Part II : Radiative transfer and Spectropolarimetry

Some interesting results

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What do we do today

- We take a look at some papers. We try to understand what they did, relying on what we learned during last 9 lectures.
- These are not the most important papers. These are the ones that I like.
- We will mention some physics we did not talk about before. I will try to explain it as much as I can.

First paper describing inversions

"Inversion of Stokes Profiles" (B. Ruiz Cobo & J.C. del Toro Iniesta, 1992).

SIR - Stokes Inversion based on Response functions.

This first succesfull attempt to fit the whole, physically realistic, stratified atmosphere to the observed Stokes profile.

They introduce response functions as derivatives of the merit function, i.e. χ^2:

$$\delta\chi^2 = \frac{2}{\nu} \sum_{k=1}^{4} \sum_{i=1}^{M} \left[I_k^{\mathrm{obs}}(\lambda_i) - I_k^{\mathrm{syn}}(\lambda_i) \right] \delta I_k^{\mathrm{syn}}(\lambda_i)$$

First paper describing inversions

Also, they use somewhat different form of the formal solution. Do not be confused if you find the term "evolution operator" ($\mathbf{O}$).

$$\boldsymbol{I}(\tau) = -\int_{\tau_0}^{\tau} \mathbf{O}\left(\tau, \tau'\right) \mathbf{K}\left(\tau'\right) S\left(\tau'\right) d\tau' + \mathbf{O}\left(\tau, \tau_0\right) \boldsymbol{I}\left(\tau_0\right)$$

Why is this approach important? Why do we have to account for depth-dependence of the parameters?

Because it leaves imprint on the spectral line profiles!

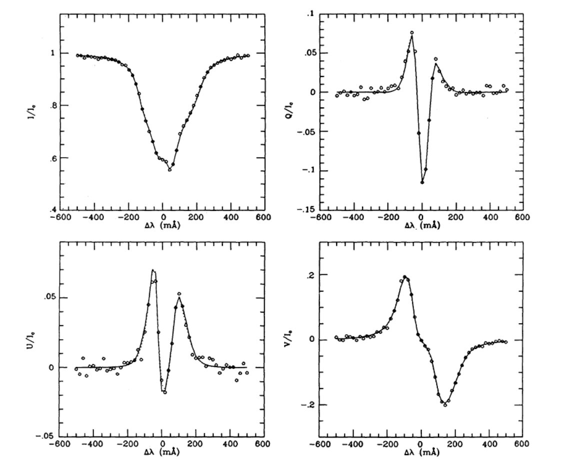


Figure 1: Synthetic spectra, with the added noise, and the inversion using SIR

Depth dependency of the physical parameters

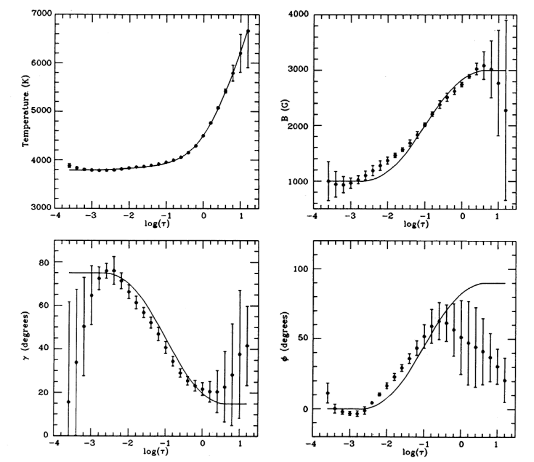


Figure 2: Retrieved atmospheres. Note the error bars.

Depth dependency of the physical parameters

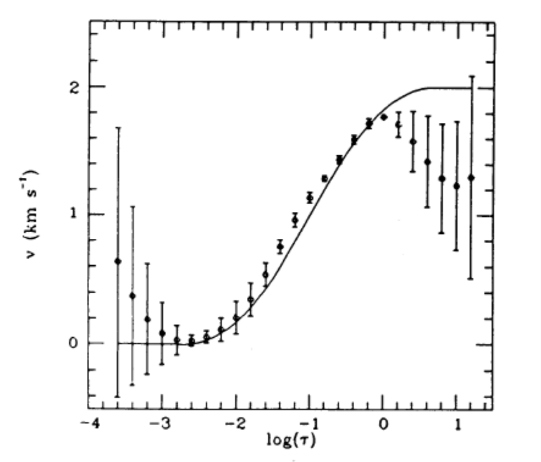


Figure 3: Retrieved velocity structure. Velocity gradients cause the line to be assymetric.

Stokes V assymetries

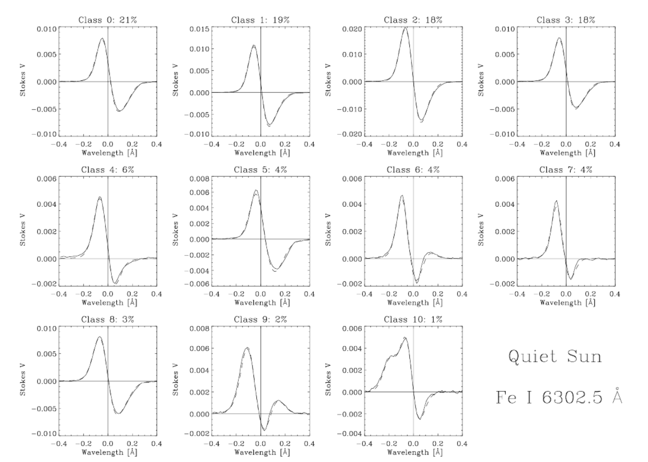


Figure 4: Different types of the Stokes V profiles found in the quiet Sun. From Sanchez Almeida & Lites (2000)

Corresponding atmosphere models

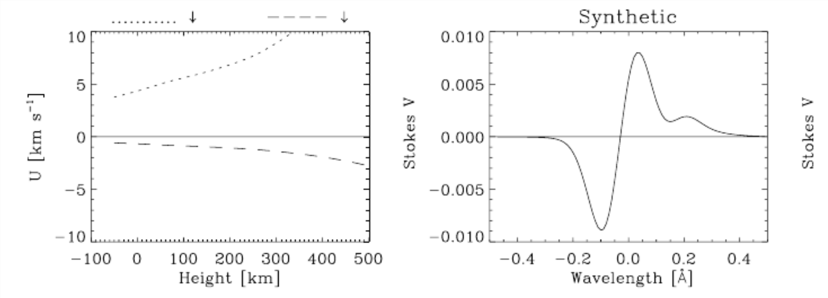


Figure 5: Generation of the assymetric profiles. Two-component atmosphere with two different velocities. From Sanchez Almeida & Lites (2000)

Assymetric profiles always imply velocity gradients (or different components, if you prefer that).

Speaking about different components

People generally like invoking this assumption. The argument is that, because of the finite spatial resolution we cannot assume that one pixel is well represented by one atmosphere.

Commonly used parameter is "filling factor":

$$\boldsymbol{I}^{\mathrm{obs}}(\lambda) = \alpha \boldsymbol{I}^{\mathrm{magnetic}}(\lambda) + (1-\alpha)\alpha \boldsymbol{I}^{\mathrm{non-magnetic}}(\lambda)$$

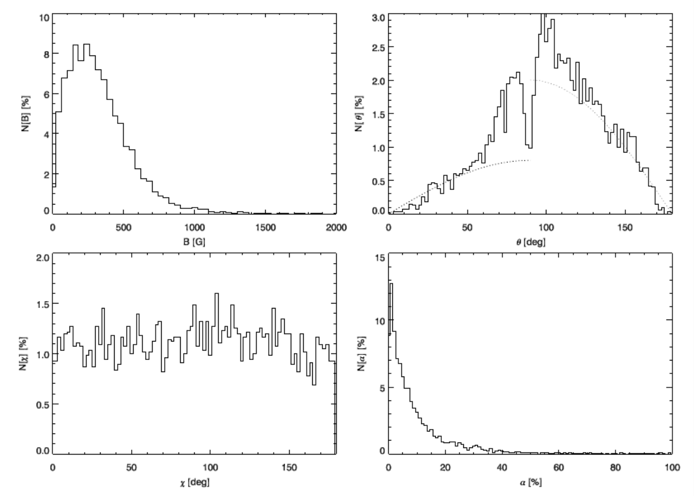


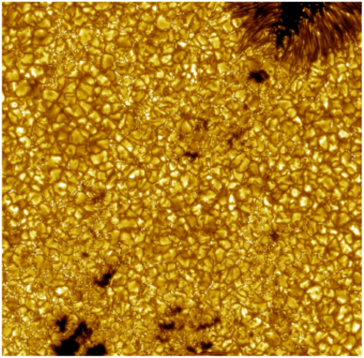
Figure 6: Inference of the magnetic field vector and the filling factor from the quiet Sun. From Martinez Gonzalez et al. (2016)

Effects of the telescope PSF

Why is the Sun so special?

$$\theta = 1.22\frac{\lambda}{D} = 0.012''$$

$$\rho = R_\odot/d = 0.004''$$



$$\theta = 1.22\frac{\lambda}{D} = 0.083''$$

$$\Delta x = \theta \times 1\mathrm{AU} = 61\ \mathrm{km}$$

What does it mean 'to resolve'?

There is always a theoretical limit to our resolution. We are usually happy if we reach diffraction limit.

We focus on the observations with high spatial resolution.

Emergent intensity from the sun is described by $\boldsymbol{I}_0(x, y, \lambda)$. What we see looks like:

$$\boldsymbol{I}(x, y, \lambda) = \boldsymbol{I}_0(x, y, \lambda) * PSF(x, y, \lambda)$$

Strictly speaking PSF depends on the location and the wavelength (Because telescope diffraction is only the tip of the iceberg).

Things become ‘smeared’

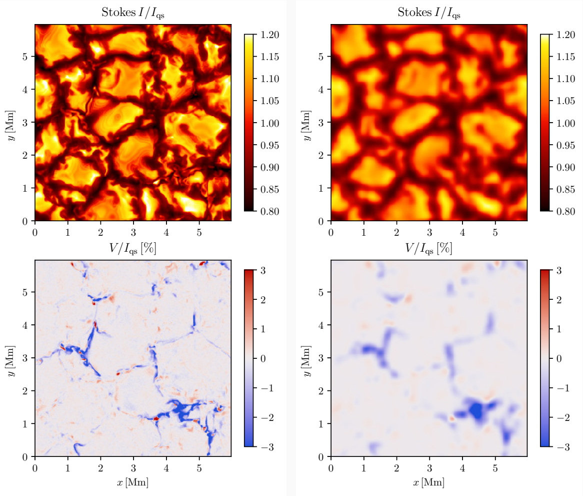


Figure 7: Left: Stokes *I* and *V* calculated for an IR Iron line from a MHD simulation. Right: Image degraded according to GREGOR telescope diffraction limit (0.27 arcsecs at 1.56 microns)

This brings interesting inference challenges

If we write $\boldsymbol{I}_0(x, y, \lambda) = f(p(x, y, \tau))$, what we actually see is (assuming const PSF):

$$\boldsymbol{I}(x, y, \lambda) = f(p(x, y, \tau)) * PSF$$

Or, we focus on one pixel, say i, j:

$$\boldsymbol{I}_{i,j} = \sum_{i'} \sum_{j'} f(p(x_{i'}, y_{j'}, \tau)) PSF_{ii',jj'}$$

Observation at one pixel is influenced by the physical parameters (strictly speaking) in each other pixel!

We have to invert whole data cubes **simultaneously!**

What does it mean?

It means that we try to find the best fit for the whole cube at once. We have $NX \times NY$ more parameters:

Who can do such thing?

"Spatially coupled inversion of spectro-polarimetric image data" (M. van Noort, 2012)

If we know the PSF, we can write one big Hessian matrix (the matrix from L-M method), for the whole set of data at once. PSF "couples" nearby pixels.

We need to solve, simultaneously, for $NX \times NY \times NM$ parameters. In real life it is tens of thousands.

But it works

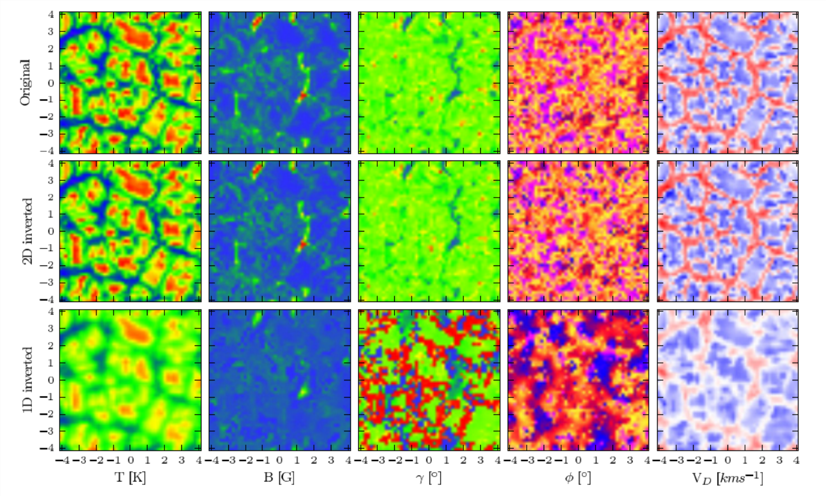
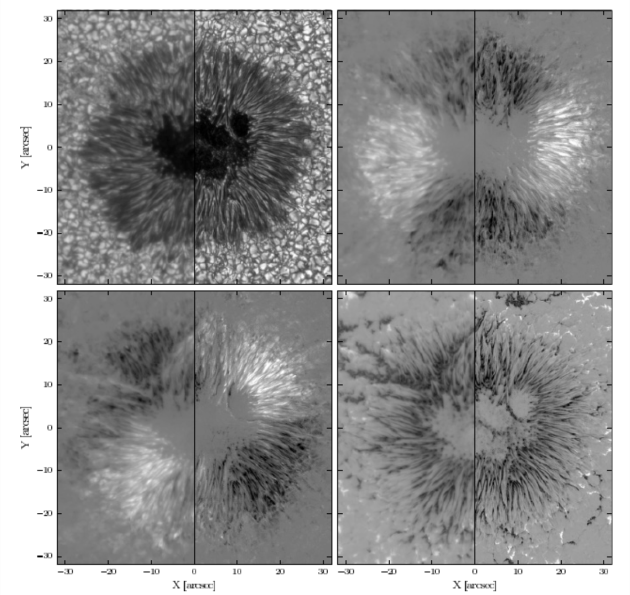


Figure 8: Top: Original simulation; Middle: Inverted with coupled inversion; Bottom: Inverted with pixel-by-pixel approach.

Come for inversion stay for the deconvolution



Another fancy thing is sparsity

We would (or 'could'), expect the parameter maps retrieved from observations to be “sparse”. That is, to notchange too much from pixel to pixel.

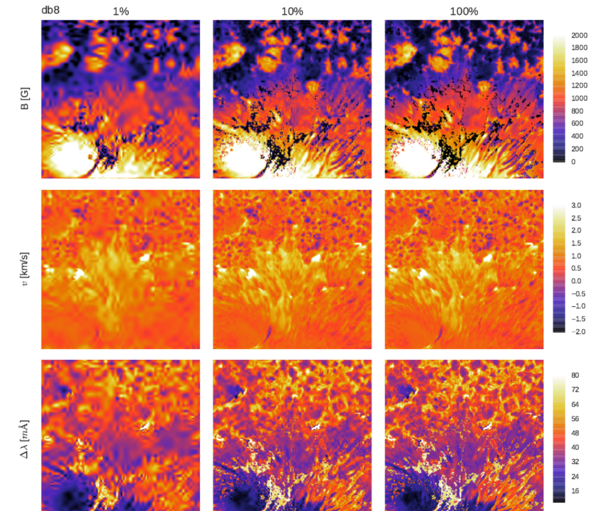
What does “sparse” mean? If we go to an another basis things are low dimensional.

For example: If we do Fourier transform, high frequencies should be zero. Etc.

This could help us reduce total amount of parameters. But again requires coupling.

Sparse inversions - compression

"Sparse inversion of Stokes profiles" by Asensio Ramos A., de la Cruz Rodriguez, J., 2012.



Sparse inversions

χ^2 for the whole map:

$$\chi_p^2 = \frac{1}{4 N_\lambda N_{\rm pix}} \sum_{k=1}^{N_{\rm pix}} \sum_{i=1}^{4} \sum_{j=1}^{N_\lambda} w_i \frac{\left[S_i\left(\lambda_j, \hat{\boldsymbol{p}}_k\right) - O_i\left(\lambda_j, k\right)\right]^2}{\sigma_{ijk}^2}$$

But when we change basis and require number of parameters in that alternate basis to be small:

$$\chi_q^2 = \frac{1}{4 N_\lambda N_{\rm pix}} \sum_{k=1}^{4} \sum_{j=1}^{N_k} w_i \frac{\left[S_i\left(\lambda_j, \left[\mathbf{W}^{-1}[\boldsymbol{q}]\right]_k\right) - O_i\left(\lambda_j, k\right)\right]^2}{\sigma_{ijk}^2}$$

This decreases the number of free parameters, but again we have to fit the whole map.

Sparse inversions - results

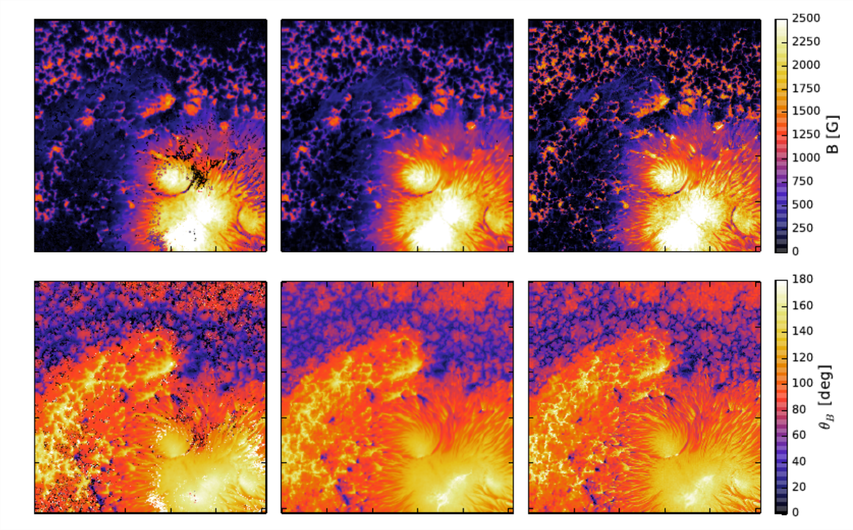


Figure 9: Left: pix-by-pix; Middle: sparse, Right: sparse + deconvolution

Not everything is in the photosphere

There are other interesting objects there, prominences, for example:

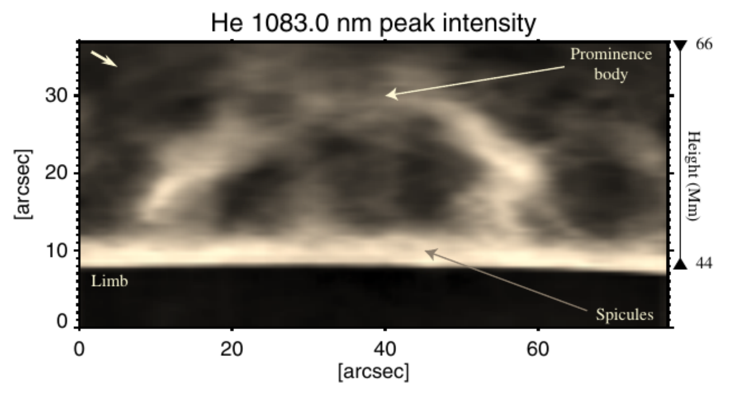


Figure 10: Prominence as seen in the He 10830 line, above the limb

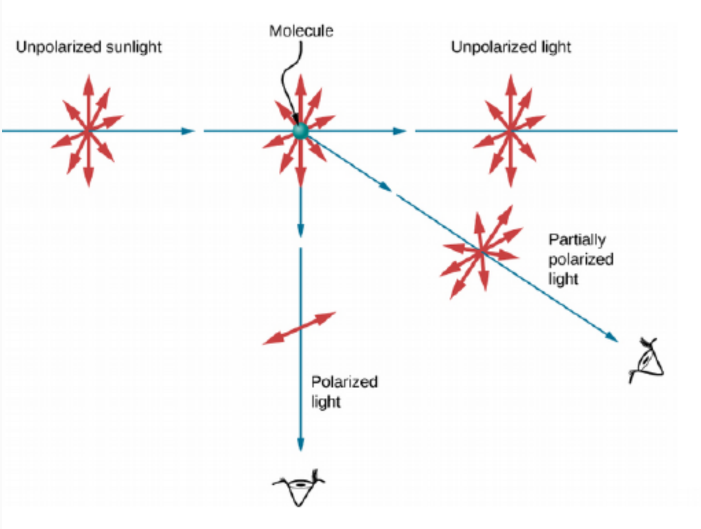
Prominence spectra formation

Prominences consist of cool chromospheric plasma, suspended in the solar corona.

Prominences emit (in the lines we are interested here) by scattering. They are an extreme example of NLTE (because their density is till very low).

Prominence spectra is polarized by additional effects: Scattering polarization and Hanle effect.

Scattering polarization



Scattering polarization in spectral lines

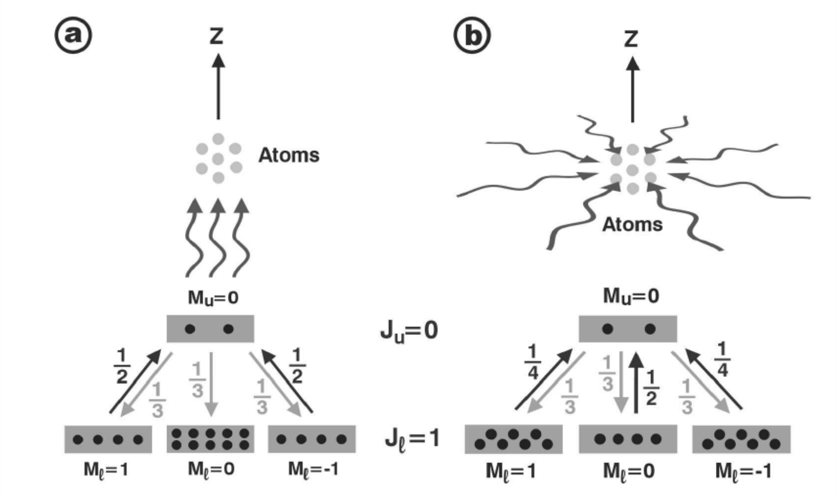


Figure 11: Selective absorption. Opposite effect is polarized emission. From Trujillo Bueno (2003)

Hanle effect

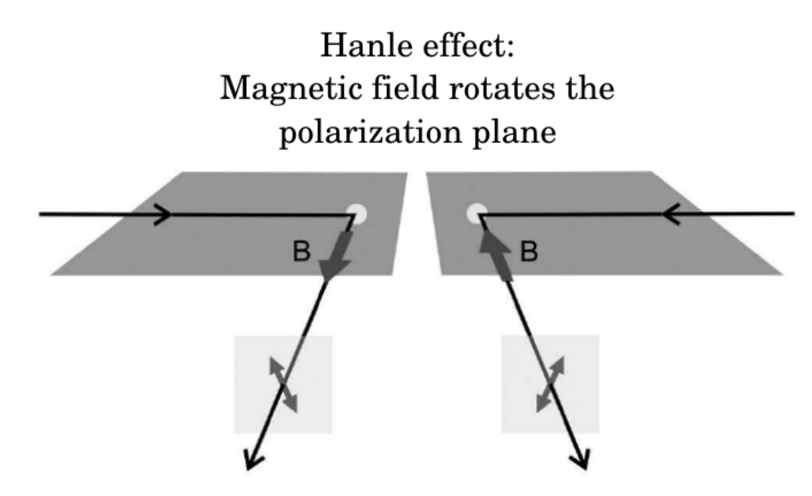
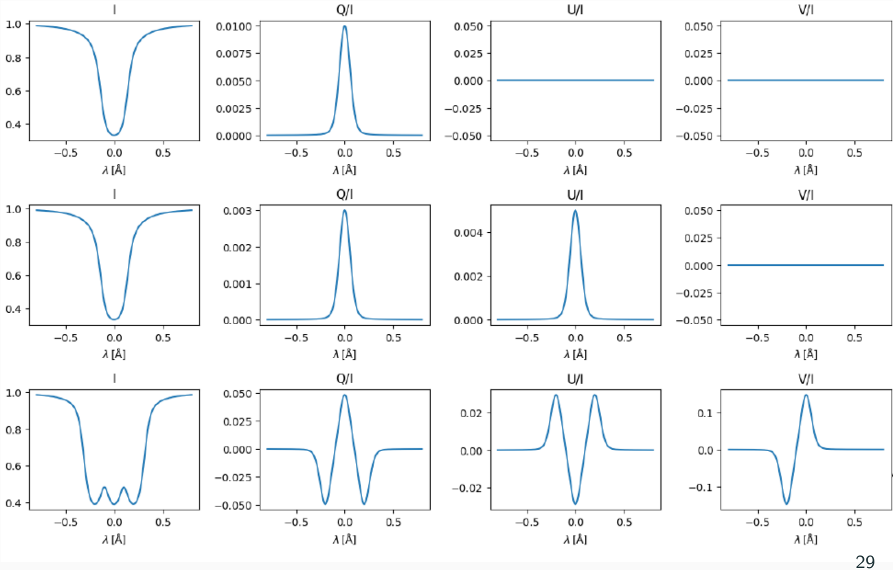


Figure 12: Presence of the magnetic field rotates the plane of polarization in spectral line scattering. From Trujillo Bueno (2006)

Zeeman vs Hanle



Polarized prominence spectra

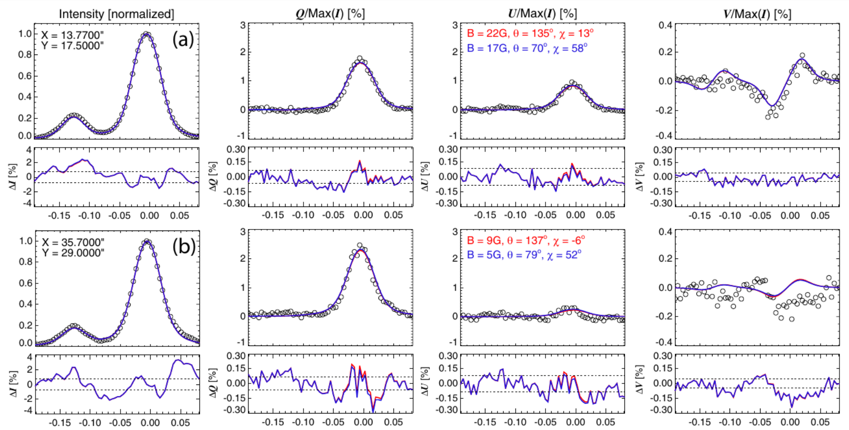
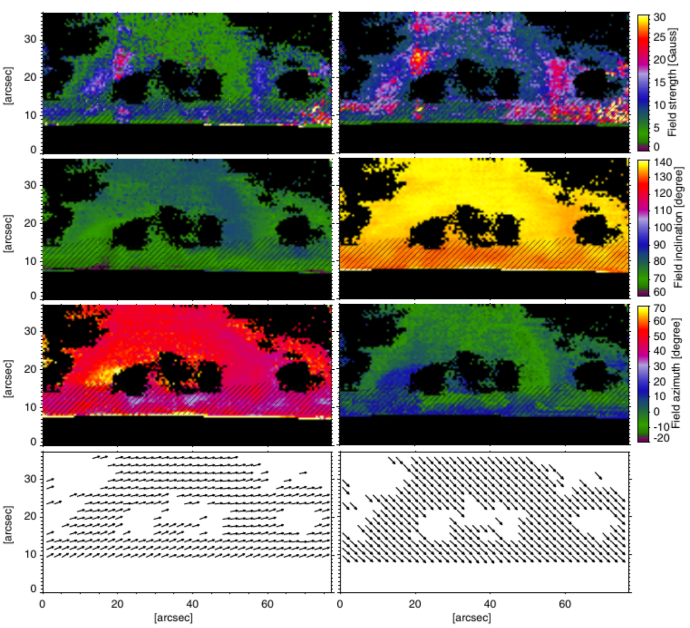


Figure 13: Two fits from Orozco Suarez et al.(2014). Note the shape of spectral lines.

Maps of the magnetic field - ambiguities



Other scattering polarization results

- Quiet Sun magnetism, insibile to Zeeman
- Multidimensional modeling, lateral effects
- Spicules magnetic fields
- Coronal magnetic fields

Complementary technique to Zeeman. Problem are very low signals.
With DKIST we hope to exploit it much more.

We are done

The aim of this part was to show you how the spectra is formed and why it is sensitive to various physical parameters.

If we know all the physics behind spectra formation, we can try to exploit it and perform inference.

It is hard. Ill-posed, full of local minima, instrumental effects, and it is slow.

However we should not surrender. There are new techniques that can help **a lot**. (Come to my LASP talk).

Thank you for the attention. Shoot all the questions and suggestions to ivan.milic (at) colorado.edu