Self-consistent polarized radiative transfer

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May 16, 2013

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Outline of the talk:

1. How does the radiation transfer in optically thick media affect the shapes of intensity and polarization of a spectral line.
2. Magnetic field diagnostics via spectropolarimetry
3. On the role of 3D polarized radiative transfer (the code PORTA).

Equations of the light-atom interaction

Statistical equlibrium equations (SEE)

- *Local radiation field* $\boldsymbol{I}(\nu, \boldsymbol{n}) = (I, Q, U, V)^{\mathrm{T}}$
- Collisions
- Magnetic field

$$\Downarrow \Downarrow \Downarrow$$

Atomic density matrix ρ^K_Q

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Radiative transfer equations (RTE)

- *From local* ρ^K_Q*:*
- Emission coefficients $\boldsymbol{\epsilon}(\nu,\boldsymbol{n}) = (\epsilon_I,\epsilon_Q,\epsilon_U,\epsilon_V)^{\mathrm{T}}$
- Absorption coefficients

$$\boldsymbol{K}(\nu,\boldsymbol{n}) = \begin{pmatrix} \eta_I & \eta_Q & \eta_U & \eta_V \\ \eta_Q & \eta_I & \rho_V & -\rho_U \\ \eta_U & -\rho_V & \eta_I & \rho_Q \\ \eta_V & \rho_U & -\rho_Q & \eta_I \end{pmatrix}$$

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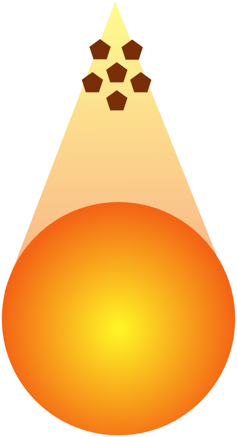
$$\frac{d}{d\tau}\boldsymbol{I}(\nu,\boldsymbol{n}) = \boldsymbol{S}(\nu,\boldsymbol{n}) - \boldsymbol{K}'\boldsymbol{I}(\nu,\boldsymbol{n})$$

where

$$\boldsymbol{S} = \boldsymbol{\epsilon}/\eta_I, \qquad d\tau = \eta_I\, ds, \qquad \boldsymbol{K}' = \boldsymbol{K}/\eta_I$$

Scattering of anisotropic radiation and the Hanle effect



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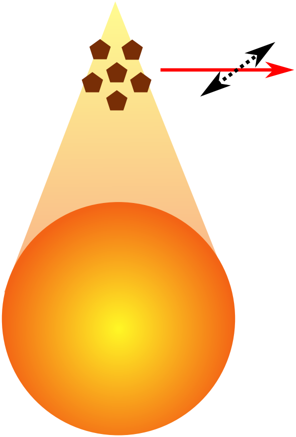

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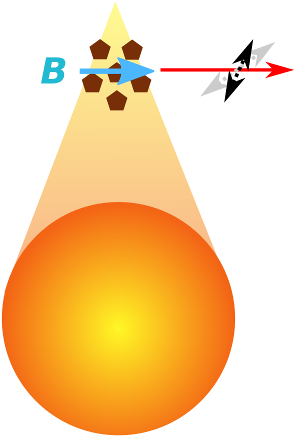

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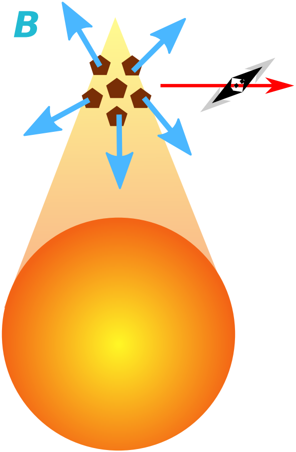

Formal solution of the radiative transfer equation

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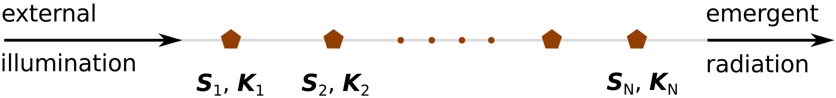
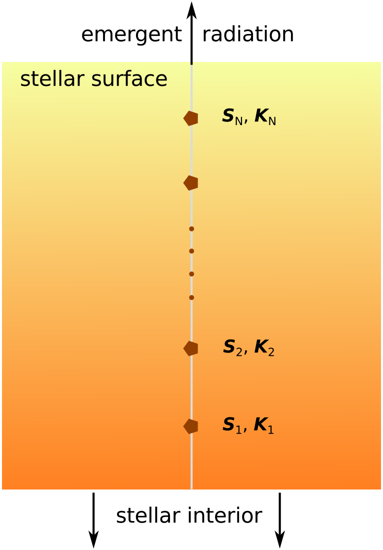


Integrated signal along the line of sight.

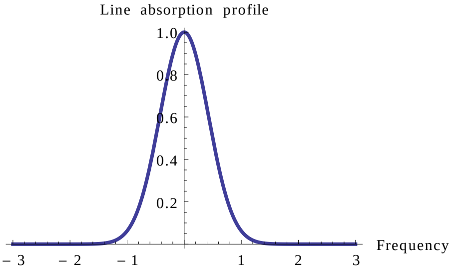
Formal solution of the radiative transfer equation



Formal solution of the radiative transfer equation

Example:

Isothermal atmosphere, constant source function S ($r = 10^{-2}$, $S = 0.1 B_{\mathrm{P}}$)



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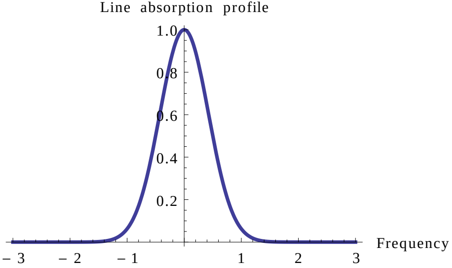
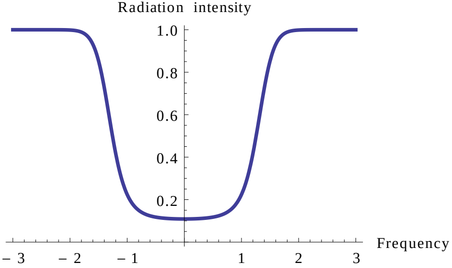
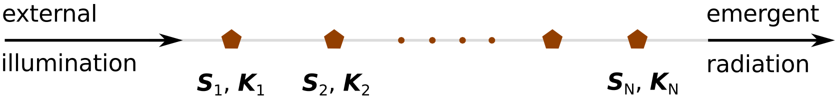
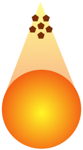




How to determine $\boldsymbol{S}$ and $\boldsymbol{K}$: Limitting cases



Optically thin medium



Optically thin, known external illumunation (solar corona).

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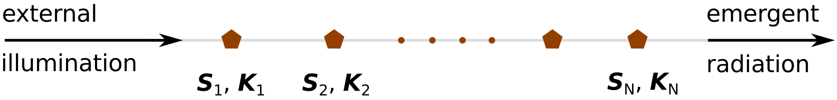

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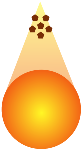

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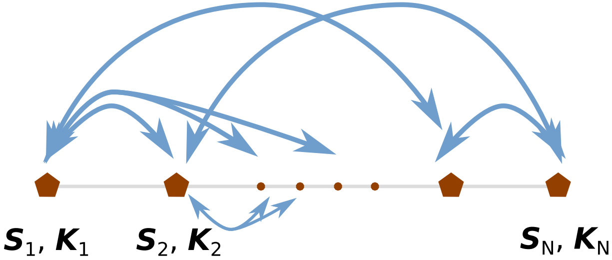
Local-thermodynamical equilibrium (LTE)

Dense plasmas, $\boldsymbol{S}$ and $\boldsymbol{K}$ from local thermal conditions (solar photosphere).

The self-consistent non-LTE problem

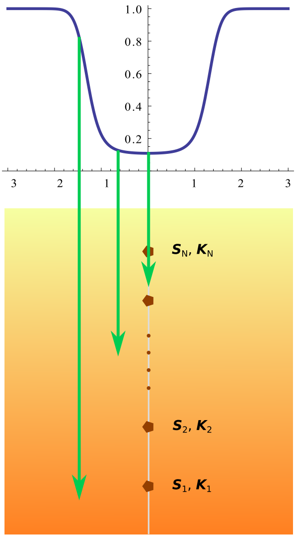
$\rho^K_Q(\boldsymbol{x})$ is coupled, via radiation transfer, with $\rho^K_Q(\boldsymbol{y})$



non-linear and **non-local**: Need of iterative solution.

(See Mihalas (1978) for the unpolarized theory)

Height of formation of a spectral line



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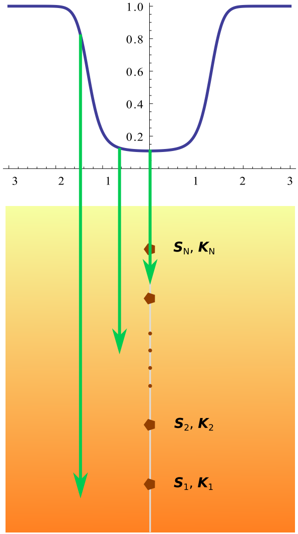
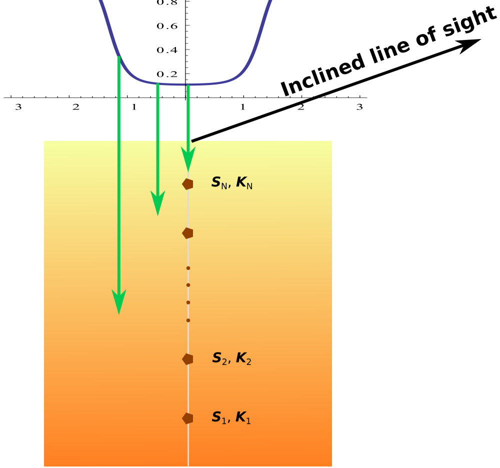
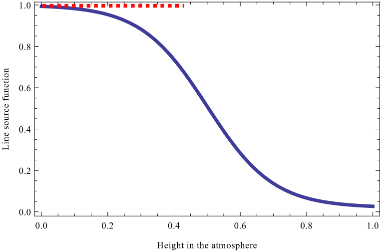


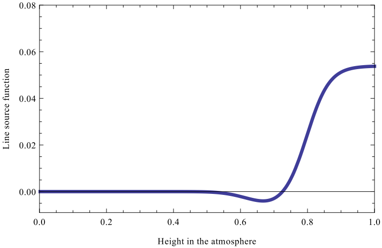


Anisotropy of radiation in an isothermal atmosphere

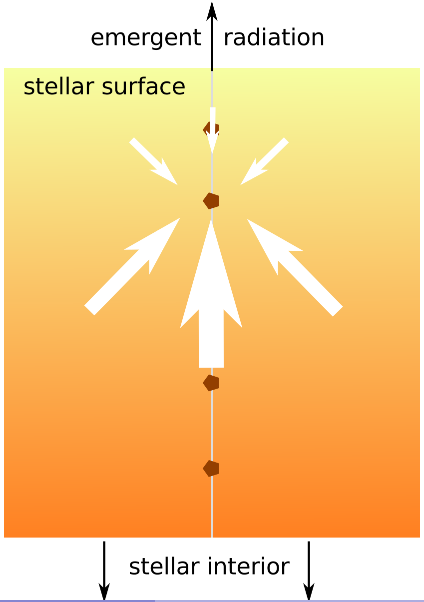
Mean intensity $J = J_0^0$



Fractional anisotropy J_0^2 / J_0^0



Observation near the stellar limb:



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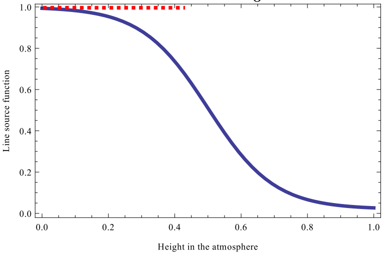

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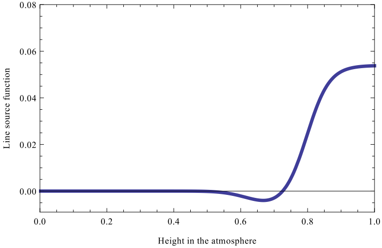

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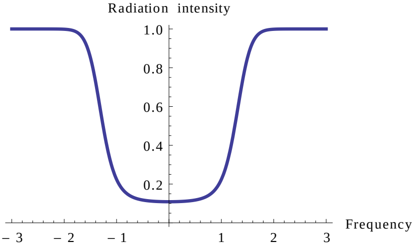
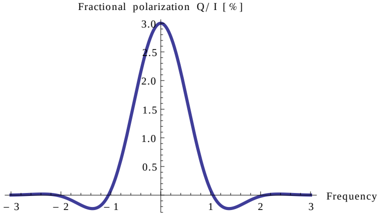
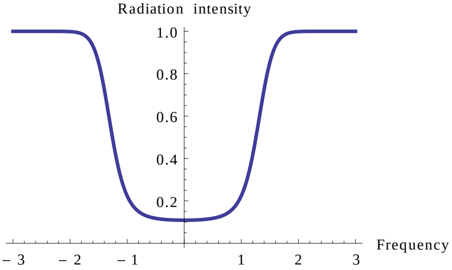
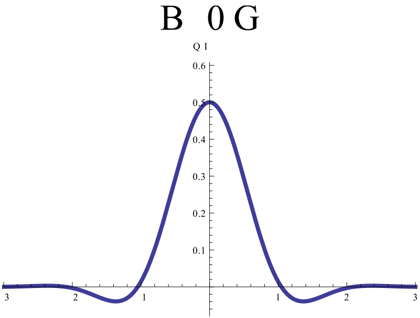




The Hanle effect of a weak unresolved magnetic field

Hα-like line near the solar limb:





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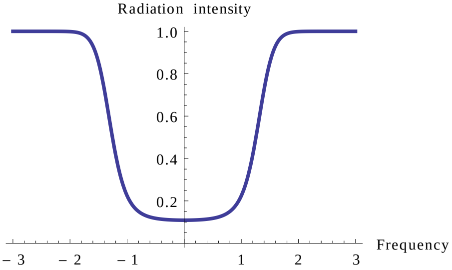

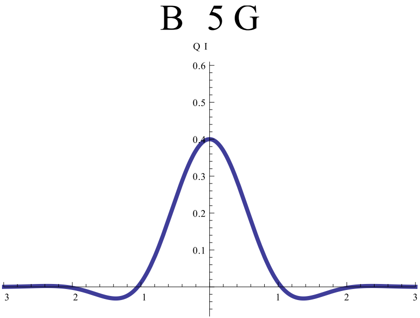

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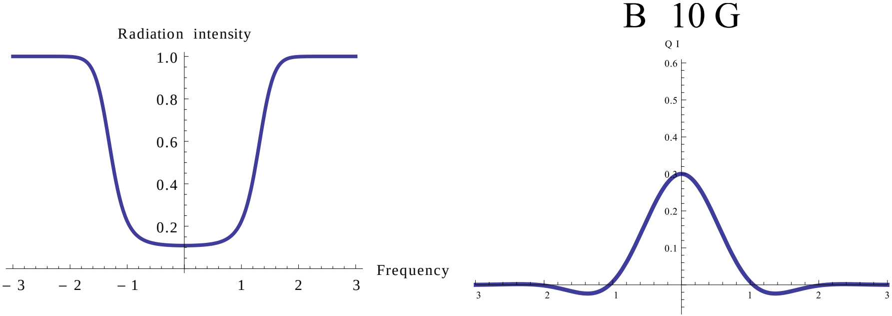

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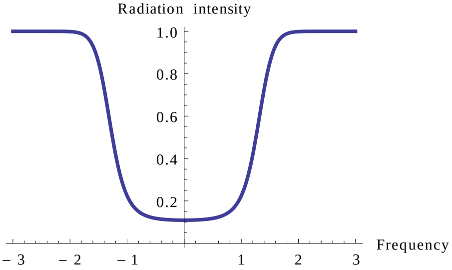
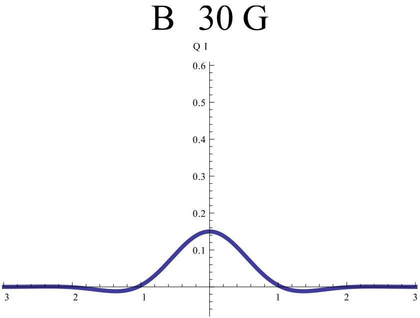
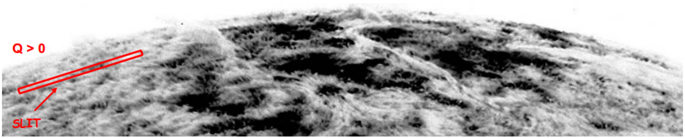




The Hanle effect of Hα line of the average Sun



(Harvey, 1978)

Observation vs synthesis in a semi-empirical FAL-C model atmosphere:

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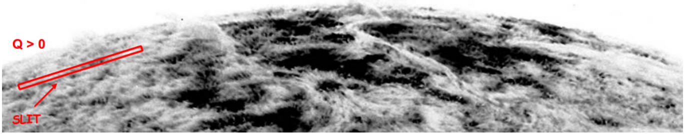

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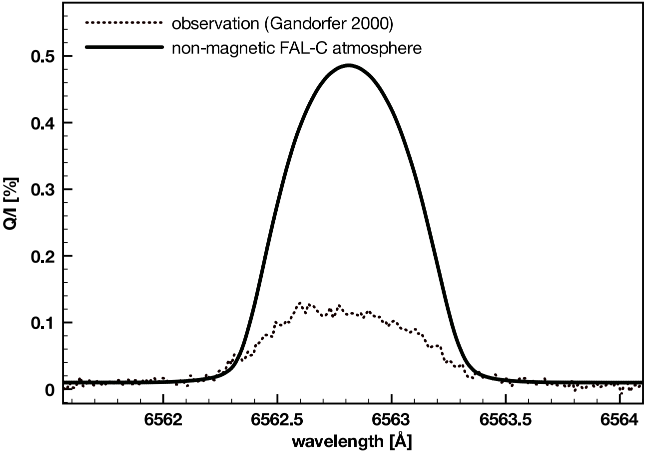

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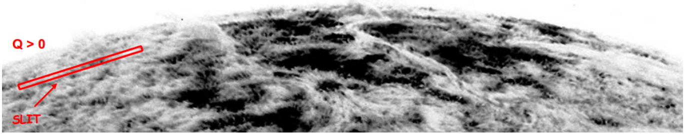

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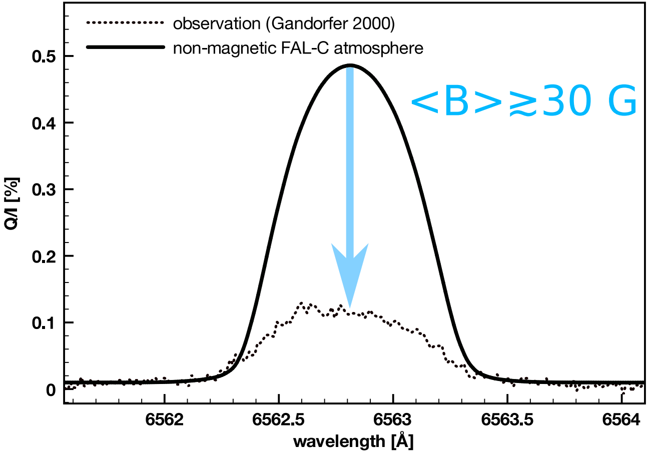
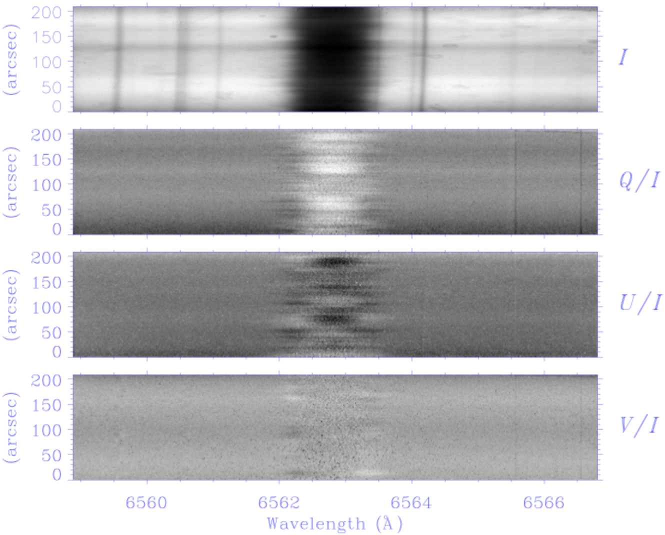


Hα: spatially resolved observation



(Courtesy of R. Ramelli & M. Bianda, IRSOL)

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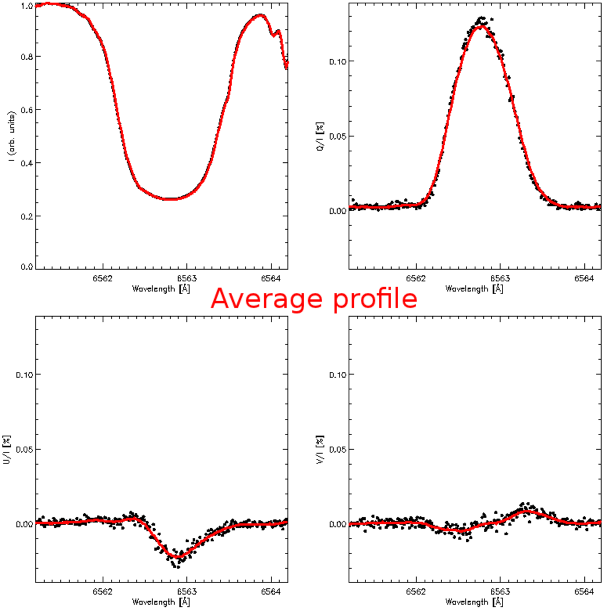

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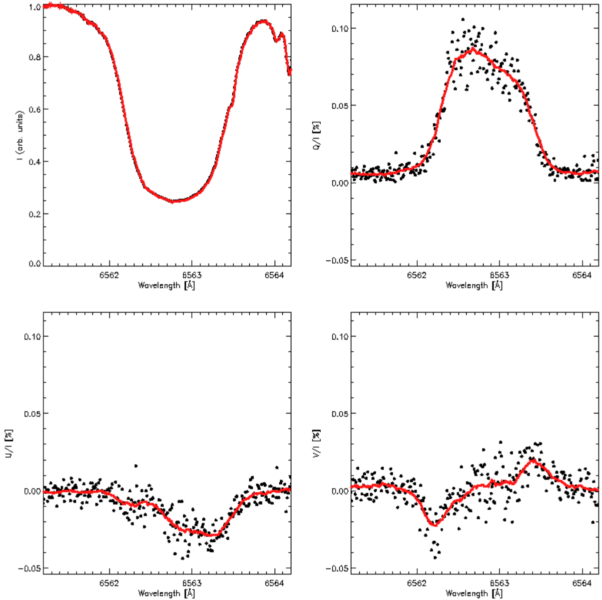

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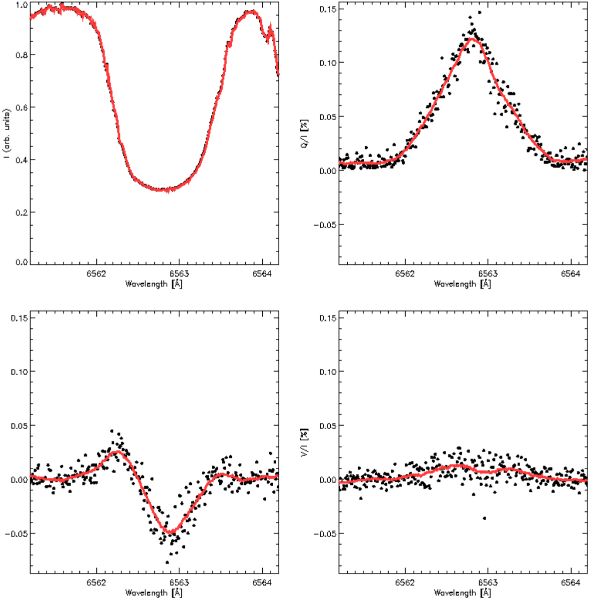
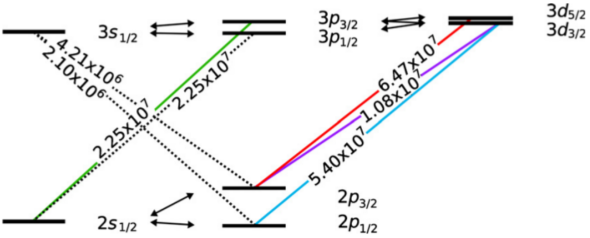
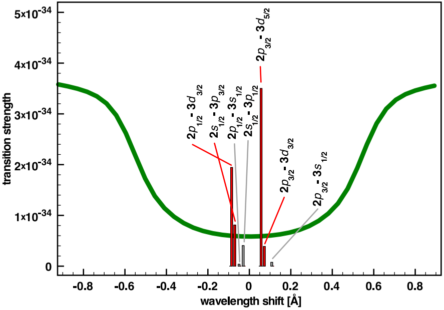
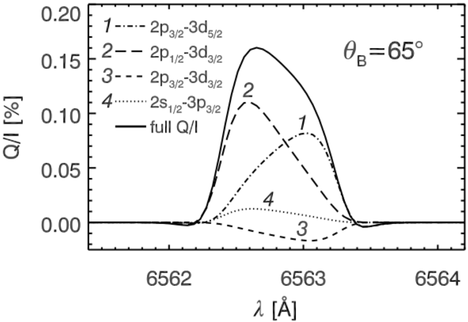


Hα as probe of magnetic field gradients







Limits of 1D modeling

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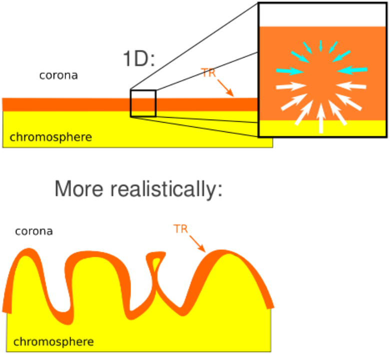

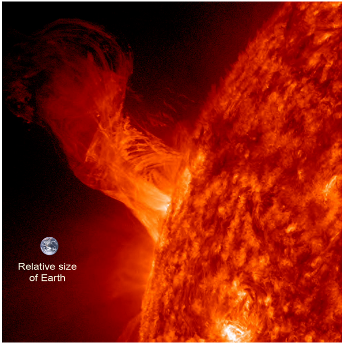

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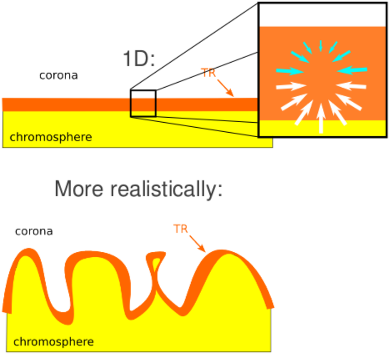

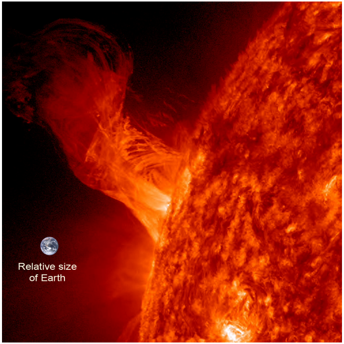

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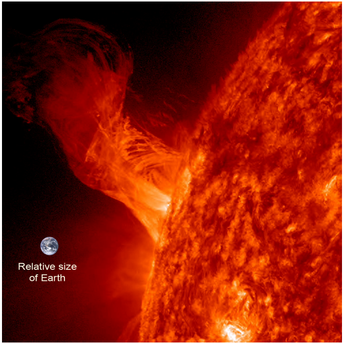

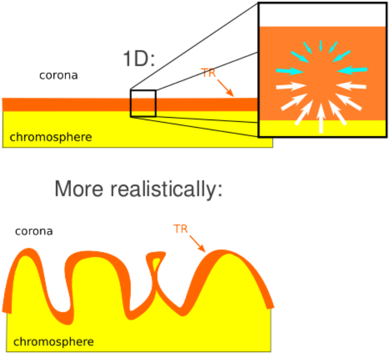

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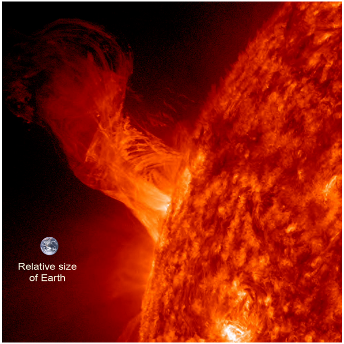
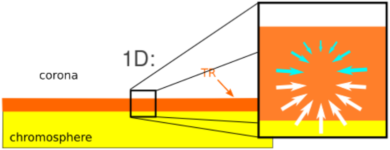
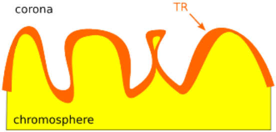




More realistically:



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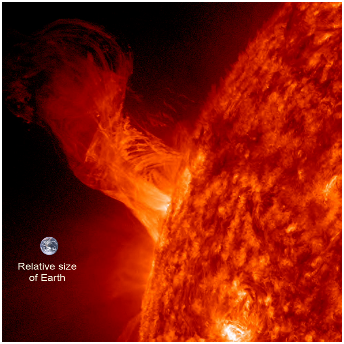

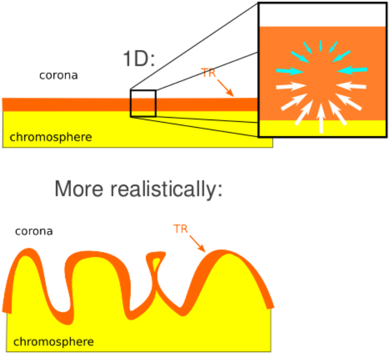

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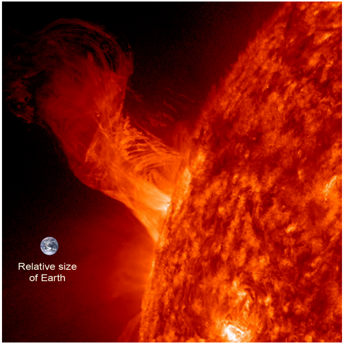

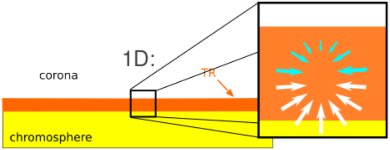

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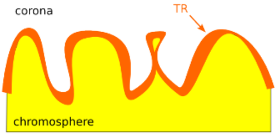

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- Need to study the role symmetry breaking effects (to disentangle them from the action of magnetic fields)
- Does not reflect the physical reality

PORTA: POlarized Radiative TrAnsfer solver

- General-purpose non-LTE transfer in 3D based on quantum theory of spectral line polarization
- Both intensity and polarization is considered
- Optical pumping in multilevel atomic systems
- Atomic polarization with the joint action of the Hanle and Zeeman effects

PORTA: POlarized Radiative TrAnsfer solver

- General-purpose non-LTE transfer in 3D based on quantum theory of spectral line polarization
- Both intensity and polarization is considered
- Optical pumping in multilevel atomic systems
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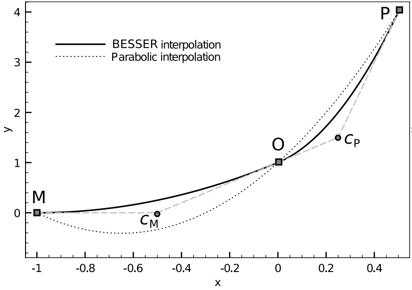
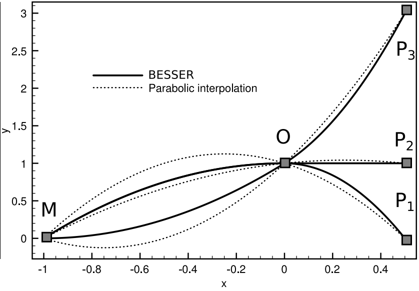
- **Accurate and stable SC solver**





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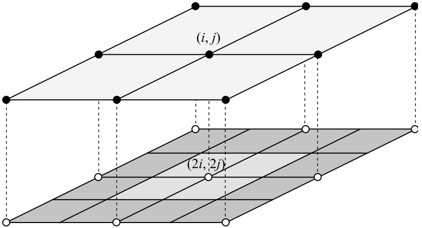
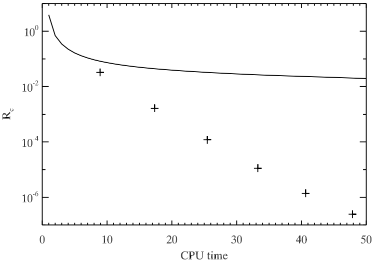
- **Non-linear multigrid method**





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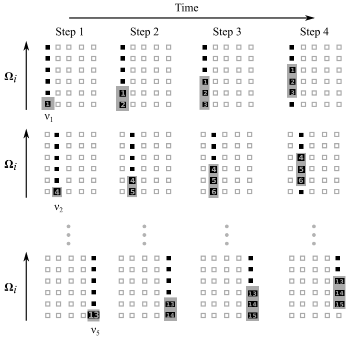
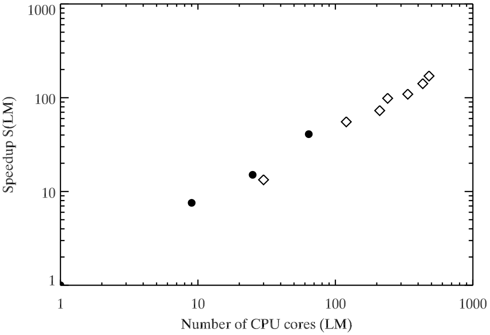
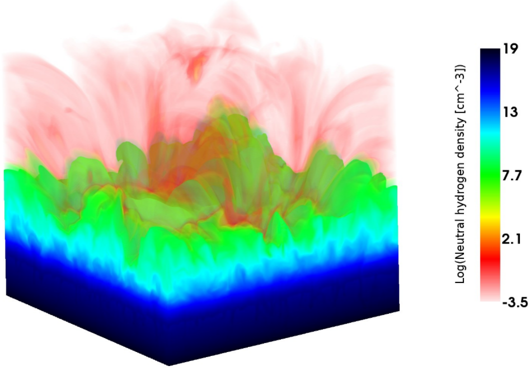
- **Massive parallelization via the Snake Algorithm:** Scaling $\sim P$





3D MHD snapshot of the solar atmosphere



(Leenaarts et al, 2012; BIFROST code)

- Enhanced network region
- RMHD simulation of 1h of solar time
- $24 \times 24 \times 16$ Mm^3
- 500^3 grid points
- Non-equlibrium hydrogen ionization

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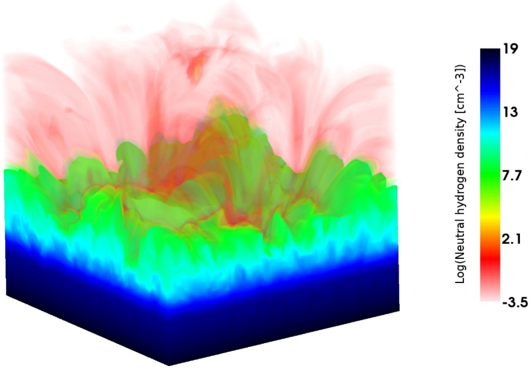

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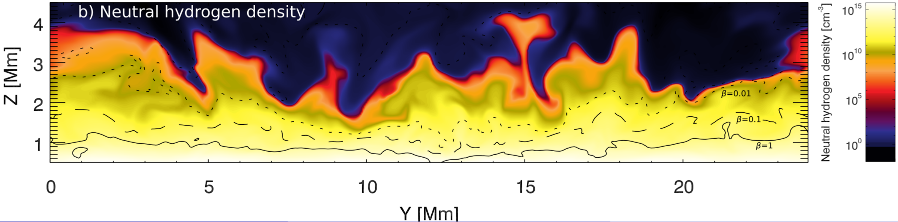
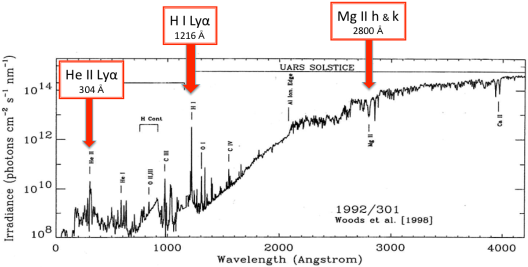


Application to the solar Lyα



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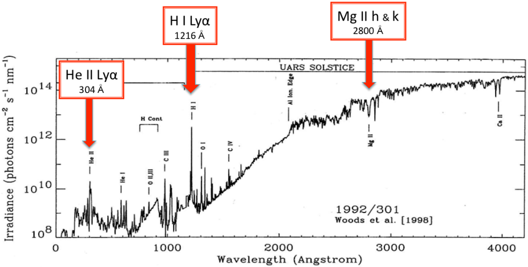
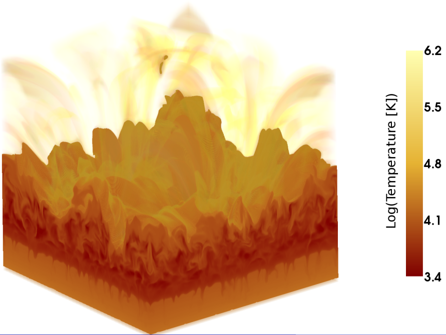
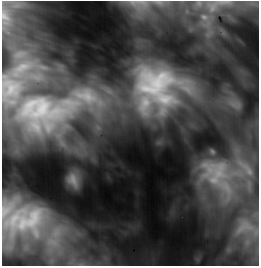




- 25 GB per snapshot
- About 10^9 unknowns, 10^{15} radiative quantities
- Computing time 1 μs per Stokes parameter^{-1}frequency^{-1}angle^{-1}
- Serial time: $\sim$ 10 years
- Parallel solution at the LaPalma supercomputer (1000 CPUs): $\sim$ 1 week

Disk-center emergent radiation

(Observation: Vourlidas et al. 2010)



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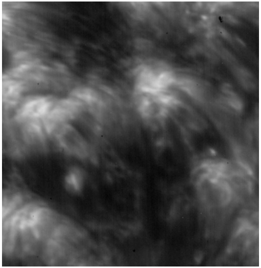

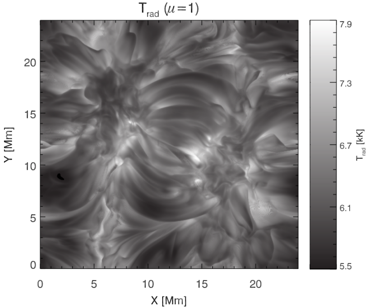

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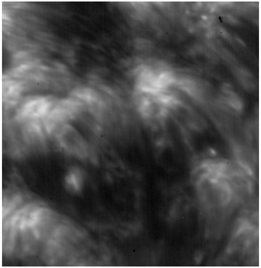
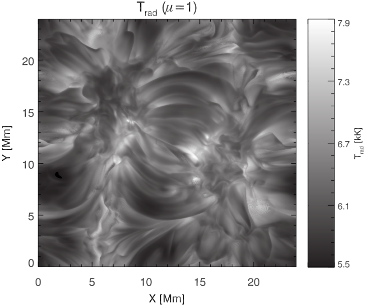
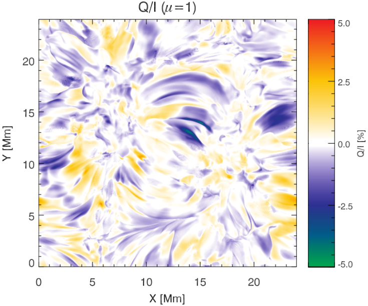
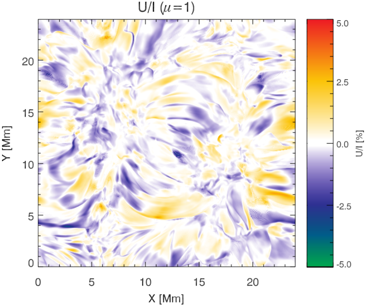


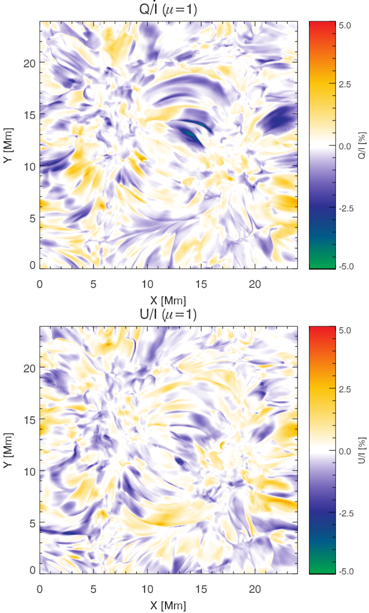






Center-to-limb variation of polarization

$\mu = 1$



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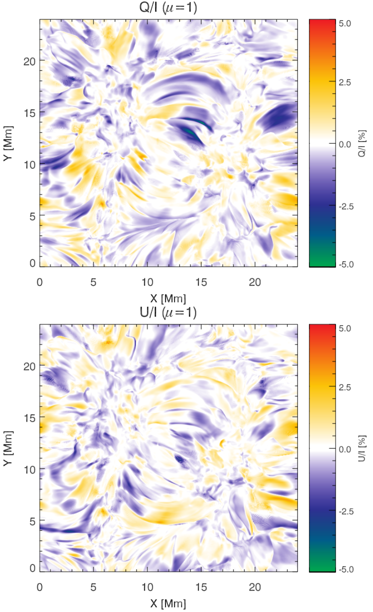
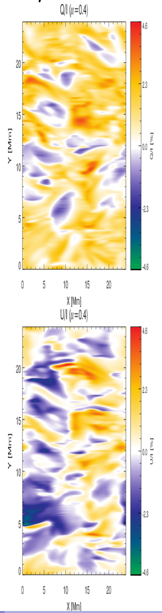
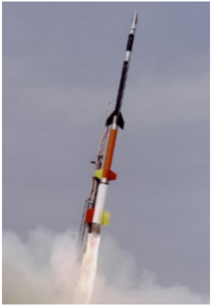


$\mu = 0.4$



The CLASP mission



- Approved NASA & JAXA sounding rocket experiment
- Lunch 2014–2015

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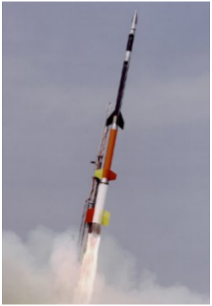

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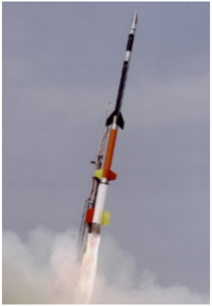

- Approved NASA & JAXA sounding rocket experiment
- Lunch 2014–2015
- **Goal #1: First detection of linear polarization of a FUV line (Lyα)**
- **Goal #2: Estimate magnetization of the upper solar chromosphere and the transition region**

Conclusions

- Line formation heights in very corrugated surfaces
- Multilevel non-LTE 3D modeling in increasingly realistic models of the solar atmosphere is the step to be made now
- 3D modeling is necessary for spatially averaged observations and even more the high-spatial resolution ones
- Comparison of 3D models and high-resolution observations (both ground based and space born: ATST, EST, SOLAR-C)
- Both Hanle and Zeeman (He I 10830, Ca II IR triplet, Hα, Mg II k, …)