Modeling of the center to limb variation of linear polarization in the spectrum of the Ca I 4227 Å line

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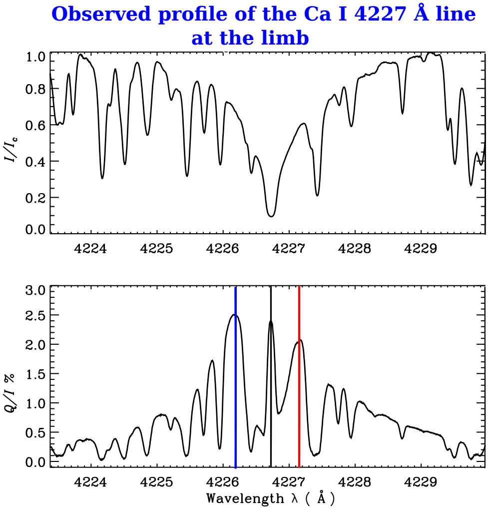
The Sun and the Second Solar Spectrum

- Coherent scattering processes in the solar atmosphere causes the emitted radiation to be linearly polarized which is referred to as the Second Solar Spectrum (SSS).

- The weak magnetic fields in the solar atmosphere leaves their signature in the SSS by modifying the spectrum at the line core - Hanle effect.

"Line" of interest - Ca I 4227 Å



- Ca I 4227 Å arises due to a $J = 0 \rightarrow 1 \rightarrow 0$ scattering transition.
- It exhibits the largest scattering polarization amplitude among all the lines in the Sun's visible spectrum.

Previous studies and Our aim

- Early studies of Ca I 4227 Å line : Brükner (1963), Stenflo (1974), Wiehr (1975), Stenflo (1980), Auer et al. (1980), Stenflo (1982), Faurobert-Scholl (1992), Faurobert-Scholl (1994), Bianda et al. (1998), Bianda et al. (1999), Bianda et al. (2003), Sampoorna et al. (2009), Anusha et al. (2010), Bianda et al. (2011), Anusha et al. (2011).

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- Our aim : To simultaneously model the (I, Q/I) profiles of the Ca I 4227 Å line observed at different lines of sight in the quiet Sun region.

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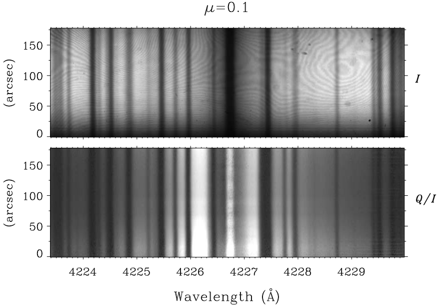
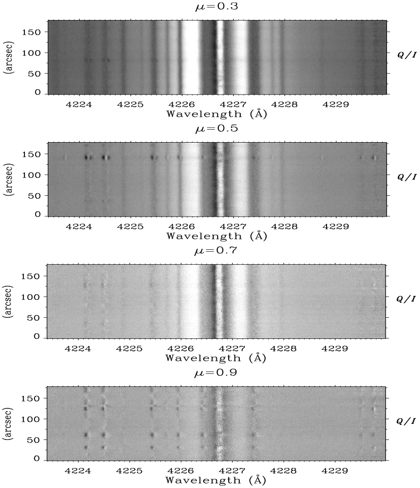
- The observed CLV of the scattering polarization can be used to constrain the height variation of various atmospheric quantities.
- Most challenging aspect of CLV modeling is to find a single model atmosphere which can fit both I and Q/I at all limb distances μ $(= \cos\theta)$ simultaneously.

The Observations

- CLV observations of the Ca I 4227 Å line were obtained with the Zurich Imaging Polarimeter-3 (ZIMPOL-3) at IRSOL in Switzerland on October 16, 2012.
- Observations were taken at 14 different μ positions - 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45, 0.50, 0.60, 0.70, 0.80, 0.90 and 1.0



Stray light correction

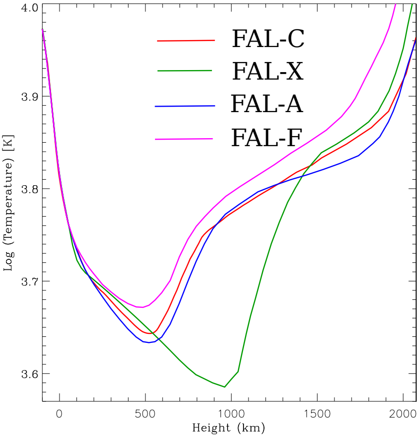


- Contribution from the spectrograph stray light in the observed profiles - 2 % of the continuum intensity.
- Both the intensity and polarization profiles are corrected for stray light

$$I_{obs} = I + sI_c$$

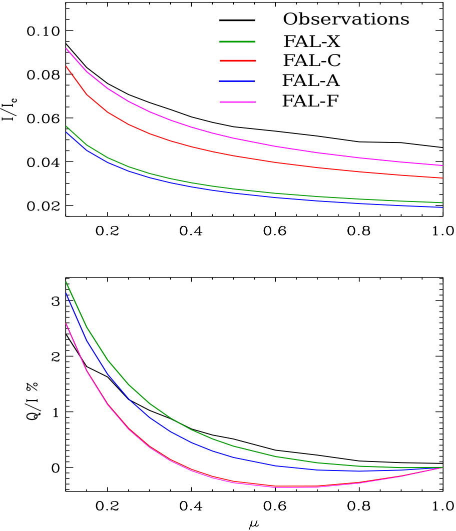
$$Q_{obs} = Q + p_z(I + sI_c) + p_s sI_c.$$

Standard 1-D model atmospheres



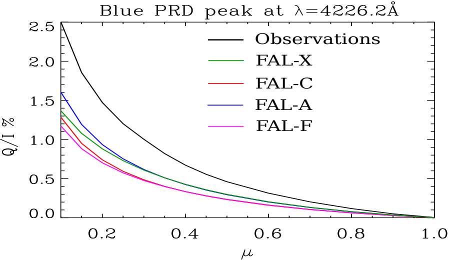
- One dimensional polarized RT equation is solved for a two-level atom taking partial frequency redistribution (PRD) in to account.
- Four standard 1-D model atmospheres of the Sun namely - FAL-A, FAL-C, FAL-F (Fontenla et al. 1993) and FAL-X (Avrett 1995) are used for studies.

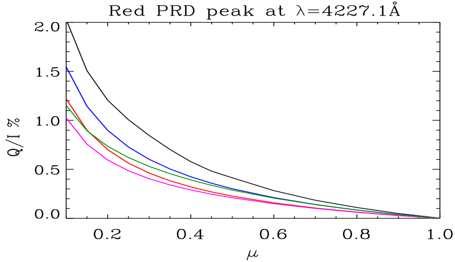
CLV behavior at line center wavelength



- Hottest model FAL-F is more suited for modeling the CLV of line center intensity.
- The same model is not at all good for Q/I fit.
- It is the coolest model FAL-X which provides the closest fit to the observed Q/I.
- Contrasting conclusion : we need two different temperatures to simultaneously fit I/I_c and Q/I at the line center.

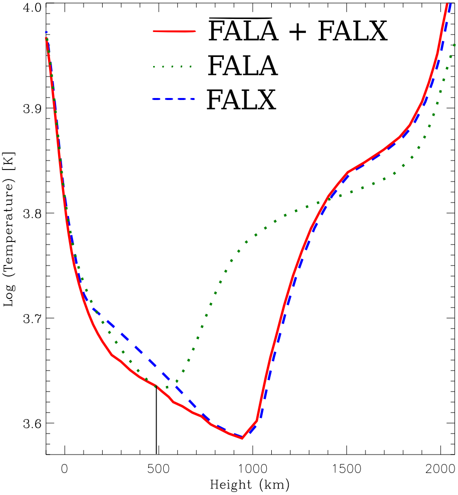
CLV behavior at blue and red PRD peaks





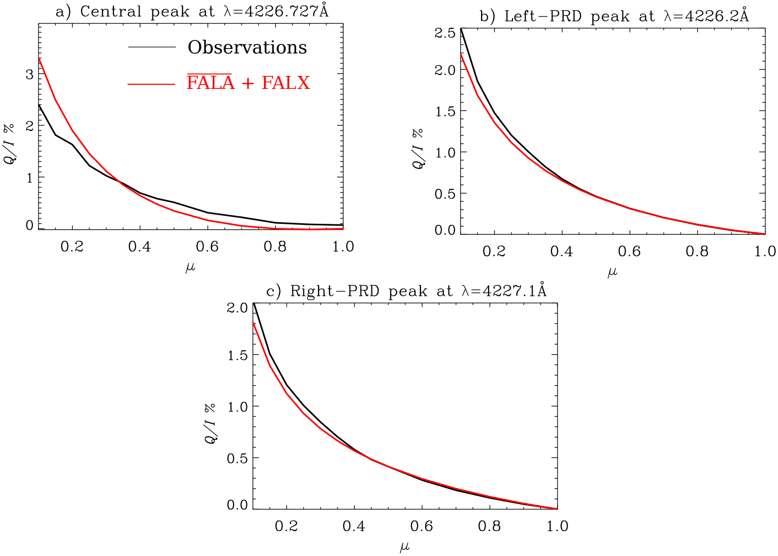
- Both FAL-F and FAL-X model atmospheres fail to provide a fit to the PRD peaks.
- Theoretical CLV profiles from the FAL-A model falls closest to the observed CLV.
- We do not find a single 1-D atmospheric model which provides a fit to the entire Stokes (I, Q/I) profile simultaneously.

Temperature structure modification

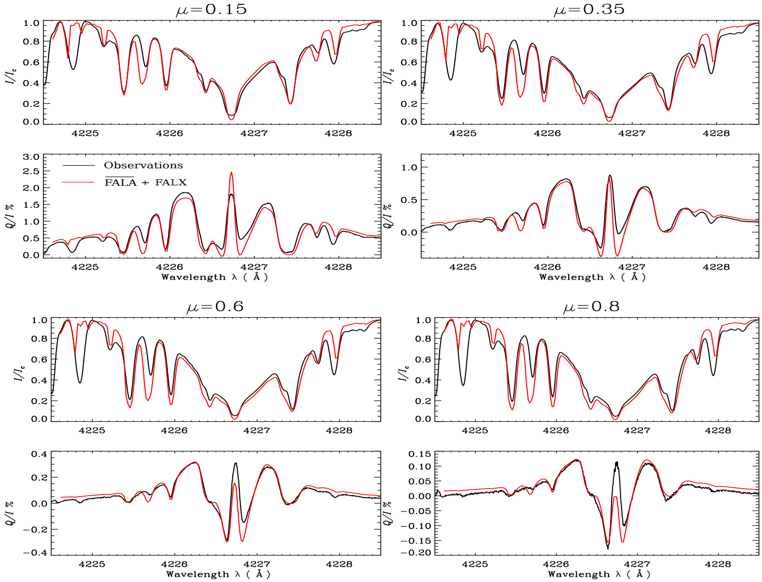


- $\overline{\text{FALA}}$ - modification of temperature structure of FAL-A at the heights where PRD peaks are formed.
- $\overline{\text{FALA}}$ model atmosphere fits the observed profiles closest at PRD peak wavelengths.
- FAL-X model atmosphere fits the observed profiles closest at line center wavelength.
- New combined model - $\overline{\text{FALA}}$ + FALX.

CLV behavior from the new model atmosphere



Full profile fit using the new model atmosphere



Consistency of modified models

- Physical consistency of the newly constructed atmospheric model has been checked - it satisfies hydrostatic equilibrium at all heights.

Observed data are obtained from Neckel & Labs (1994)

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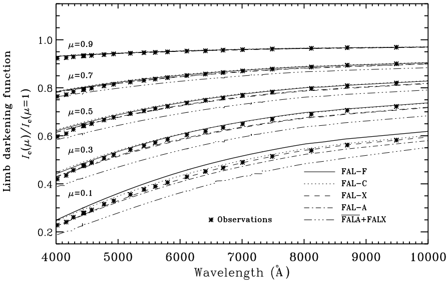
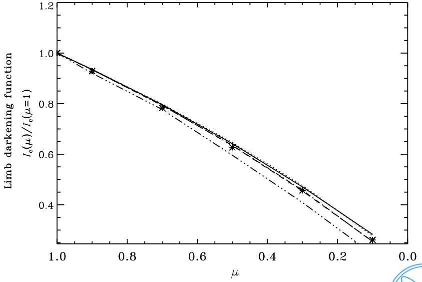
- Fit to the CLV of the continuum intensity over a range of wavelength.

CLV of the continuum



CLV of the limb darkening function near the line center of the Ca I 4227 Å line



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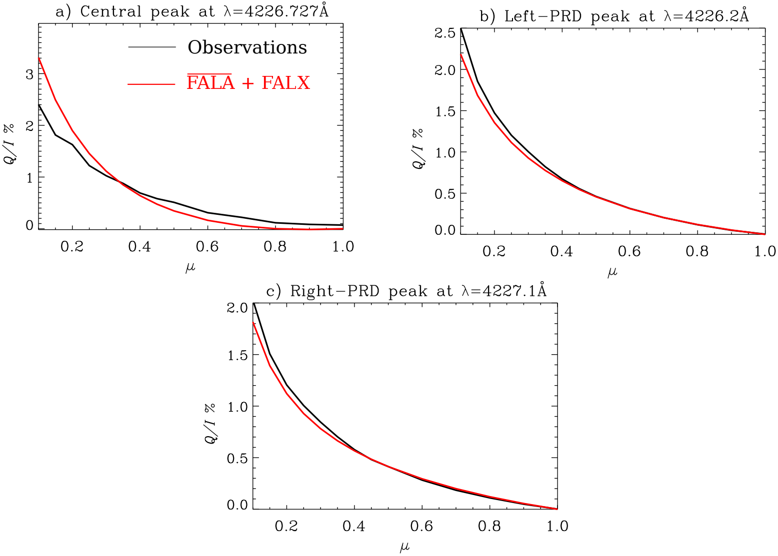
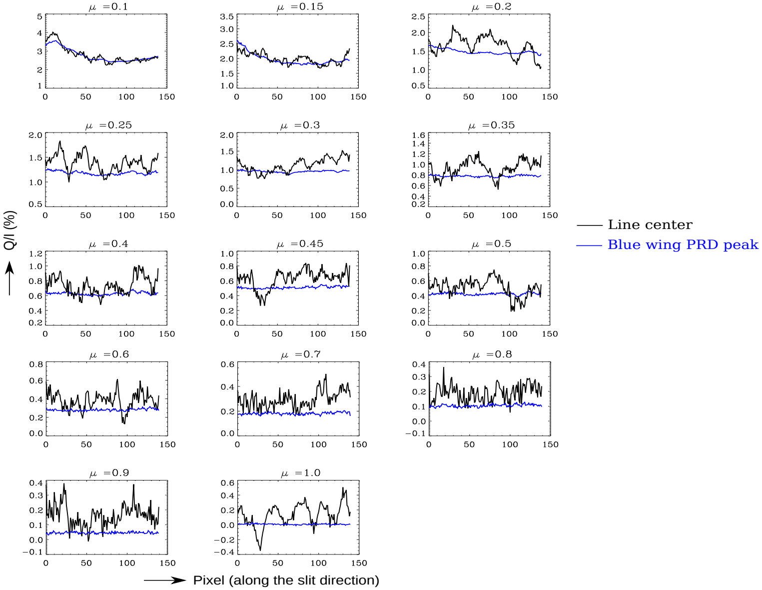


Variation along the slit



Correction of the line core polarization amplitude

$$(Q/I)^{line\ center}_{corrected} = \frac{(Q/I)^{line\ center}_{uncorrected}}{P_b} < P_b >$$

$P_b = (Q/I)^{blue\ wing\ peak}$ for each pixel and $< P_b >$ is the spatial average of P_b along the slit.

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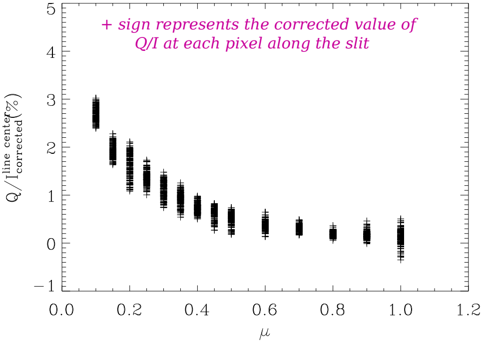


Envelope fitting method

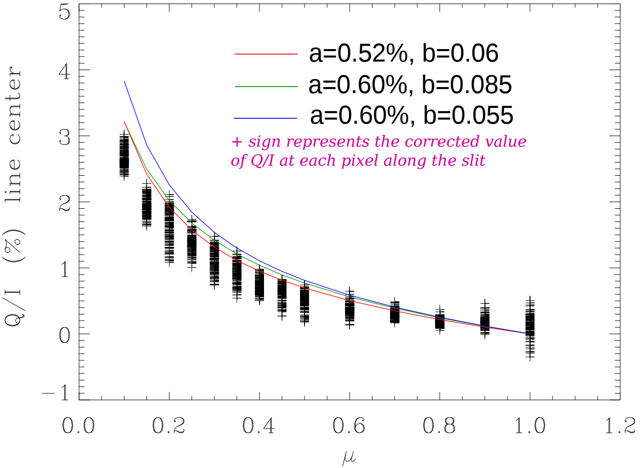
Non-magnetic value of Q/I [1]

$$\frac{Q}{I} = \frac{a(1-\mu^2)}{\mu + b}$$

a and b are the best fit free parameters.

[1] Stenflo et al. (1997), Bianda et al. (1998, 1999)

Envelopes for CLV of line center data



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Hanle depolarization k_H for a canopy field [2]

$$k_H = 1 - 0.75 \sin^2 \alpha_2,$$

where α_K is the Hanle mixing angle

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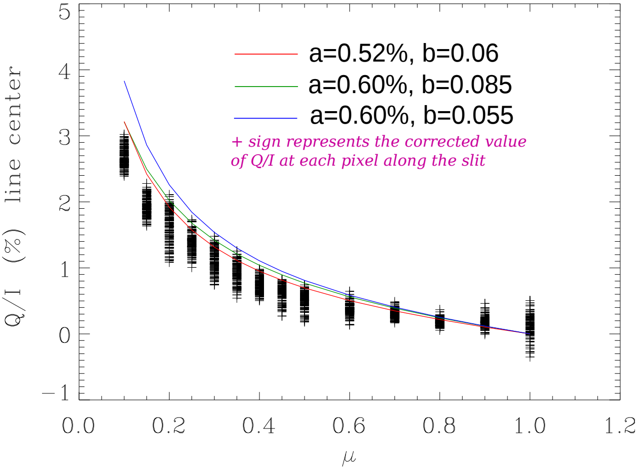

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Field strength B to be determined [2]

$$B = \frac{\tan \alpha_K}{K} \frac{B_0}{k_c^{(K)}}$$

$k_c^{(K)} \rightarrow$ collisional branching ratio for the $2K$-multipole
$B_0 \rightarrow$ characteristic field strength for the Hanle effect

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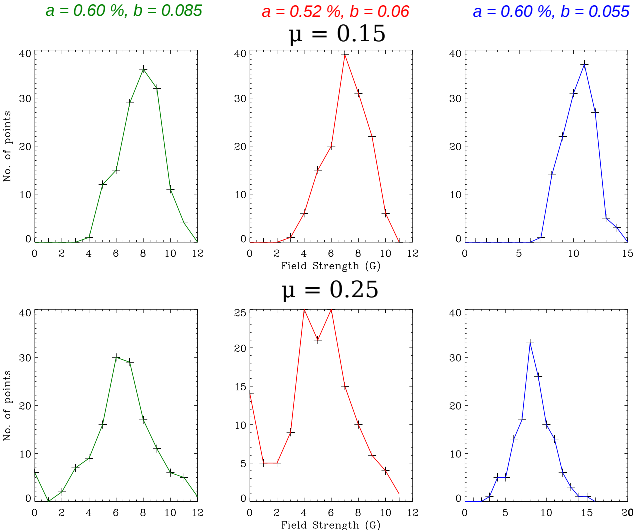
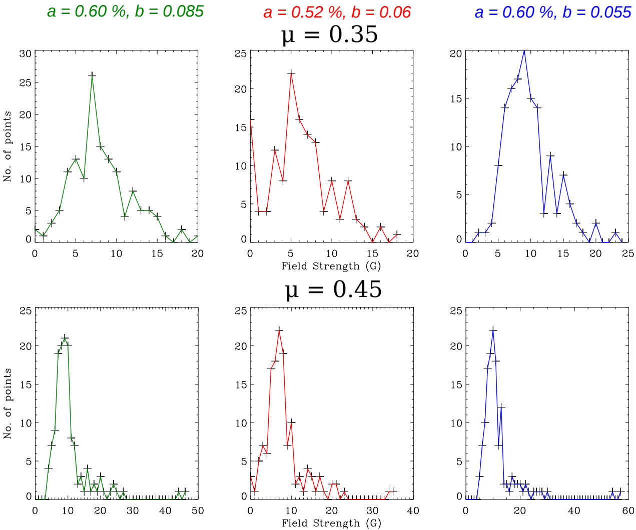
Histogram of the field strength



Histogram of the field strength cont...



Summary

- Aim: to obtain a simultaneous fit to the (I, Q/I) CLV data of the Ca I 4227 Å line using a single 1-D atmosphere.
- We were successful only to the extent of obtaining a good fit to the CLV of the Q/I throughout the profile.
- Even for this, it was necessary to modify the standard FAL models, and construct new combined model.
- New combined model fails to reproduce the observed CLV of the continuum limb-darkening function and the CLV of the observed line core intensity.

Conclusions

- To simultaneously satisfy the various observational constraints it is therefore unavoidable to go beyond 1-D models.
- This failure of 1-D models in order to simultaneously fit the $(I, Q/I)$ CLV profiles do not restrain the use of the Ca I 4227 Å as a tool to map the depth dependence of the magnetic fields.
- The failure of 1-D modeling approach is not at all a "technical failure" → it has nothing to do with the weakness of our approach.
- Instead it is a "profound failure" → complexity of the solar atmosphere to represent in terms of a single 1-D atmosphere.

THANK YOU