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Multi-dimensional radiative transfer for modeling the chromospheric polarized spectrum

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One-dimensional chromospheric atmospheres

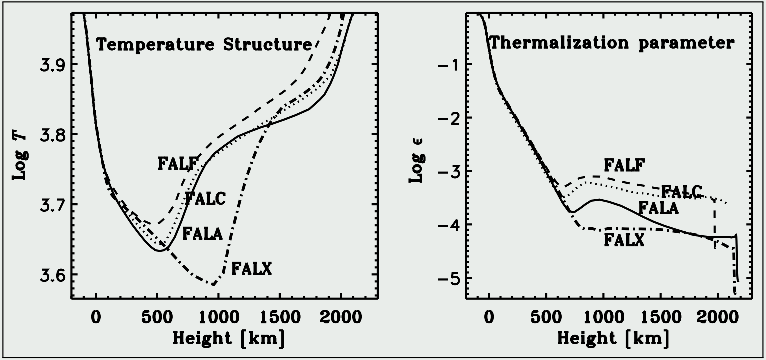


Figure: Temperature structure and the thermalization parameter in one-dimensional FAL atmospheres showing the nature of chromosphere (Fontenla et al. 1996). (This figure is reproduced from Anusha et al. 2010).

PRD in line scattering

Observed Spectrum

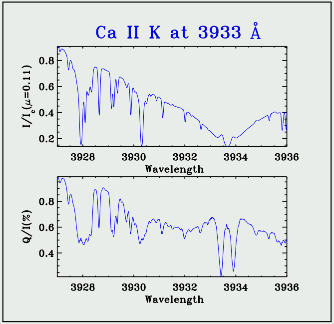


Figure: Ca II K line at 3933Å observed near the limb (using ZIMPOL II at KPNO, USA by J. O. Stenflo and others.) Credit: Dr. R. Holzreuter.

Why PRD

- **Partial frequency redistribution (PRD)** in line scattering $\Rightarrow$ correlations exist between the frequencies of **incident** and **scattered** photons. PRD is represented by two types of functions, namely, $r_{\rm II}$ and $r_{\rm III}$.
- **PRD becomes necessary** to model lines such as **Ca II K at 3933 Å** or **Ca I 4227 Å** with strong linear polarization signals in the line wings.

Multi-dimensional polarized transfer

What we use

- The transfer calculations that we discuss here are done using **two-level atom PRD scattering theory** of Domke & Hubeny (1988) and Bommier (1997a,b) respectively for resonance scattering including collisions and the Hanle effect.

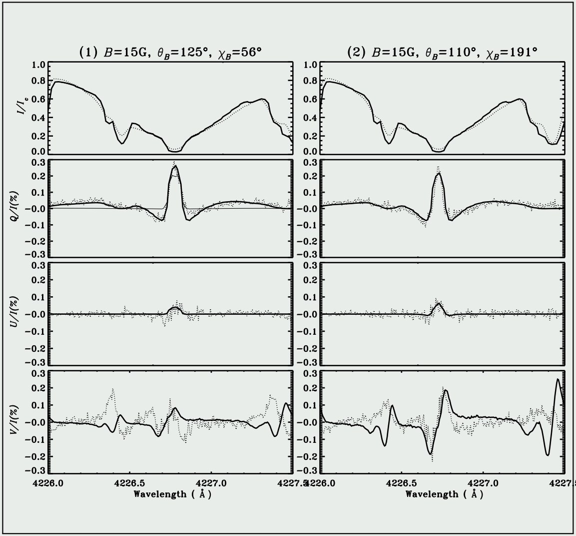
The transfer equation

$$-\frac{1}{\kappa_{\rm tot}(\boldsymbol{r},x)}\boldsymbol{\Omega}\cdot\boldsymbol{\nabla}\boldsymbol{I}(\boldsymbol{r},\boldsymbol{\Omega},x)=[\boldsymbol{I}(\boldsymbol{r},\boldsymbol{\Omega},x)-\boldsymbol{S}(\boldsymbol{r},\boldsymbol{\Omega},x)],$$

- $\boldsymbol{I}=(I,Q,U)^T$ - Stokes vector, $\boldsymbol{S}$ - Source vector.
- $\boldsymbol{r}=(\mathrm{x},\mathrm{y},\mathrm{z})$ - position vector of the ray ($\boldsymbol{\Omega}$), $\kappa_{\rm tot}$ - total opacity, x - frequency in reduced units.

PRD in modeling the scattering polarization

Ca I 4227 Å line at near disc center



Forward scatt. poln. modeling : Anusha et al. (2011)

- The theoretical Q/I, U/I profiles are computed from the **Hanle effect** and the V/I profiles from the **Zeeman effect**.
- In the left panels the thin solid lines represent the profiles computed under the **assumption of CRD**.

PRD in Multi-D transfer

Observed Spectrum

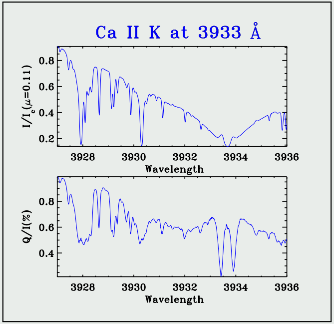


Figure: Ca II K at 3933Å line observed near the limb (observed using ZIMPOL II at KPNO, USA by J. O. Stenflo and others.) Credit: Dr. R. Holzreuter.

Modeling

- In Anusha & Nagendra (2013) we **applied PRD+multi-D RT** to the **Ca II line at 3933 Å** .
- We used a **composite atmosphere** was constructed using a **2D snapshot of the 3D MHD simulation** of the photosphere combined with **columns of 1D atmosphere** representing the chromosphere.

Solar atmosphere approximation

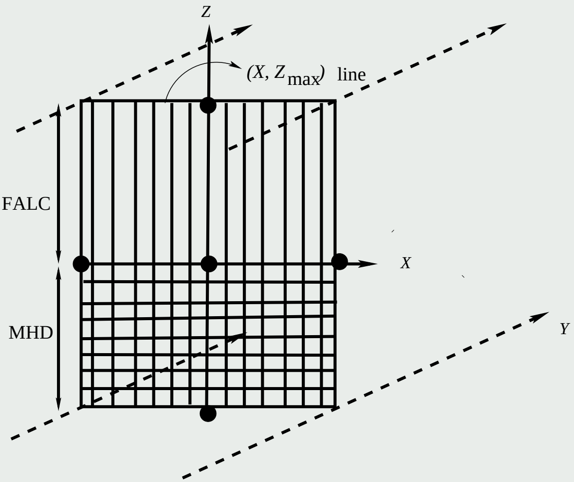


Figure: 2D spatial variation in photosphere and FALC in chromosphere.

Hanle effect in Ca II K line

MHD + FALC

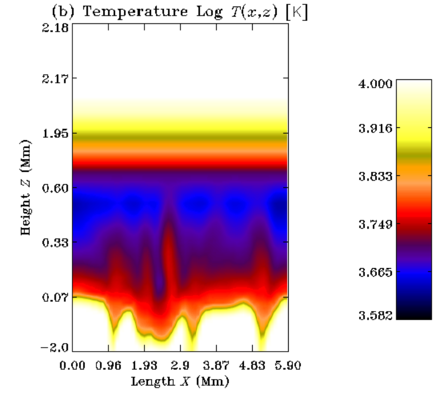


Figure: Temperature structure in the chosen MHD+FALC atmosphere.

Approximate 2D atmosphere

- **Horizontal variation of temperature** below ∼ 0.65 Mm is due to MHD effects.
- Above ∼ 0.65 Mm there **exists no horizontal inhomogeneity**.
- The vertical variation of temperature in these layers is the same as the **temperature variation in 1D FALC** atmosphere.

Hanle effect in Ca II K line

Contribution function (with S_I)

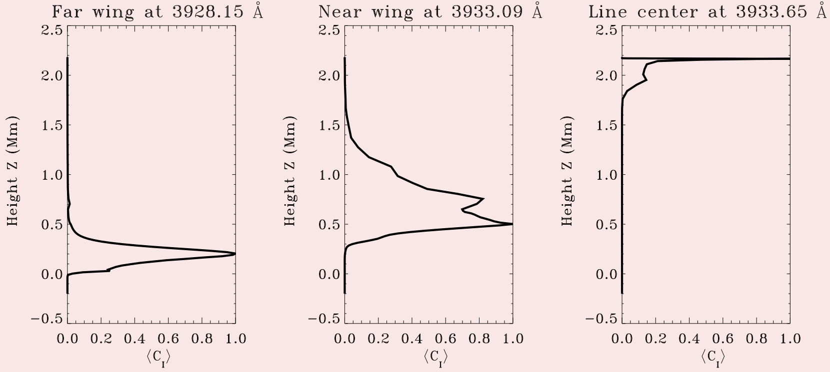


Figure: Spatially averaged contribution functions at near-disk-center for different wavelength points in the line.

Hanle effect in Ca II K line

The line formation heights (in Mm)

λ	Near-limb	Near-disk-center
3928.15 Å	0.25 Mm	0.2 Mm
3933.09 Å	0.65 Mm	0.5 Mm
3933.50 Å	2.15 Mm	1.27 Mm
3933.65 Å	2.16 Mm	2.16 Mm
3933.80 Å	2.16 Mm	1.17 Mm

Observed profile

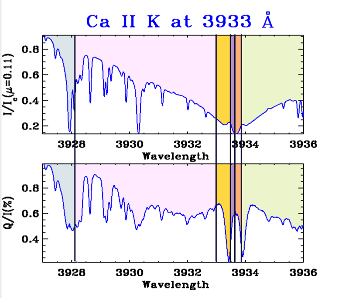
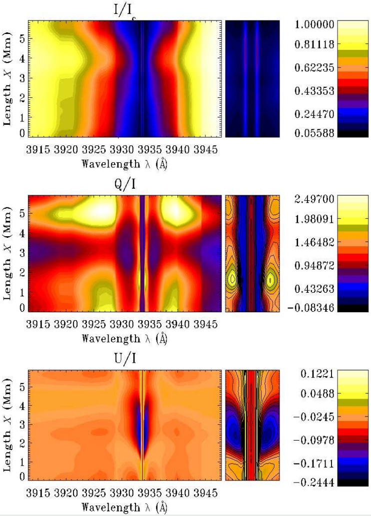
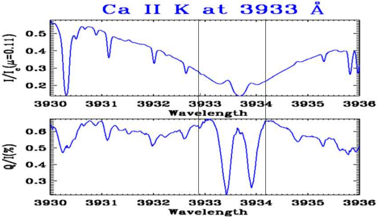


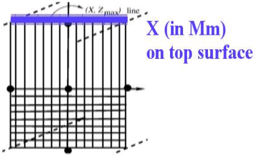
Figure: Line formation heights

Hanle effect in Ca II K line

Spatial variation of $(I/I_c, Q/I_c, U/I_c)$: RH+POLY2D







1. Inhomogeneous polarization in the line wings.
2. Homogeneous polarization in the line core.
3. Periodic nature of solution in spatial direction.

Figure: $(\mu, \varphi) = (0.3, 160°)$, $(B, \theta_B, \chi_B) = (20\,\mathrm{G}\,, 45°, 225°)$.

Hanle effect in Ca II K line

Spatial variation of $(I/I_c, Q/I_c, U/I_c)$: RH+POLY2D

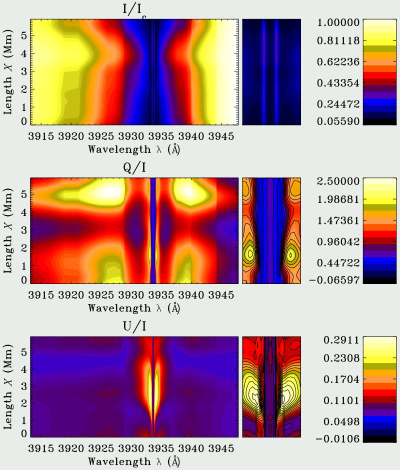


Figure: $(\mu, \varphi) = (0.3, 200^\circ)$, $(B, \theta_B, \chi_B) = (20\,\mathrm{G}\,, 75^\circ, 225^\circ)$.

Hanle effect in Ca II K line

Ca I 4227 CCD image

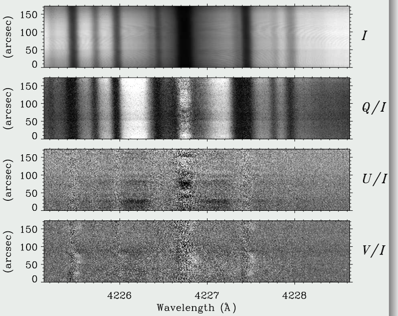


Figure: Observed using ZIMPOL II taken at limb near a quiet region ($\mu = 0.11$). From Sampoorna et al. (2009).

Connection with other observations

- **Spatial variations** are observed the **wings of chromospheric Ca I 4227 Å line** (Bianda et al. 2003, Sampoorna et al. 2009), which the authors refer to as the **enigmatic wing features**.
- We find **similar spatial inhomogeneities** also in the **wings of Ca II K line**, which is again a chromospheric line.
- Such **wing signatures** in chromospheric lines can possibly be explained using the **spatial structuring** of the atmosphere.

Hanle effect in Ca II K line

Ca II K line CCD image

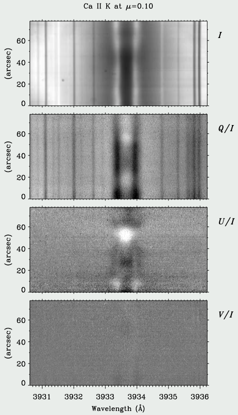


Figure: Limb observations taken at KPNO using ZIMPOL II, in a quiet region. From Stenflo (2006); Credit: J. O. Stenflo

Connection with other observations

- **Ca II K line at 3933 Å** shows **strong spatial variation in the line core** (Stenflo 2006). It is due to :
  - **spatially varying magnetic fields** (Hanle effect) and
  - **spatial inhomogeneities in the atmosphere** itself.
- **Spatial and angle dependent** B, or the use of a model atmosphere with **spatial inhomogeneity in the chromosphere** may explain spatially varying line core polarization.

Hanle effect in Ca II K line

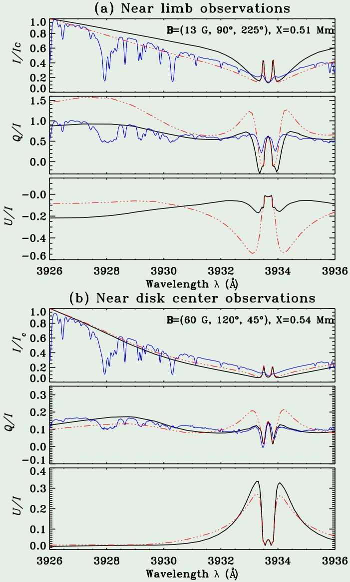
Comparison with Observations

- In Holzreuter et al. (2006), Holzreuter & Stenflo (2007a) and Holzreuter & Stenflo (2007b) the authors study in detail, **Q/I in Ca II K line at 3933 Å** using different **1D solar model atmospheres**. They conclude that :

  1. none of the **existing 1D model atmospheres** can reproduce the observed $(I/I_c, Q/I)$ at all μ values.
  2. by **modifying the temperature structure** they could find optimum fits to the observed $(I/I_c, Q/I)$.
  3. **multi-D MHD atmospheres, with multi-D transfer** may be necessary to fit the observations at different μ values simultaneously using a **single MHD atmosphere**.

Hanle effect in Ca II K line

Model profiles and observations



Comparison with observations

- **Blue solid lines** : Observations.
- **Red dash-triple-dotted lines** : emergent, spatially averaged model profiles.
- **Black solid lines** : spatially resolved model profiles.
- **Wing fit is reasonable** since line **wings are formed below 0.65 Mm** where the atmosphere is represented by **MHD simulations**.
- **Core fit is poor** because the **line forming layers** are still represented by **1D FALC part** of the composite model.

Conclusions

PRD with polarized Multi-D transfer

- This work represents the **first attempt to use PRD** in **polarized multi-D radiative transfer** studies.
- This work is an **initial step** towards more-realistic modeling of the **chromospheric lines** than using 1D atmospheres.
- **PRD** as the **line scattering mechanism is essential** to model strong chromospheric lines (the approximation of CRD leads to nearly zero linear polarization in the line wings).
- The **MHD structuring in the atmosphere** is the cause of **spatial inhomogeneities in the wings** of the $(Q/I_c, U/I_c)$ profiles of strong chromospheric lines.

Conclusions

Multi-D polarized transfer with PRD

- Our study clearly indicates that **MHD structuring** in the chromosphere (as in the photosphere) is important to obtain **simultaneous fit** to the **line core** and the **line wing observations** of $(I/I_c, Q/I_c, U/I_c)$ of the chromospheric lines at all the lines of sight.
- To achieve this goal, **we need 3D MHD model atmospheres**, because only **3D models can properly represent** the solar **chromospheric inhomogeneities**.

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