>Si</th>
<th>Fe</th>
<th>Cr</th>
<th>Ti</th>
<th>Ca</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>★</td>
<td>−3.5</td>
<td>−3.73</td>
<td>−3.19</td>
<td>−4.20</td>
<td>−4.54</td>
<td>−7.93</td>
<td>−5.71</td>
</tr>
<tr>
<td>☉</td>
<td>−1.1</td>
<td>−4.53</td>
<td>−4.59</td>
<td>−6.40</td>
<td>−7.14</td>
<td>−5.73</td>
<td>−4.51</td>
</tr>
</tbody>
</table>
Hydrogen Lines

Calculation with individual abundance + magnetic field
Increase of log $g$ value from 3.8 to 4.0 is required
Fluxes (ESO UVES pipeline)
### Colors

<table>
<thead>
<tr>
<th></th>
<th>observed</th>
<th>mag+ind. abn.</th>
<th>ind. abn.</th>
<th>scaled-solar abn.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b - y$</td>
<td>-0.095</td>
<td>-0.057</td>
<td>-0.044</td>
<td>-0.026</td>
</tr>
<tr>
<td>$m_1$</td>
<td>0.183</td>
<td>0.141</td>
<td>0.135</td>
<td>0.116</td>
</tr>
<tr>
<td>$c_1$</td>
<td>0.411</td>
<td>0.572</td>
<td>0.586</td>
<td>0.581</td>
</tr>
<tr>
<td>$\Delta a$</td>
<td>0.070</td>
<td>0.054</td>
<td>0.031</td>
<td>0.014</td>
</tr>
<tr>
<td>$X$</td>
<td>0.762</td>
<td>0.937</td>
<td>0.957</td>
<td>0.942</td>
</tr>
<tr>
<td>$Y$</td>
<td>0.076</td>
<td>0.088</td>
<td>0.045</td>
<td>0.032</td>
</tr>
<tr>
<td>$Z$</td>
<td>-0.067</td>
<td>-0.044</td>
<td>-0.029</td>
<td>-0.016</td>
</tr>
</tbody>
</table>

### Conclusion

Magnetic models allows to achieve a better fit to all the observed colors and should be used for spectra analysis of stars with strong magnetic fields.
## Previous Models

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stepien (1978)</td>
<td>Parameterized current distribution + requirement of static equilibrium</td>
</tr>
<tr>
<td>Peterson &amp; Theys (1981)</td>
<td>Radiative diffusion of charged particles</td>
</tr>
<tr>
<td>Hubbard &amp; Dearborn (1982)</td>
<td>Gradient of the toroidal magnetic field</td>
</tr>
</tbody>
</table>
## Previous Observations

<table>
<thead>
<tr>
<th>Madej (1984,1988)</th>
<th>Photometric studies of magnetic and non-magnetic stars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kroll (1989)</td>
<td>Spectroscopy of hydrogen lines</td>
</tr>
</tbody>
</table>

No other systematic spectroscopic surveys have been made

**Reason**

The observational aspect of the problem is too complex and high-resolution observations are needed (required accuracy of H-lines processing is about 0.1%)
General Assumptions

- The stellar surface magnetic field is dominated by dipolar or dipole+quadrupolar force-free component in all atmospheric layers.
- Due to the axial symmetry of the surface field, its evolution creates an electric current with only an azimuthal component, so that $j_\phi \sim P^1_n(\cos \theta)$.
- Static equilibrium of atmospheric layers.
- Stellar rotation, Hall’s currents and ambipolar diffusion are neglected.
Hydrostatic Equation

\[ \nabla P_{\text{total}} = \rho \mathbf{g} + \mathbf{F}_L \]
\[ \mathbf{F}_L = \frac{1}{c} \mathbf{j} \times \mathbf{B} \]

\[ \frac{\partial P_{\text{total}}}{\partial r} = -\rho \mathbf{g} \pm \frac{1}{c} \sigma_\perp \sum_n E^{(n)} \langle 0_1(\mu) \rangle \sum_n B^{(n)} \]

- \( P_{\text{total}} \) — total pressure (gas+radiation)
- \( \mathbf{g} \) — gravitational acceleration
- \( \sigma_\perp \) — electric conductivity across \( \mathbf{B} \)-lines
- \( E^{\text{eq}} \) — electric field intensity at stellar equator

Problems with \( E^{(n)} \)

These are unknown quantities and are free parameters in the model.

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Observations

- A0p star with a weak dipolar magnetic field ($\sim 1 \, kG$)
- BOES echelle spectrograph of the 1.8 m telescope of the Korean Astronomy Observatory (KAO)
- Observations were carried out in a course of 20 observing nights in a period from January 2004 to April 2005
- Resolution $R = 45\,000$, working wavelength region is from 3500Å to 10 000Å
- Star shows equatorial (phases 0.25, 0.75) as well as polar regions (phases 0.0, 0.5)
- Expected accuracy of the reduction of Balmer line profiles is about 0.2 – 0.3%
Observations

H-lines Variability

- Hβ
- Hγ

HD 40312 (θ Aurigae)

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Model Parameters

**Main Parameters**

\[ T_{\text{eff}} = 10400 \text{ K}, \quad \log g = 3.6, \quad \nu \sin i = 55 \text{ km s}^{-1}, \quad R = 5.1 \pm 0.4 R_\odot \]

**Abundances**

Abundances had been derived using Doppler Imaging technique (Kuschnig et al., 2004)

<table>
<thead>
<tr>
<th>phase</th>
<th>He</th>
<th>Mn</th>
<th>Si</th>
<th>Cr</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>-2.32</td>
<td>-5.28</td>
<td>-3.35</td>
<td>-5.12</td>
<td>-3.86</td>
</tr>
<tr>
<td>0.25</td>
<td>-2.32</td>
<td>-5.27</td>
<td>-3.27</td>
<td>-5.35</td>
<td>-3.86</td>
</tr>
<tr>
<td>0.50</td>
<td>-2.40</td>
<td>-5.35</td>
<td>-3.09</td>
<td>-4.99</td>
<td>-3.63</td>
</tr>
<tr>
<td>0.75</td>
<td>-2.32</td>
<td>-5.50</td>
<td>-3.22</td>
<td>-4.75</td>
<td>-3.69</td>
</tr>
</tbody>
</table>
Standard Deviation

Abundances Effect

![Graphs showing Hβ and Hγ with standard deviation (σ) and wavelength shift (Δλ) on the x-axis.](image)
Inward-directed Lorentz Force

Standard Deviation

HD 40312 (θ Aurigae)
Standard Deviation

Outward-directed Lorentz Force

![Graphs showing standard deviation](image)

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Magnetic field effects in atmospheres of CP stars
Phase-resolved Variability of H-lines ($F_i - F_{0.056}$)

**Hβ**

**Hγ**
Variation of Effective Gravity

\( g_{\text{eff}} \) vs. \( \log \tau_{\text{Ross}} \)

\begin{align*}
g_{\text{eff}}/g & \quad \text{vs.} \quad \log \tau_{\text{Ross}} \\
g_{\text{eff}}/g & \quad \text{vs.} \quad \log \tau_{\text{Ross}}
\end{align*}
Summary and Discussion

- Variation of hydrogen line profiles in HD 40312 atmosphere
- It is argued in numerical computations that chemical abundances can not produce observed variability
- Interpretation within the framework of simple Lorentz force model
- Both inward- and outward-directed Lorentz force have been considered under the assumption of dipole and dipole+quadrupole magnetic field geometries
- It is shown that the good agreement with observation is obtained if the outward-directed Lorentz force is applied
- The adapted values of induced equatorial electric field was \( E_{eq} \sim 1 - 2 \times 10^{-11} \) CGS units
Braithwaite & Spruit, 2004

Stable configuration of magnetic field is obtained as a combination of toroidal and poloidal components

Landstreet et al., 2007

Link between stellar ages and field strengths in open clusters: decrease of field strength for stars with $M > 3M_\odot$