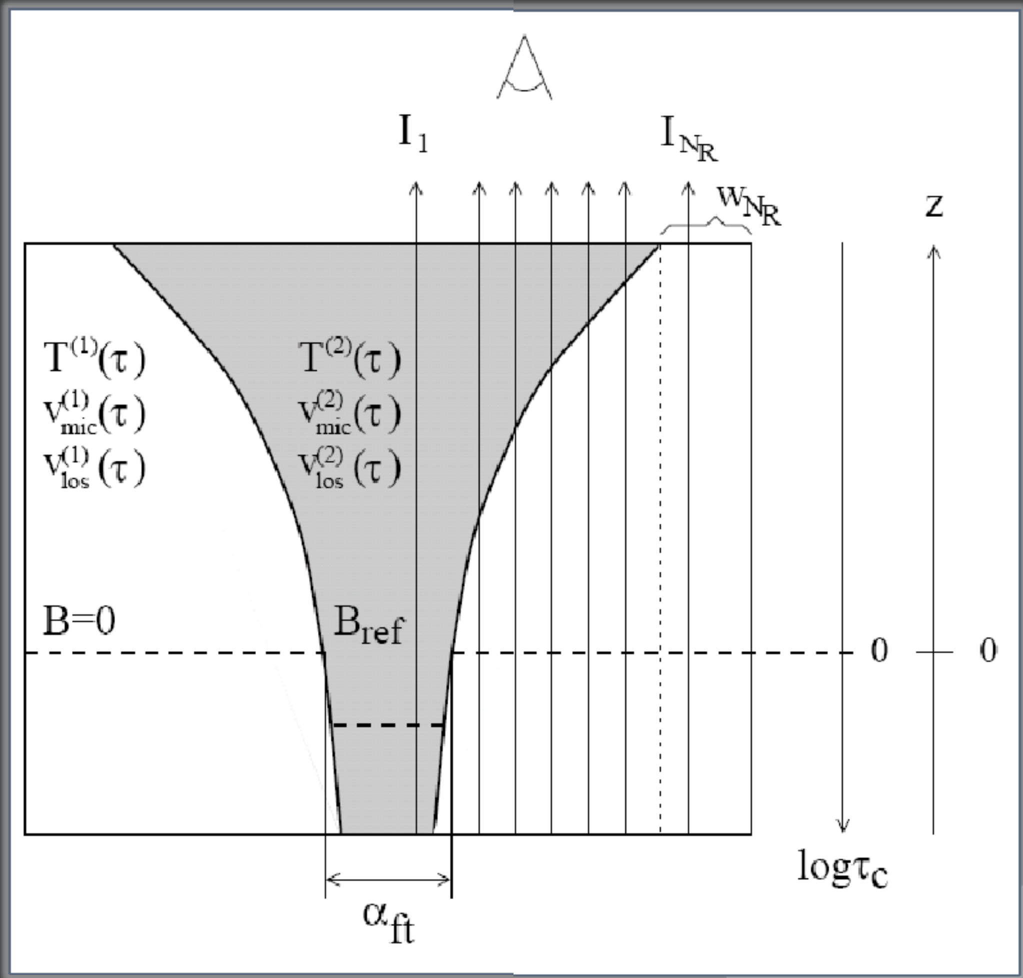
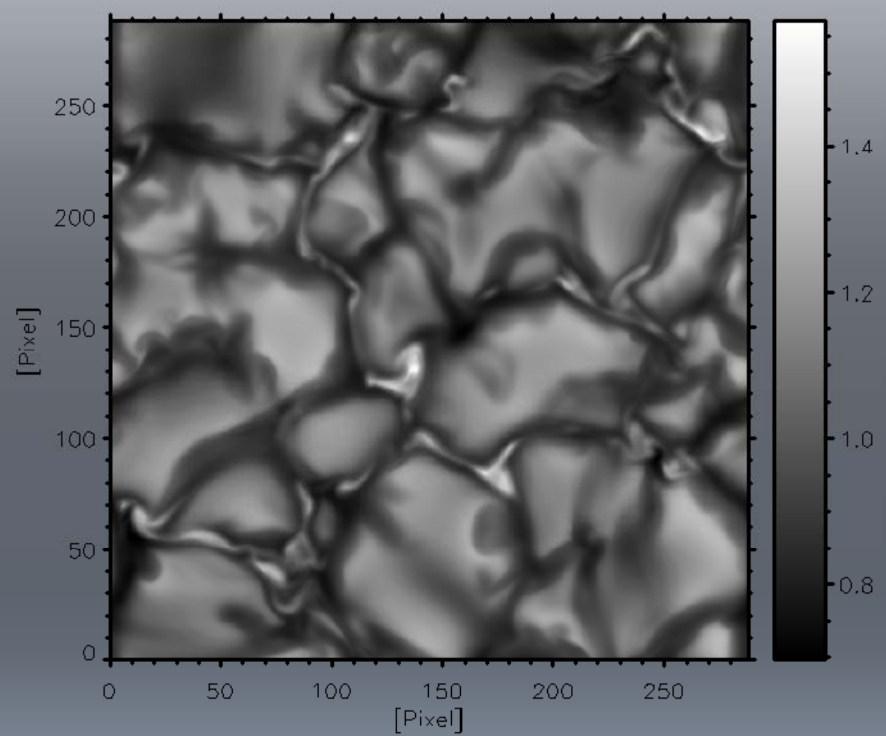
SPINOR
Inversions based on RFs

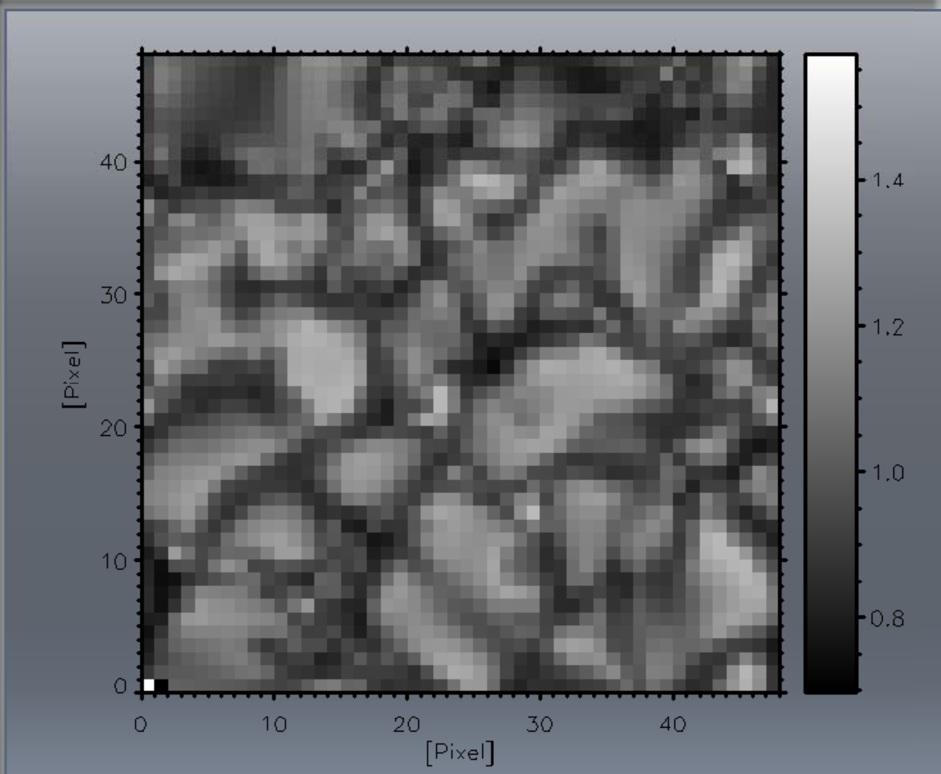


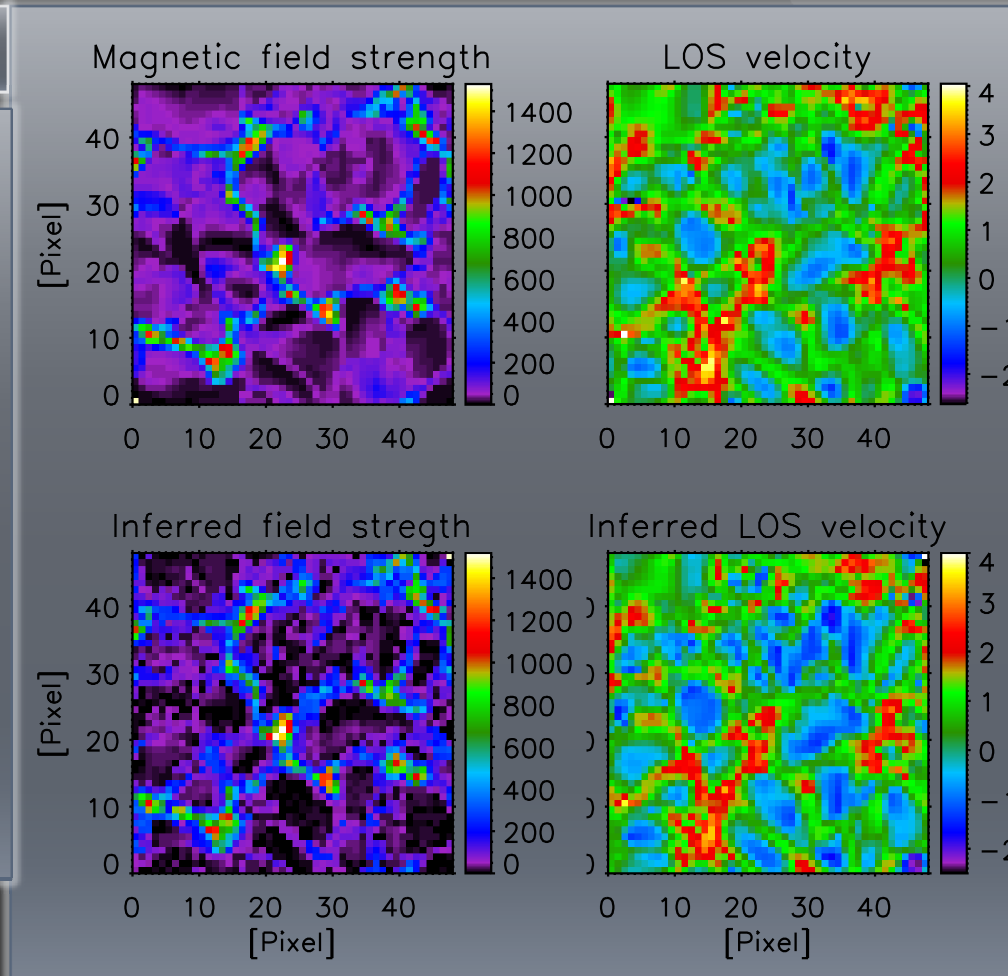
Asymmetric profiles and ME (1)

MHD-Simulations (Vögler et al. 2005)



Asymmetric profiles and ME (2)





- Fe I 630.1 and 630.2 profiles degraded to SP pixel size
- Maps of inferred B and v_{LOS} very similar to real ones!

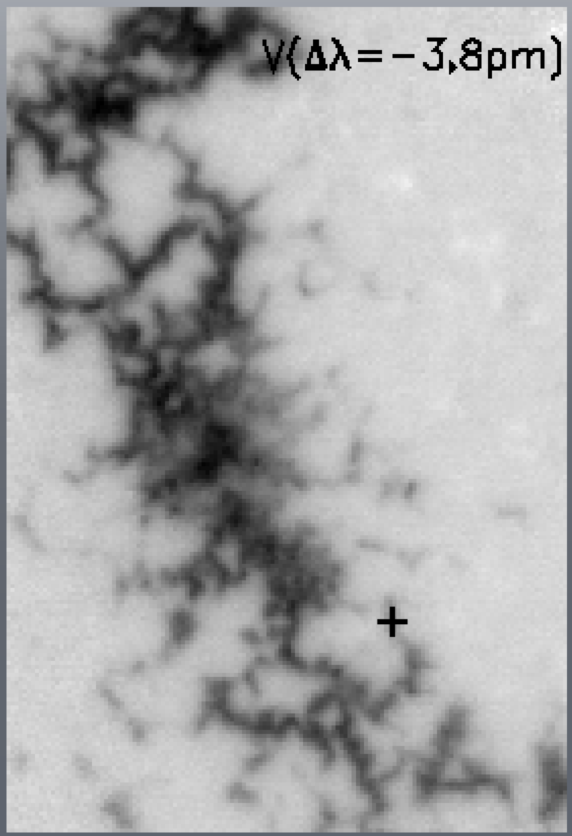
Inversions with gradients

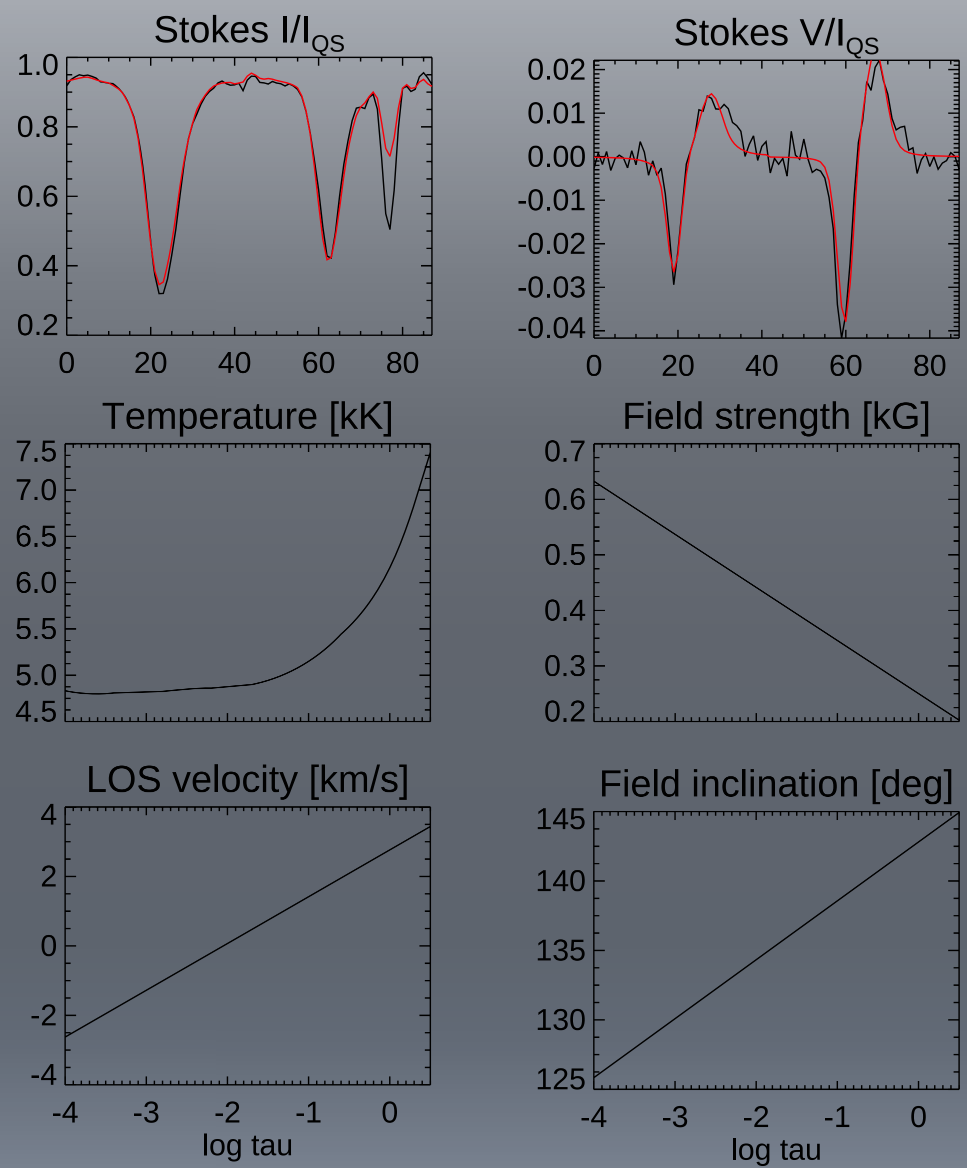
- Inversion codes capable of dealing with gradients
  - Are based on numerical solution of RTE
  - Provide reliable thermal information
  - Use *less free parameters than ME* codes (7 vs 8)
  - Infer stratifications of physical parameters with depth
  - Produce better fits to asymmetric Stokes profiles

- Height dependence of atmospheric parameters is needed for
  - easier solution of the 180° azimuth disambiguity
  - 3D structure of sunspots and pores
  - Magnetic flux cancellation events
  - Polarity inversion lines
  - Dynamical state of coronal loop footpoints
  - wave propagation analysis
  - …

Example: SIR inversion

Bellot Rubio et al. (2007)





- Spatial resolution: ~0.4"
- VIP + TESOS + KAOS
- Inversion: SIR with 10 free parameters

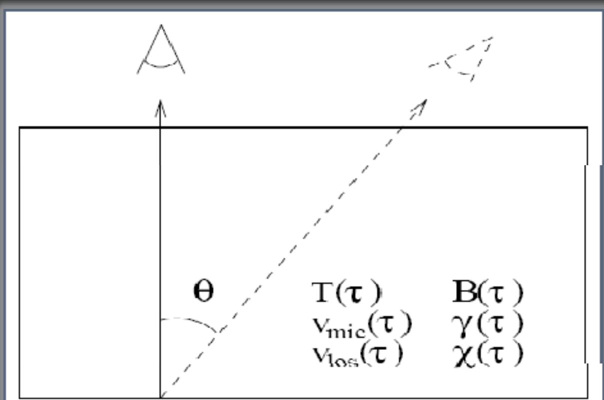
Non-ME Inversion Codes

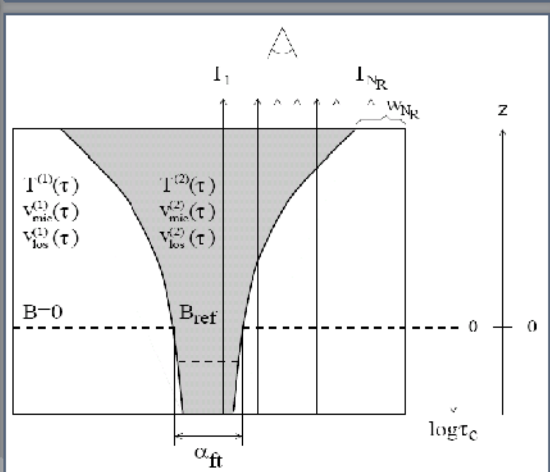
SIR	Ruiz Cobo & del Toro Iniesta (1992)	1C & 2C atmospheres, arbitrary stratifications, any photospheric line
SIR/FT	Bellot Rubio et al. (1996)	Thin flux tube model, arbitrary stratifications, any photospheric line
SIR/NLTE	Socas-Navarro et al. (1998)	NLTE line transfer, arbitrary stratifications
SIR/GAUS	Bellot Rubio (2003)	Uncombed penumbral model, arbitrary stratifications
SPINOR	Frutiger & Solanki (2001)	1C & 2C (nC) atmospheres, arbitrary stratifications, any photospheric line, molecular lines, flux tube model, uncombed model
LILIA	Socas-Navarro (2001)	1C atmospheres, arbitrary stratifications
MISMA IC	Sánchez Almeida (1997)	MISMA model, arbitrary stratifications, any photospheric line

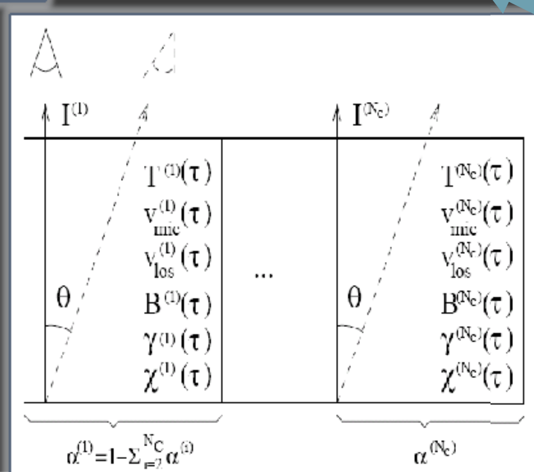
SPINOR core: the synthesis

- RTE has to be solved for
  - each spectral line
  - each line-of sight
  - each iteration

→ efficient computation required!







atmospheric parameters:

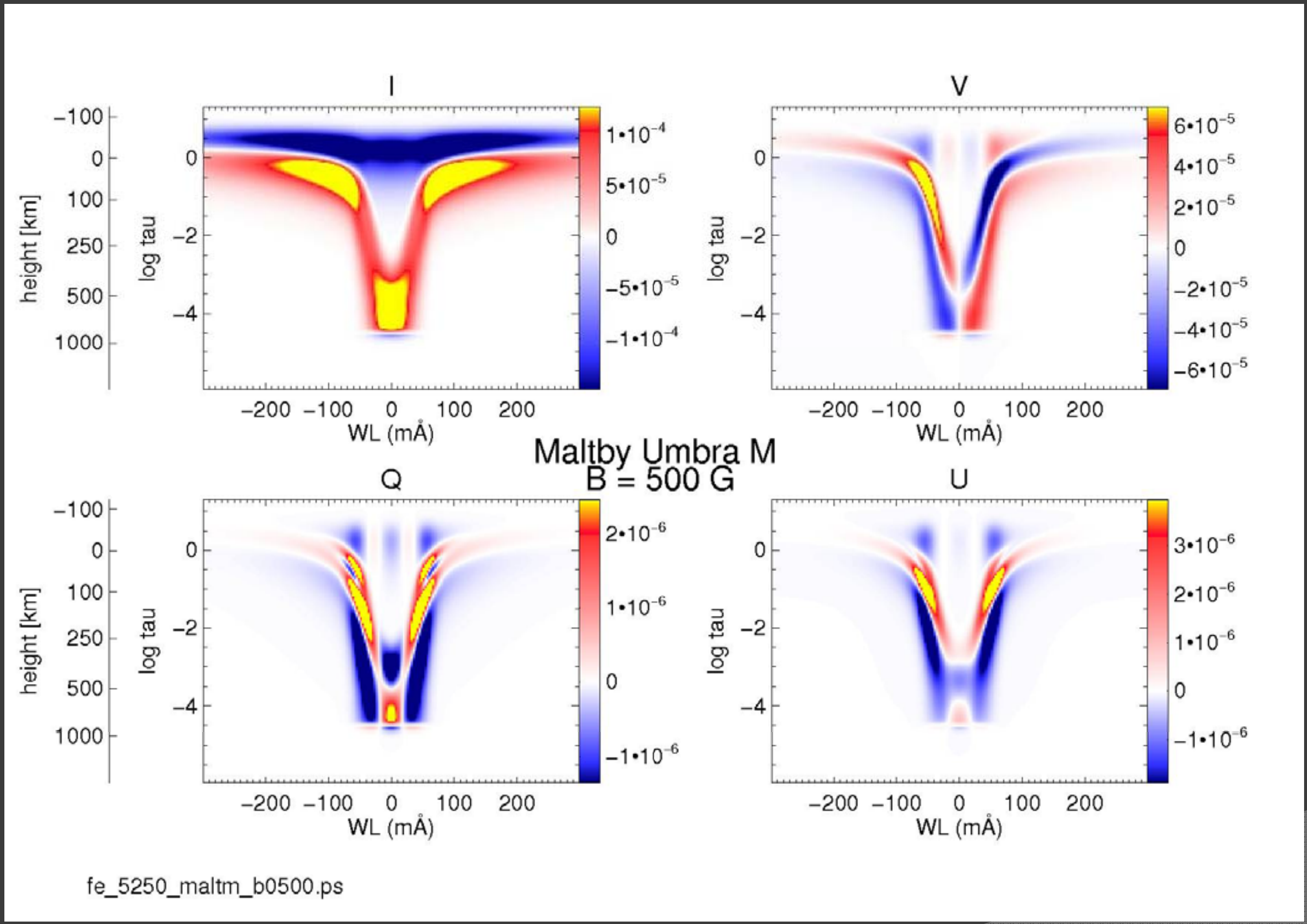
height / tau dependent

T	...	gas temperature
B	...	magn. field strength
γ,φ	...	incl. / azimuth angle of B
v_{LOS}	...	line-of sight velocity
v_{mic}	...	micro-turbulent velocity

height independent

A_X	...	abundance (A_H=12)
G	...	grav. acc. at surface
v_{mac}	...	macro-turbulence
v_{inst}	...	instr. broadening
v_{abs}	...	abs. velocity Sun-Earth

Stokes sepctrum diagnostics
CFs and RFs



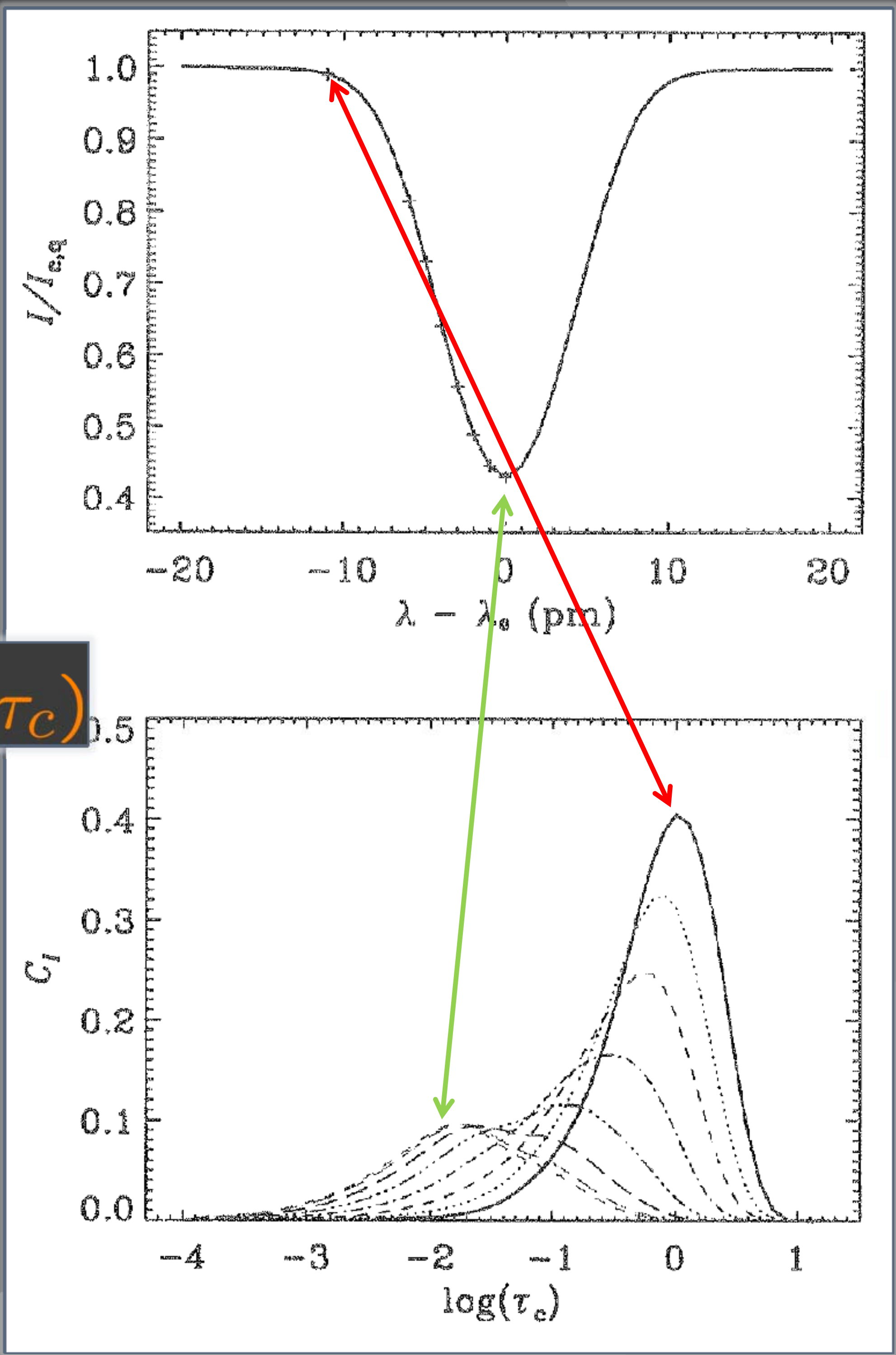
Contribution Functions (1)

The contribution function (CF) describes how different atmospheric layers contribute to the observed spectrum.

Mathematical definition:
CF ≡ integrand of formal sol. of RTE (here isotropic case, no B field):

$$C(\tau_c) \equiv \mathrm{e}^{-\int_0^\infty k(t)\mathrm{d}t} k(\tau_c) S(\tau_c)$$

line core: highest formation
wings: lowest formation



Intuitively: profile shape indicates atmospheric opacity. Medium is more transparent (less heavily absorbed) in wings.
→ one can see „deeper“ into the atmosphere at the wings.

Contribution functions (2)

The general case:

$$\mathbf{C}(\tau_c) \equiv \mathbf{O}(0,\tau_c)\mathbf{K}(\tau_c)\mathbf{S}(\tau_c)$$

Height of formation:

„This line is formed at x km above the reference, the other line is formed at y km …"

→ caution with this statement is highly recommended!

→ CFs are strongly dependent on model atmosphere

→ different physical quantities are measured at different atmospheric heights

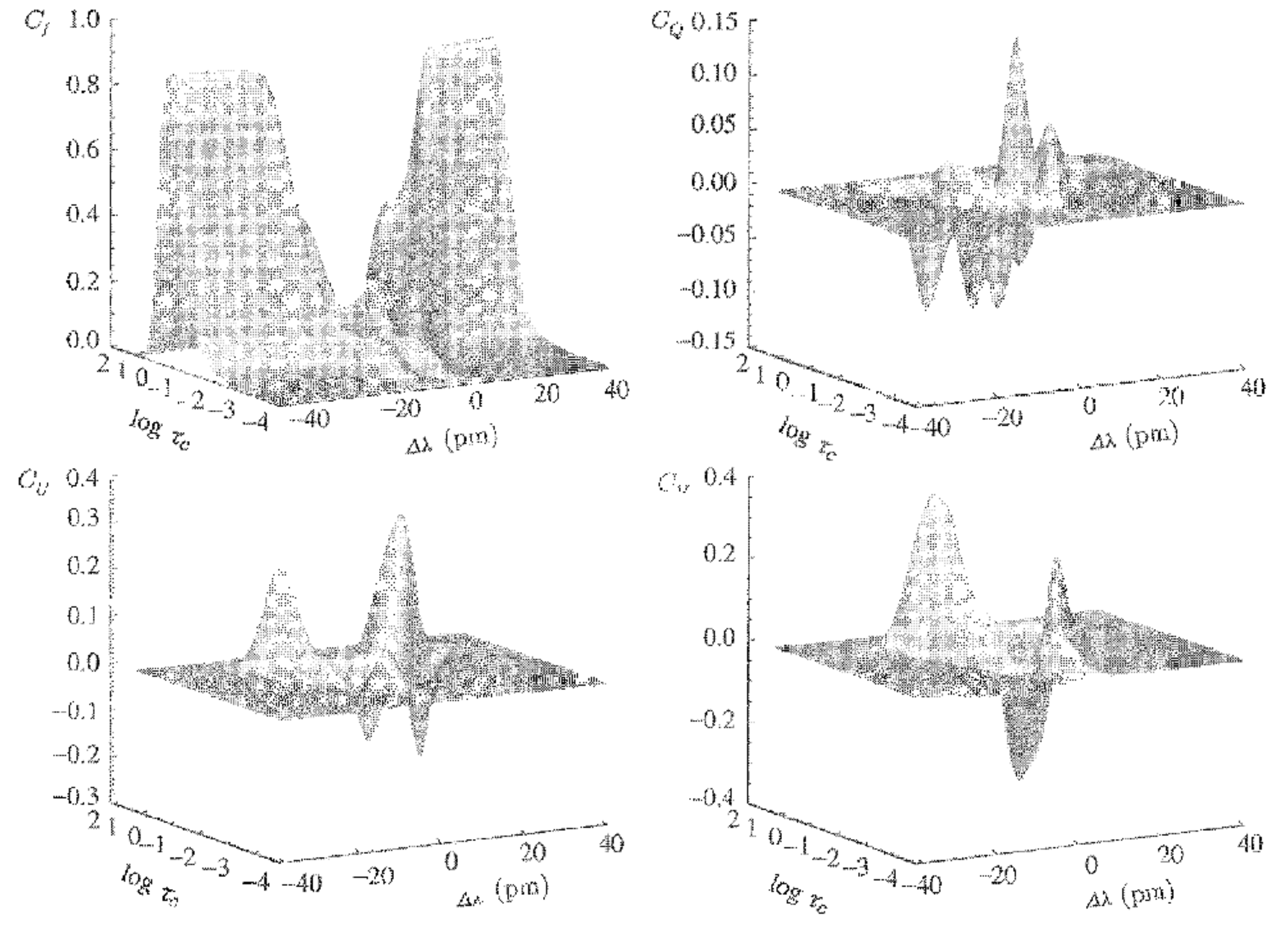
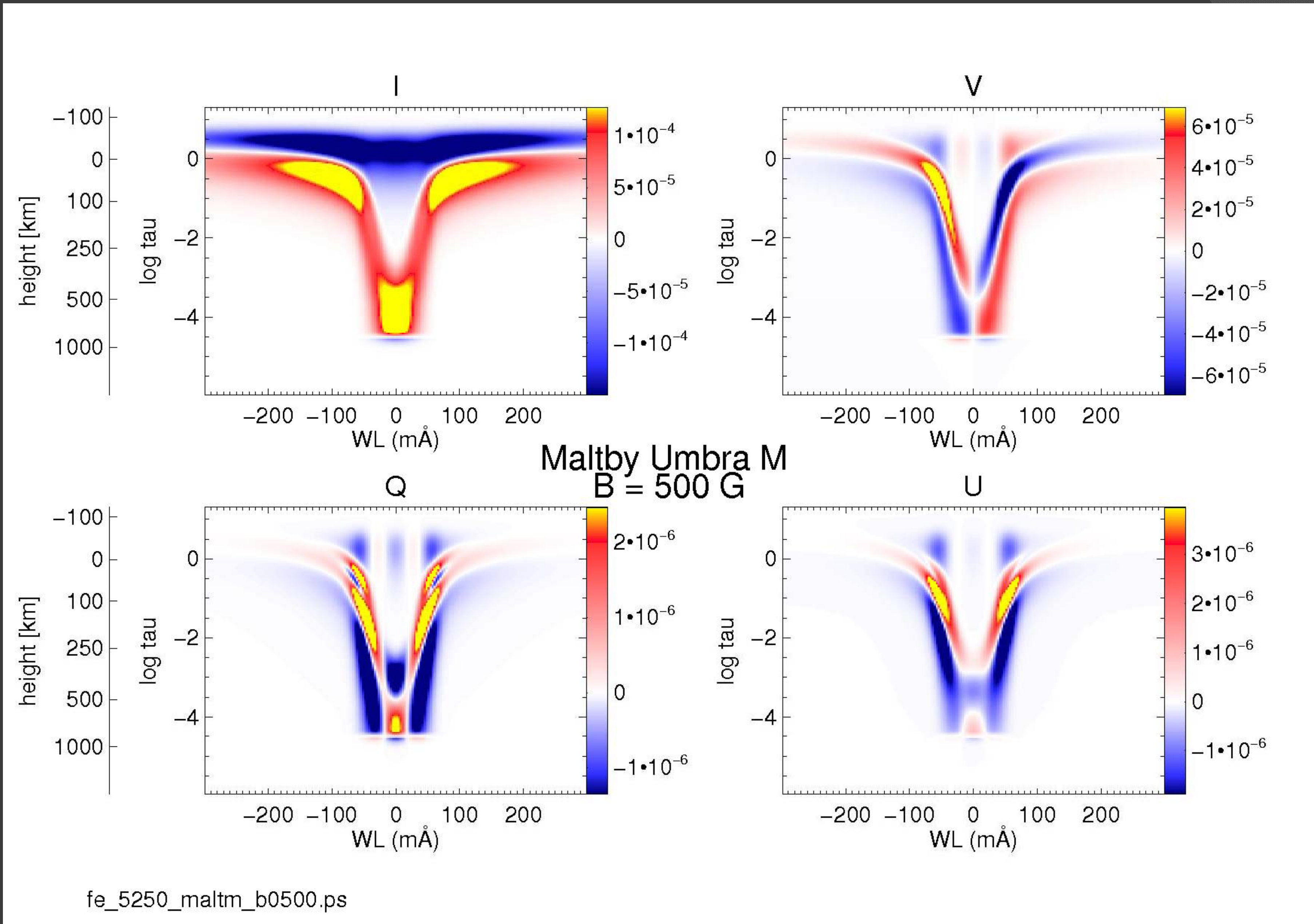
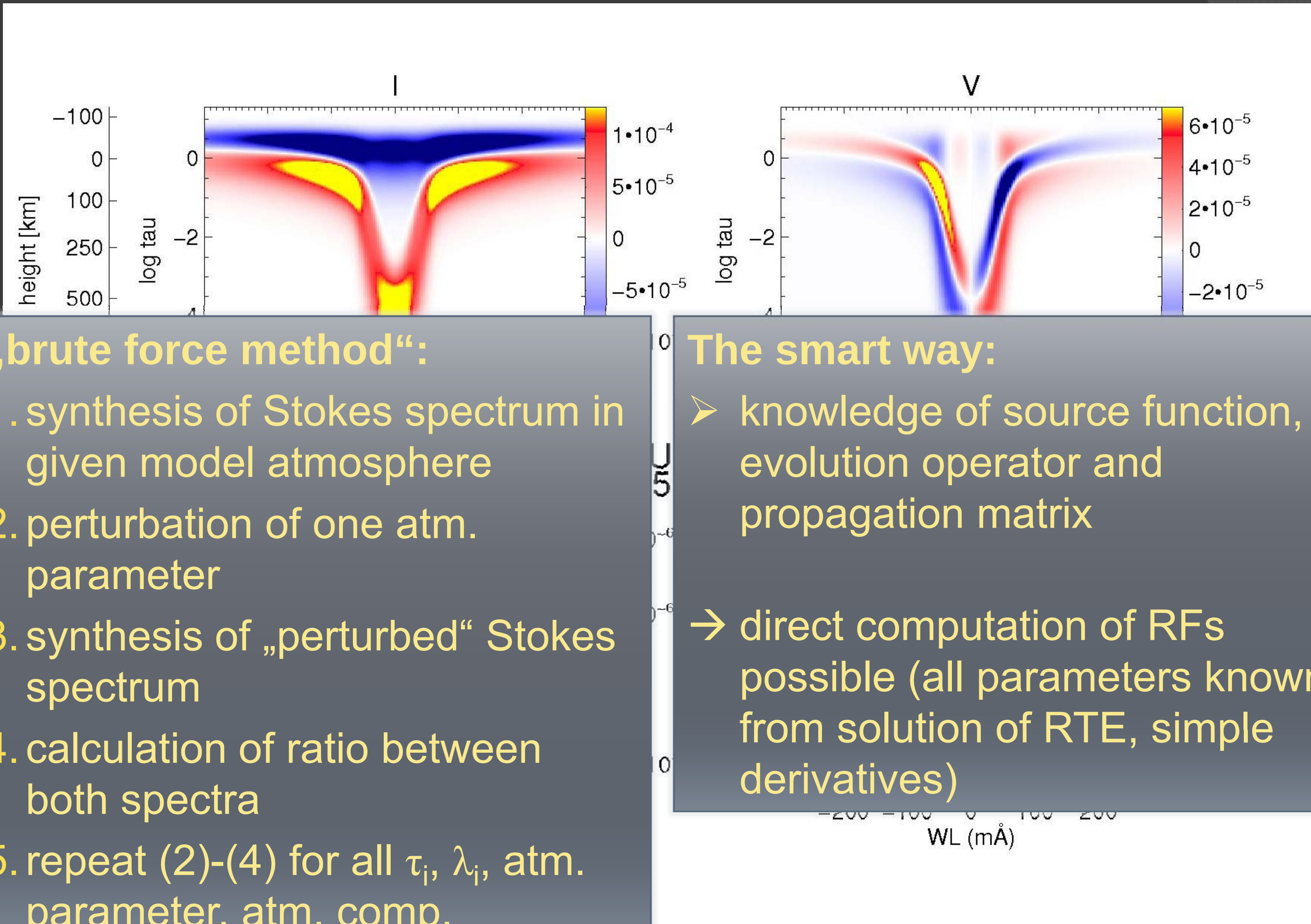


Fig. 10.6. Contribution function of the Fe I line at 630.25 nm in the penumbral model of Fig. 9.3. Wavelength is along the Y axis and logarithmic optical depth along the X axis.

Response Functions



Response Functions



„brute force method":

1. synthesis of Stokes spectrum in given model atmosphere
2. perturbation of one atm. parameter
3. synthesis of „perturbed" Stokes spectrum
4. calculation of ratio between both spectra
5. repeat (2)-(4) for all τ_i, λ_i, atm. parameter, atm. comp.

The smart way:

- knowledge of source function, evolution operator and propagation matrix

→ direct computation of RFs possible (all parameters known from solution of RTE, simple derivatives)

Response functions

Linearization: small perturbation in physical parameters of the model atmosphere propagate „linearly" to small changes in the observed Stokes spectrum.

$$\delta\mathbf{K}(\tau_c) = \sum_{i=1}^{m} \frac{\partial \mathbf{K}}{\partial x_i}\delta x_i(\tau_c),\ \delta\mathbf{S}(\tau_c) = \sum_{i=1}^{m} \frac{\partial \mathbf{S}}{\partial x_i}\delta x_i(\tau_c)$$

introduce these modifications into RTE:

$$\frac{\mathrm{d}(\mathbf{I}+\delta\mathbf{I})}{\mathrm{d}\tau_c} = (\mathbf{K}+\delta\mathbf{K})(\mathbf{I}+\delta\mathbf{I}-\mathbf{S}-\delta\mathbf{S})$$

only take 1st order terms, and introduce $\tilde{\mathbf{S}} = \delta\mathbf{S} - \mathbf{K}^{-1}\delta\mathbf{K}(\mathbf{I}-\mathbf{S})$

$$\tilde{\mathbf{C}}(\tau_c) \equiv \mathbf{O}(0,\tau_c)\mathbf{K}(\tau_c)\tilde{\mathbf{S}}(\tau_c) \equiv \sum_{i=1}^{m} \mathbf{R}_i(\tau_c)\delta x_i(\tau_c)$$

contribution function to perturbations of observed Stokes profiles

response functions

Response Functions (2)

RFs have the role of partial derivatives of the Stokes profiles with respect to the physical quantities of the model atmosphere:

$$\delta \mathbf{I}(0) = \sum_{i=1}^{m} \int_0^\infty \mathbf{R}_i(\tau_c)\delta x_i(\tau_c)\mathrm{d}\tau_c$$

In words:
If x_k is modified by a unit perturbation in a restricted neighborhood around τ_0, then the values of R_k around τ_0 give us the ensuing variation of the Stokes vector.

Response function units are inverse of their corresponding quantities (e.g RFs to temperature have units K^{-1})

RFs – Example: Fe 6302.5

model on the left is:

- 500 K hotter
- 500 G stronger
- 20° more inclined
- 50° larger azimuth
- no VLOS gradient
  (right: linear gradient)

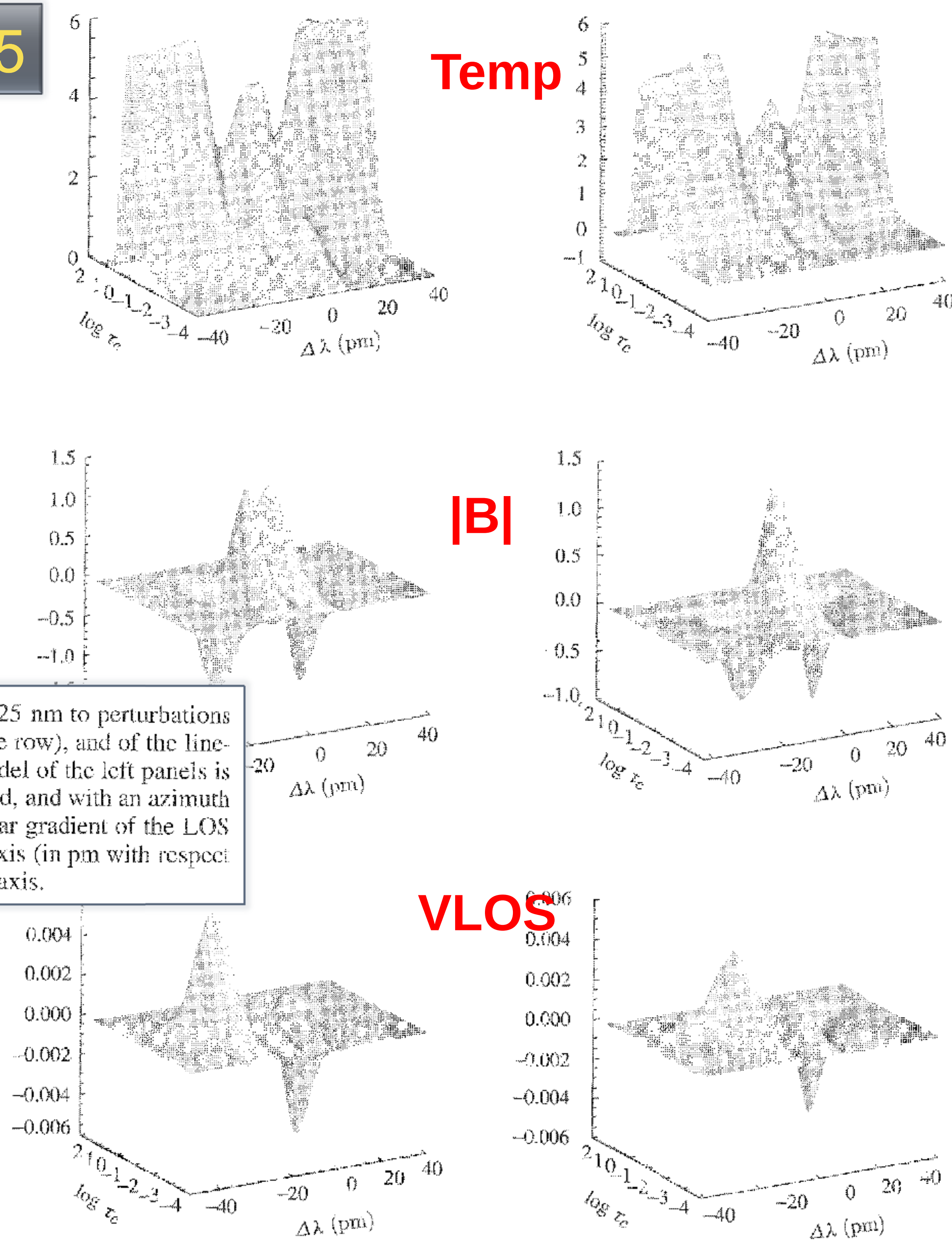
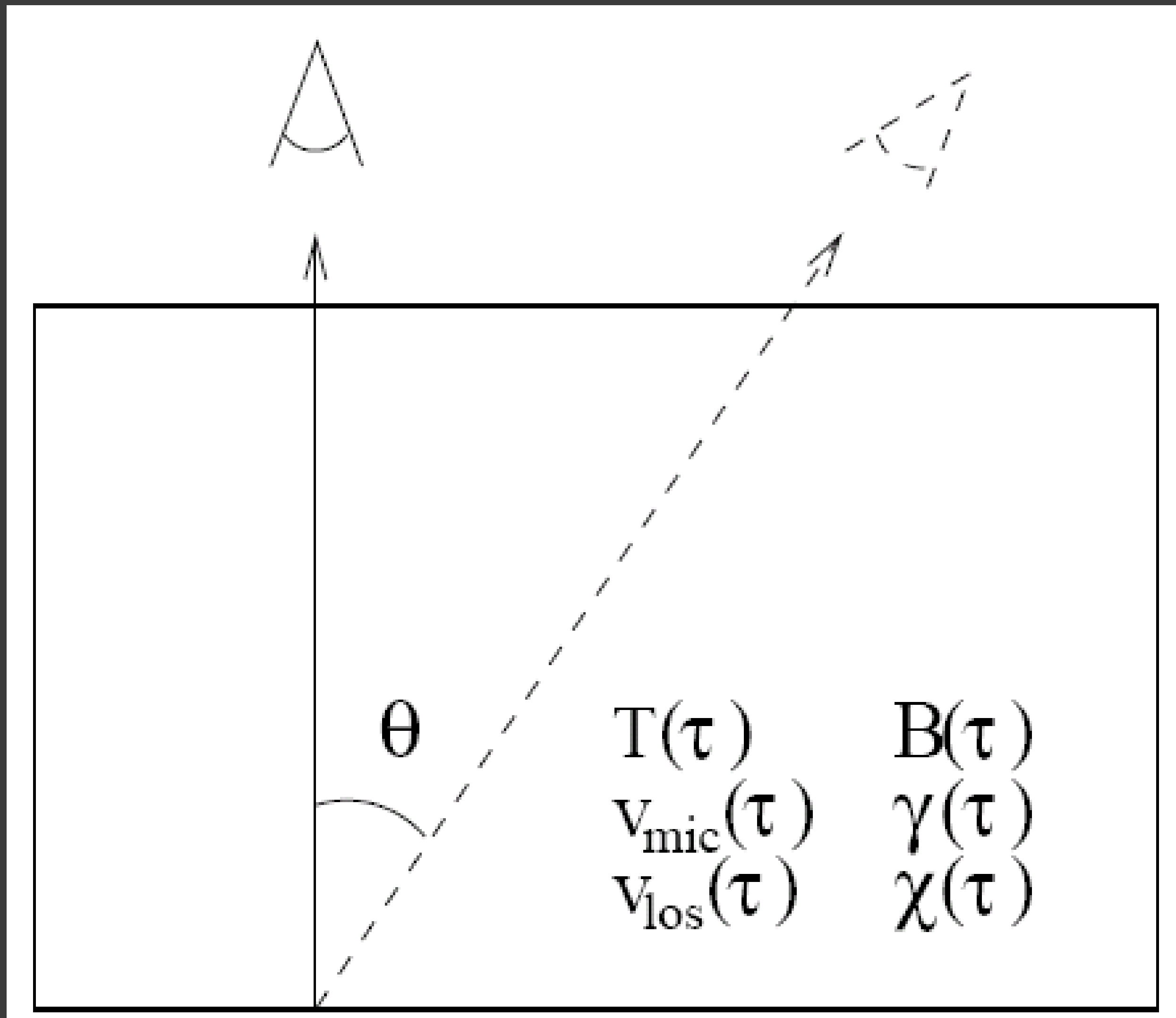
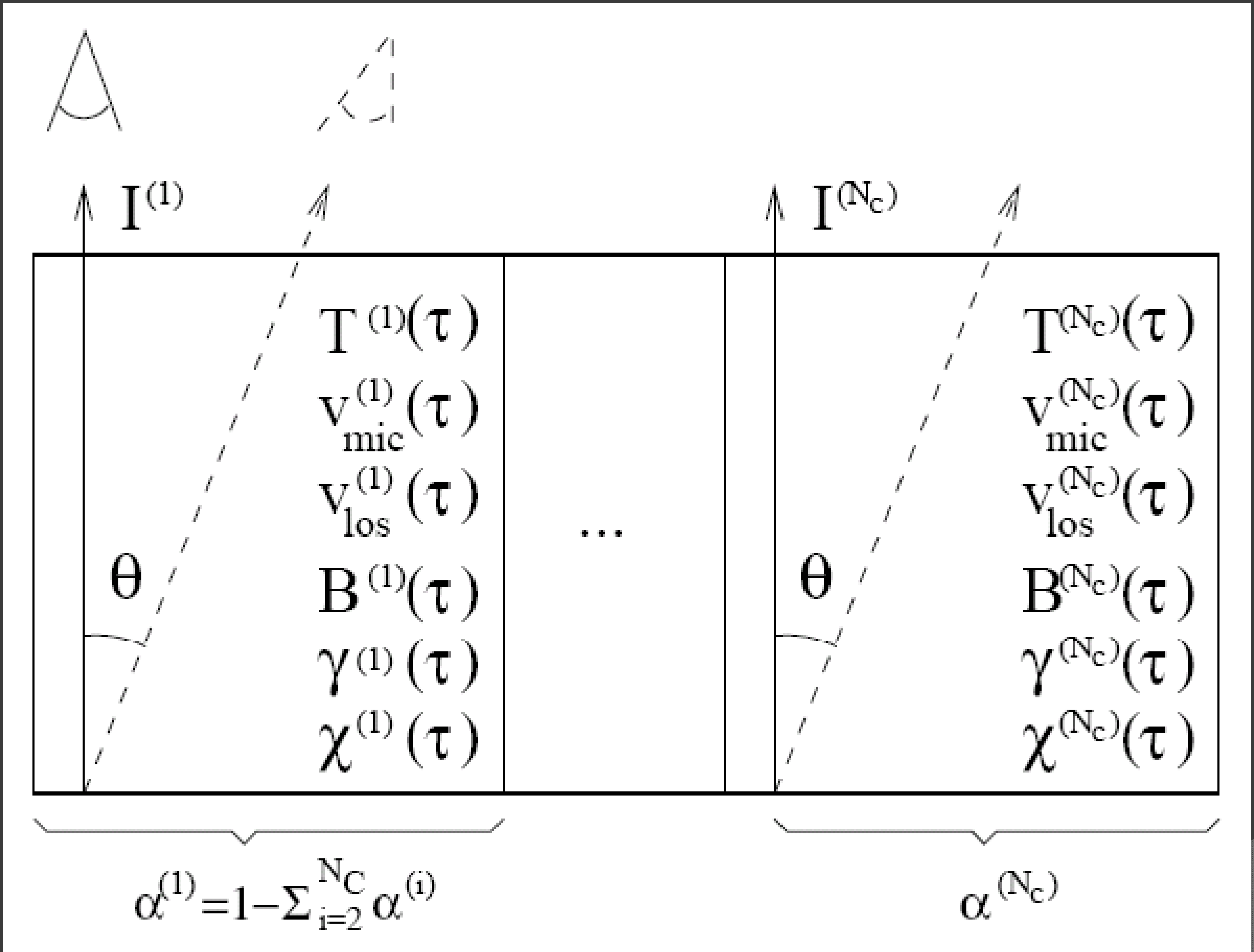


Fig. 10.8. Response functions of Stokes I of the Fe I line at 630.25 nm to perturbations of the temperature (top row), of the magnetic field strength (middle row), and of the line-of-sight velocity (bottom row) in two model atmospheres. The model of the left panels is 500 K hotter, has a magnetic field 500 G stronger, 20° more inclined, and with an azimuth 50° larger than the model of the right panels. The latter has a linear gradient of the LOS velocity whereas the former is at rest. Wavelength is along the Y axis (in pm with respect to the center of the line) and logarithmic optical depth along the X axis.

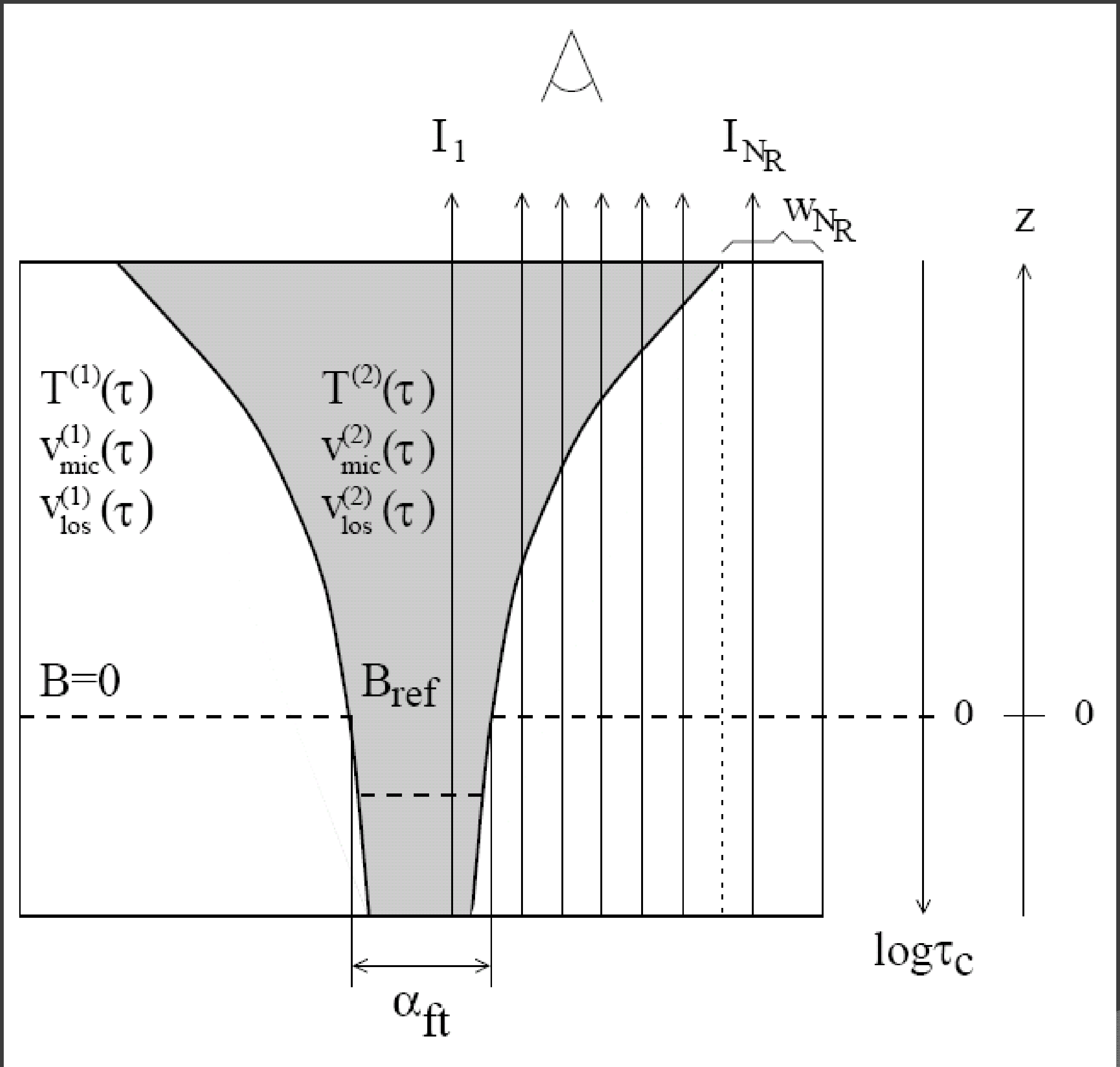
SPINOR: complex model atmospheres



The even more complex case:



The fluxtube case:



The complex fluxtube case:

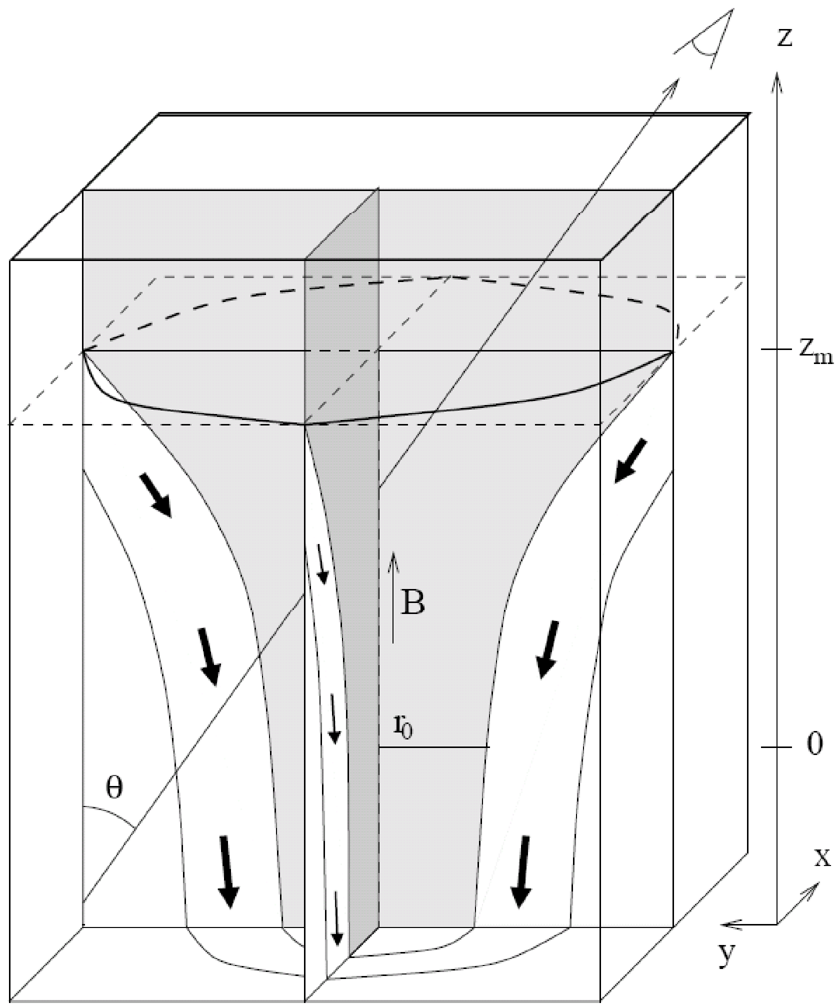


Figure 7.4: *Vertical cuts through schematic flux-tube cell. The shaded area represents the flux-tube interior filled with a magnetic field. The non-magnetic surroundings are expected to harbor strong downflows (thick arrows) along the tube boundaries. Net velocities as seen by the observer, i.e. Doppler shifts entering the radiative transfer equations, are obtained by projection on the lines of sights (thin arrows). For position away from disk center ($\mu = \cos\theta < 1$), the flux tube thus must be treated as a quasi 3-dimensional structure.*

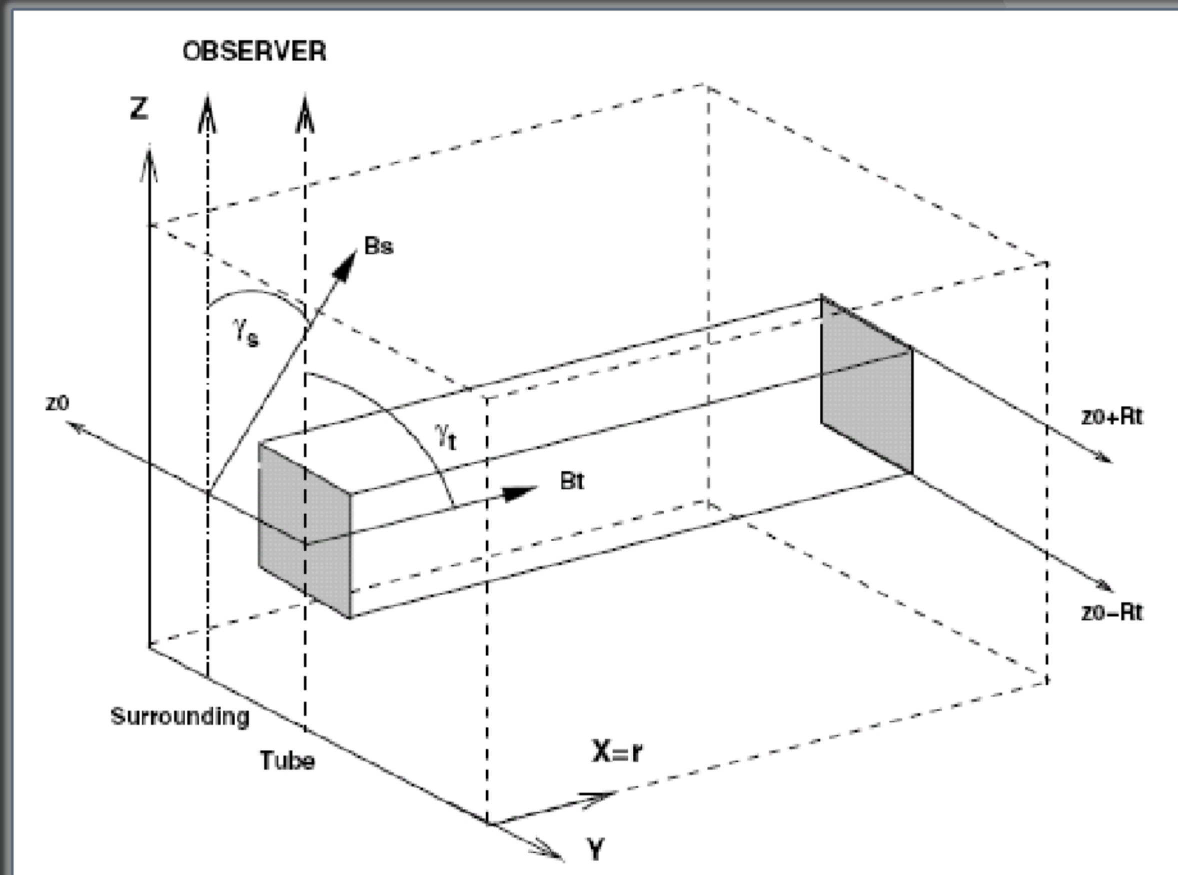
SPINOR: Versatility

- Plane-parallel, 1-component models to obtain averaged properties of the atmosphere
- Multiple components (e.g. to take care of scattered light, or unresolved features on the Sun). Allows for arbitrary number of magnetic or field-free components (turns out to be important, e.g. in flare observations, where we have seen 4-5 components).
- Flux-tubes in total pressure equilibrium with surroundings, at arbitrary inclination
  - in field-free (or weak-field surroundings)
  - embedded in strong fields (e.g. sunspot penumbra, or umbral dots)
  - includes the presence of multiple flux tubes along a ray when computing away from disk centre
  - efficient computation of lines across jumps in atmospheric quantities
- Integration over solar or stellar disk, including solar/stellar rotation
- molecular lines (S. Berdyugina)
- non-LTE (MULTI 2.2, not tested yet, requires brave MULTI expert)

Penumbral Flux Tubes

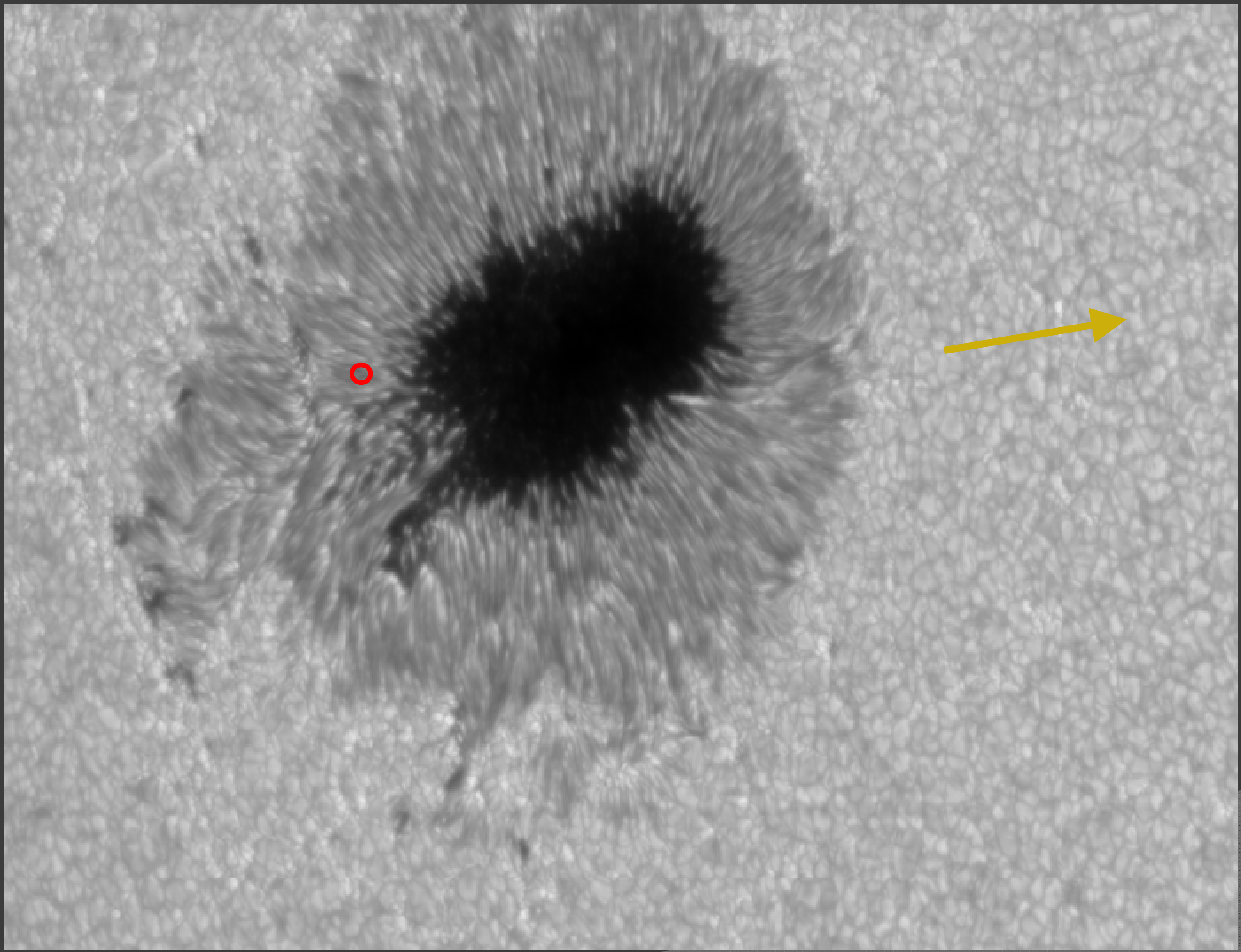
Borrero et al. 2006

- SPINOR applied to:
  Fe I 6301 + 6302
  Fe I 6303.5
  Ti I 6303.75
- 1st component:
  tube ray (discontinuity at boundary)
- 2nd component:
  surrounding ray



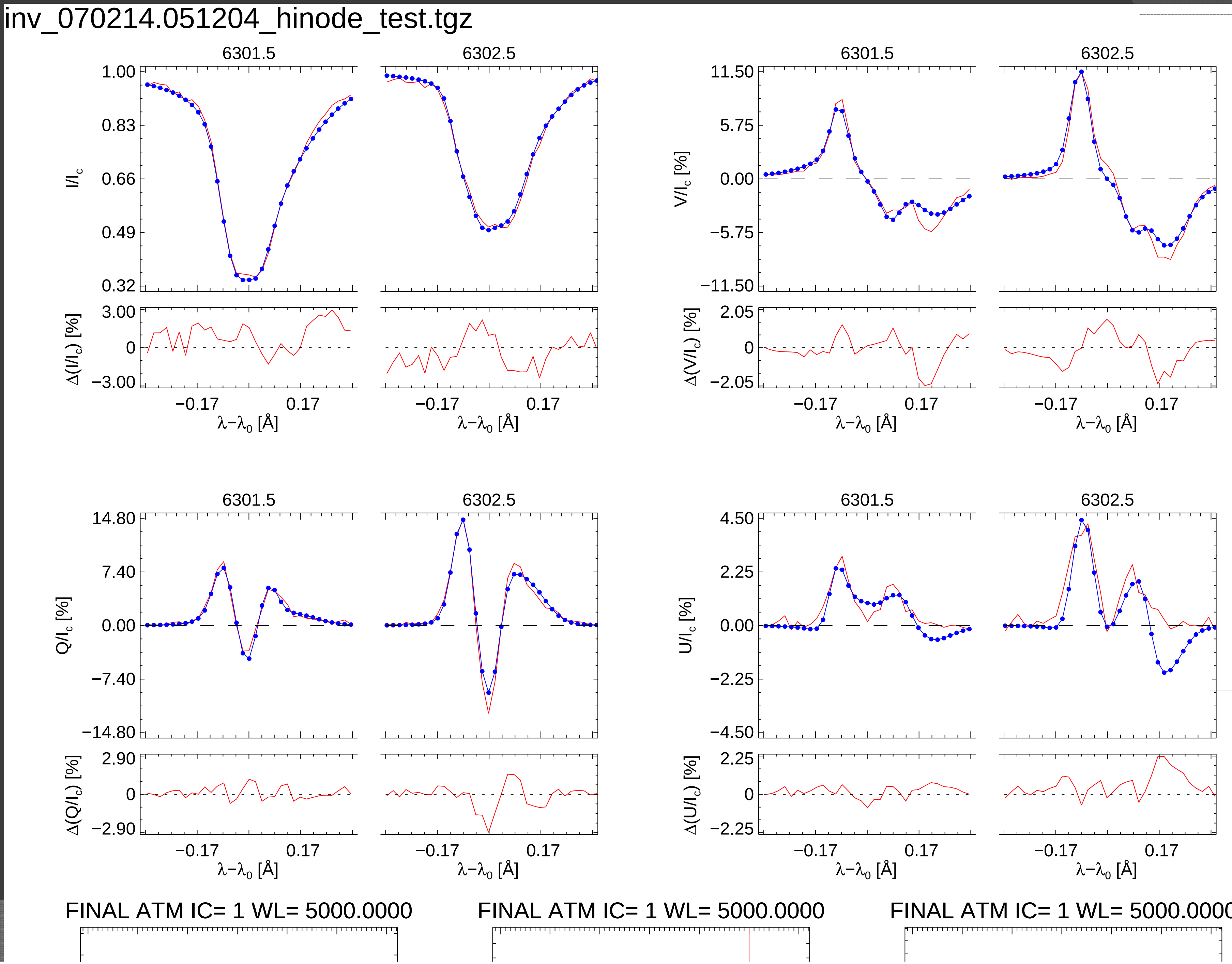
SPINOR & HINODE

Hinode SOT: 10-11-2006



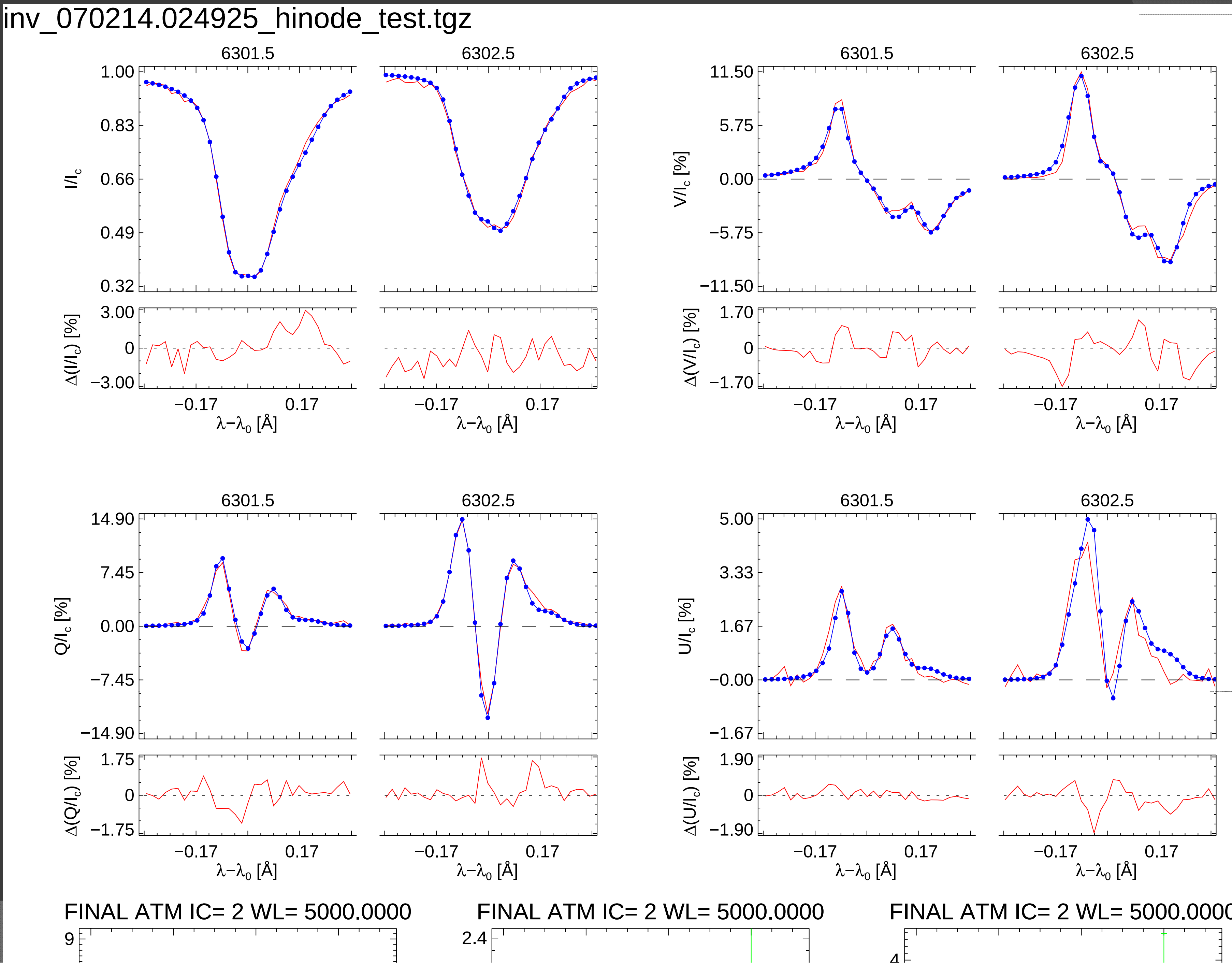
SPINOR & HINODE

1 magnetic component, 5 nodes



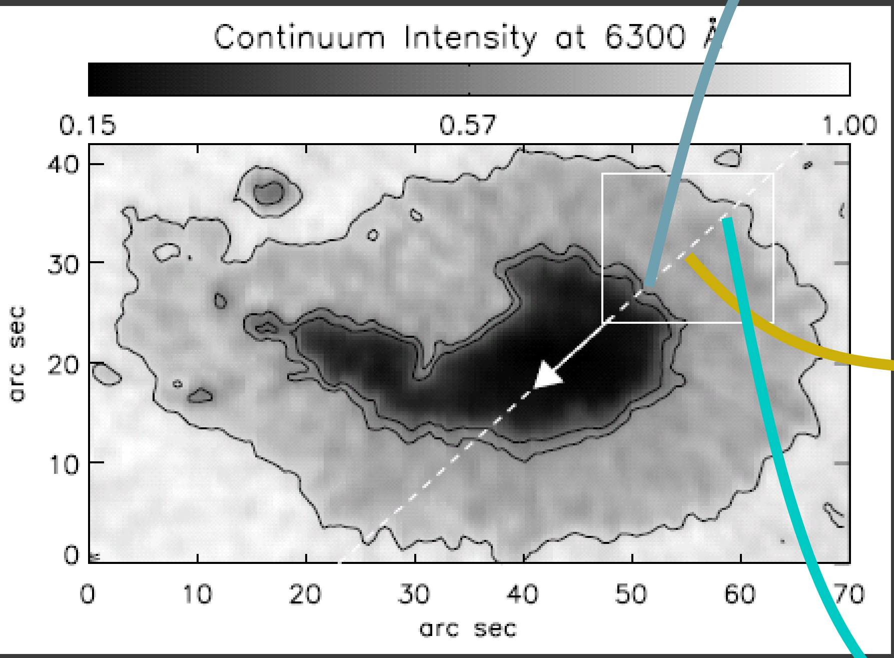
SPINOR & HINODE

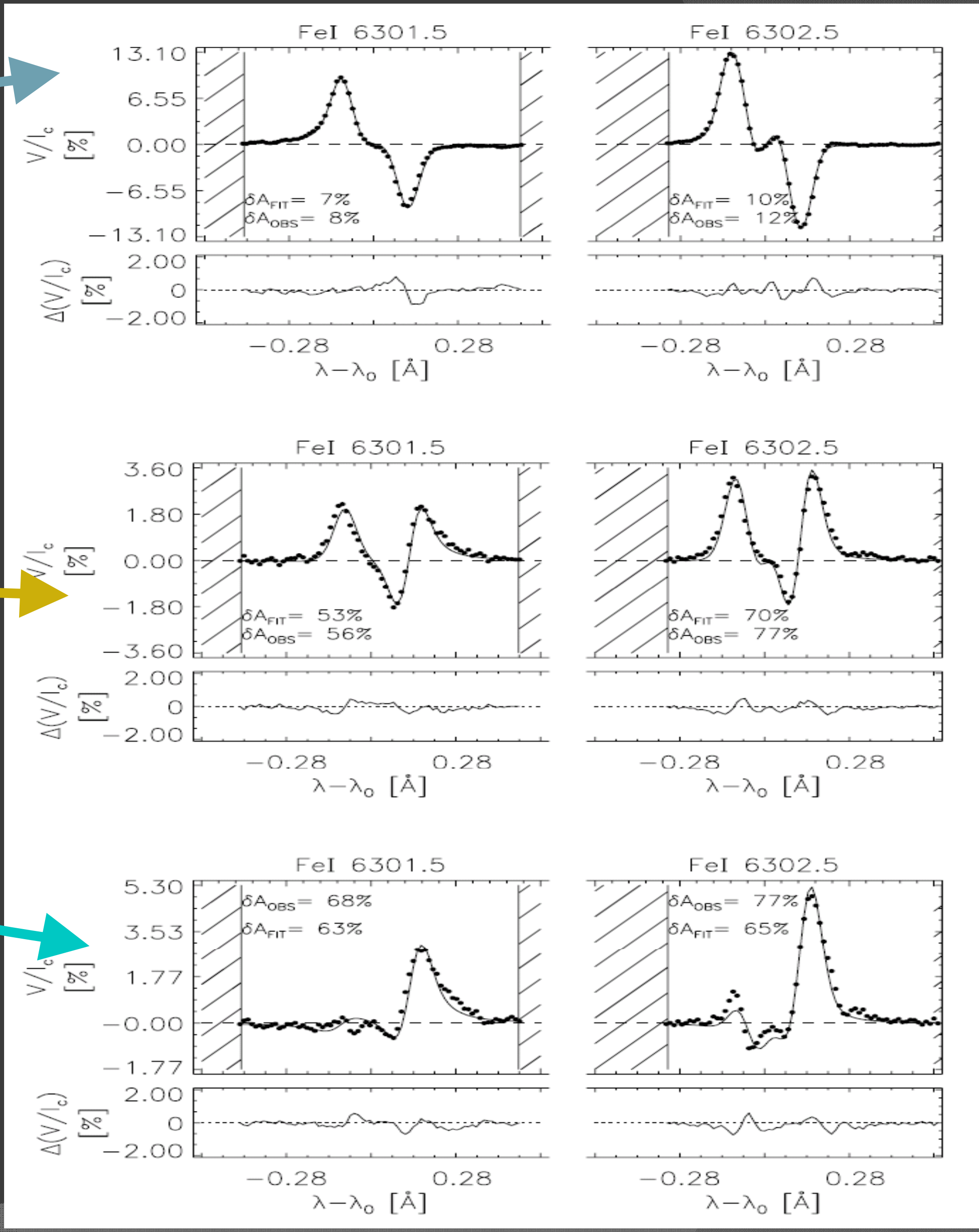
flux tube model



Penumbral Flux Tubes

Borrero et al. 2006





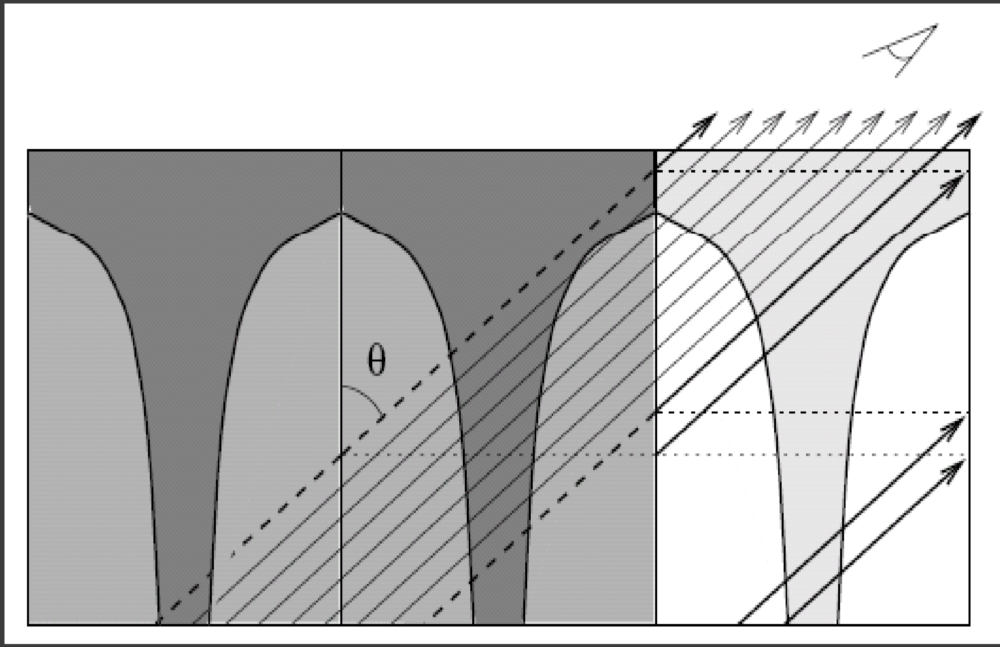
→ confirms uncombed model

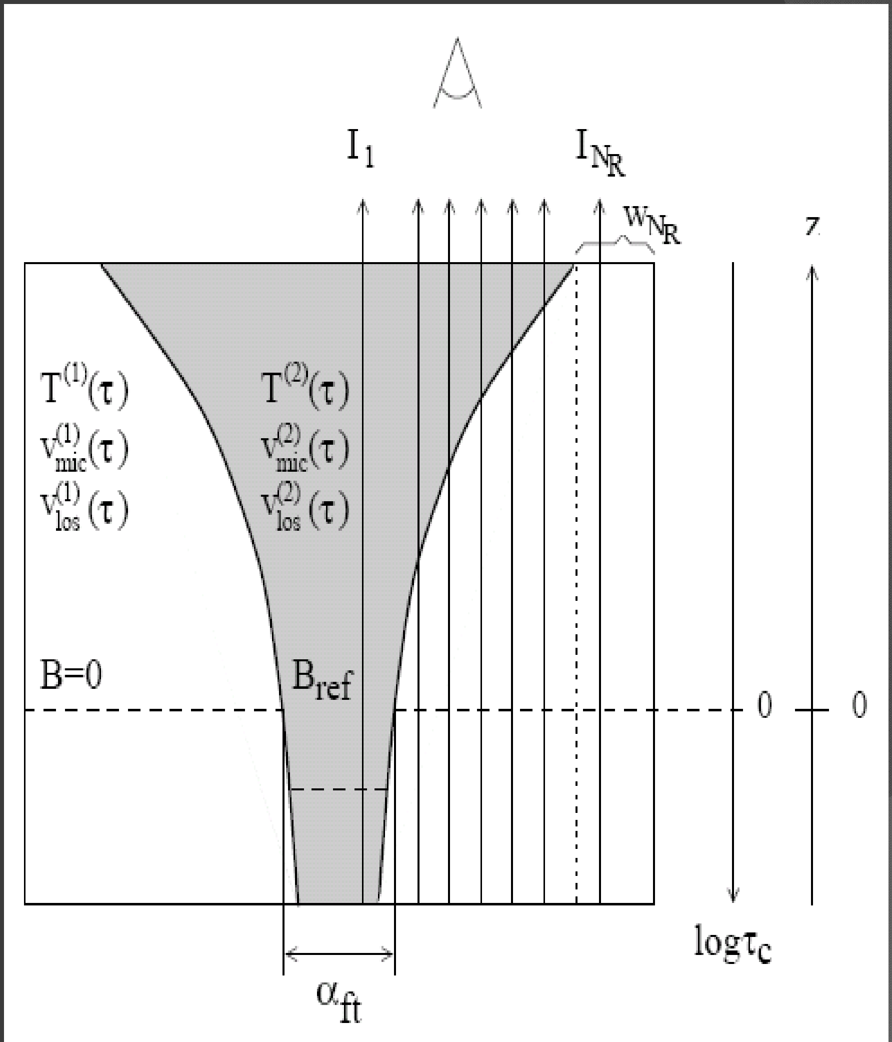
→ flux tube thickness 100-300 km

Multi Ray Flux Tube

Frutiger (2000)

multiple rays
→ pressure balance
→ broadening of flux tube

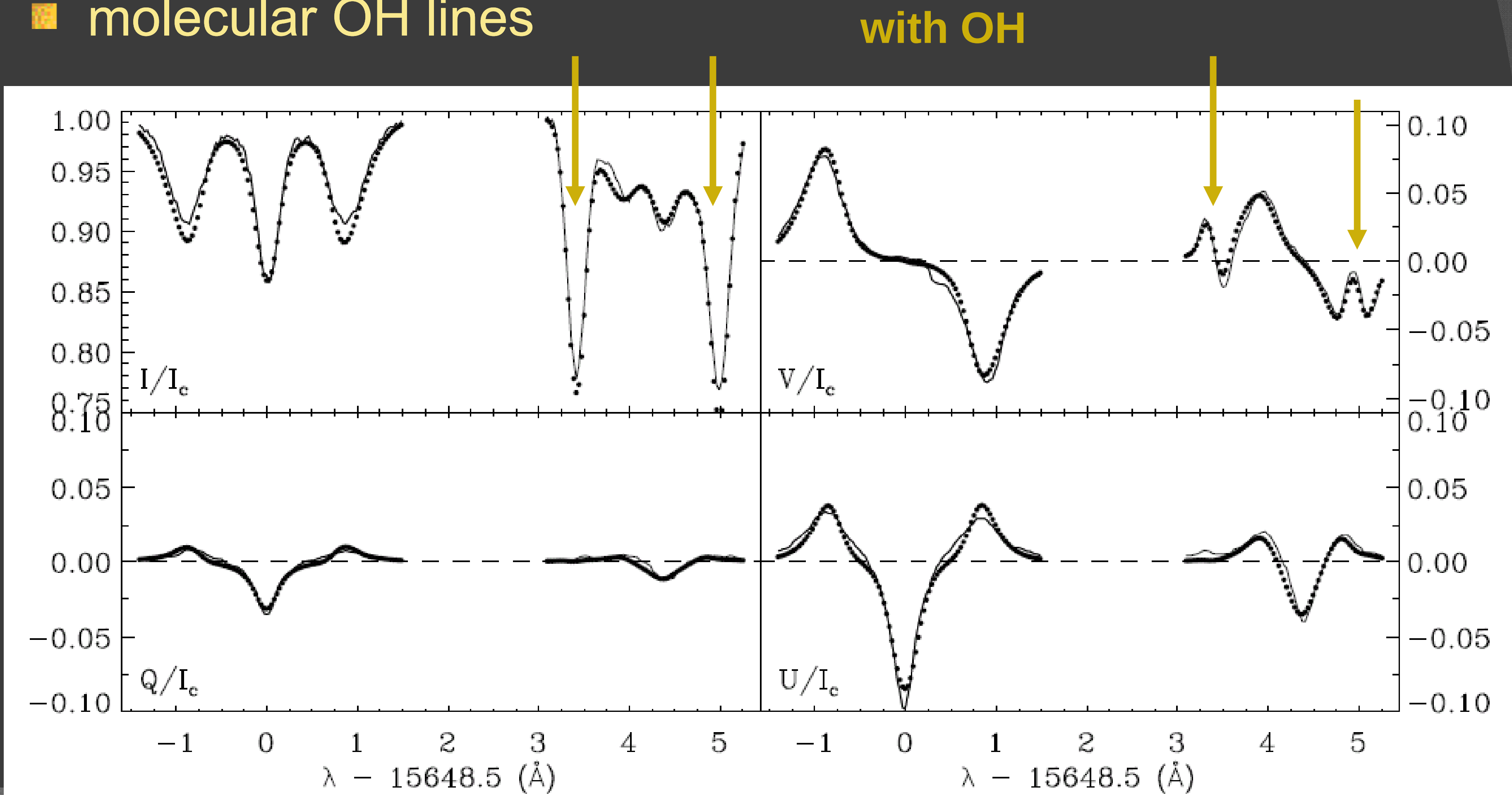




2-comp model Sunspot + molecular lines

Mathew et al. 2003

- SPINOR applied to:
  Fe I 15648 / 15652
- 1 magn. comp (6 nodes)
  1 straylight comp.
- molecular OH lines

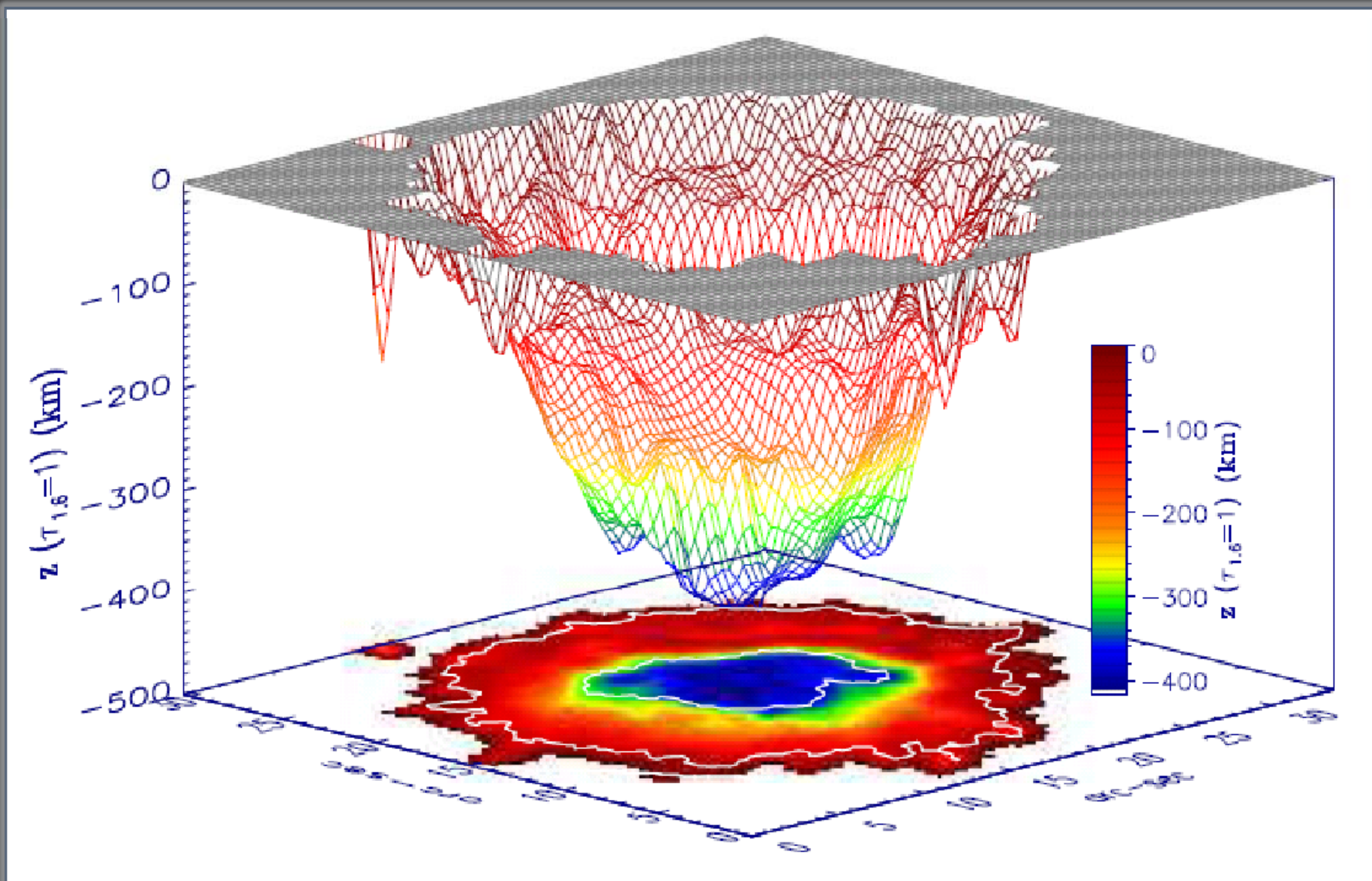


Wilson Depression

Mathew et al. 2003

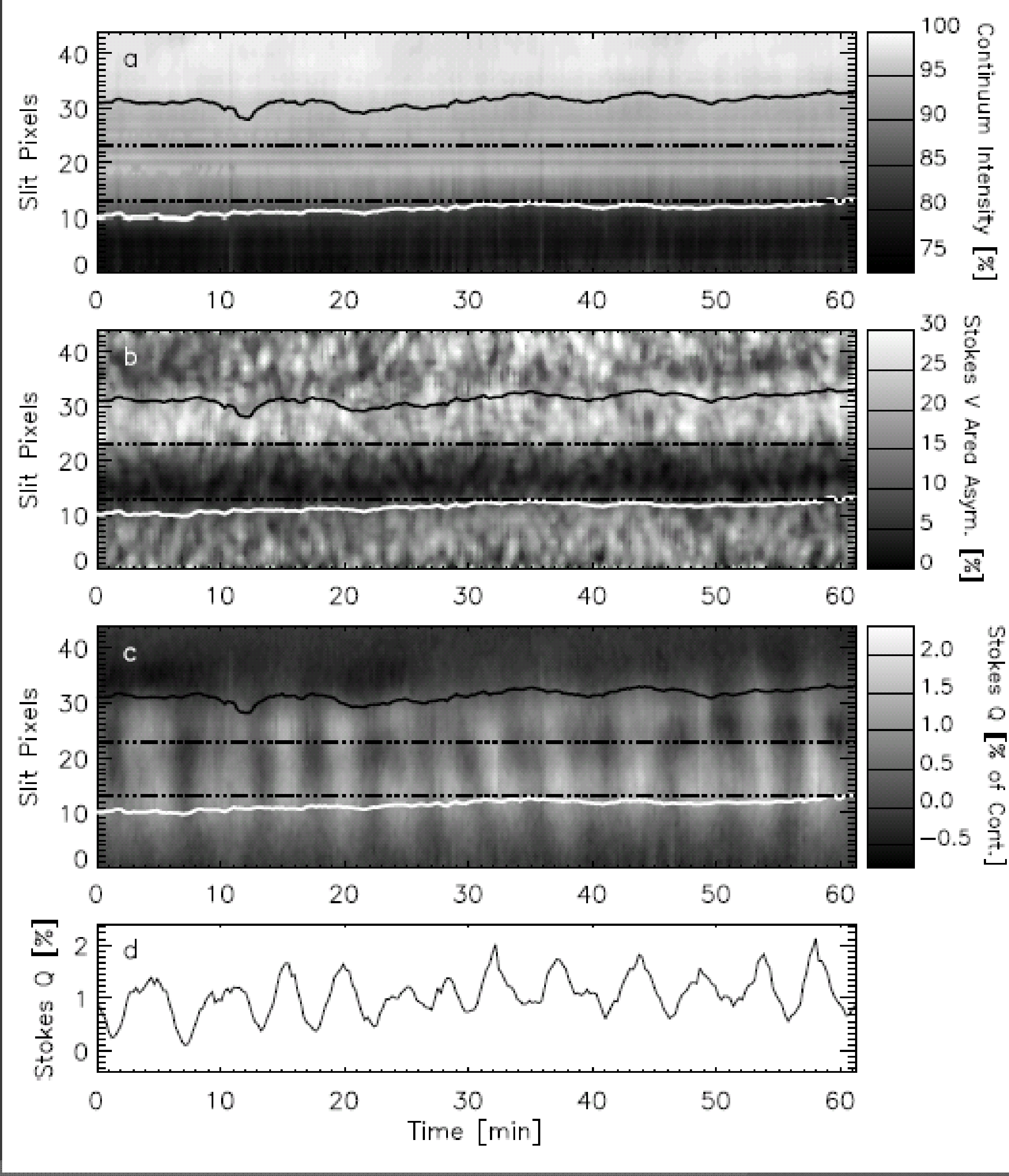
- SPINOR applied to:
  Fe I 15648 / 15652
- 1 magn. comp (4 nodes)
  1 straylight comp.
- molecular OH lines

- investigation of thermal-magnetic relation



Penumbral Oscillations

- oscillations observed in Stokes-Q of FeI 15662 and 15665
- calc. phase difference between Q-osc.
  → time delay
- 2-C inversion with straylight:
  → FT-component
  → magn. background
- RF-calc: difference in formation height (velocity): ~20 km
- relate time delay to speed of various wave modes



Bloomfield et al. [2007]

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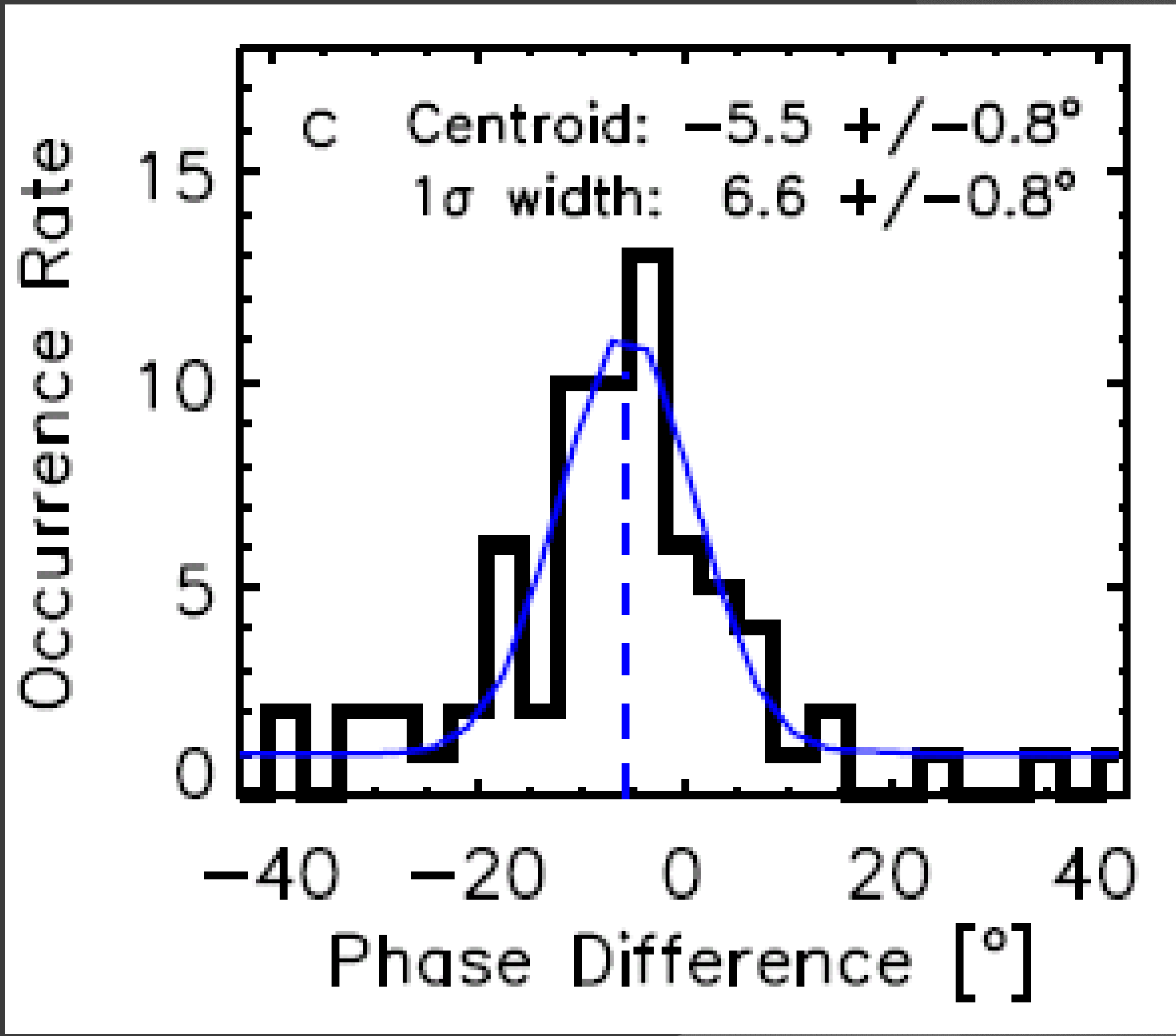

Bloomfield et al. [2007]

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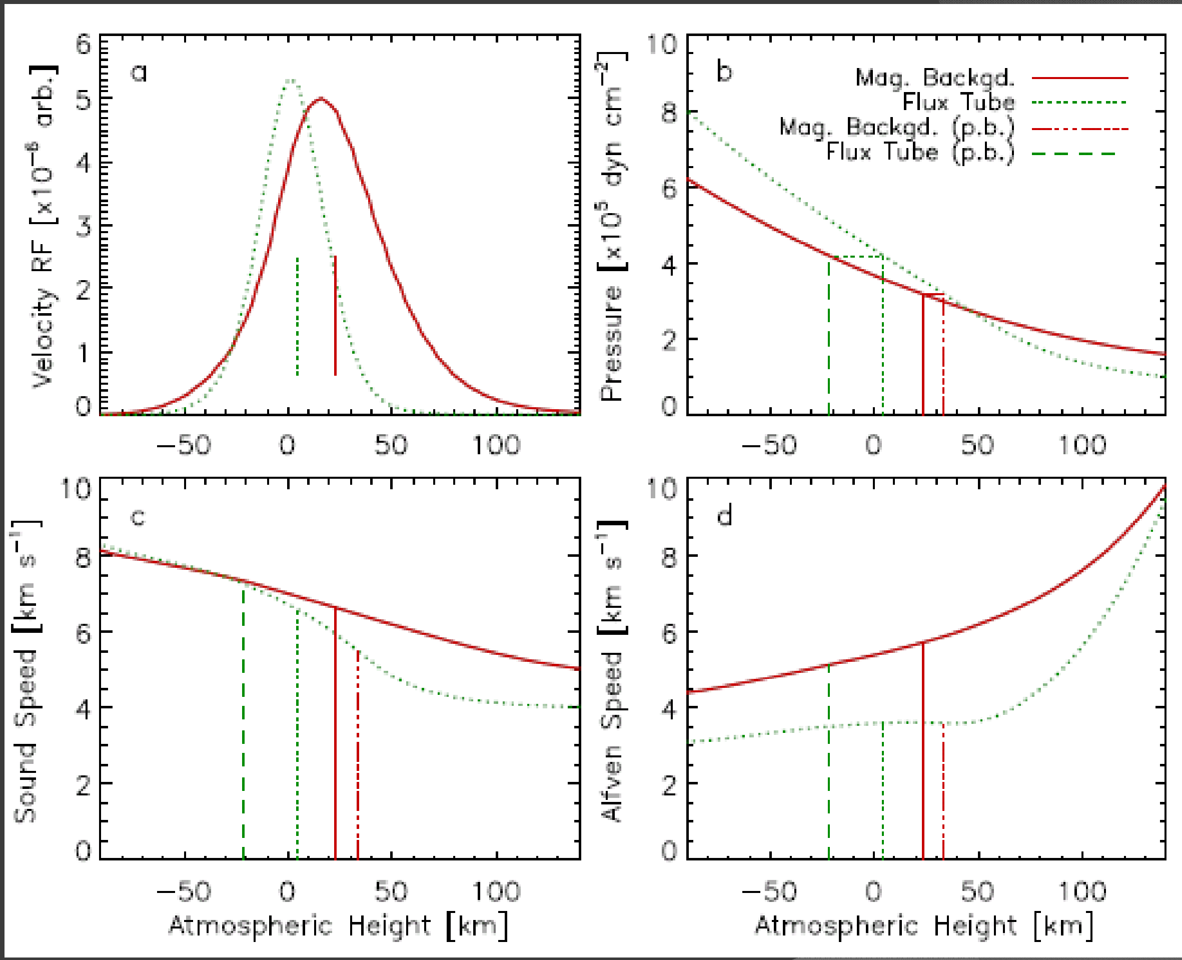

Bloomfield et al. [2007]

Penumbral Oscillations

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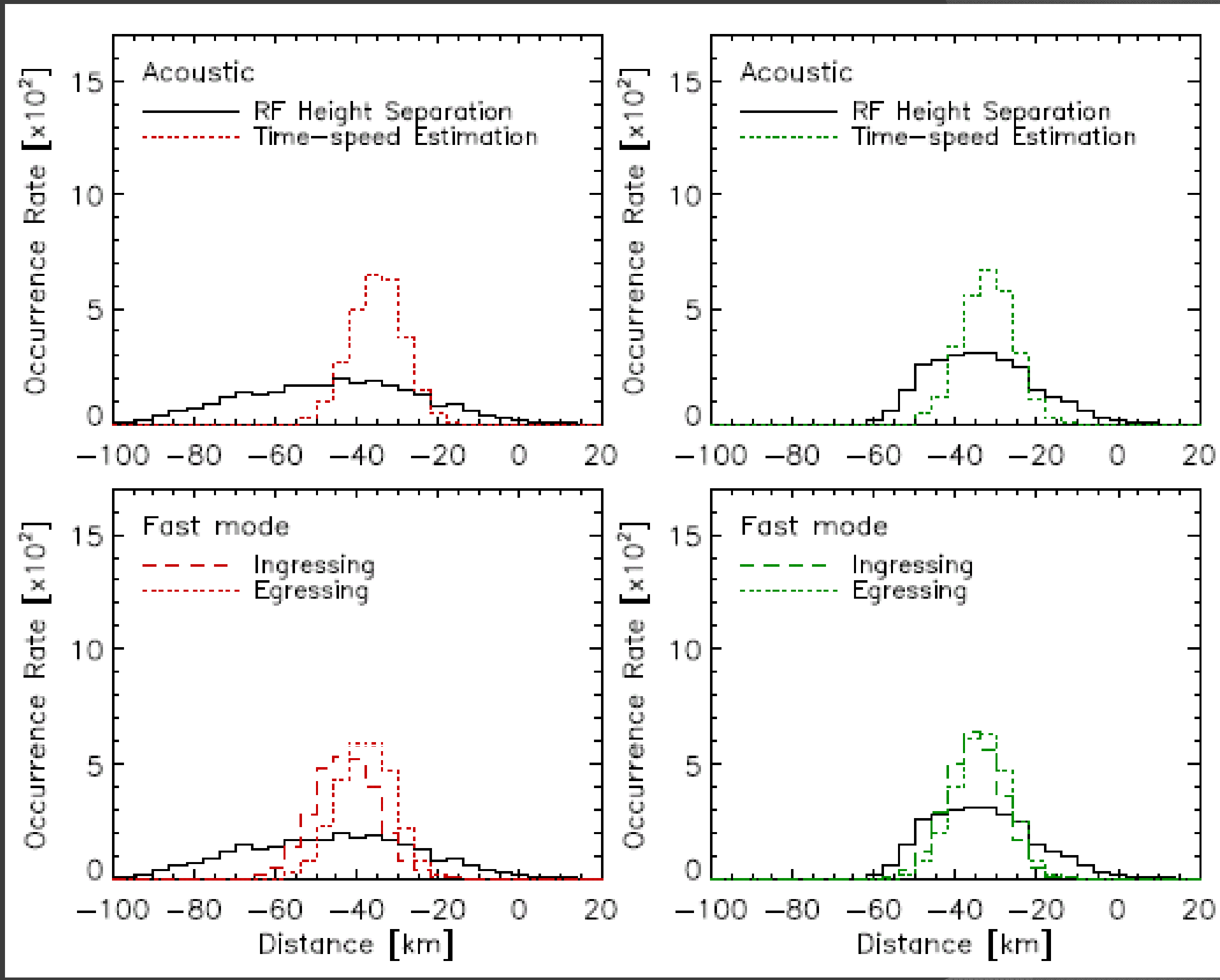


→ best agreement for: fast-mode waves propagating 50° to the vertical

Bloomfield et al. [2007]

Analysis of Umbral Dots (1)

Riethmüller et al., 2008

Analysis of 51 umbral dots using SPINOR:

- 30 peripheral, 21 central UDs
- nodes in log(τ): -3,-2,-1,0 (spline-interpolated)
- of interest: atomspheric stratification
  - T(τ), B(τ), VLOS(τ)
  - INC, AZI, V_{MIC}, V_{MAC} const.
- no straylight (extensive tests showed, that inversions did not improve significantly)

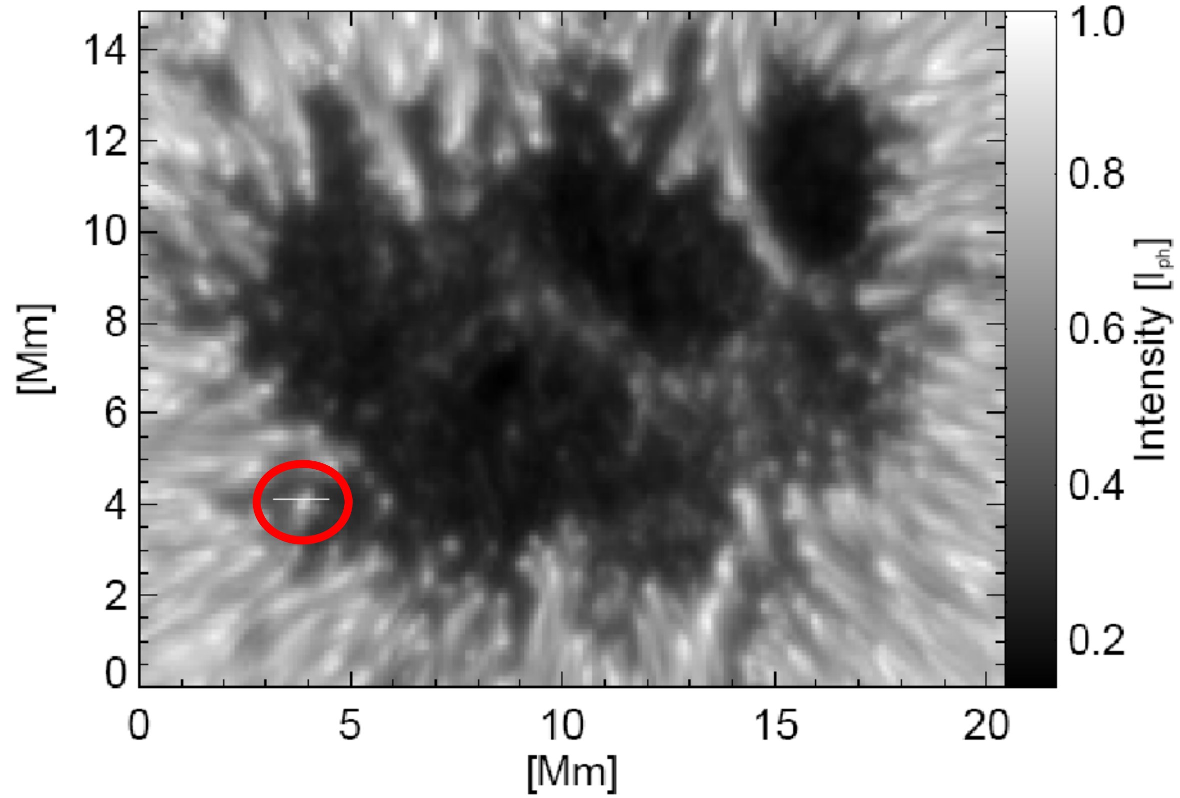
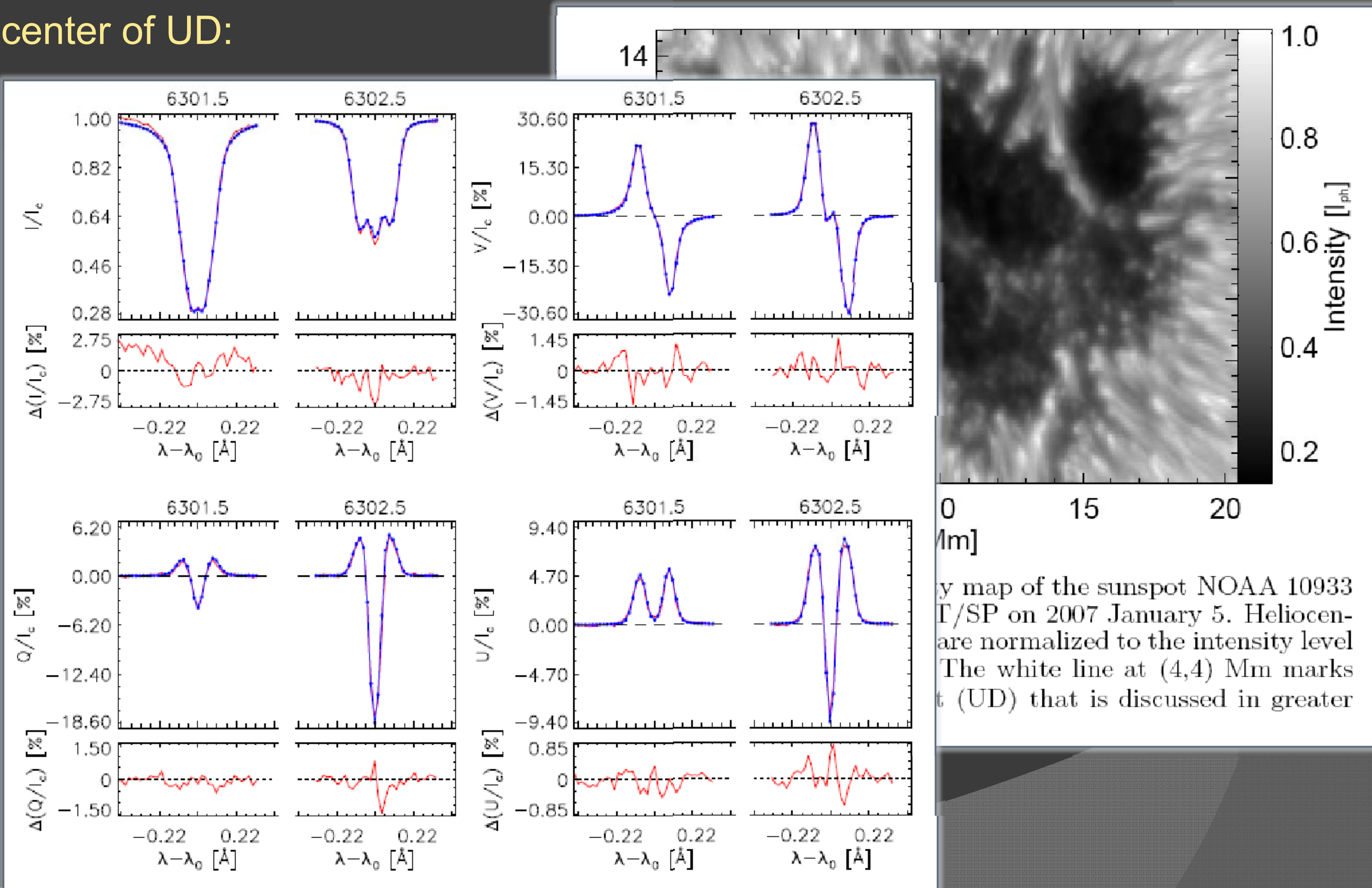


FIG. 1.— Continuum intensity map of the sunspot NOAA 10933 as observed by the *Hinode* SOT/SP on 2007 January 5. Heliocentric angle is $\theta = 4°$. Intensities are normalized to the intensity level of the quiet photosphere I_{ph}. The white line at (4,4) Mm marks the cut through an umbral dot (UD) that is discussed in greater detail.

Analysis of Umbral Dots (2)

Riethmüller et al., 2008

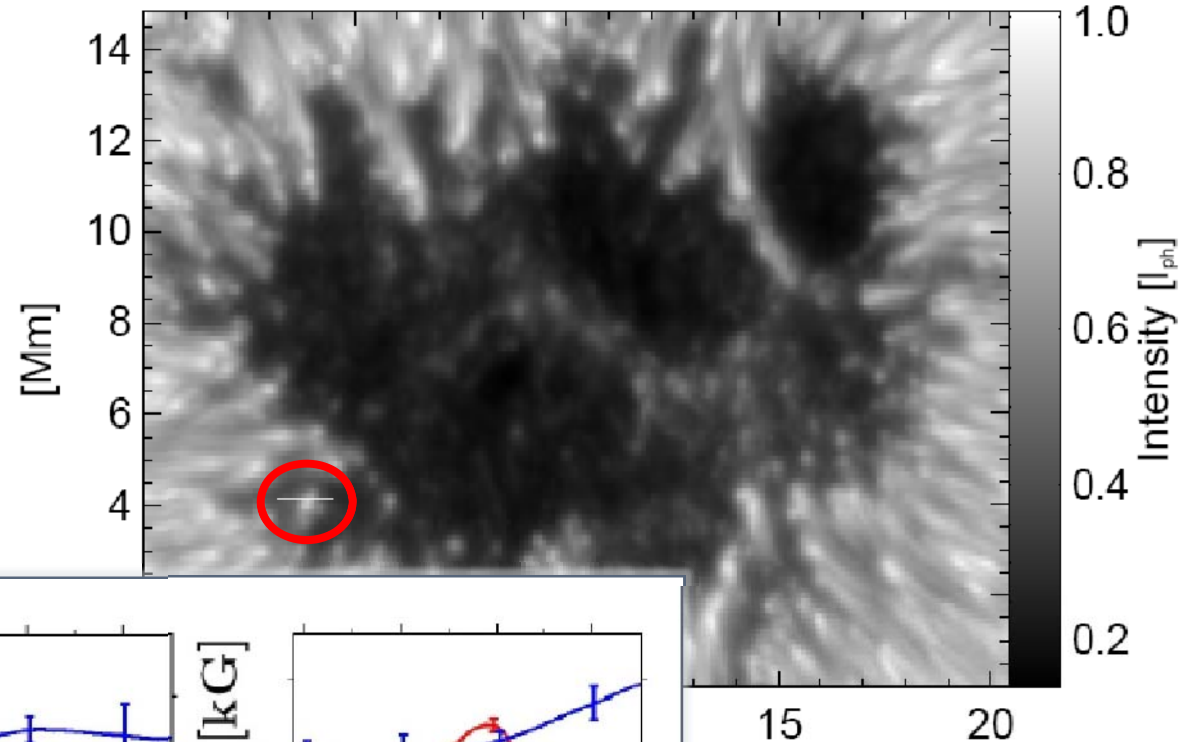
center of UD:



Analysis of Umbral Dots (3)

Riethmüller et al., 2008

atmospheric stratification retrieved in center (red) and the diffuse surrounding (blue)



of the sunspot NOAA 10933
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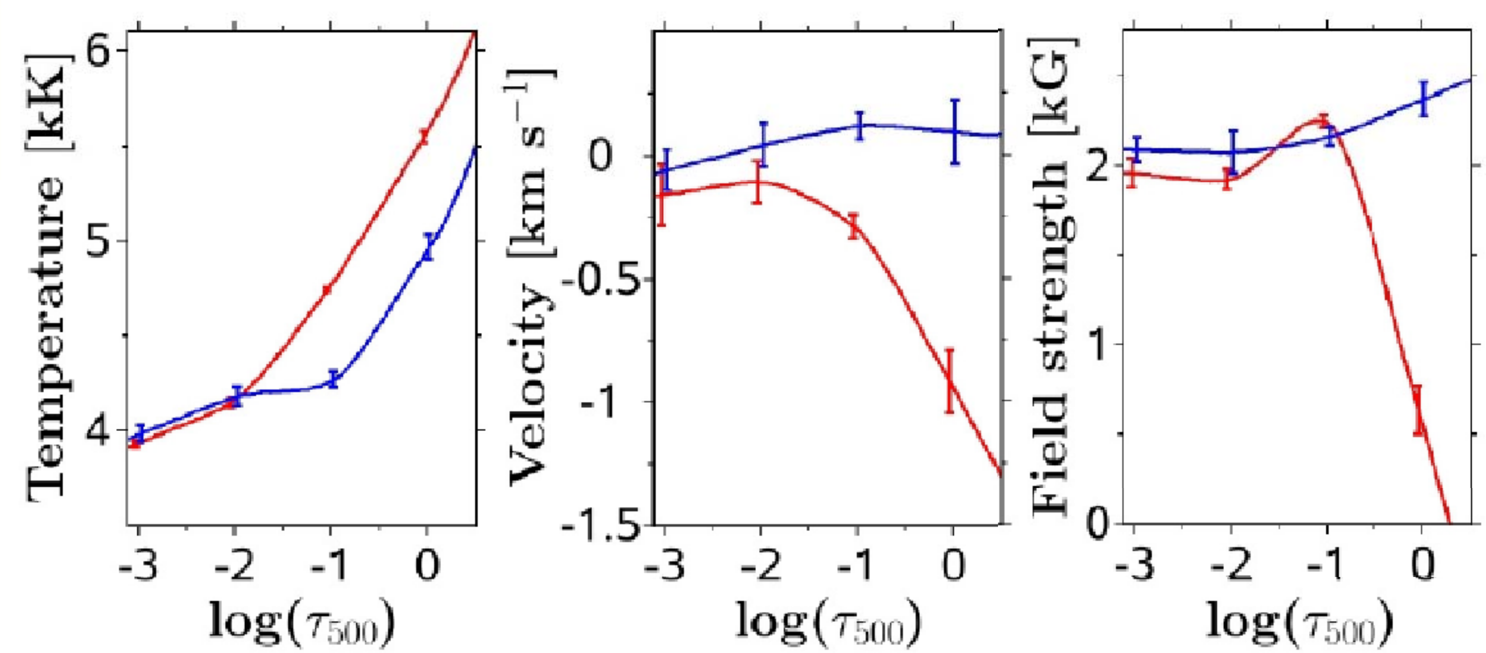
that is discussed in greater



Analysis of Umbral Dots (4)

Riethmüller et al., 2008

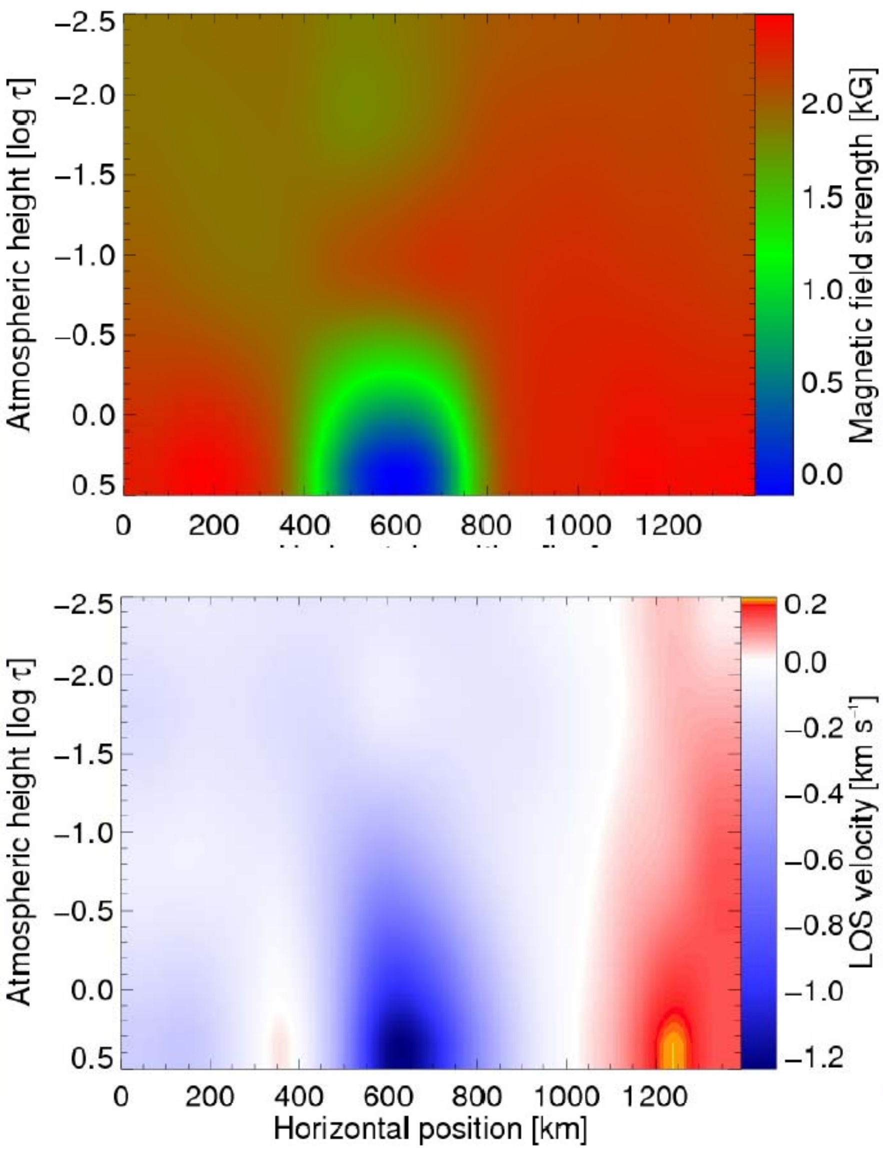
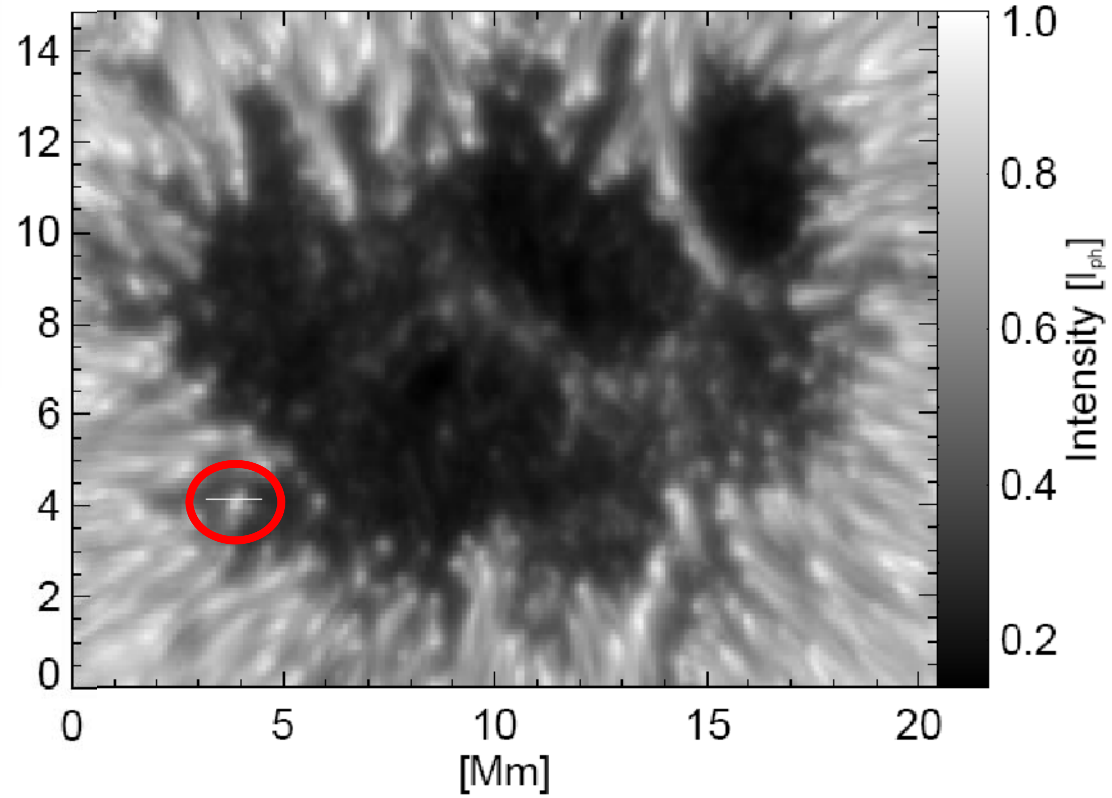


FIG. 5.— Vertical cut through the UD marked in Figure 1 in the direction indicated by the white line. Colors of the top panel indicate magnetic field strength. The bottom panel shows LOS velocity. Negative velocities are upflows.



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Vertical cut through UD

Analysis of Umbral Dots (5)

Riethmüller et al., 2008

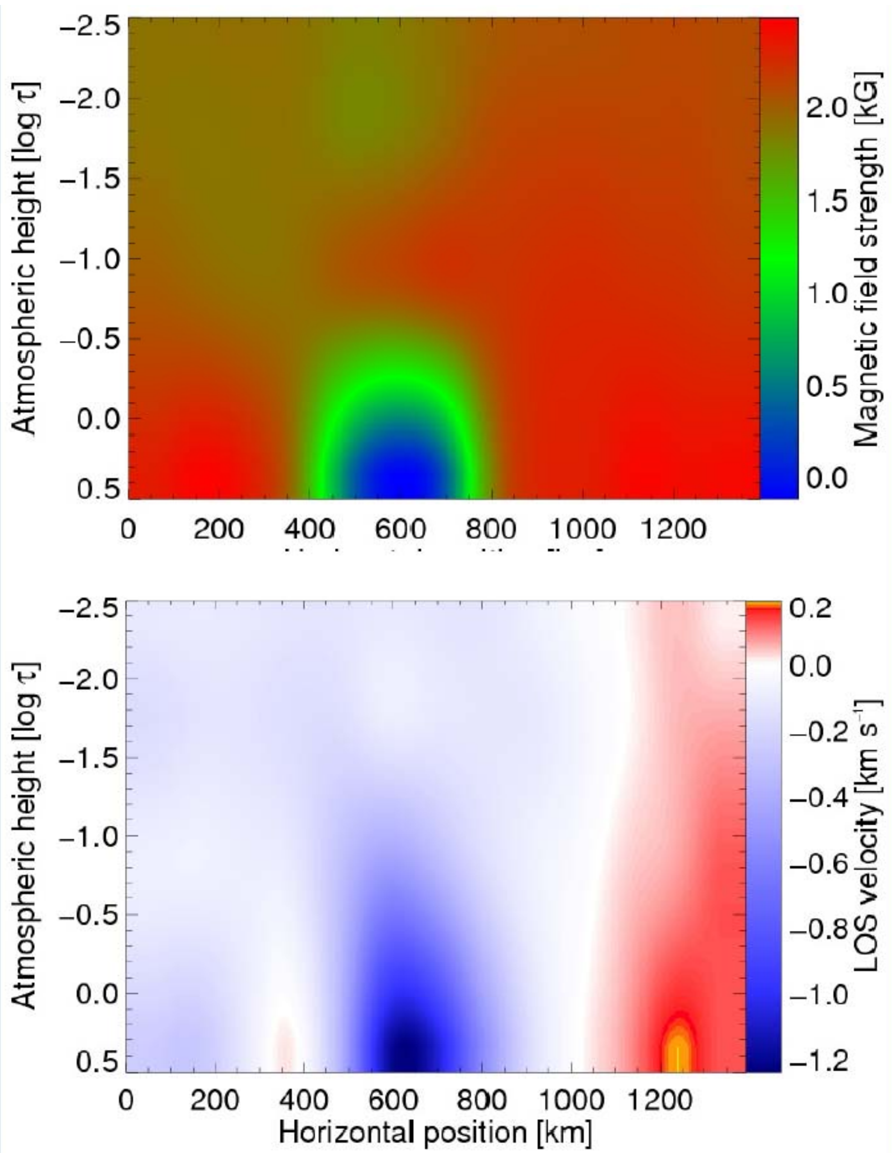


FIG. 5.— Vertical cut through the UD marked in Figure 1 in the direction indicated by the white line. Colors of the top panel indicate magnetic field strength. The bottom panel shows LOS velocity. Negative velocities are upflows.

Conclusions:

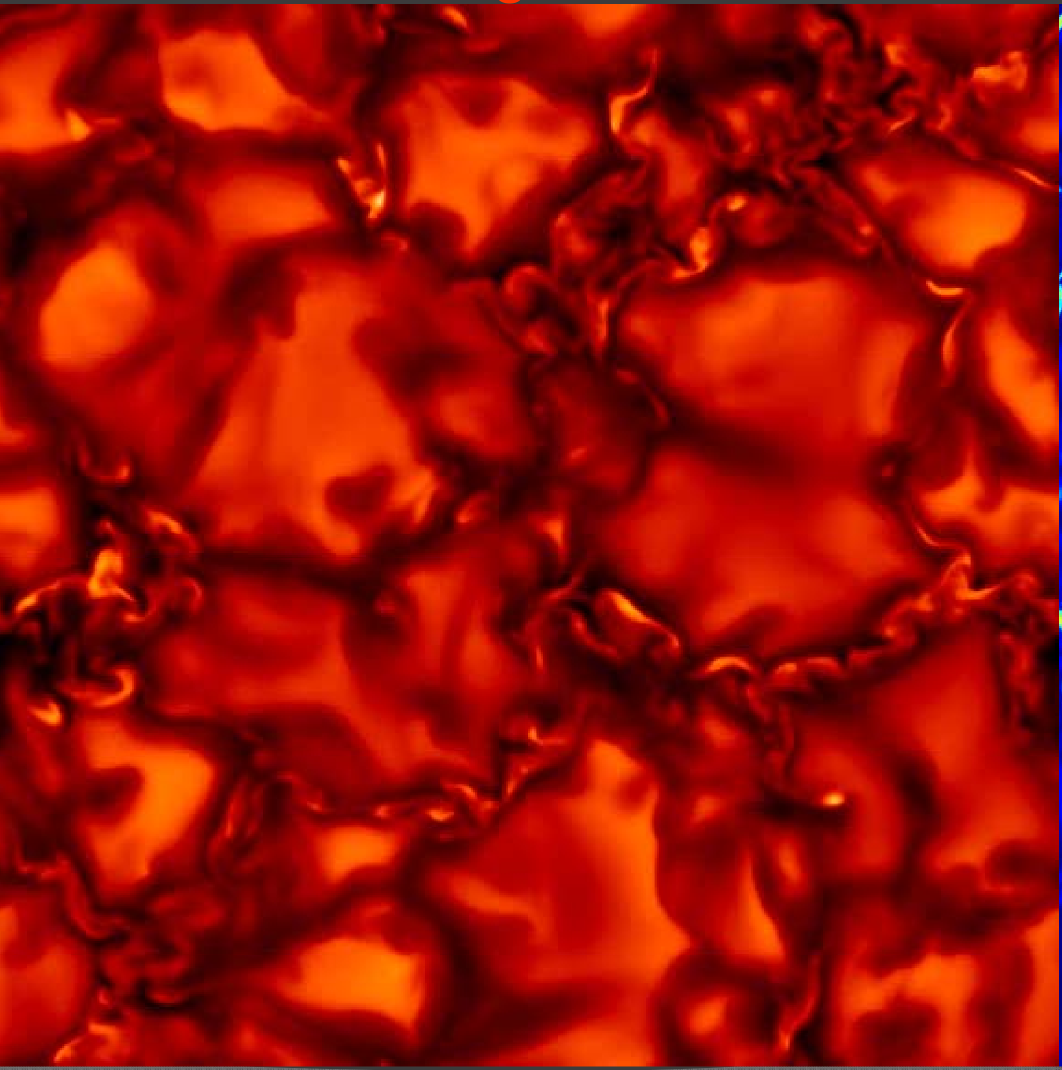
- inversion results are remarkably similar to simulations of Schüssler & Vögler (2006)
  - UDs differ from their surrounding mainly in lower layers
  - T higher by ~ 550 K
  - B lower by ~ 500 G
  - upflow ~ 800 m/s
- differences to V&S:
  - field strength of DB is found to be depth dependent
  - surrounding downflows are present, but not as strong and as narrow as in MHD (resolution?)

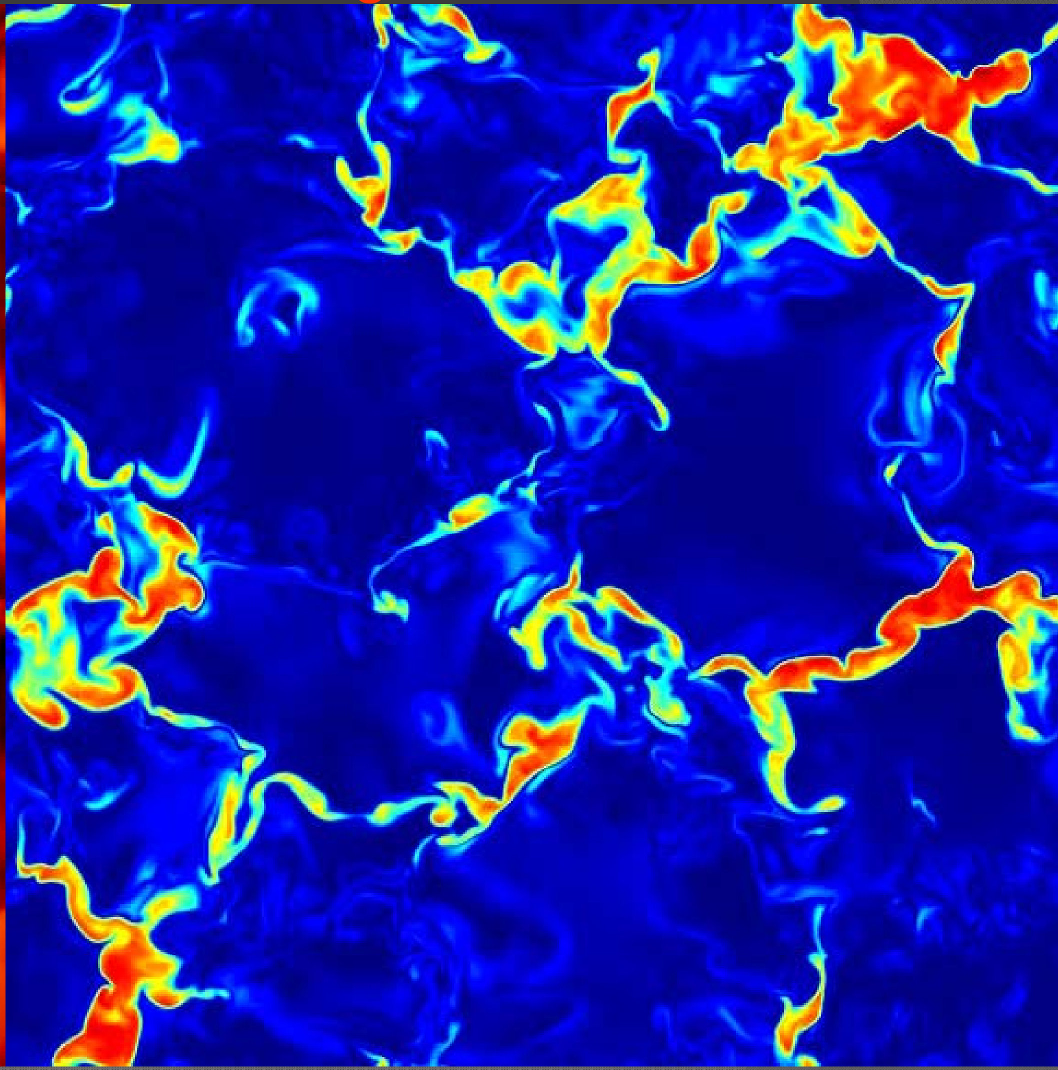
Analysis of Hi-Res Simulations (forward calc.)

Vögler & Schüssler

$\langle B_z \rangle$ = 200 G; Grid: 576 x 576 x 100 (10 km horiz. cell size)

Brightness | Magnetic field .

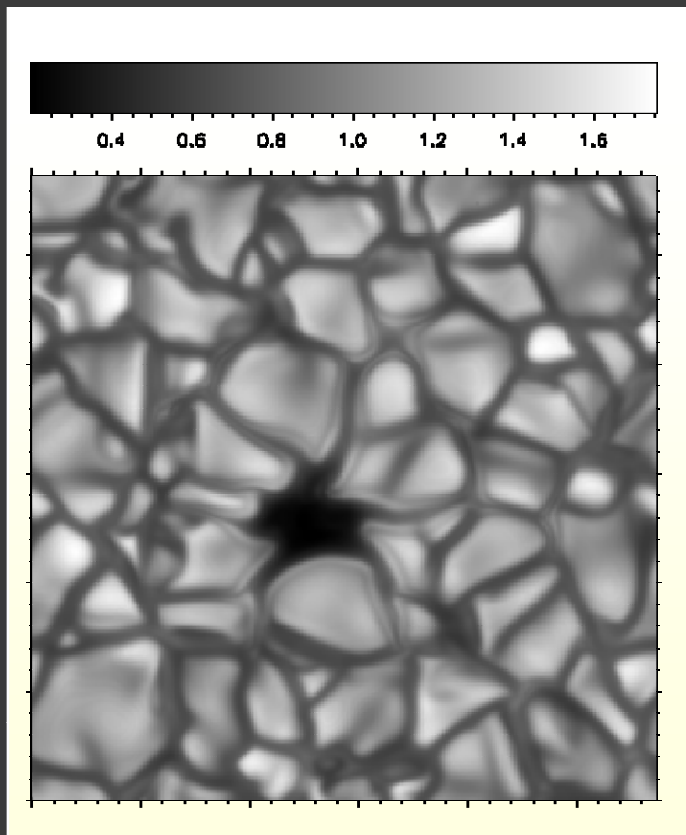


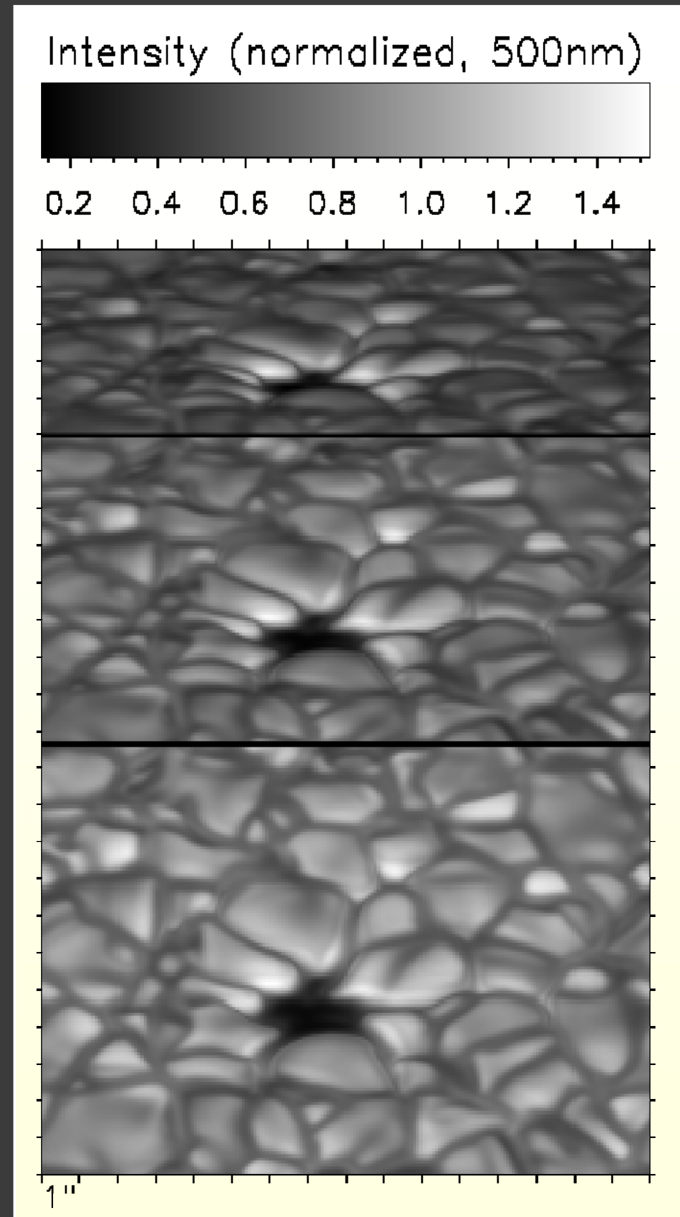


Pore simulation: brightening near the limb

R. Cameron et al.

$\mu=1$





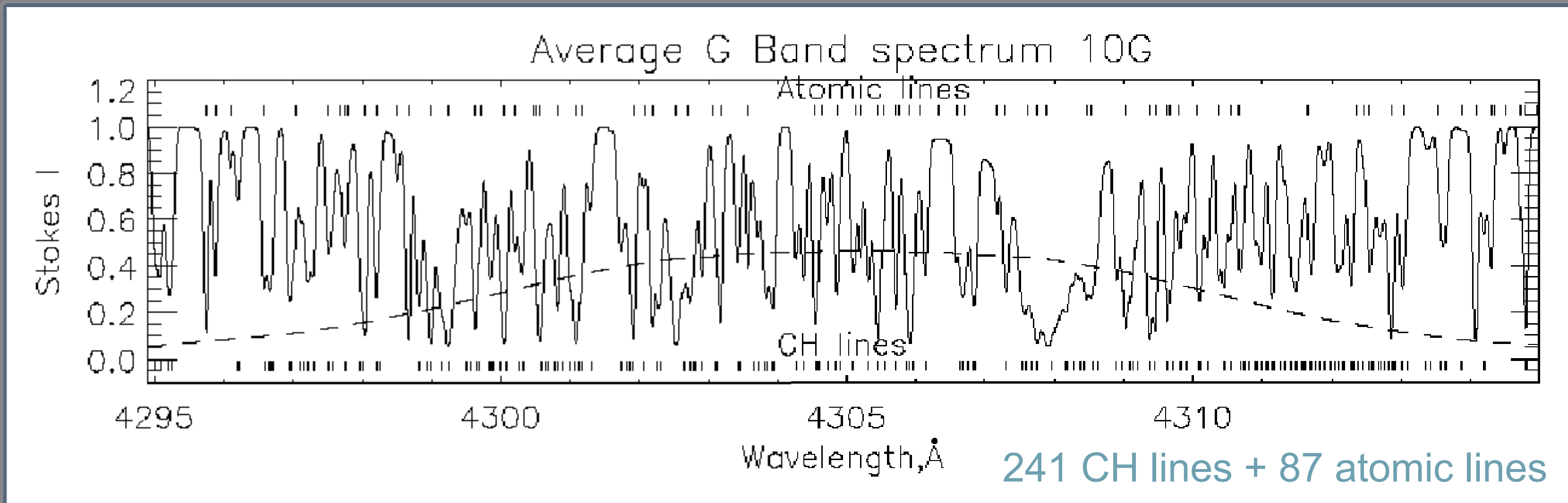
$\mu=0.3$

$\mu=0.5$

$\mu=0.7$

SPINOR: G-band spectrum synthesis

G-Band (Fraunhofer): spectral range from 4295 to 4315 Å contains many temperature-sensitive molecular lines (CH)



For comparison with observations, we define as G-band intensity the integral of the spectrum obtained from the simulation data:

$$I_G = \int_{4295\ A}^{4315\ A} I(\lambda)\, d\lambda$$

[Shelyag, 2004]

SPINOR: Installation and first usage

Stopro & Spinor Introduction

Andreas Lagg · Max-Planck-Institut für Sonnensystemforschung · Katlenburg-Lindau, Germany

Download from http://www.mps.mpg.de/homes/lagg

GBSO download-section → spinor

use *invert* and *IR$soft*

Exercise IV
SPINOR installation and basic usage

- install and run SPINOR
- atomic data file, wavelength boundary file
- use xinv interface
- SPINOR in synthesis (STOPRO)-mode
- 1^{st} inversion:
  Hinode dataset of HeLIx^{+}
- play with noise level / initial values / parameter range
- change log(τ) scale
- try to get the atmospheric stratification of an asymmetric profile
- invert HeLIx^{+} synthetic profiles

Examples: http://www.mps.mpg.de/homes/lagg
→ Abisko 2009 → spinor → abisko_spinor.tgz
unpack in spinor/inversions:

```
cd spinor/inversions ; tar xfz abisko_spinor.tgz
```