Three-dimensional Radiative Transfer Modeling of the Hanle and Zeeman Effects in Chromospheric and Transition Region Lines

Jiří Štěpán

Astronomical Institute, Czech Academy of Sciences
Ondřejov, Czech Republic

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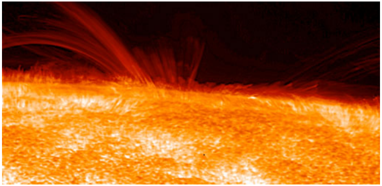
Four STSMs at Instituto de Astrofísica de Canarias

- June 2012
- November 2012
- June 2013
- June 2015

Collaborations with **Prof. Javier Trujillo Bueno, Dr. Luca Belluzzi, Mr. Tanausú del Piño Alemán**

Spectropolarimetric modeling of the solar chromosphere

- Chromosphere: **The most enigmatic layer of the solar atmosphere.**
- **Magnetic fields** modulate the energy propagation to the corona



- More than 90% of it are weakly magnetized **quiet regions** (with presumably $\langle B \rangle \sim 10\,\mathrm{G}$).
- Diagnostics: Via **strong optically thick spectral lines** (hydrogen Lyα, Hα, Ca II 8542, etc.)
- Optical thickness + low density $\rightarrow$ **NLTE line formation** $\rightarrow$ self-consistent RT needed)

Magnetic sensitivity of the chromospheric lines

- **Quiet chromosphere**: Hot and weakly magnetized $\rightarrow$ **Zeeman effect is usually very weak**
- But many of the lines are sensitive to **scattering polarization and Hanle effect** (i.e., modification of linear polarization due to action of weak magnetic fields)

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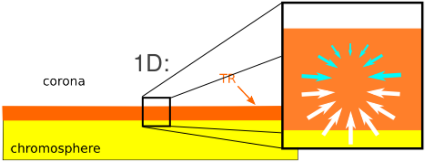
The Hanle effect:

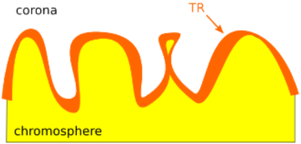
- Insensitive to temperature
- Very **broad range of sensitivities** of spectral lines to the field strength (from mG to kG)

The need for 3D modeling

Geometry plays a crucial role in the scattering polarization.



More realistically:



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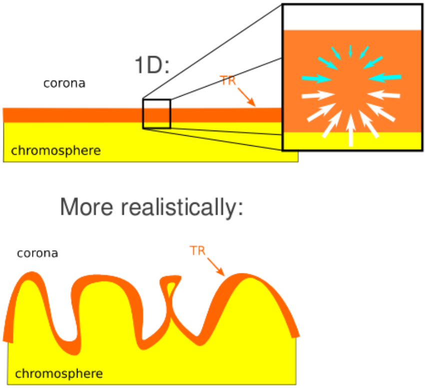

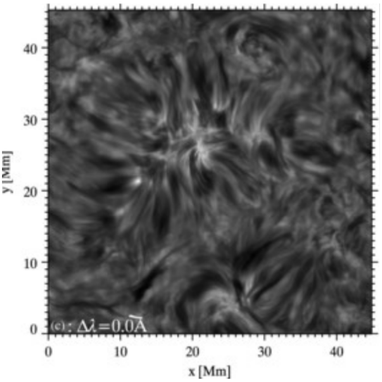

STSM #1 (June 2012): First applications of PORTA

To study the the atmosphere in full 3D we need:

- **Realistic simulations** of the solar atmosphere (3D MHD)
- Numerical tools for forward **synthesis of the polarized spectra**

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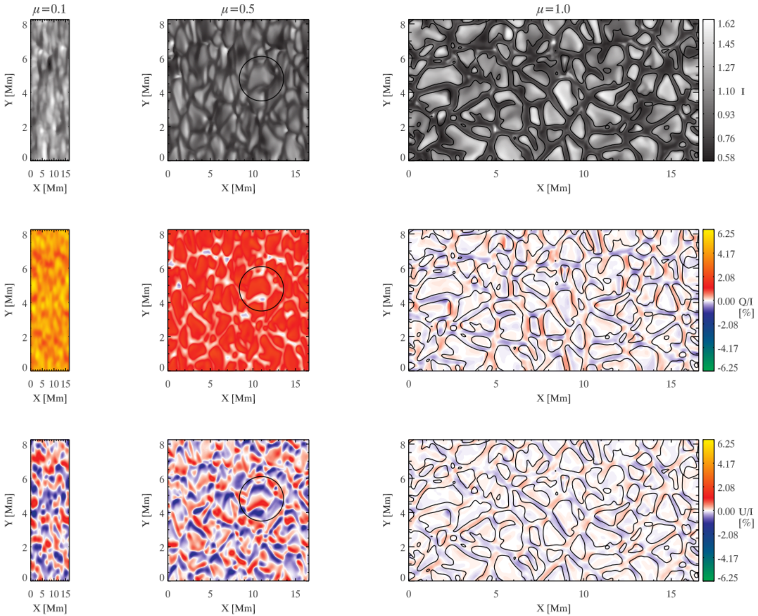
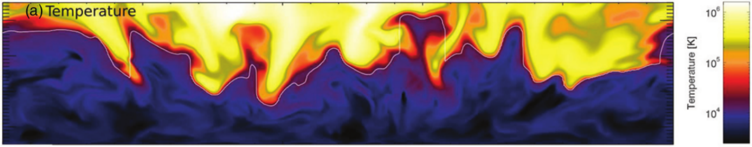
The STSM in June 2012:

- We have already had a general-purpose 3D NLTE solver **PORTA** developed in the previous years
- But the code was only developed for **serial calculations**, hence only applicable to small problems
- First realistic test: Scattering polarization in the **wing of the H & K doublet of Ca** II including J-state interference


μ=0.1
μ=0.5
μ=1.0
Y [Mm]
X [Mm]
1.62
1.45
1.27
1.10 I
0.93
0.76
0.58
6.25
4.17
2.08
0.00 Q/I [%]
-2.08
-4.17
-6.25
0.00 U/I [%]

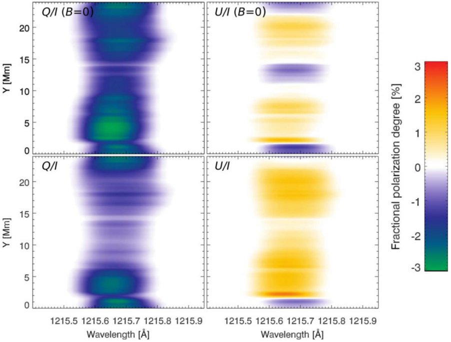
STSM #1 (June 2012): First applications of PORTA

Hydrogen Lyα line of the upper solar chromosphere motivated by the rocket experiment **CLASP**.



- We have used a snapshot from **3D MHD simulation of the group of Prof. Mats Carlsson (Univ. of Oslo)**
- NLTE synthesis in a **2D vertical slice** of the model

A glimpse of an enormous **spatial variability** of the signals **sensitive to the presence of magnetic fields**:

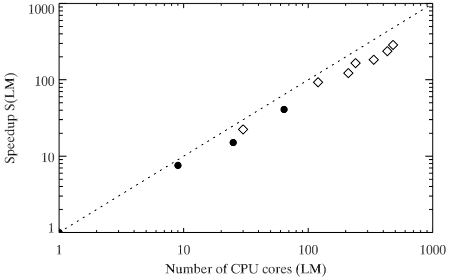


(Štěpán et al. 2012)

Full 3D solution was impossible with serial version of PORTA: 3D snapshots contains $\sim 10^8$ mesh points; single NLTE solution would last for several years.

STSM #2 (November 2012): Parallelization of PORTA

- Between June a November 2012 we have worked on **parallelization of the code** using original algorithms
- During the second STSM at IAC we have **finished and extensively tested the new code** up so several hundreds CPU cores (almost linear scaling has been confirmed)...
- ...and we wrote the ensuing **paper** (Štěpán & Trujillo Bueno 2013)



STSM #3 (June 2013): Hydrogen Lyα line in full 3D

- In late 2012 and early 2013, we have be running PORTA at the **MareNostrum supercomputer** (Barcelona Supercomputing Center) to get the **full 3D solution of the Lyα line** problem.
- CPUs in use per iteration: ~ 2000, total CPU time: $\sim 1\,$Mh

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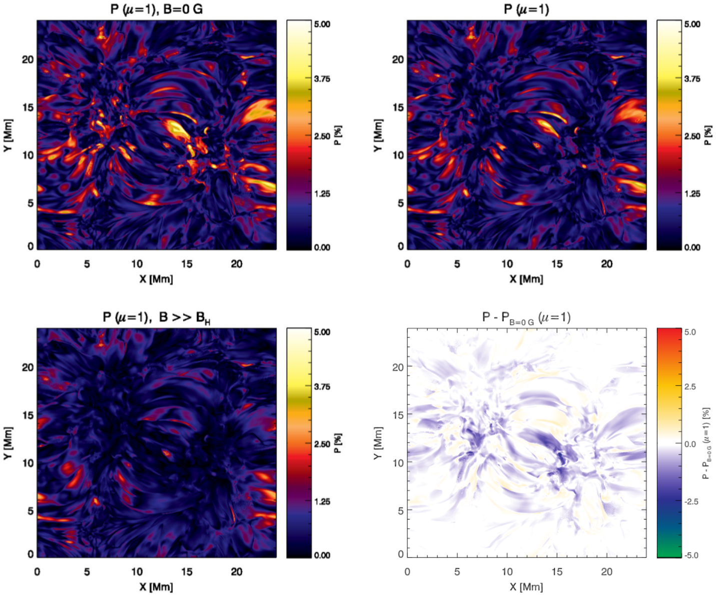
Analysis performed within the STSM #3:

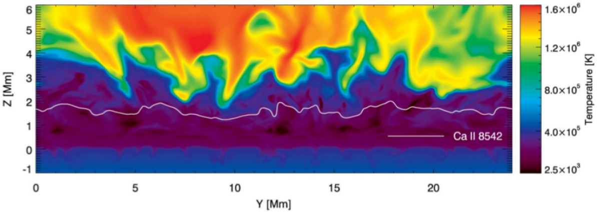
- The complexity of the 2D result from 2012 was confirmed but the **data are much richer** and more realistic (Štěpán et al. 2015).
- **B** tends to depolarize the linear polarization signals
- We have obtained **measurable statistical quantities** sensitive to **B** to be used in comparison with the CLASP data (more in Javier's talk).



P (μ=1), B=0 G
P (μ=1)
P (μ=1), B >> B_H
P - P_B=0 G (μ=1)
X [Mm]
Y [Mm]
P [%]
P - P_B=0 G (μ=1) [%]
0.00
1.25
2.50
3.75
5.00
-5.0
-2.5
0.0
2.5
5.0
0
5
10
15
20

STSM #4 (June 2015): Infrared triplet of Ca II

Results obtained and analyzed during the STSM #4:



- Ca II IR triplet around 850 nm (mid-chromospheric lines)
- Mainly sensitive to **orientation** of magnetic field
- We found that **3D solution is necessary**
- In contrast to Lyα: Strong **sensitivity to velocity fields**
- **Zeeman effect** starts to significantly interfere with the Hanle effect

(Štěpán & Trujillo Bueno 2015)

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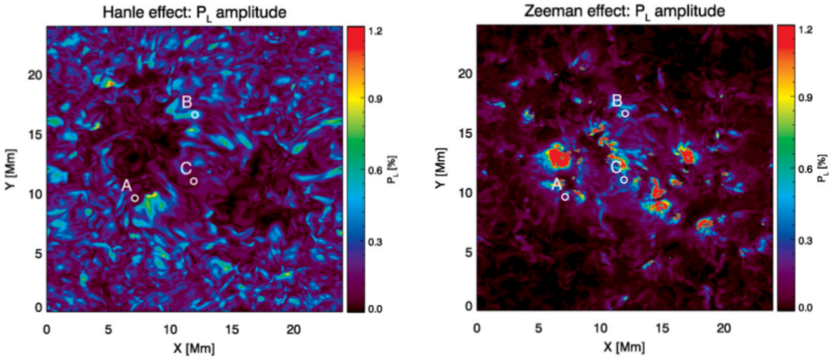

Summary

- Other lines being currently studied: Mg II k, Hα
- Magnetic field mostly acts as effectively turbulent in the considered models and mostly **depolarizes the lines**
- Depending on the spectral line, **gradients of the velocity fields** produce (de)polarization up to the same order of magnitude as magnetic fields
- Of the same order of magnitude is the **impact of horizontal thermal inhomogeneities** of the atmosphere

Conclusions and Outlook

- **Comparison of observations and forward synthesis provides test for the the MHD simulations**
- In order to disentangle the role of individual processes, **multi-line modeling and observations with the new-generation solar telescopes** seems to be necessary
- **Statistical comparison** of the models with observations and models may be a possible way to proceed

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and in particular to

Dr. Hervé Lamy