CLVPOL

Polarized radiative transfer

Linear polarization

Non-LTE, spectral line & continuum

1D atmosphere + magnetic field
(Hanle effect)

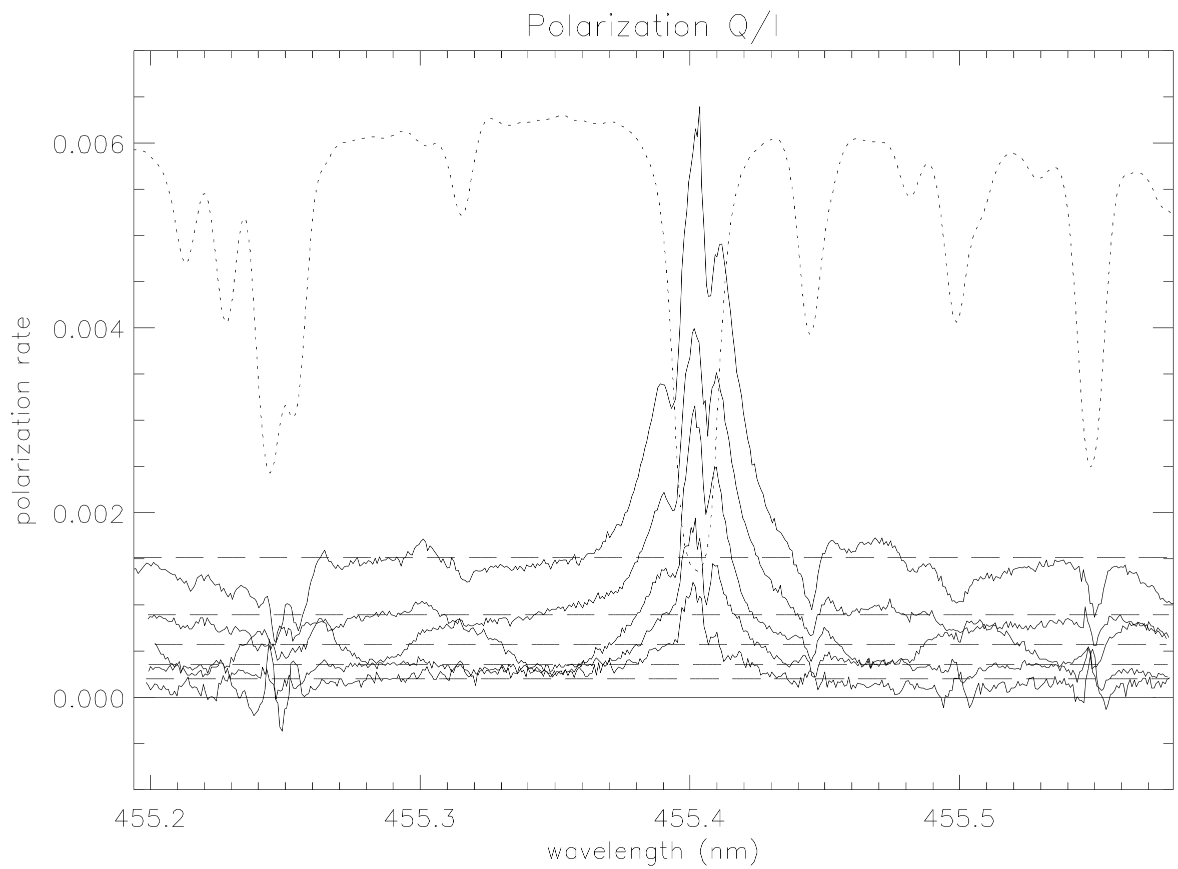
Astrophysical context

Magnetism of the quiet Sun:

Mixed polarity magnetic fields at small scales

Diagnostics with the Hanle effect

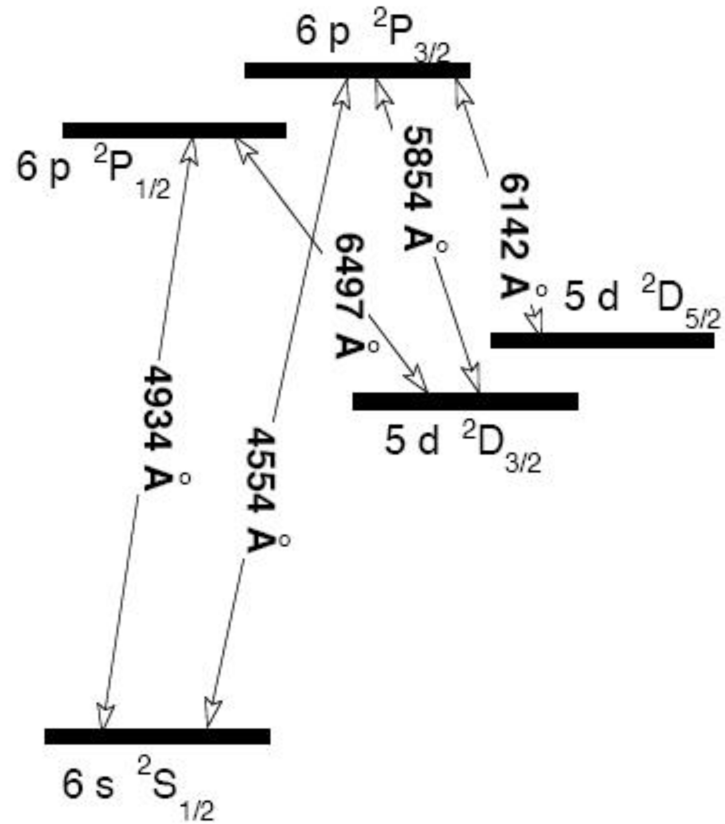
Example of application
Linear polarization of the BaII 455.4 line



Themis observations

(V. Bommier 2007)

Simplified BaII atomic model



Hyperfine structure of the odd isotopes is neglected

Source terms

• *In the continuum*:

Thermal +

Rayleigh and Thomson scattering

• *In the line* (equivalent two-level formalism)

Thermal creation

\+ Creation of line photons due to multi-level coupling

\+ Scattering of line photons

Some equations

The linearly polarized radiation field is described by a
3-component vector (I,Q,U) (Stokes parameters).
We assume that the absorption matrix is a scalar (unpolarized lower level)

$$\frac{\partial \vec{I}}{\partial s} = -\left(k_c + k_L \phi(\nu)\right)\vec{I} + \overrightarrow{j(\nu)} \quad \rightarrow \quad \mu \frac{d\vec{I}}{d\tau} = (\beta + \phi(\nu))\left[\vec{I} - \vec{S}\right]$$

$$\left(\beta = \frac{k_c}{k_L}\right)$$

$$d\tau = -k_L ds = -k_L \frac{dz}{\mu} \qquad \vec{S} = \frac{\vec{j}}{k_c + k_L \phi(\nu)} = \frac{\phi(\nu)\overrightarrow{S_L} + \beta B_p \vec{1}}{\phi(\nu) + \beta}$$

Optical depth variable
(1D medium)

Source vector

NB: The absorption coefficients in the line (k_L) and continuum (k_c) are computed with a non-LTE unpolarized RT code (MULTI)

Line source vector

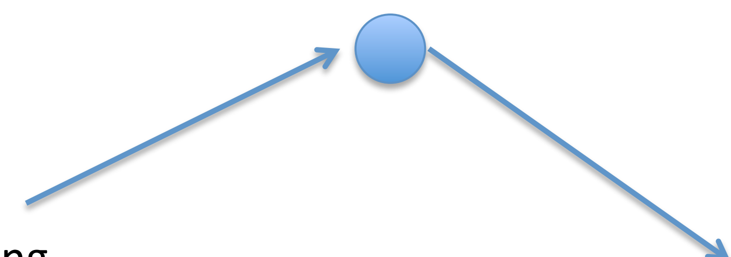
Equivalent two-level approach

$$\overrightarrow{S_L}(\Omega,\nu,\tau) = (1-\varepsilon')\int_0^\infty \frac{R(\nu,\nu')}{\phi(\nu)} d\nu' \oint \frac{d\Omega'}{4\pi} P(\Omega,\Omega',\vec{B})\vec{I}(\Omega',\nu',\tau) + \eta B_p(\tau)$$

Partial frequency redistribution

(3 x3) Hanle phase matrix

Destruction and creation of line photons from multi-level coupling are taken into account in ε' and η (equivalent two-level approach)



Incoming photon (ν',Ω')

Scattered photon (ν,Ω)

Method of solution (1)

- Generalized Feautrier method

$$[P_H(\Omega, -\Omega', \boldsymbol{B})] = [P_H(\Omega, \Omega', \boldsymbol{B})][M_H],$$

$$[P_H(-\Omega, \Omega', \boldsymbol{B})] = [M_H][P_H(\Omega, \Omega', \boldsymbol{B})],$$

where

$$[M_H] = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{pmatrix}.$$

We introduce the "Feautrier variables"

$$\boldsymbol{u}(\tau, x, \Omega) = \tfrac{1}{2}\{\boldsymbol{I}(\tau, x, \Omega) + [M_H]\boldsymbol{I}(\tau, x, -\Omega)\},$$

$$\boldsymbol{v}(\tau, x, \Omega) = \tfrac{1}{2}\{\boldsymbol{I}(\tau, x, \Omega) - [M_H]\boldsymbol{I}(\tau, x, -\Omega)\},$$

Feautrier (60's)

$$\frac{\mu}{\phi(x)+\beta}\frac{\partial \boldsymbol{u}}{\partial \tau}=-\boldsymbol{v},$$

$$\frac{\mu}{\phi(x)+\beta}\frac{\partial \boldsymbol{v}}{\partial \tau}=\boldsymbol{S}(\tau, x, \Omega)-\boldsymbol{u}.$$

S depends on the variable u only

We obtain a 2nd order differential equation for u (like in the standard Feautrier method) that is solved by a second order discretization scheme.

At each depth point l: $$\boxed{\hat{A}_l\,\vec{u}_{l-1} - \hat{B}_l\,\vec{u}_l + \hat{C}_l\,\vec{u}_{l+1} = \vec{L}_l}$$

At each depth point: inversion of Matrix of dimensions $(3x\ Nf\ x\ Nd)^2$

Method of solution (2)

- The polarization is small: iterative method
- First step: solution of the equation for Stokes I (with Q=U=0)
- Computation of the source vector
- Formal solution of the polarized RT with known source term
  -> $I^{(1)}$, $Q^{(1)}$, $U^{(1)}$
- Back to computation of the source vector, etc ...
  Lambda Iteration for the polarization.

For the first step one may use MULTI, RH, etc ...
any non-LTE RT code.

Line Scattering term

Mixture of RII and RIII frequency redistribution and of Isotropic and Hanle phase matrix.

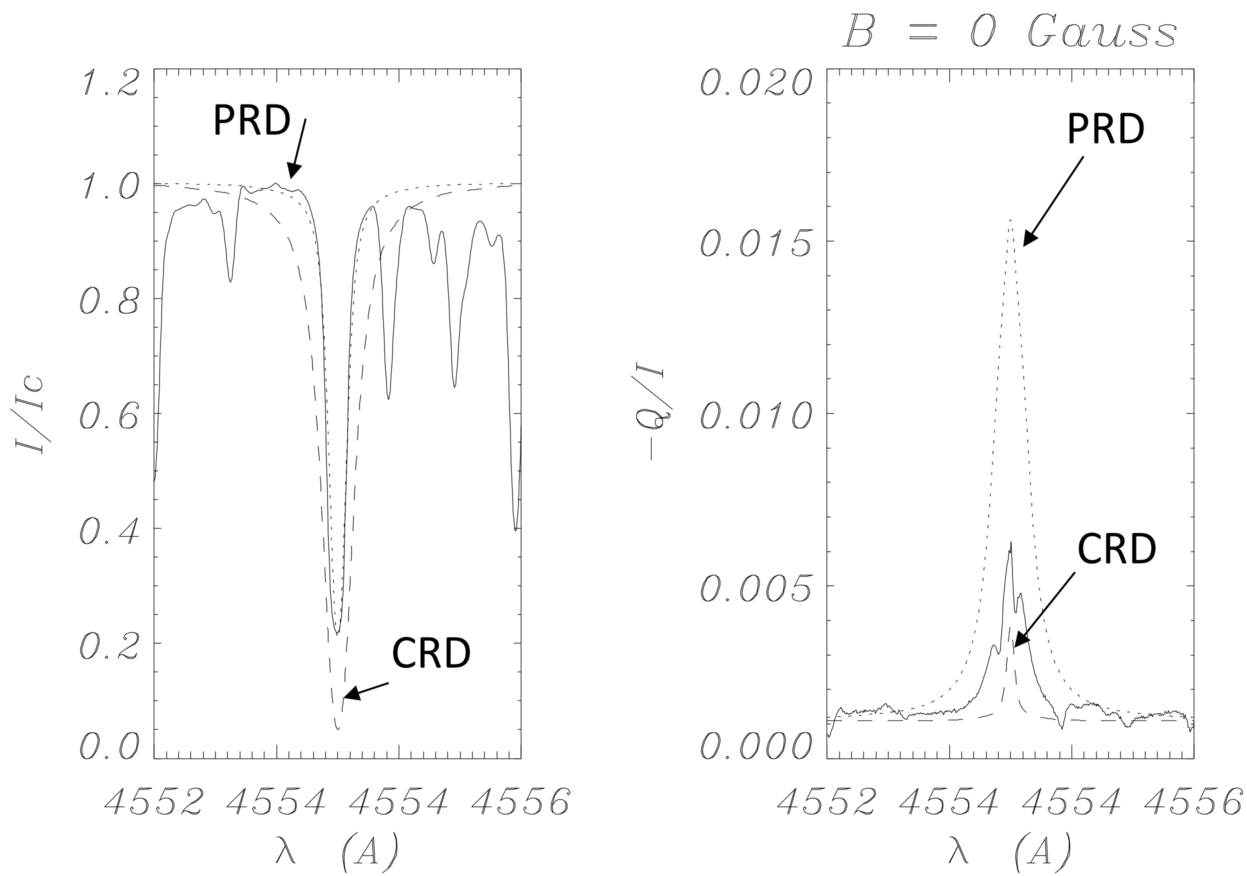
$$\mathbf{sc}(\tau, x, \Omega) = \left\{ \int_{-\infty}^{+\infty} (\gamma R_{\mathrm{II}}(x, x') + b R_{\mathrm{III}}(x, x'))\,\mathrm{d}x' \times \int \frac{\mathrm{d}\Omega'}{4\pi} \boldsymbol{P}_{\mathrm{R}}(\Omega, \Omega') \boldsymbol{I}(\tau, x', \Omega') + c \int_{-\infty}^{+\infty} R_{\mathrm{III}}(x, x')\,\mathrm{d}x' \times \int \frac{\mathrm{d}\Omega'}{4\pi} \boldsymbol{P}_{\mathrm{is}} \boldsymbol{I}(\tau, x', \Omega') \right\} \frac{1}{\phi(x)}, \tag{8}$$

Domke & Hubeny, 1988, ApJ

Bommier, 1997, A&A

BaII 455.4 nm line

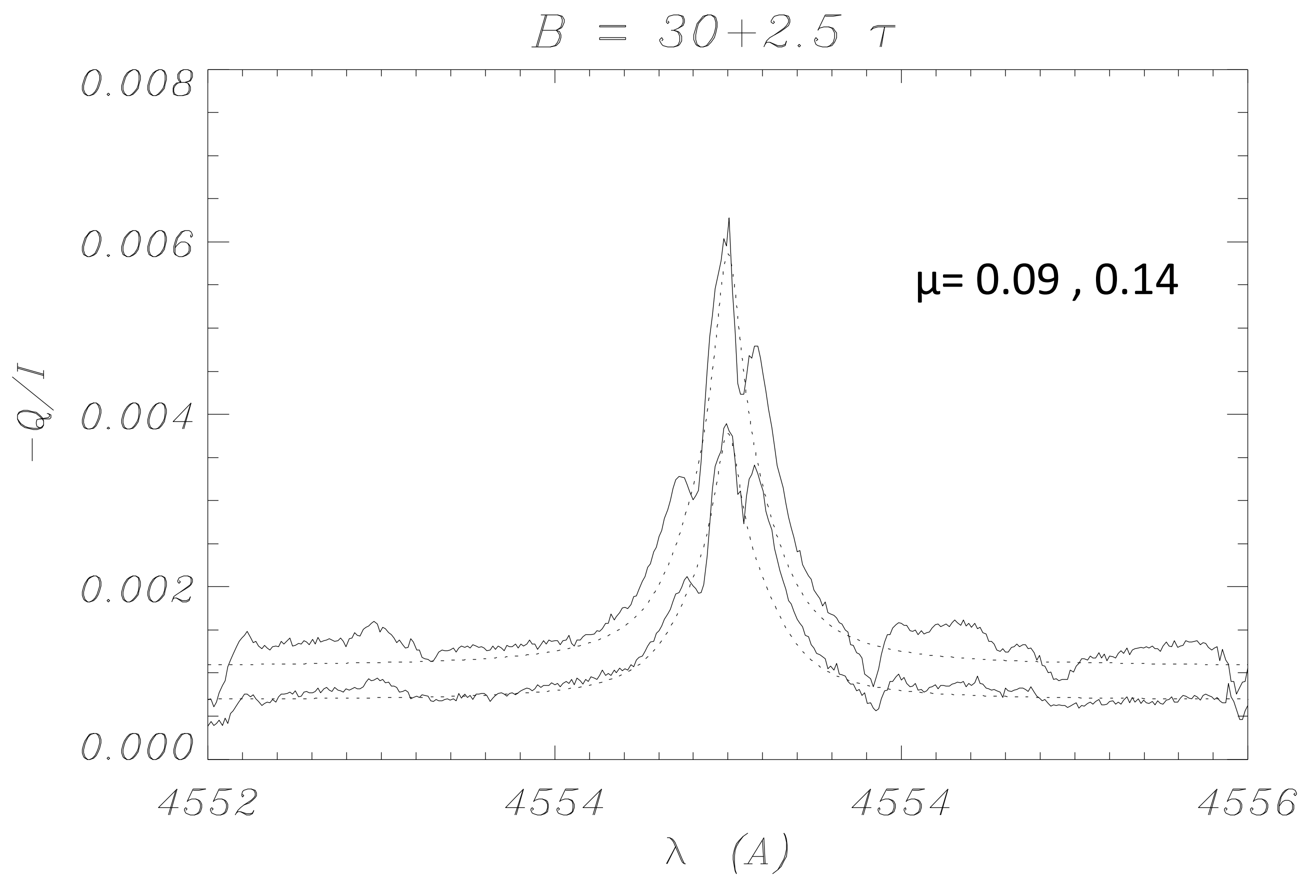
Non-LTE model, PRD versus CRD

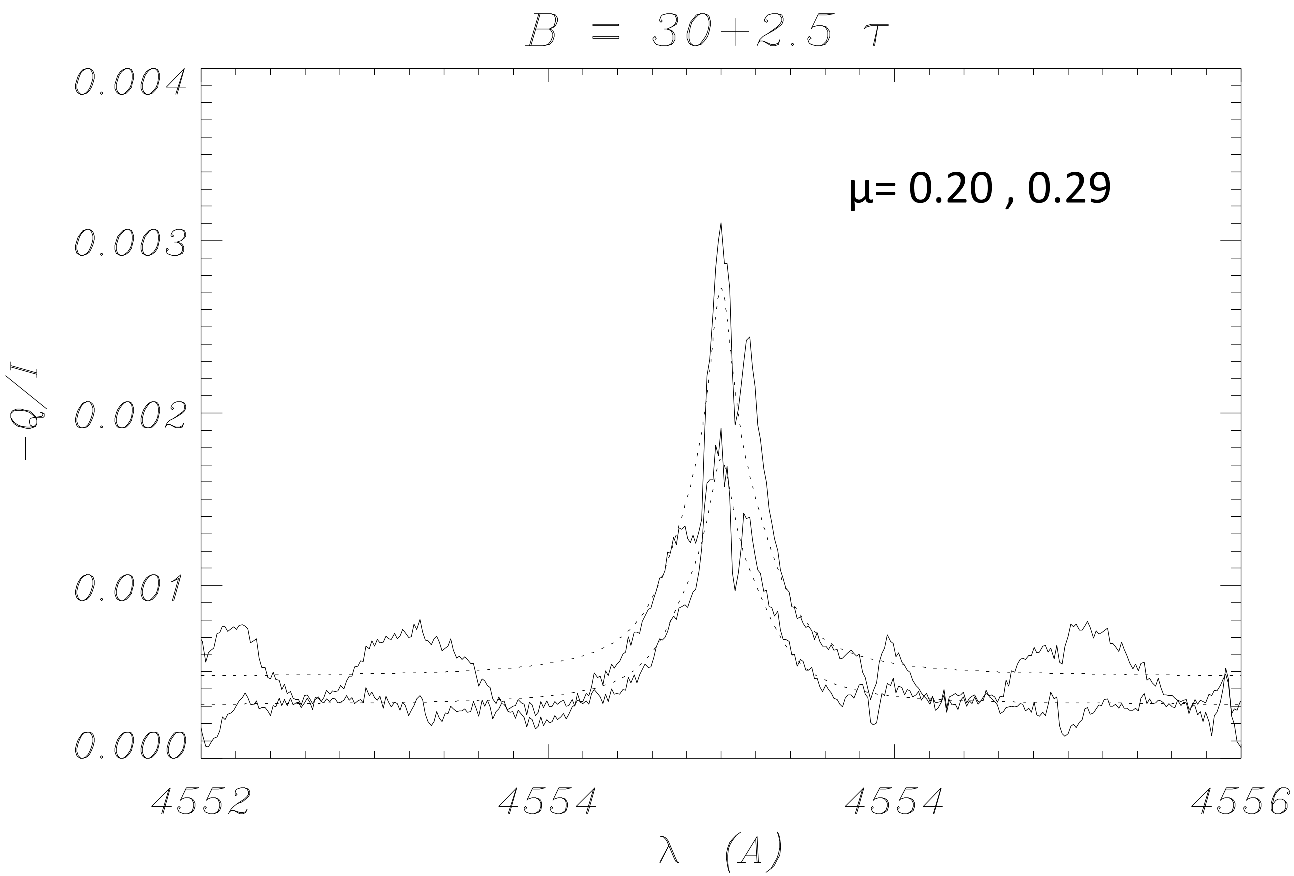


μ = 0.09

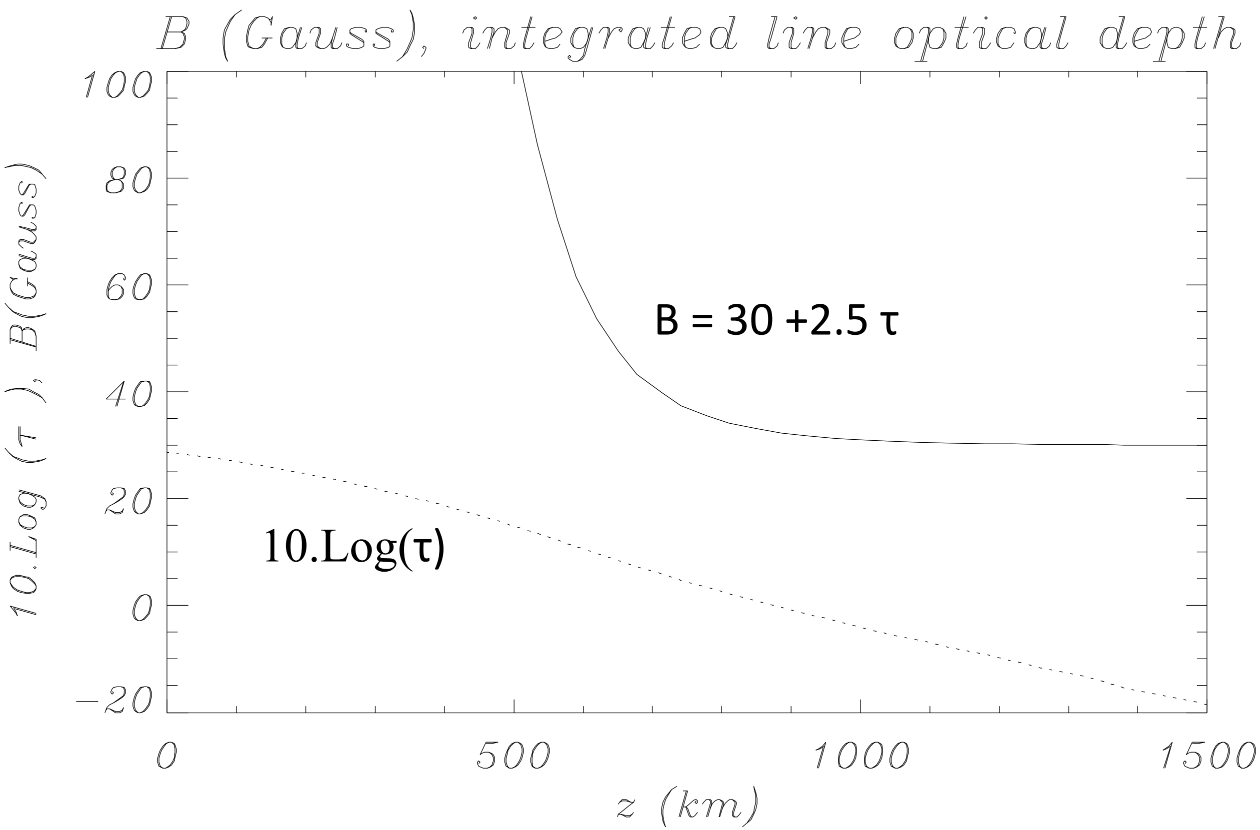
Partial Frequency Redistribution plays a crucial role

BaII linear polarization:
with depth-dependent turbulent magnetic field
observations / model calculations





The magnitude and the width of the central peak are both well fitted, for all the observed line of sight.



Linear variation with optical depth -> exponential decrease with z

Conclusion

- *CLVPOL: 1D code for non-LTE polarized radiative transfer*
- *Linear polarization due to scattering*
- *continuum (Rayleigh-Thomson scattering) and spectral lines, with Hanle effect and Partial frequency redistribution.*
- *Assumptions*

- *the absorption coefficient is a scalar (unpolarized lower line-level)*
- *Multi-level coupling does not affect the linear polarization, except for additionnal creation and destruction of photons in the line (equivalent two-level approach for the source vector).*
- *Not user friendly …*