Results from Chromospheric Magnetic Field Measurements

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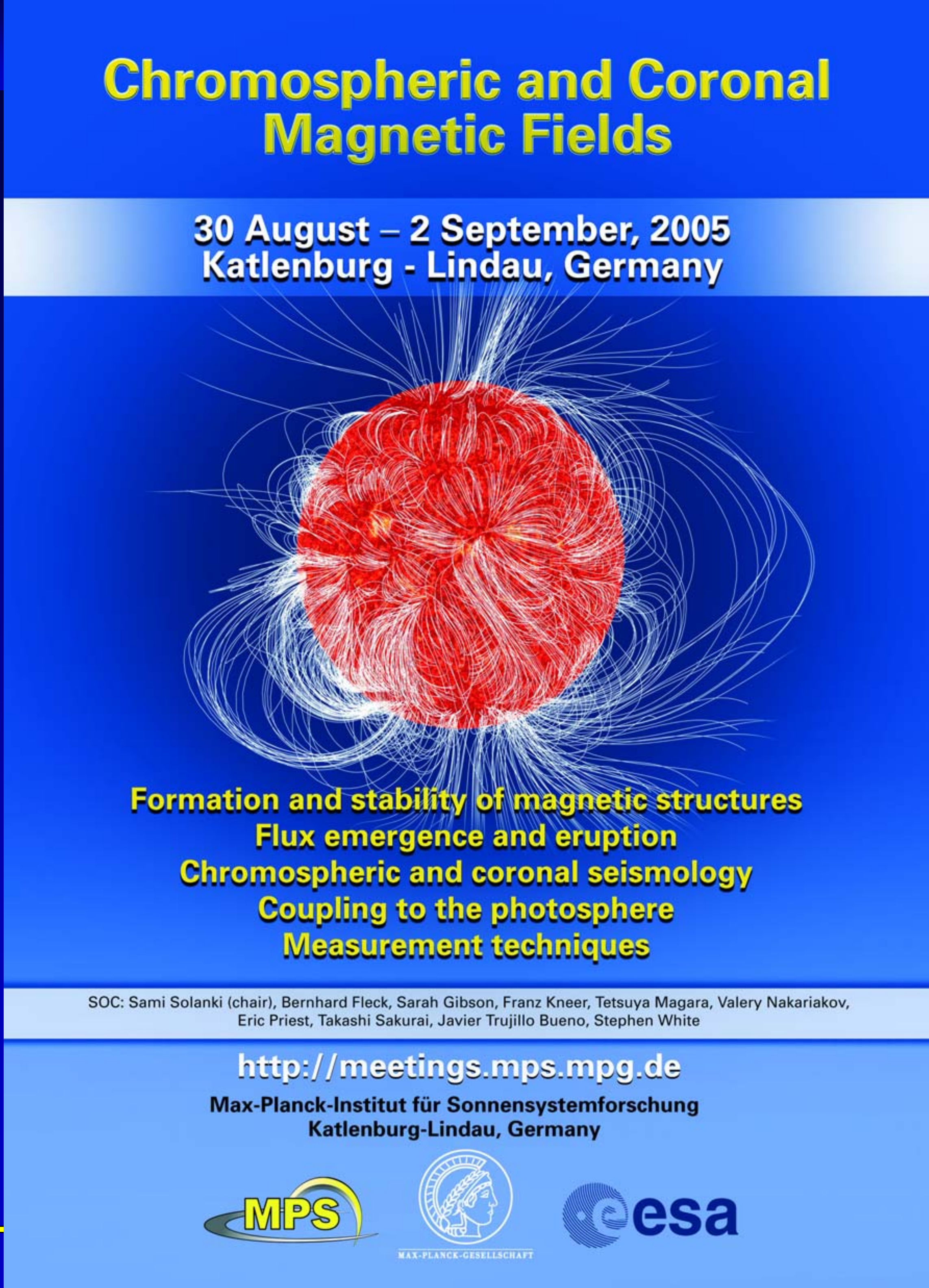
Outline:

- The average chromosphere
- Magnetic structures
    - network and inter-network
    - canopy
    - spicules
- Result:
    - Zeeman/Hanle/Paschen-Back diagnostics
    - photospheric extrapolations
    - chromospheric current sheet
    - “uncombed” chromosphere

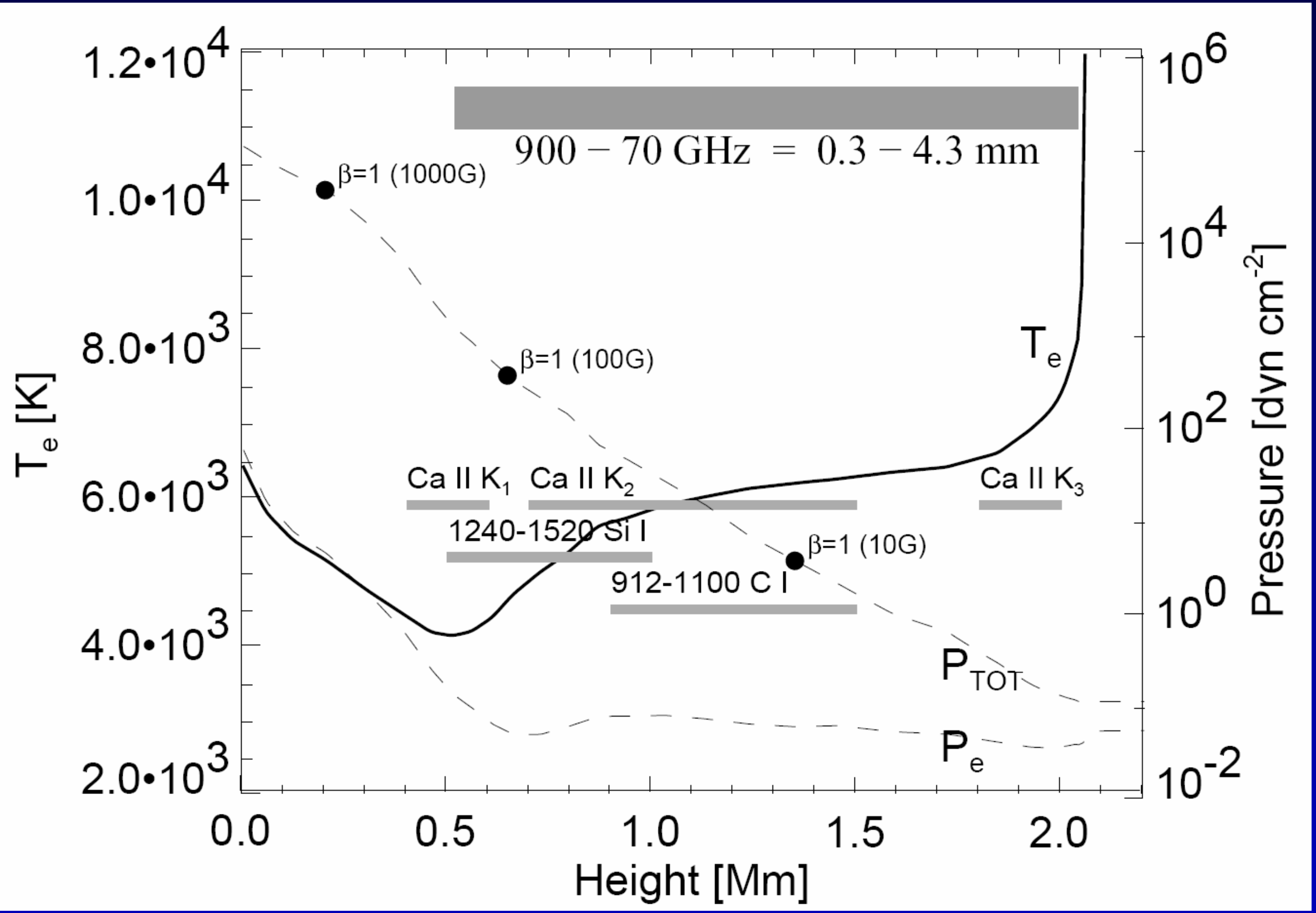
CCMag

- ~110 participants
- Tuesday, Aug 30 to Friday, Sep 2
- program on MPS homepage



The Chromosphere

- Photosphere: dominated by gas pressure and fluid motions
- Corona: dominated by magnetic field
- Chromosphere:
  - Structure determined by magnetic field
  - dynamics by oscillations and flows



(Peter 2002)

Chromosphere: plane-parallel layers between the temperature minimum and the onset of the coronal temperature rise (eg. Vernazza 1981, Fontenla 1993).

Structures in the Chromosphere

Quiet:
- grains (network / inter-network)
- spicules, mottles & fibrils
- canopy
- CO clouds

active regions:
- sunspots
- plages
- flare ribbons
- surges
- loops
- current sheets
- reversed Evershed flow

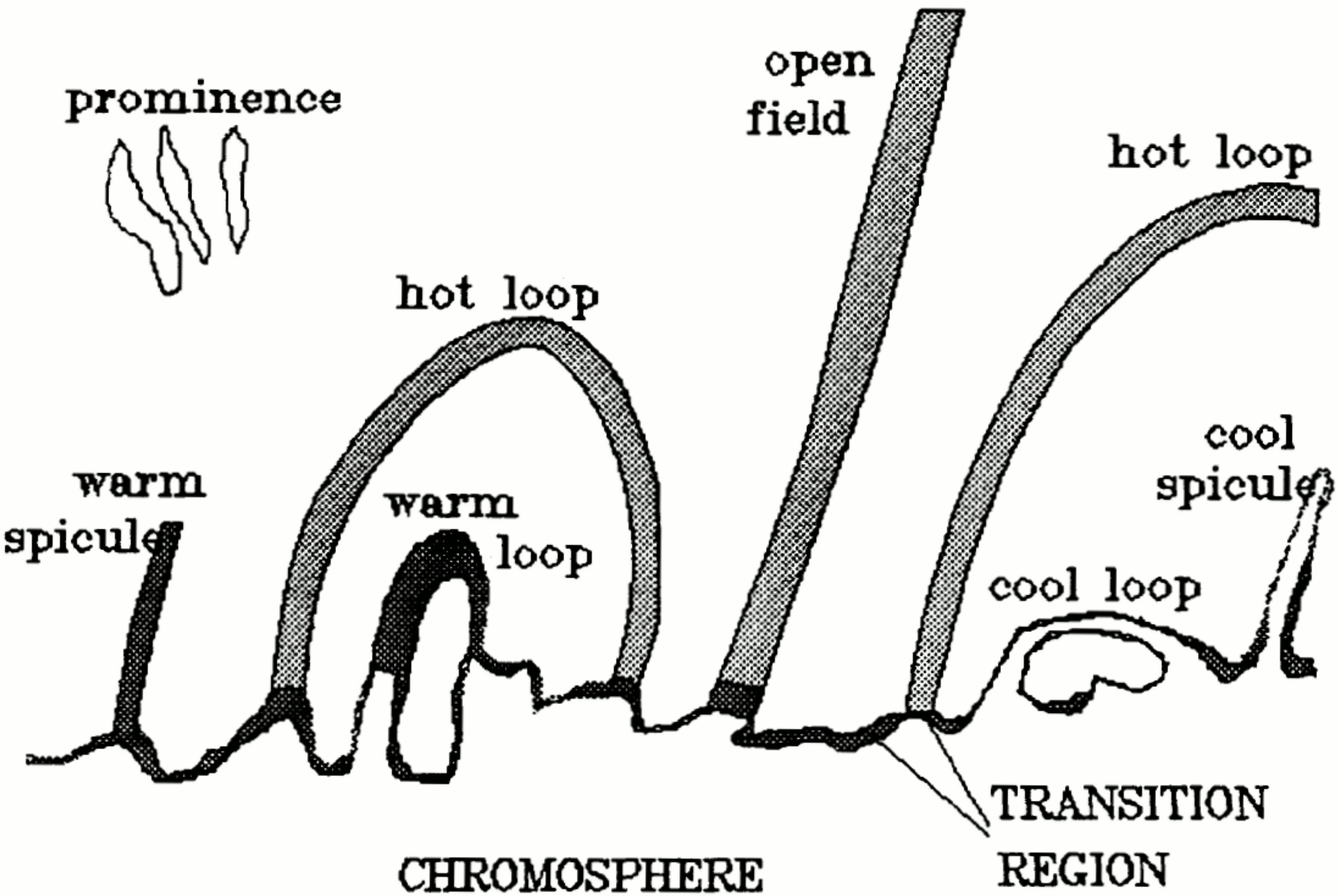
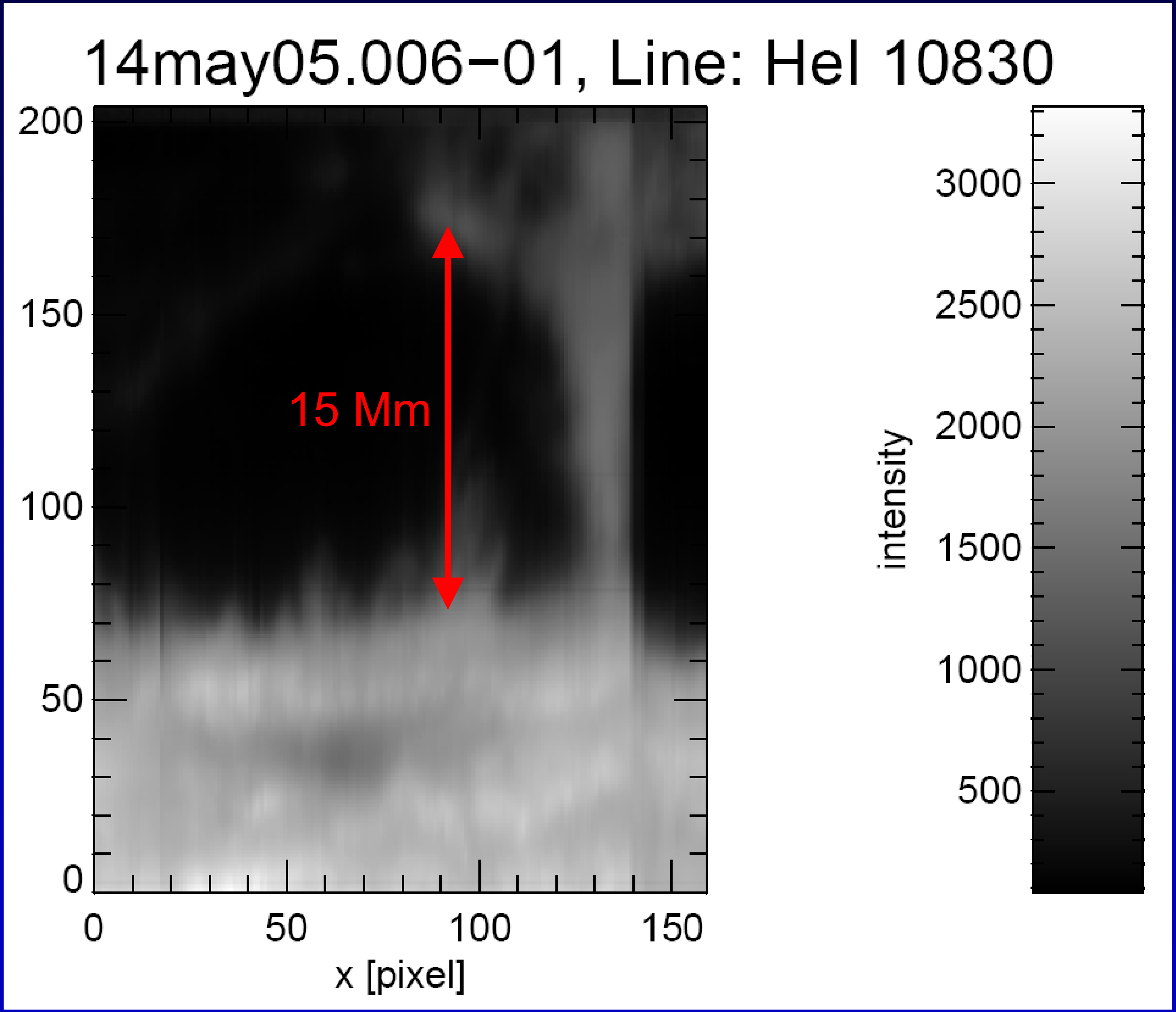


FIG. 2.—Sketch indicating some of the magnetic structures observed in the low corona. We show cool material (about 10^4 K) in the chromosphere and also in spicules, loops, and prominence material; warm material (about 10^5 K) in the transition region including loops and spicules; and hot material (about 10^6 K) in the loops and open fields.

(Fontenla 1993)

Temperature Stratification?

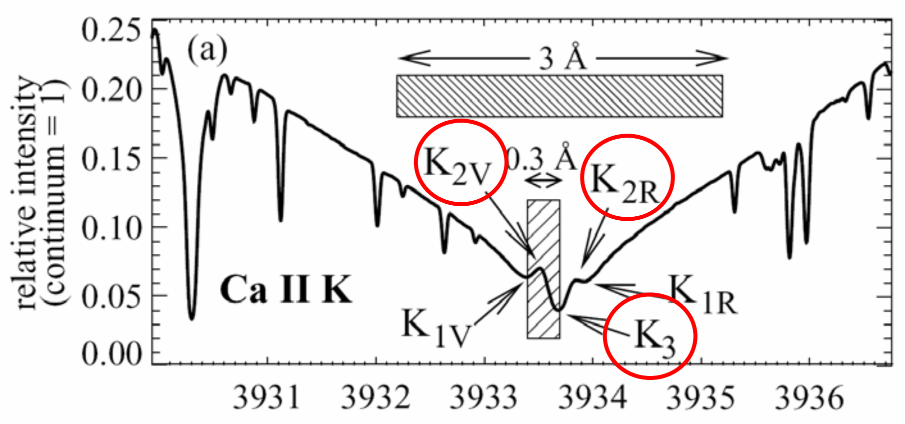


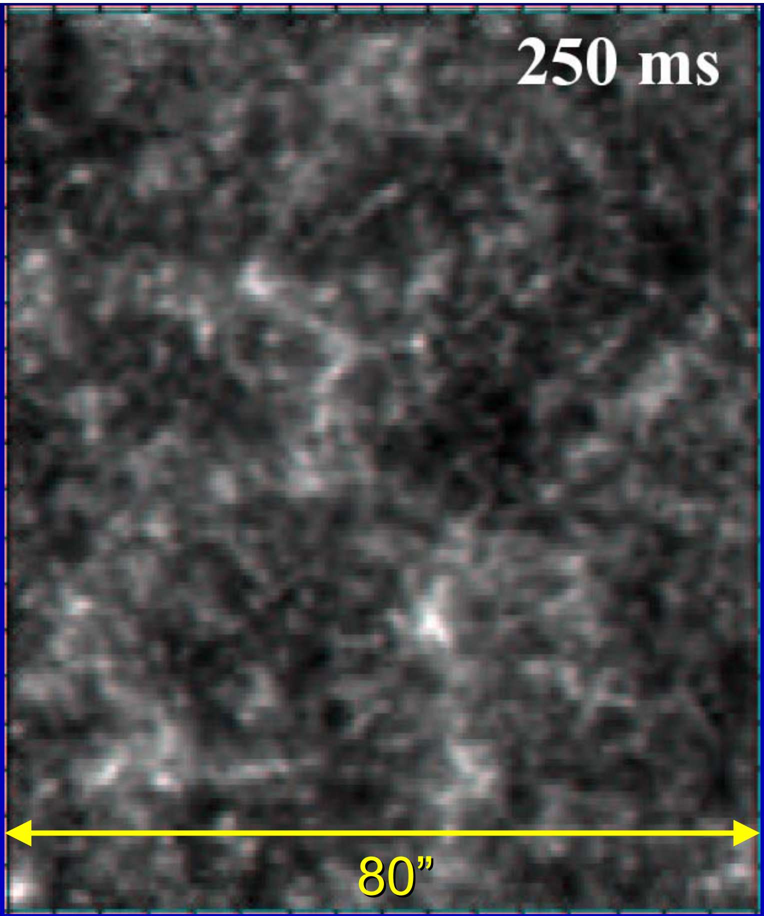
T ~ 10^4 K, formation height ~ 1800 km ??

VTT – TIP2, May 2005

The Network

- most obvious structure in chromosphere
- “reversed granulation”
- cell size: 20-30 Mm
- correlated with super-granules
- clusters of kG fluxtubes (Spruit, 1977)
- central upflow of hot material
- slow (few 100 m/s) radially outward directed flow
- magnetic flux concentrations emerge and are buffeted around towards cell boundaries
- Ca II H&K bright points in network and in internetwork
- Are network & internetwork grains of same nature?



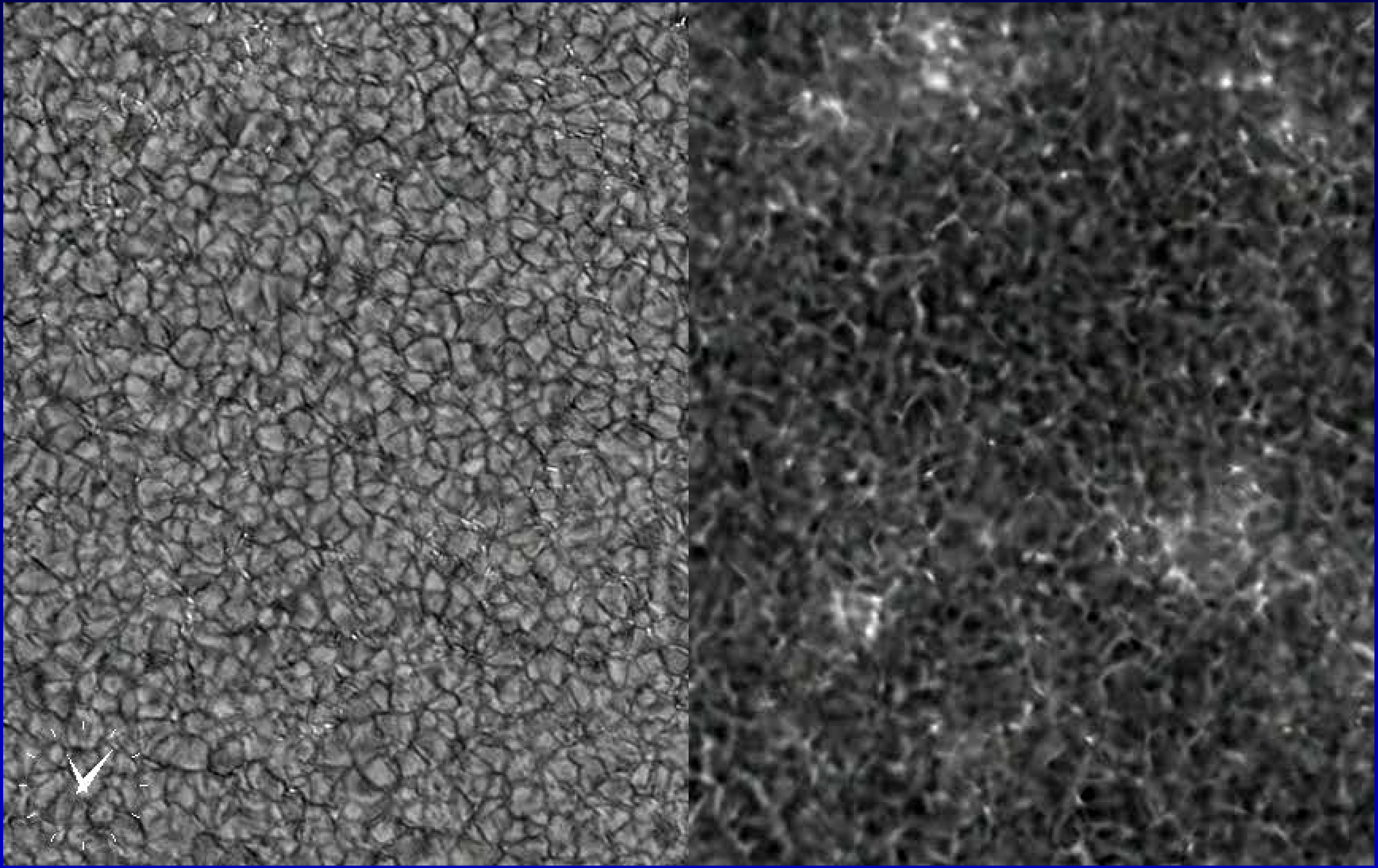


(Ca II K_{2V}, VTT, Schmidt & Tritschler)

Grain Motions

G-band

Ca II H



(DOT-movie, Dec 8 2002)

Ca II network / internetwork bright points

Internetwork (non-network, cell interior):

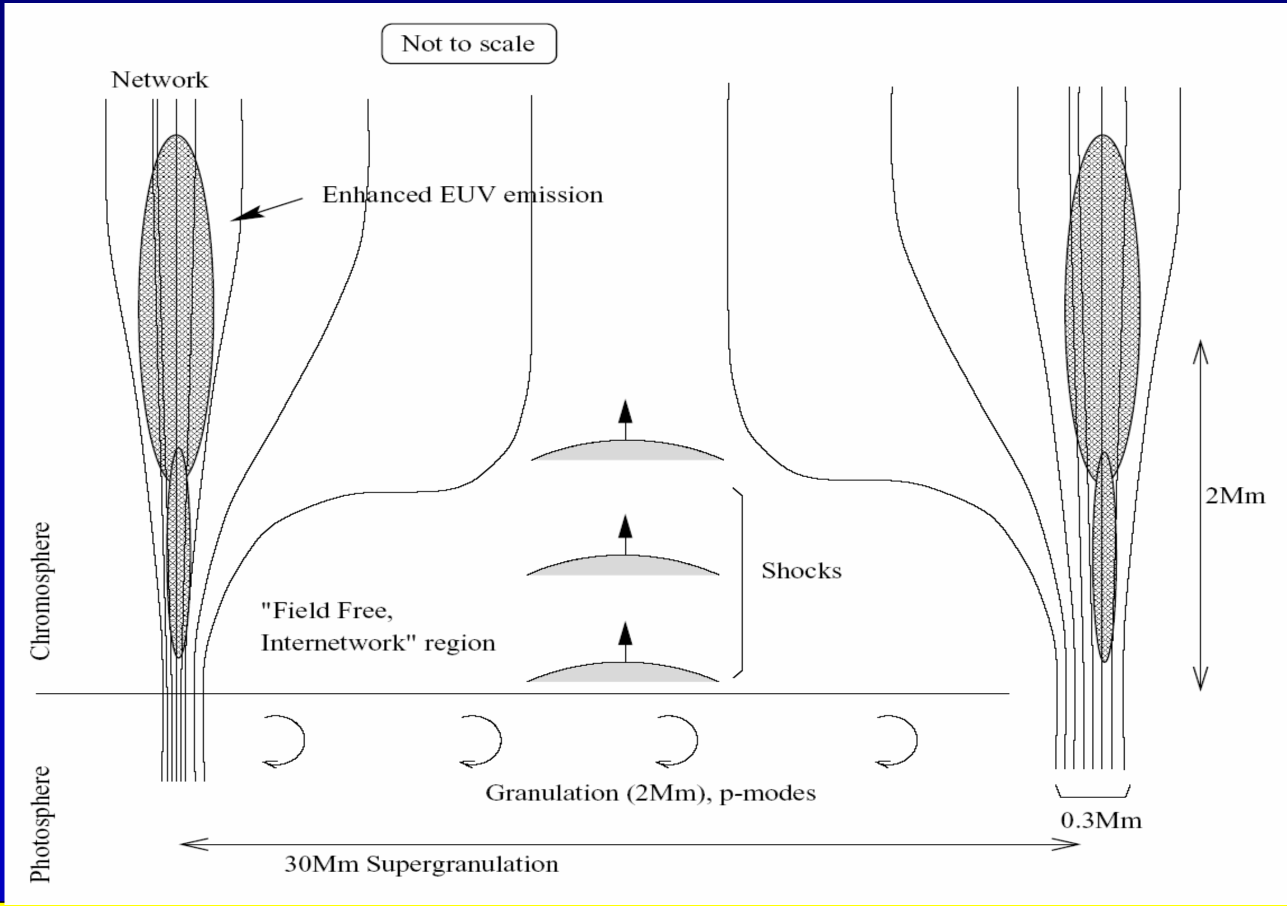
- inter-network grains appear quasiperiodically (2-5 min, Kneer, 1986)
- grain size: ~1” (W. Schmidt)
- signature of upward propagating, weak acoustic shocks driven by photospheric, piston-like motions steepening into shocks (Carlsson & Stein, 1997)
  - ➔ no magnetic structure
  - ➔ no temperature minimum

Wedemeyer 2004: confirms shock wave dominance

Kalkofen: too cool, Ayres (2002): too hot

Network:

- oscillations 5-20 min (e.g. Lites, 1993)
- grain size: >1”
- nature: chromospheric heating along strong field clusters (Judge & Peter, 1998)



Magnetic Canopy

(Gabriel, 1976)

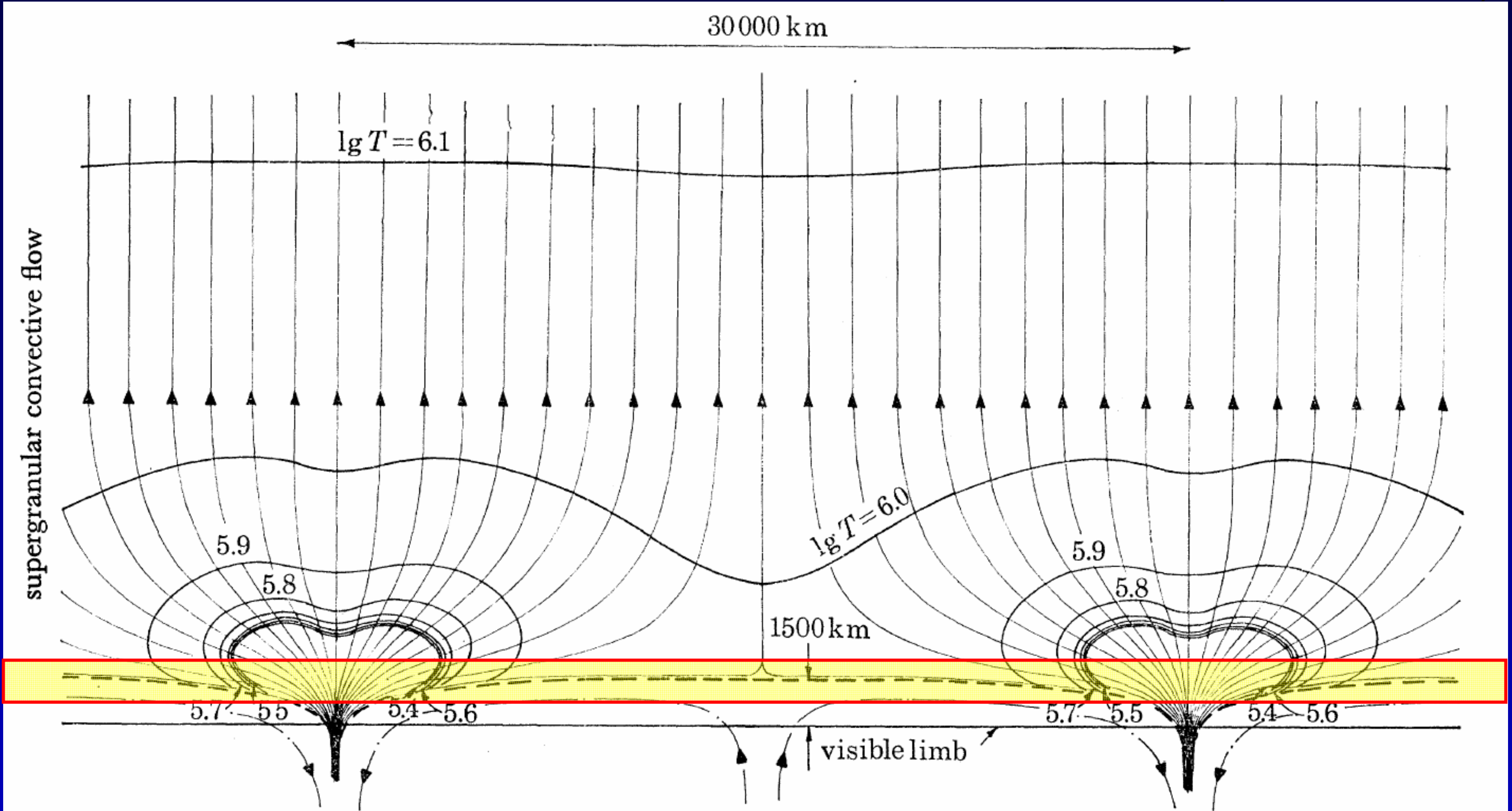
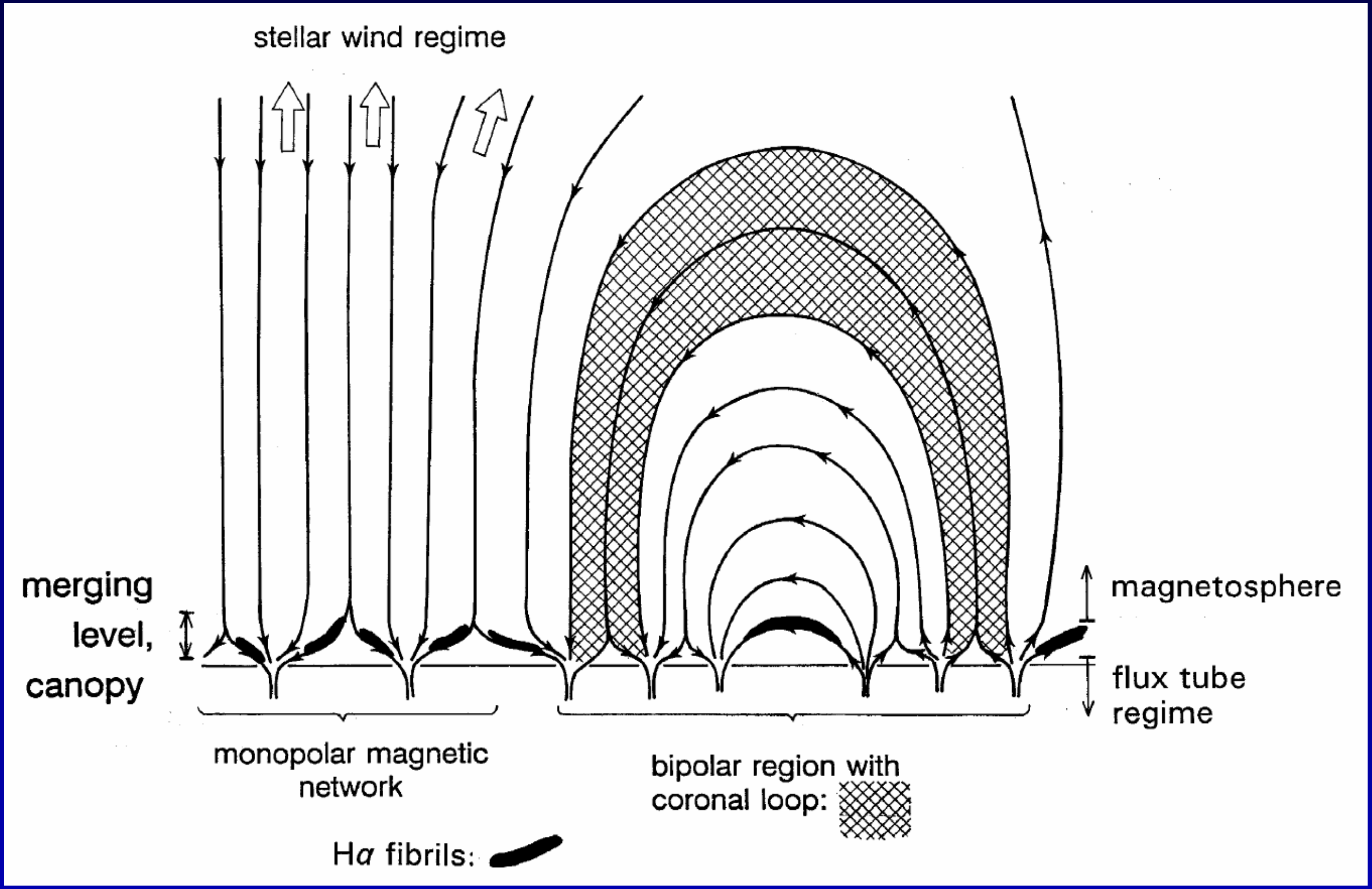


FIGURE 5. The proposed structure of the network model based upon energy balance (model C), showing the convection cell, magnetic field lines and contours of constant temperature. The primary transition region is indicated by the converging contours of temperature. The secondary transition region is shown by the dashed line.

Giovanelli (1980), Solanki & Steiner (1990): lower canopy height (600-1200 km)

Magnetic Canopy

- canopy arches over interiors of supergranular cells
- chromosphere completely covered by magnetic vault, independent of photospheric polarities



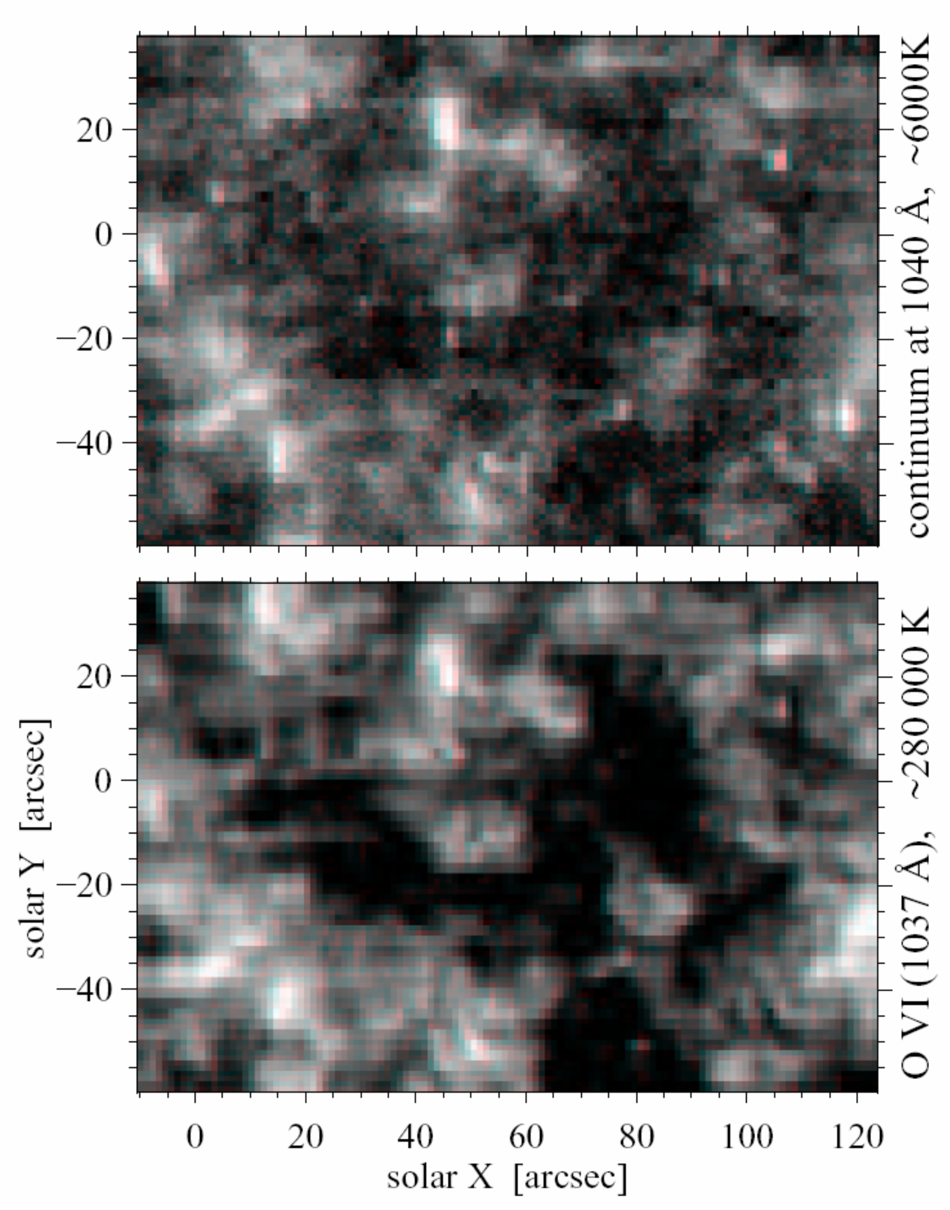
(Schrijver & Zwaan, 2000)

Magnetic Canopy?

- co-spatial images in C I continuum (6000 K) and O VI (280000 K)
- same size of network patches in chromosphere and corona

  ➔ compatible with idea of canopy?

- possible explanation:
  emission caused by magneto-acoustic waves which can penetrate the chromosphere only if the magnetic field is vertical
  ➔ emission only directly above bright network patches

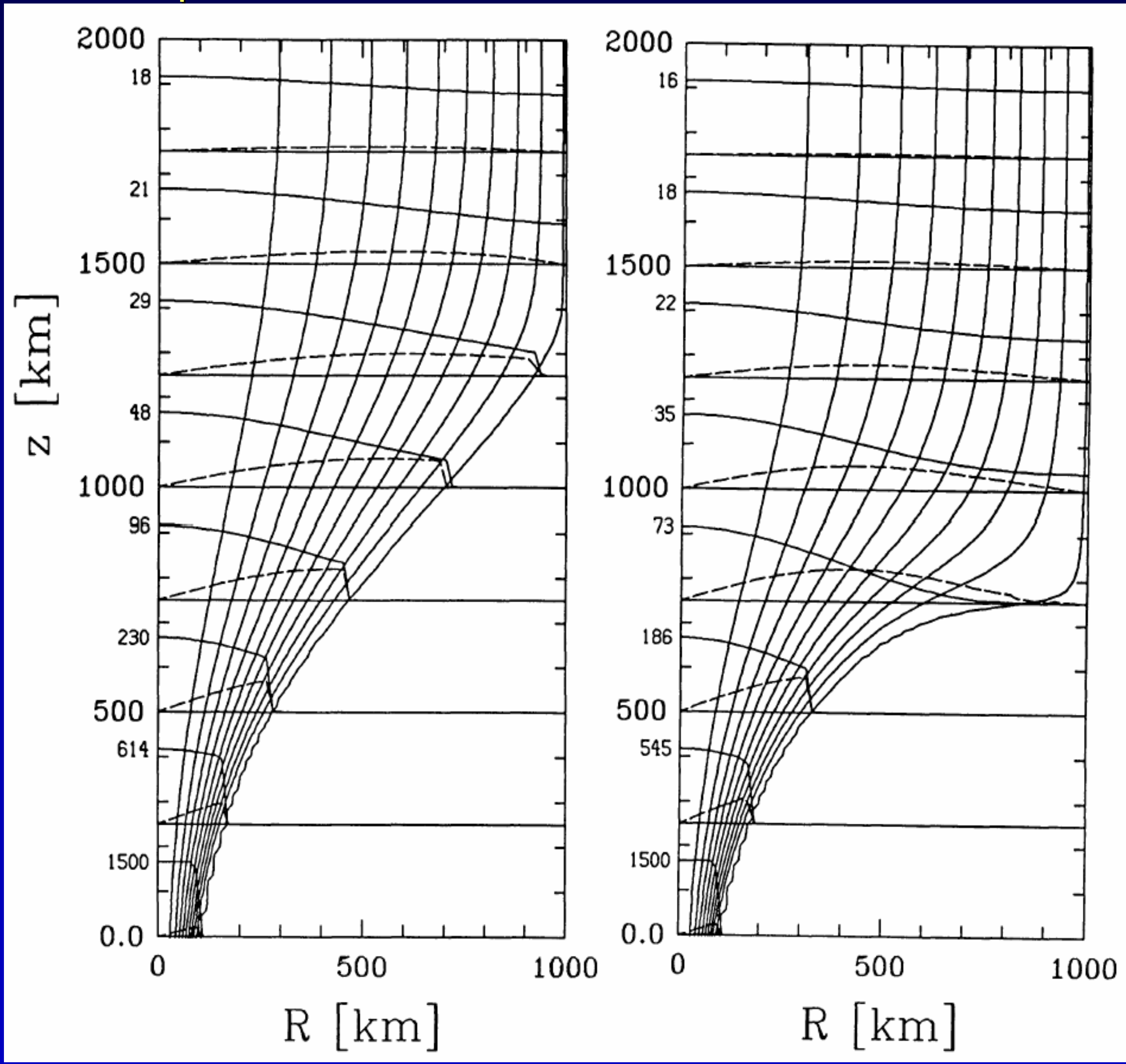


(Peter, 2002)

Theoretical Aspects of Canopy Fields

- Solanki & Steiner (1990): cool atmosphere required outside flux tubes (expected from CO-clouds, Ayres 2002)
- magnetic flux tubes merge below 700-1200 km
- upper boundary even if magnetic filling factor is very small
- small FF: nearly horizontal canopy

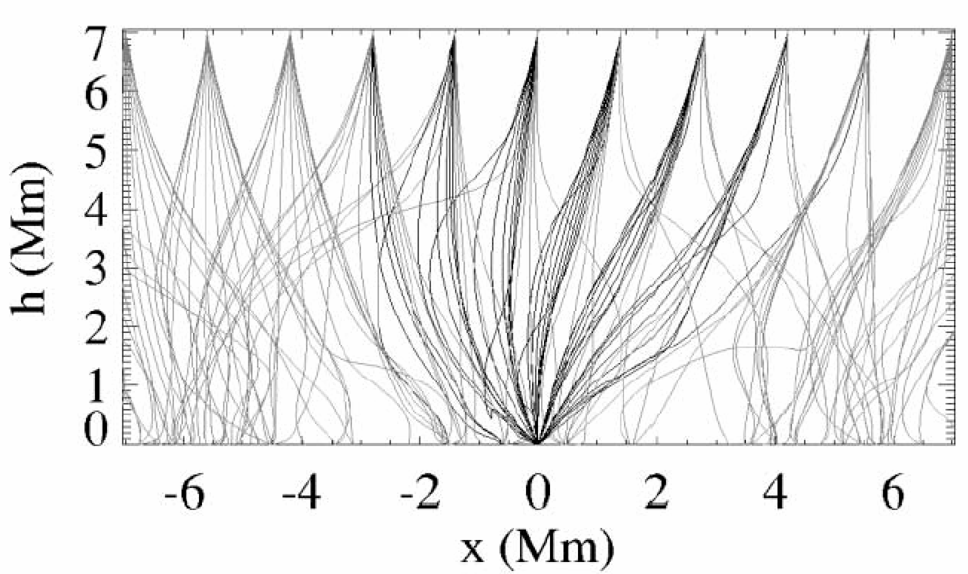
Temp: inside = outside   outside cooled (CO clouds?)



Theoretical Aspects of Canopy Fields

- relatively strong internetwork fields (few Mx/cm^2) destroy classical canopy (wineglass shape)
  ➔ 50% of coronal field rooted in internetwork
- canopy field lines return to photosphere near parent flux tube
- Sanchez-Almeida (2004): bright points in internetwork tracing magnetic field concentrations

Schrijver & Title (2003)



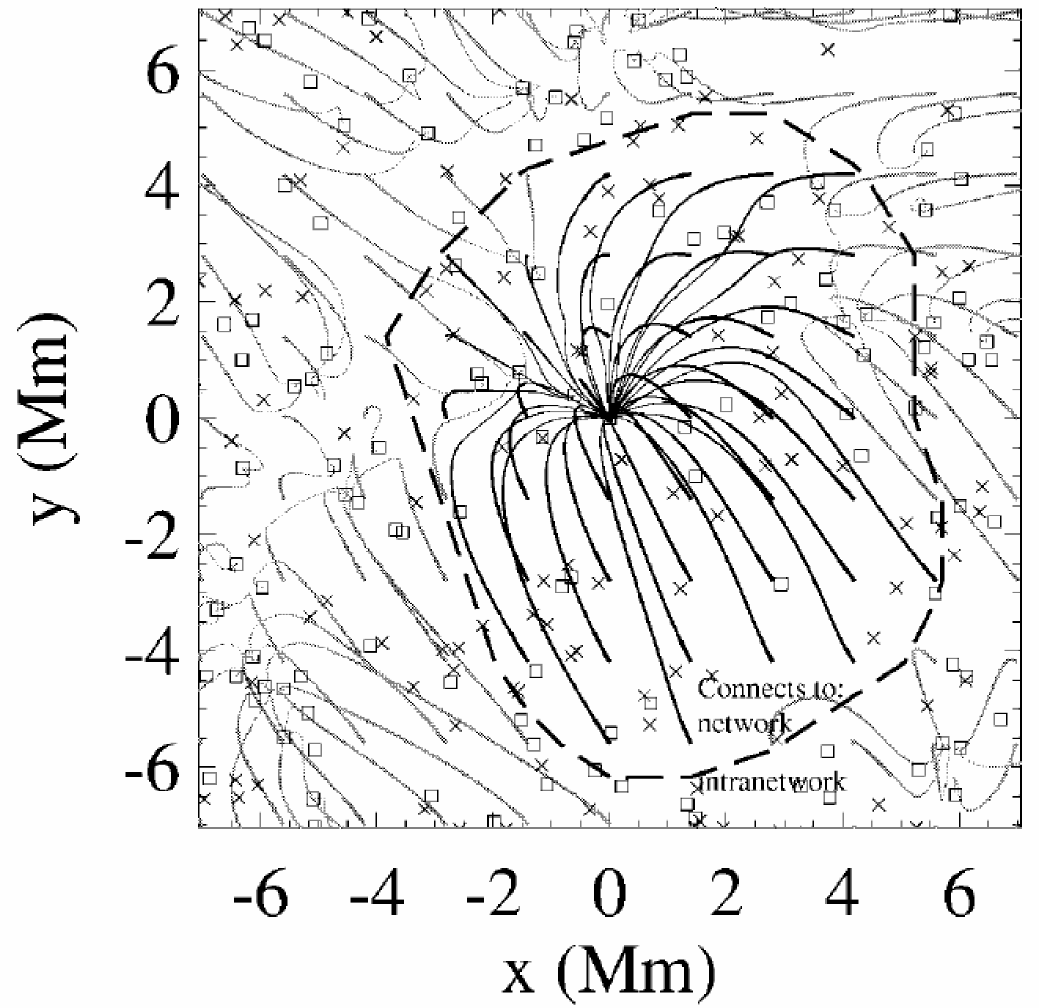


FIG. 4.—Similar to Fig. 1 but showing the field lines starting from a grid 7 Mm above the source plane. Field lines terminating on the central network source are black and on the internetwork sources gray. The dashed curve encloses the flux from the network source that reaches up to greater than 7 Mm; without internetwork field that perimeter would equal the field of view, thus forming the classical network canopy that covers the entire photosphere.

Measurements of Canopy Fields

- Landi degl'Innocenti (1998): Na I D scattering polarization
  ➔ less than fraction of 1 G
- Bianda (1998, 1999): strong evidence for horizontal, canopy like fields (10 G range)
- Stenflo (2002): clear canopy signal (25-35 G) over a semi-quiet region with moderate facular activity (Zeeman + Hanle diagnostics in Na D1)

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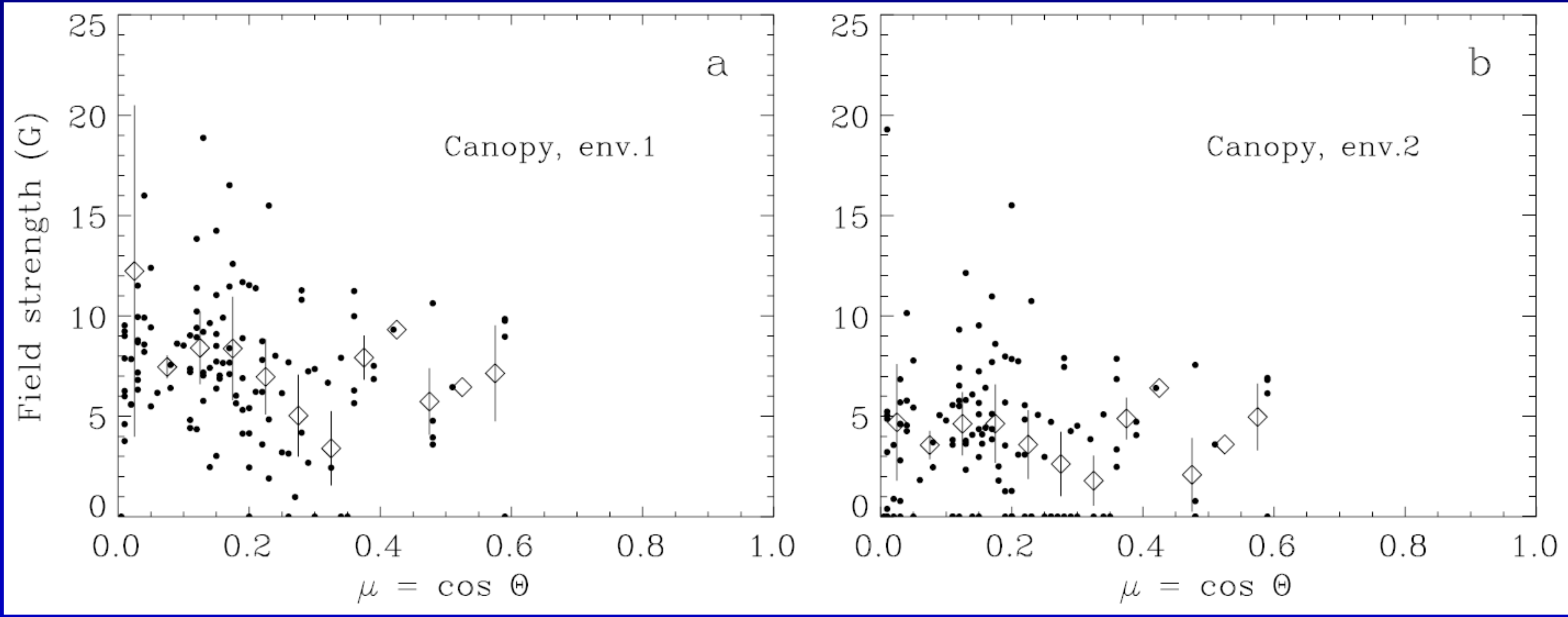

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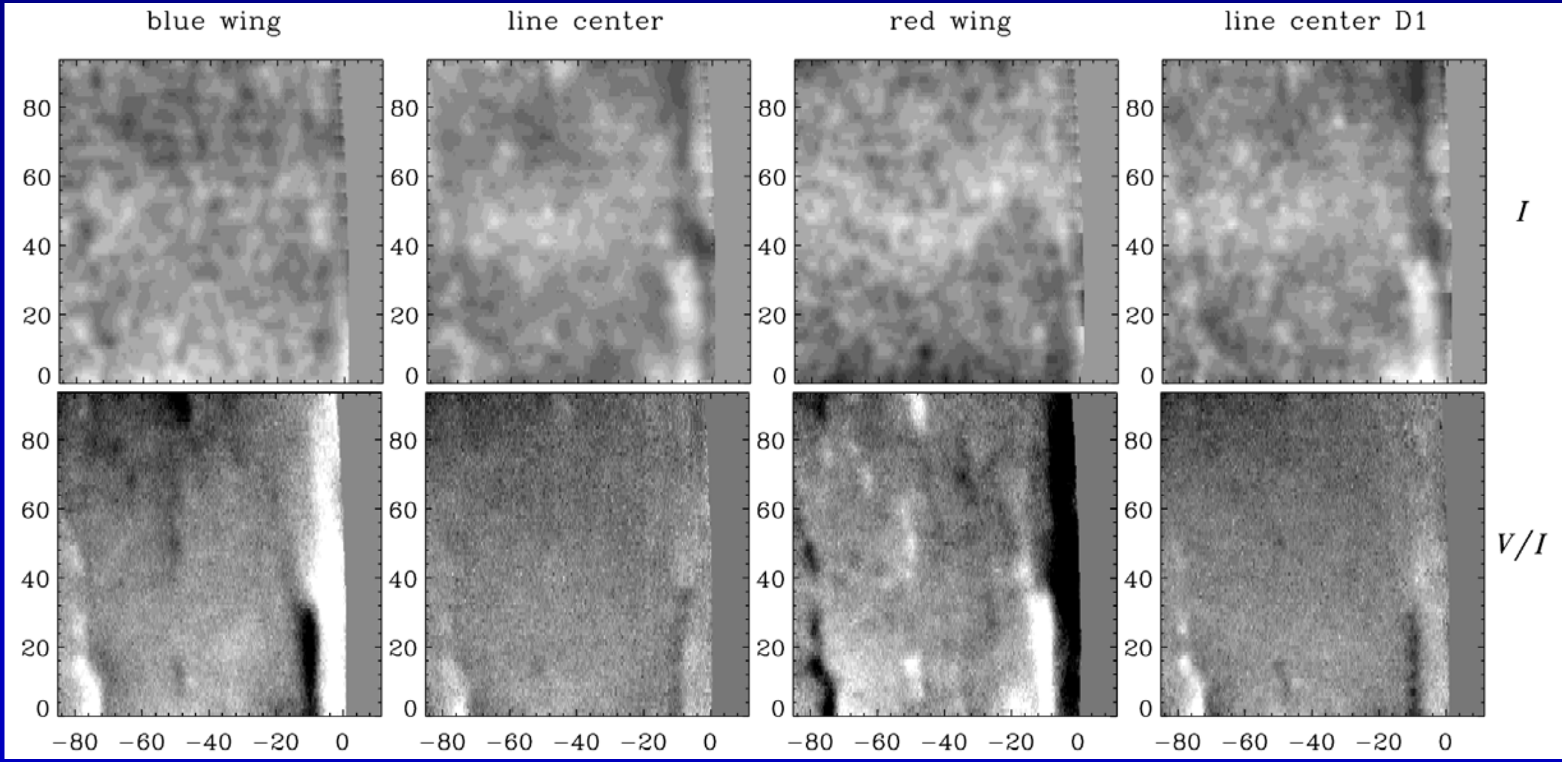
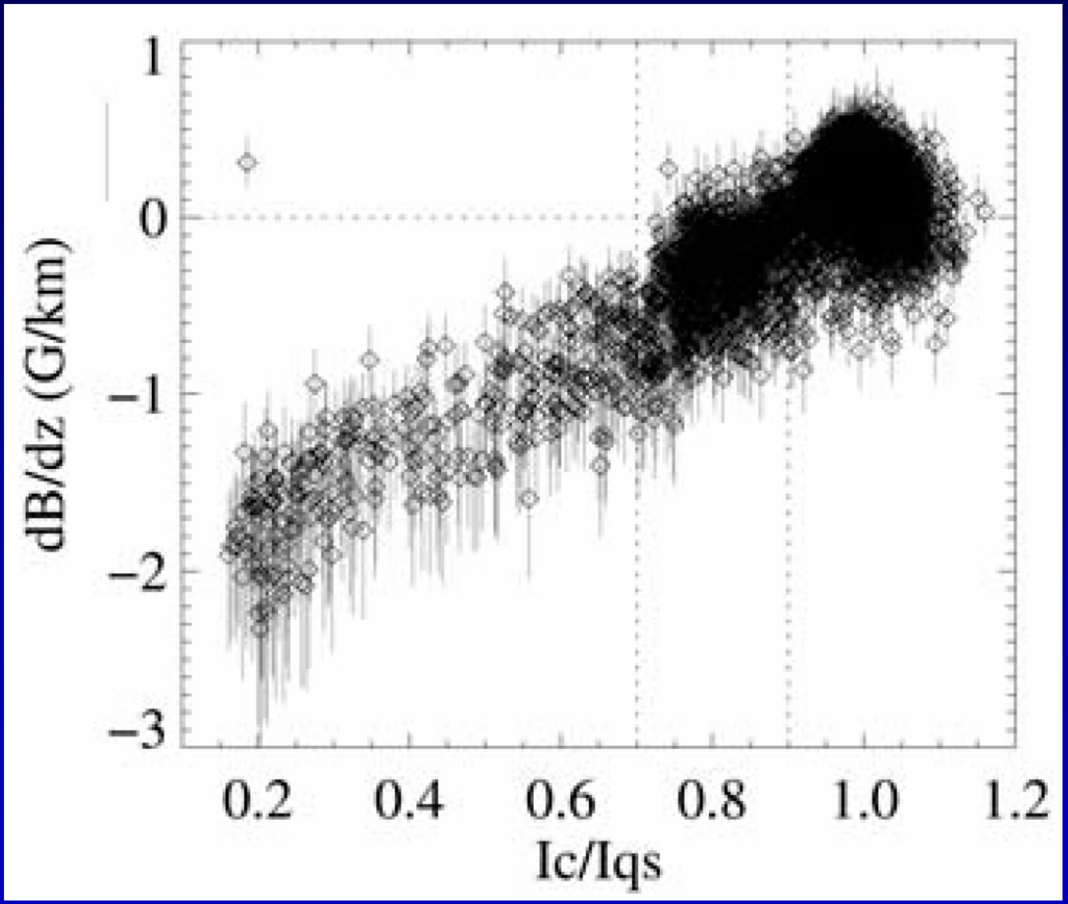


Measurements of Canopy Fields

- Leka (2004):
  direct detection of superpenumbral canopy
  (Fe 630 + Na I D)
- Acoustic mapping of the magnetic canopy, β=1 layer acts as magnetic canopy for waves (Finsterle, 2004)
- Zhang (CCMag, Tuesday):
  little evidence for horizontal fields using Hβ magn. field measurements + TRACE 171A data



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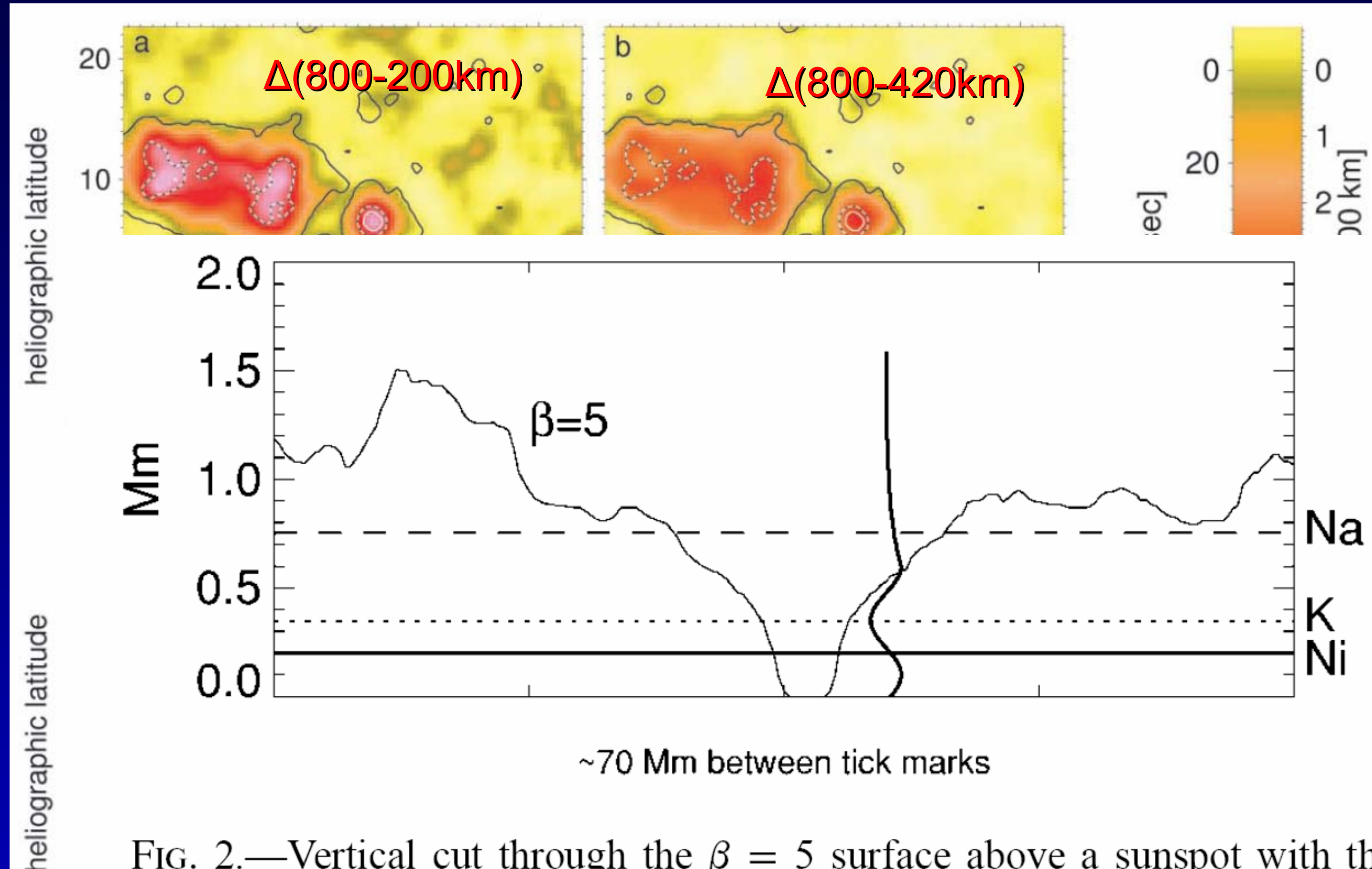


FIG. 2.—Vertical cut through the $\beta = 5$ surface above a sunspot with the horizontal lines indicating the formation heights for the Ni (*solid line*), K (*dotted line*), and Na (*dashed line*) lines. The position of the cut is marked by the red line in Fig. 3*d*. Our reflection model is visualized by a schematic wave train (wavelength not to scale). The upward traveling wave is reflected at the $\beta = 5$ surface, and only its evanescent tail reaches the Na layer. For simplicity the reflected wave is not shown. Fig. 8 of Rosenthal et al. (2002) suggests that the reflected wave travels downward at an angle away from the sunspot.

Spicules (on disk: mottles, low-lying, horizontal: fibrils)

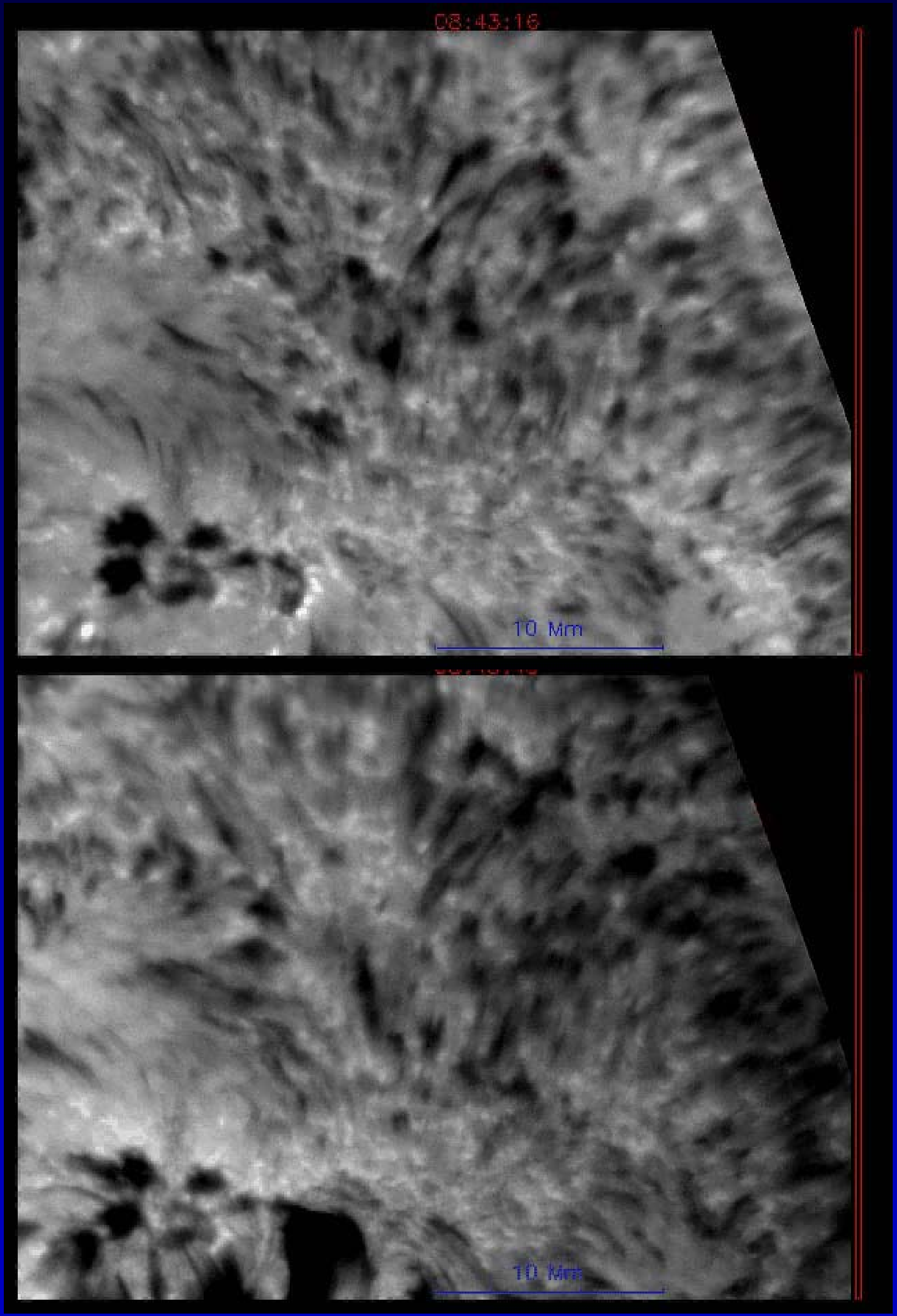
De Pontieu et al., 2004

- short lived features (5-10 min)
- dynamic upward jets (20 km/s)
- mass flux: 100x of solar wind flux
- most of the material flows back to photosphere
- temperatures 5000 – 15000 K
- diameter < 500 km
- p, T scale heights larger than for gas at hydrostatic equilibrium

Models: energy deposition due to

- velocity / pressure pulse near base of flux tube
- pressure pulse at localized region in flux tube
- Alfvén waves at the base of flux tubes

(review by Sterling, 2000)



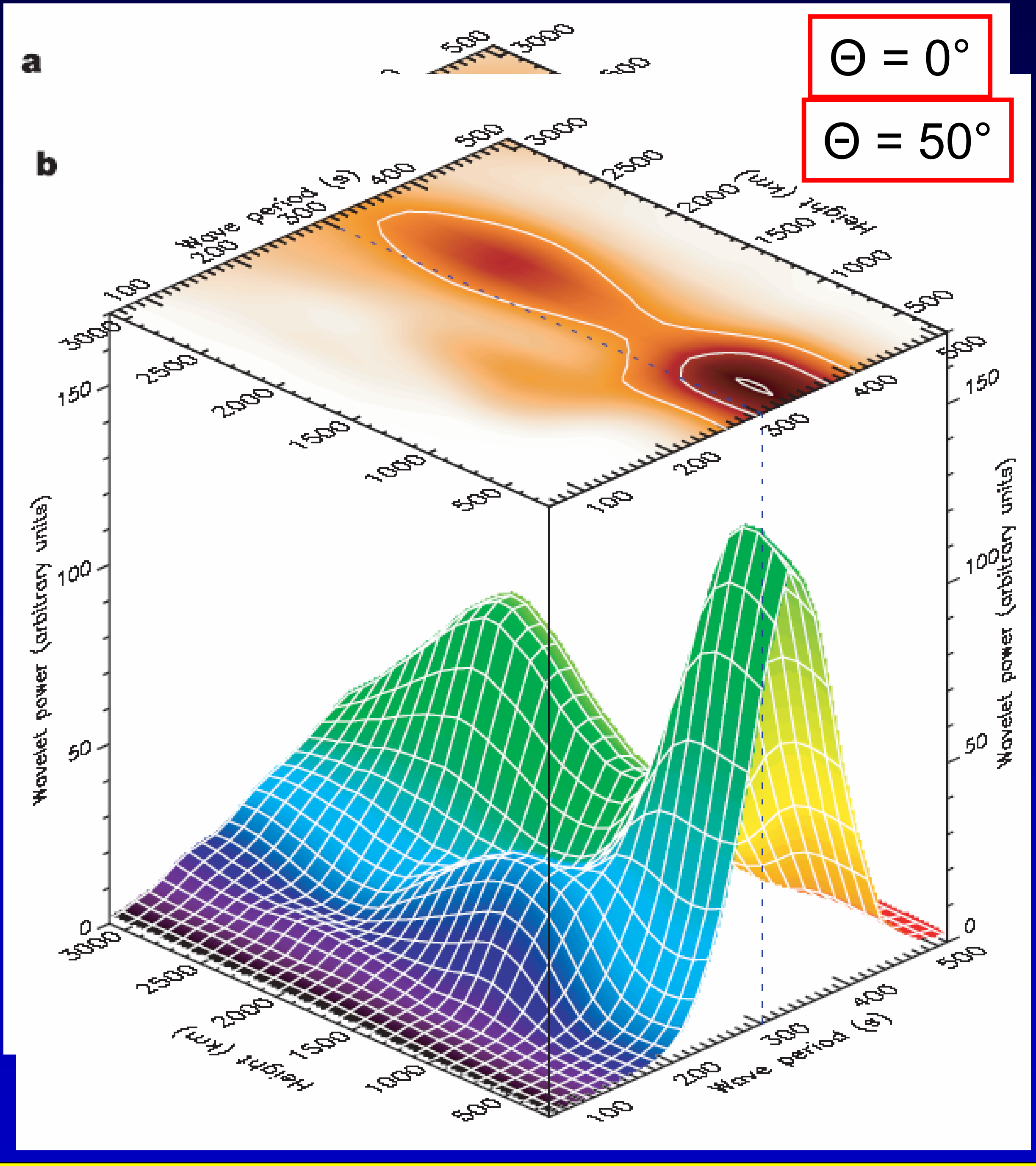
Spicules

periodic spicules (5-min oscillations)

- influence of p-modes first suggested by Suematsu (1990)
- but: acoustic waves are evanescent in chromosphere for vertical fields
- but: p-modes can leak significantly into the chromosphere if field is highly inclined

  reduced gravity (~ cos Θ) increases acoustic cut-off

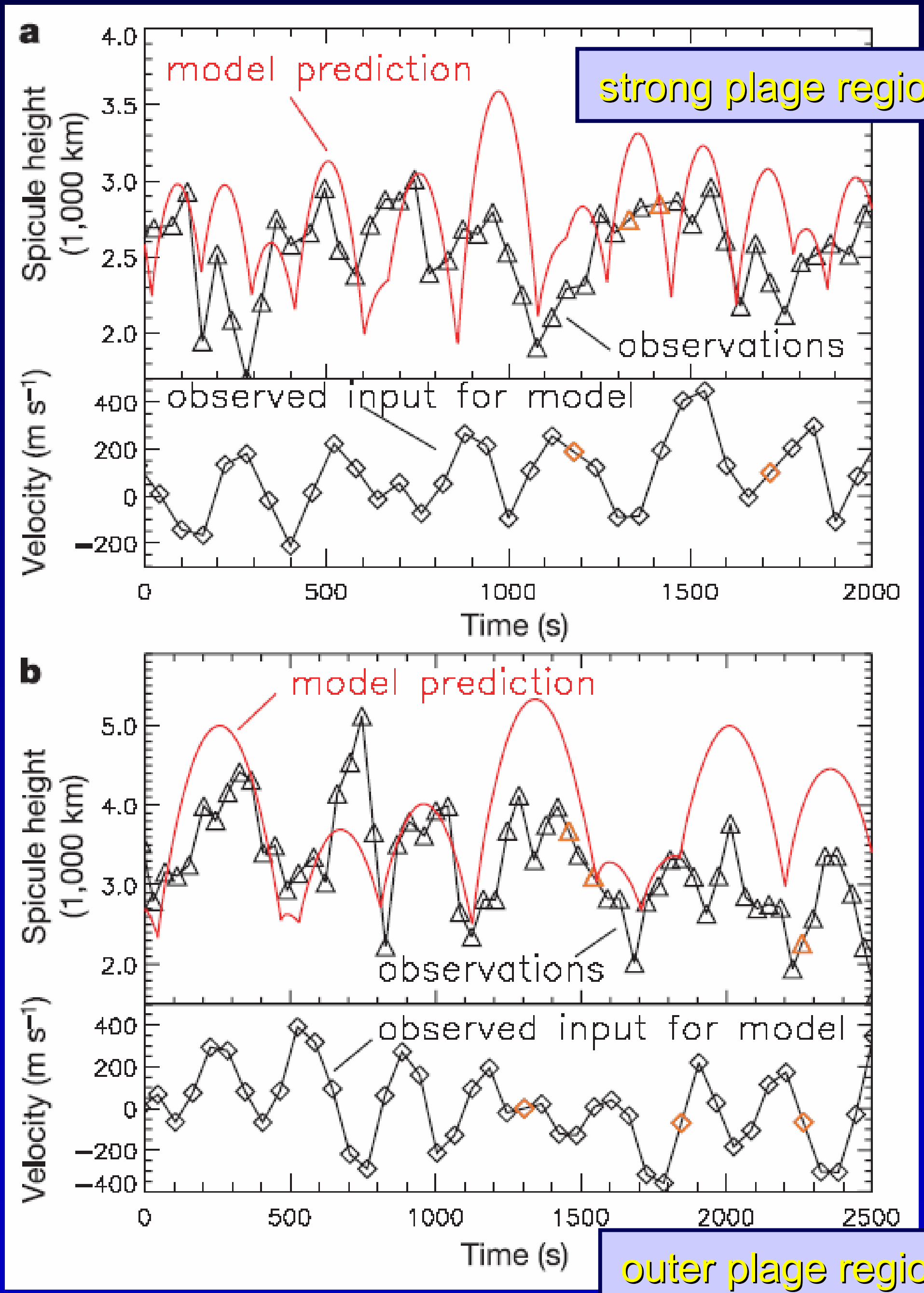
De Pontieu et al., 2004
de Wijn, CCMag Thursday



Spicules

- good match between observed photospheric velocity oscillation & spicule height & occurance

- observers: measure the magnetic field inclination!



strong plage region, θ = 0°

outer plage region, θ = 50°

De Pontieu et al., 2004

Magnetic field in spicules

- Hanle / Zeeman diagnostics of spicule in He 1083 nm multiplet
- 1st direct empirical demonstration of magnetized, spicular material
- magnetic field parameters (2000 km):
  - B = 10 G
  - Θ = 35° (to local vertical)
  - $v_{Thermal}$ = 22 km/s

➔ consistent with inclination needed for p-mode penetration

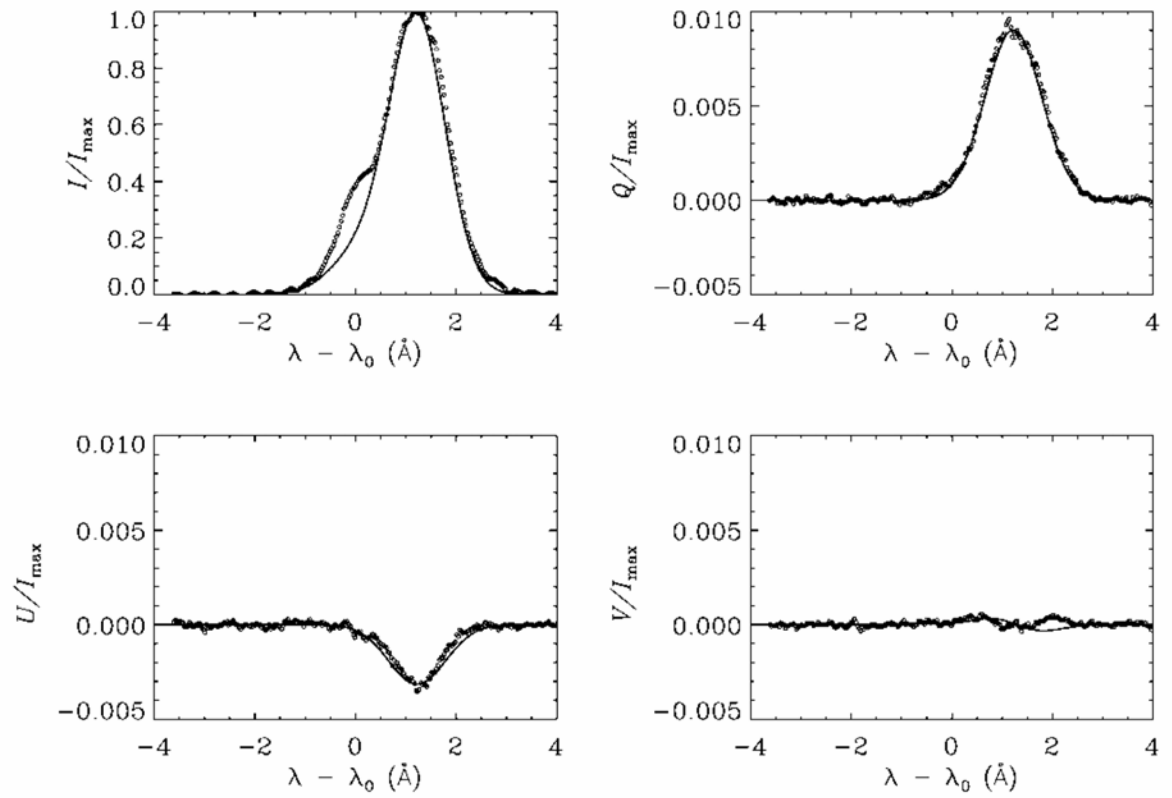


FIG. 1.—*Open circles*: Observed Stokes profiles at one of the spatial points that show nonzero Stokes U signals in the observed (quiet-Sun) chromospheric spicules. The reference direction for Stokes Q is the parallel to the solar limb. The origin of the wavelength scale corresponds to the blue component of the He I λ10830 multiplet. *Solid line*: Optically thin theoretical modeling for strength $B = 10$ G, inclination $\theta_B = 35°$, azimuth $\chi_B = 172°$, and a thermal velocity of 22 km s^{-1}. The alternative determination $B = 10$ G, $\theta'_B = 180° - \theta_B$, and $\chi'_B = -\chi_B$ gives the same theoretical Stokes profiles. See footnote 6 for the definition of the angles θ_B and χ_B.

see also Lopez Ariste (2005 + CCMag, Wed)

Trujillo Bueno et al., 2005

Hanle Effect (1)

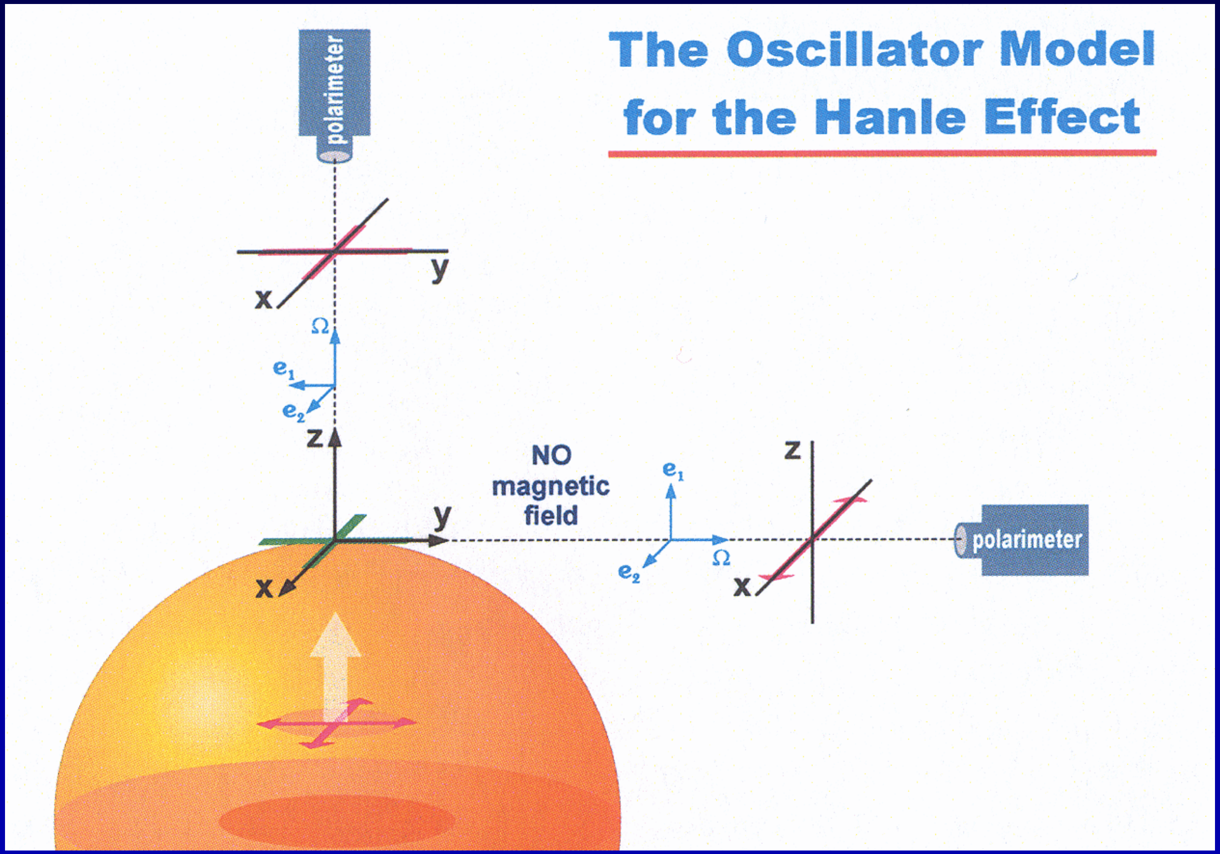
(Trujillo-Bueno, 2002,

Landi Degl'Innocenti, 1982)

non magnetic case:

anisotropic illumination of atoms (3 independent, damped oscillators in x,y,z) with unpolarized light

- no polarization in forward scattering
- complete linear polarization in 90° scattering



→ ***scattering polarization***

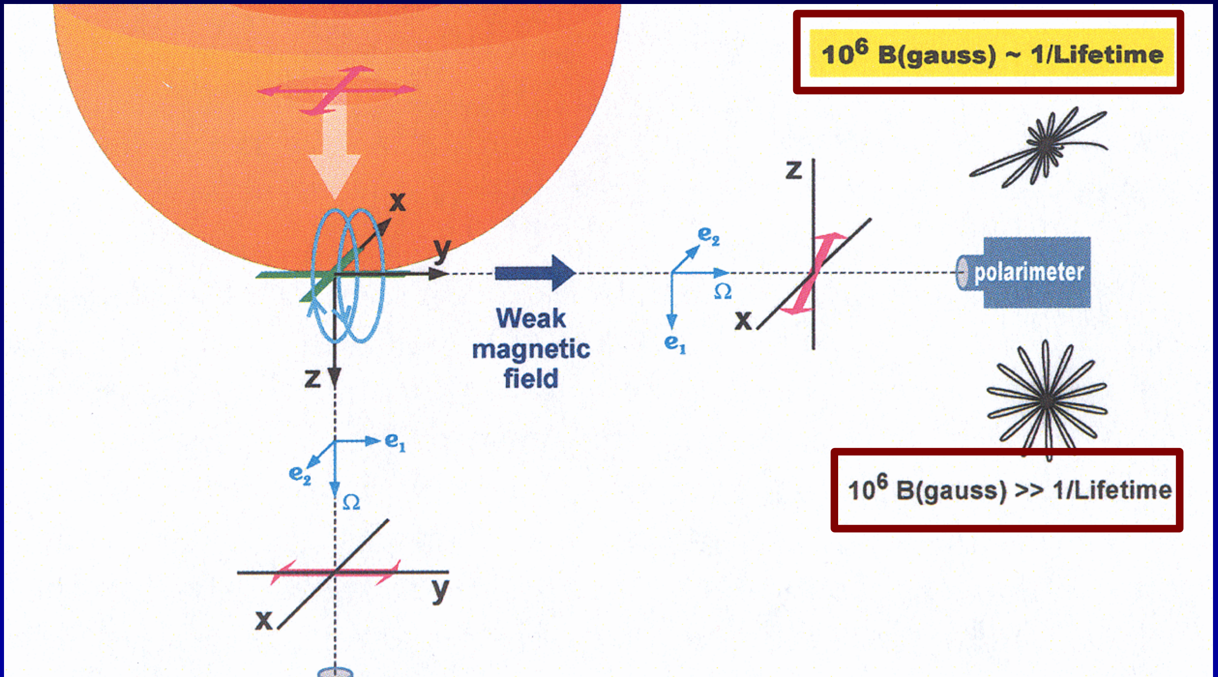
Hanle effect:
modification of (atomic) polarization caused by the action of a magnetic field

Hanle-Effect (2)

Trujillo-Bueno (2002)

magnetic case:
now the 3 oscillators are not independent:

- 1 osc. along B (ω0)
- 2 osc. around B (ω_0-ω_L ; ω_0+ω_L)
- damped oscillation precesses around B
  → rosette like pattern
  → damping time tlife = 1/γ



$$10^6 B g_J \approx 1/t_{life}$$

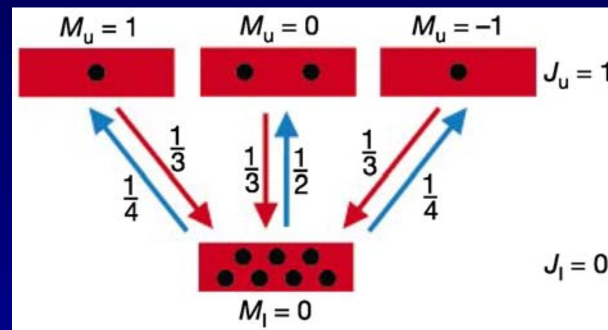
- $\omega_B >> 1/t_{life}$
  - forward scattering: max. polarization along ±y
  - 90° scattering: no polarization
- $\omega_B \approx 1/t_{life}$
  - forward scattering: weaker, but still ±y
  - 90° scattering: lin.pol. in Q, U, smaller than in non-magnetic case

He 1083: atomic polarization

'normal' case: upper level atomic polarization

Transition:

$J = 0 \rightarrow 1 \rightarrow 0$

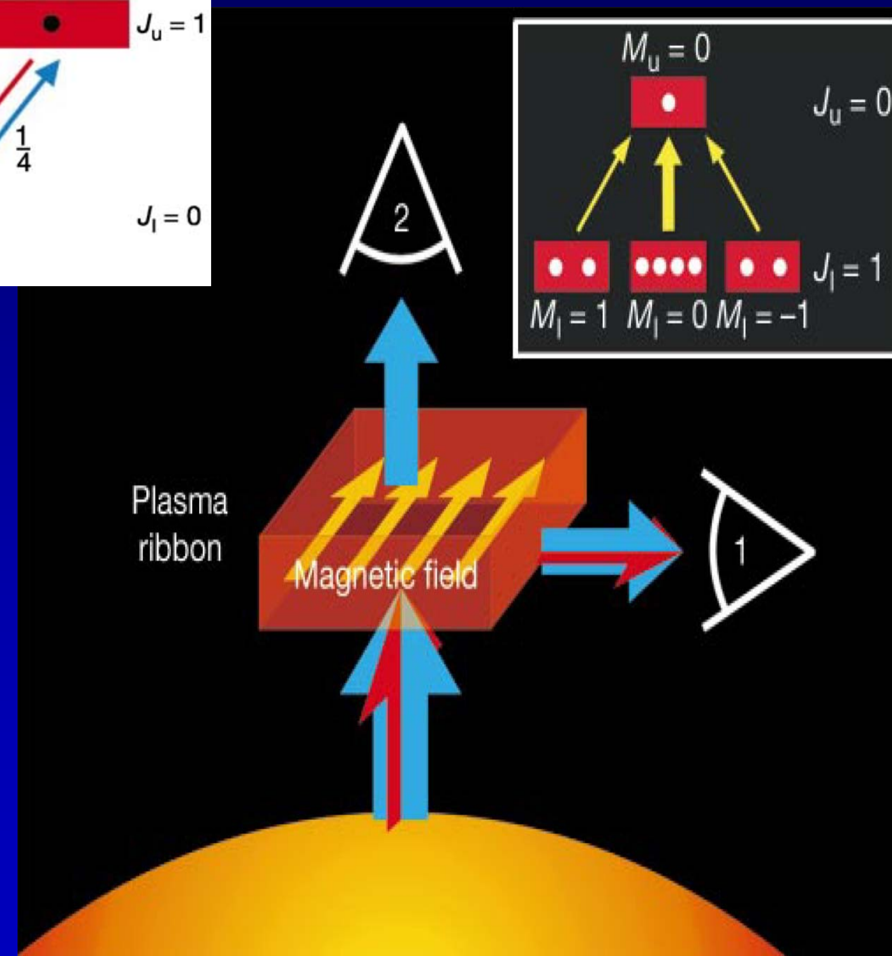


Blue Line (J_L=1, J_U=0):
degenerate lower level
- upper level cannot carry atomic polarization

→ emitted beam to (1) unpolarized
→ transmitted beam (2) has excess of linear polarization ⊥ to B (=dichroism)

Red Lines (J_L=1, J_U=2 and J_L=1, J_U=1):
degenerate upper & lower level
- both levels carry atomic polarization

→ emitted beam to (1) polarized
→ transmitted beam (2) has excess of linear polarization ⊥ to B

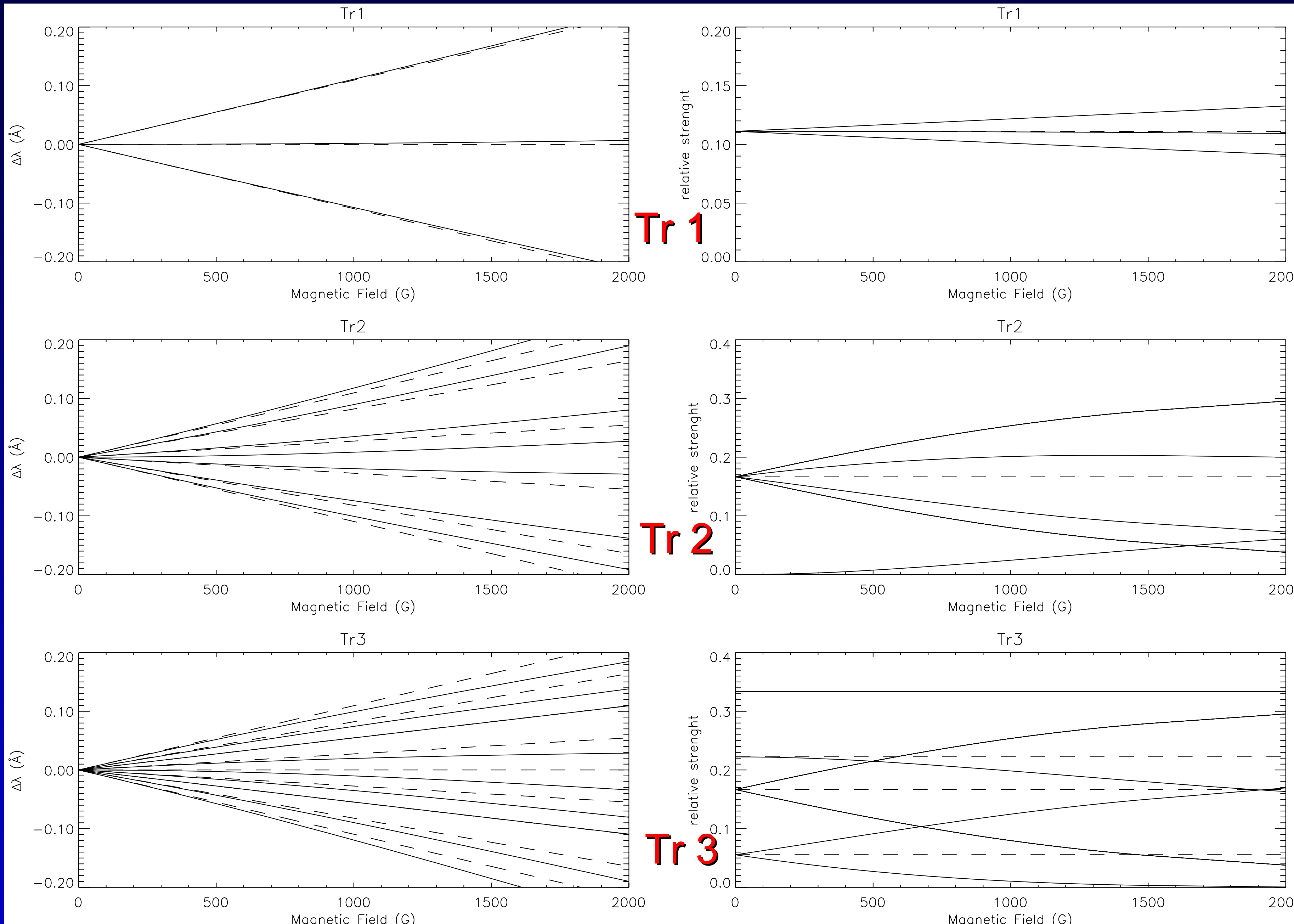


Trujillo-Bueno, 2002

Paschen-Back Effect in He 10830

Socas Navarro, 2004

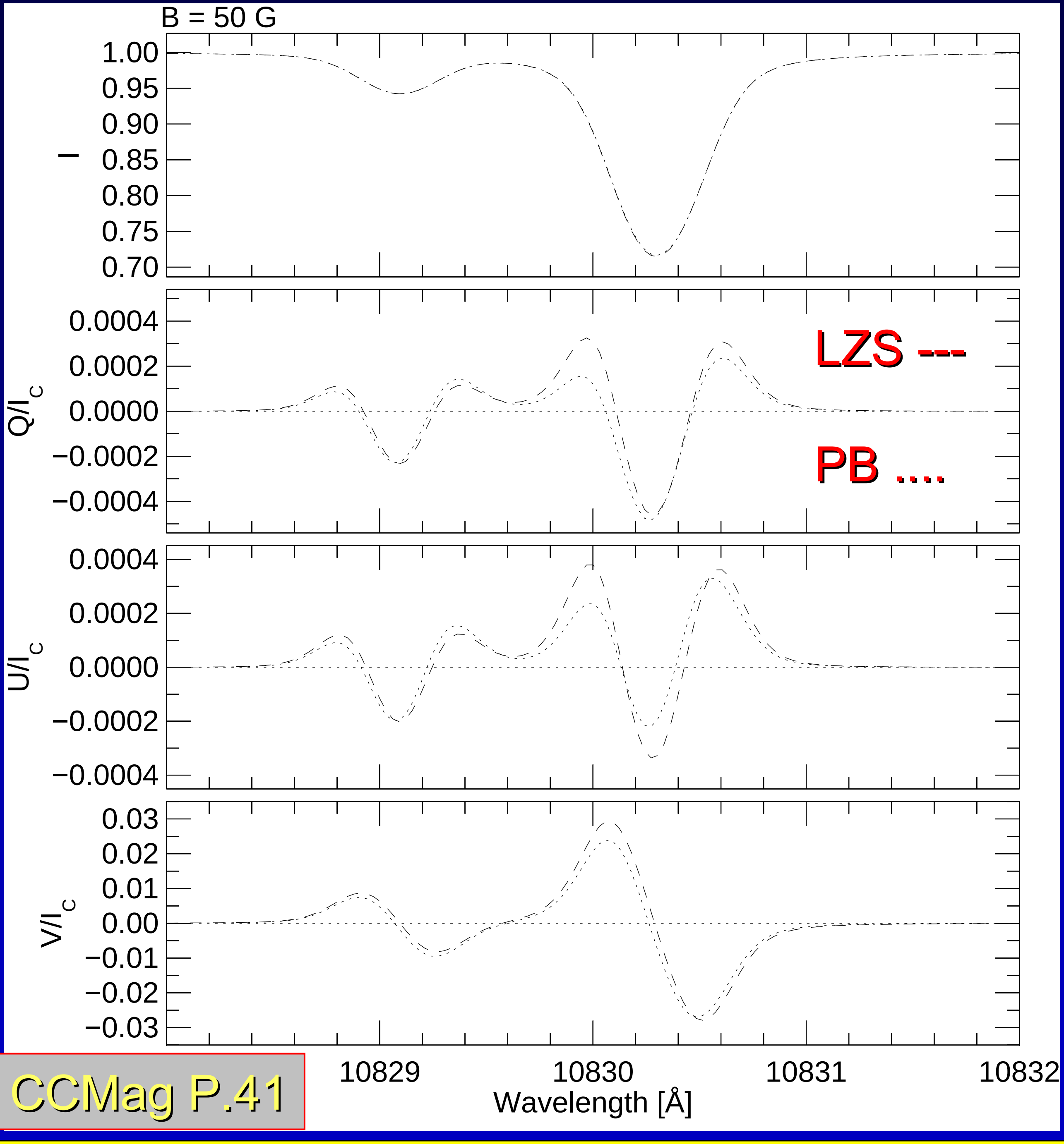
line shift [Å]



line strength

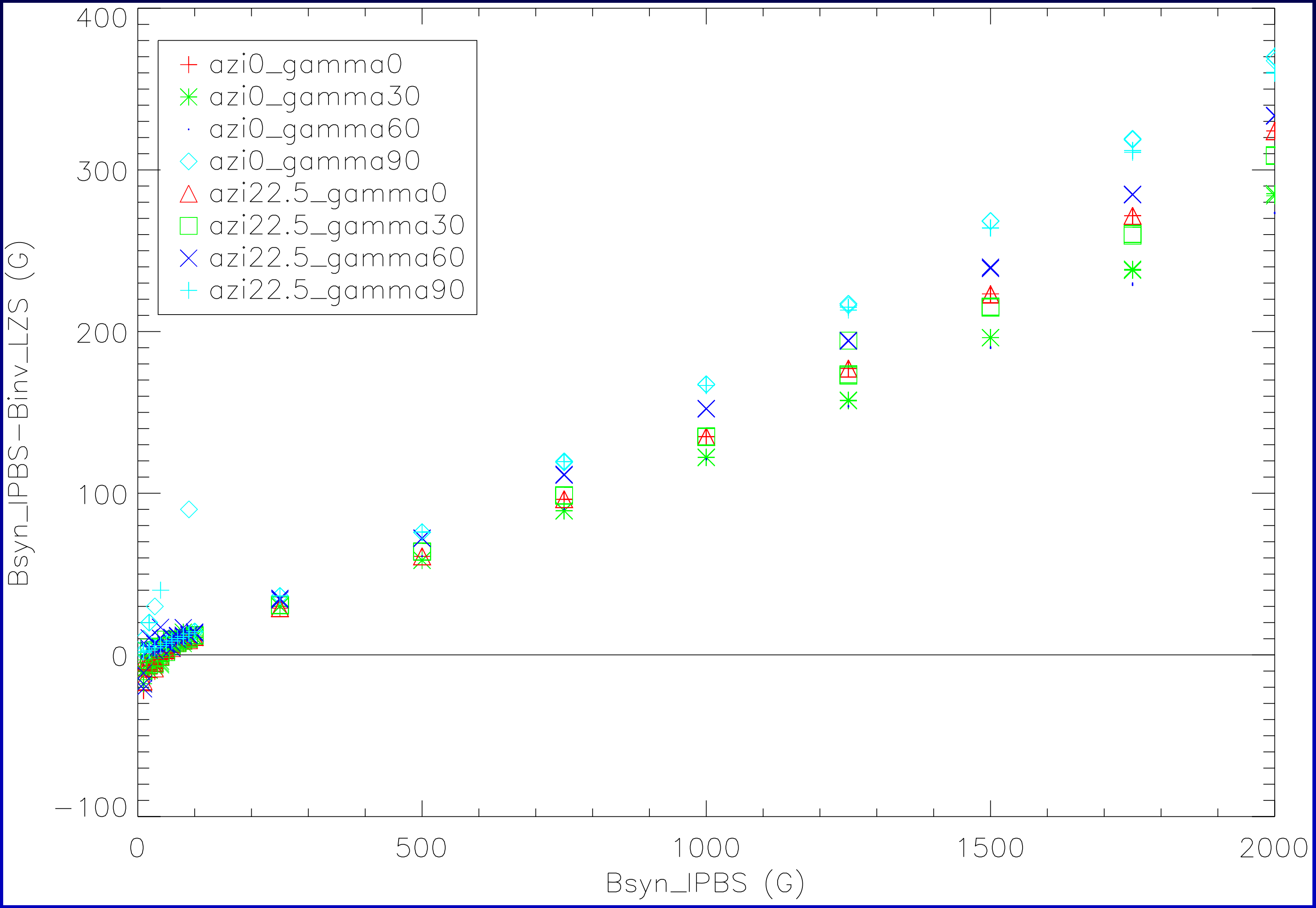
magnetic field strength [G]

Paschen-Back: Influence profiles / results



See C. Sasso, CCMag P.41

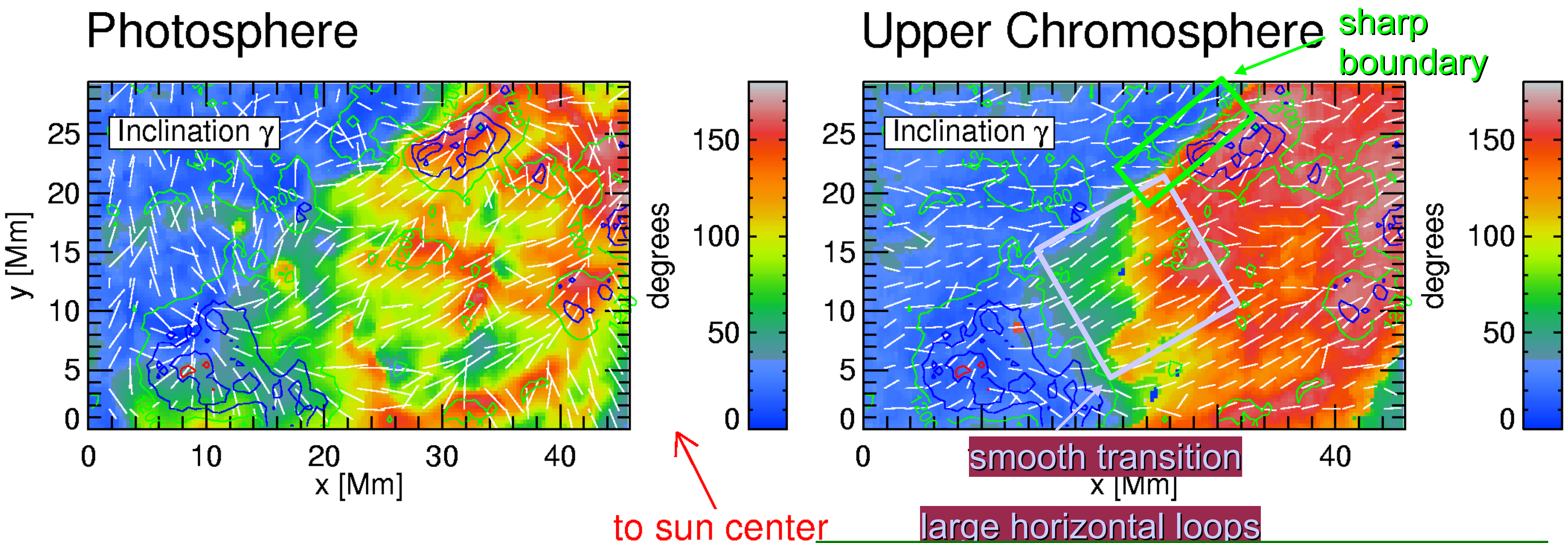
Paschen-Back: Influence profiles / results



See C. Sasso, CCMag P.41

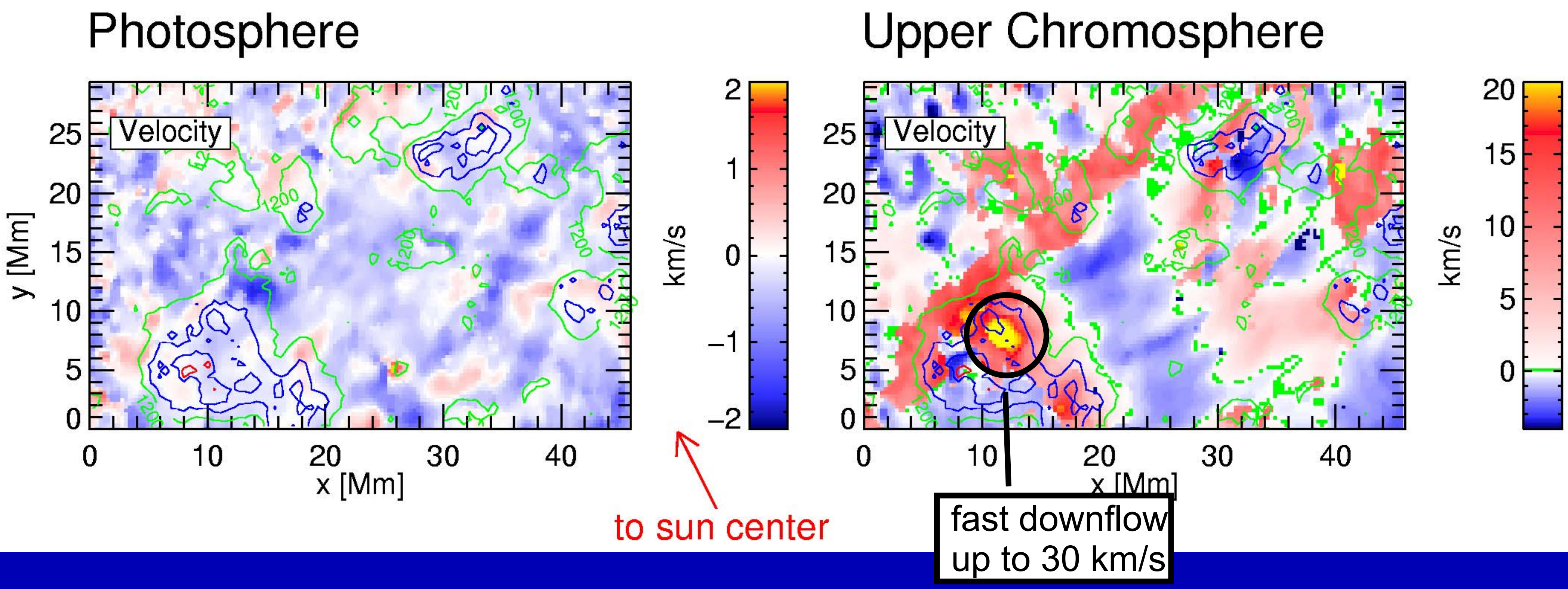
Example: Hanle / Zeeman diagnostics on emerging flux region

(Solanki, 2003)

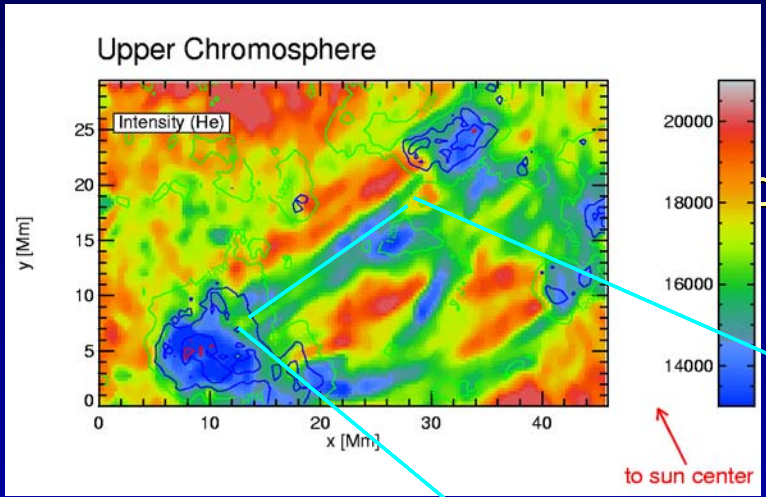


two polarities not connected in chromosphere
or
loops of extremely small horizontal extent

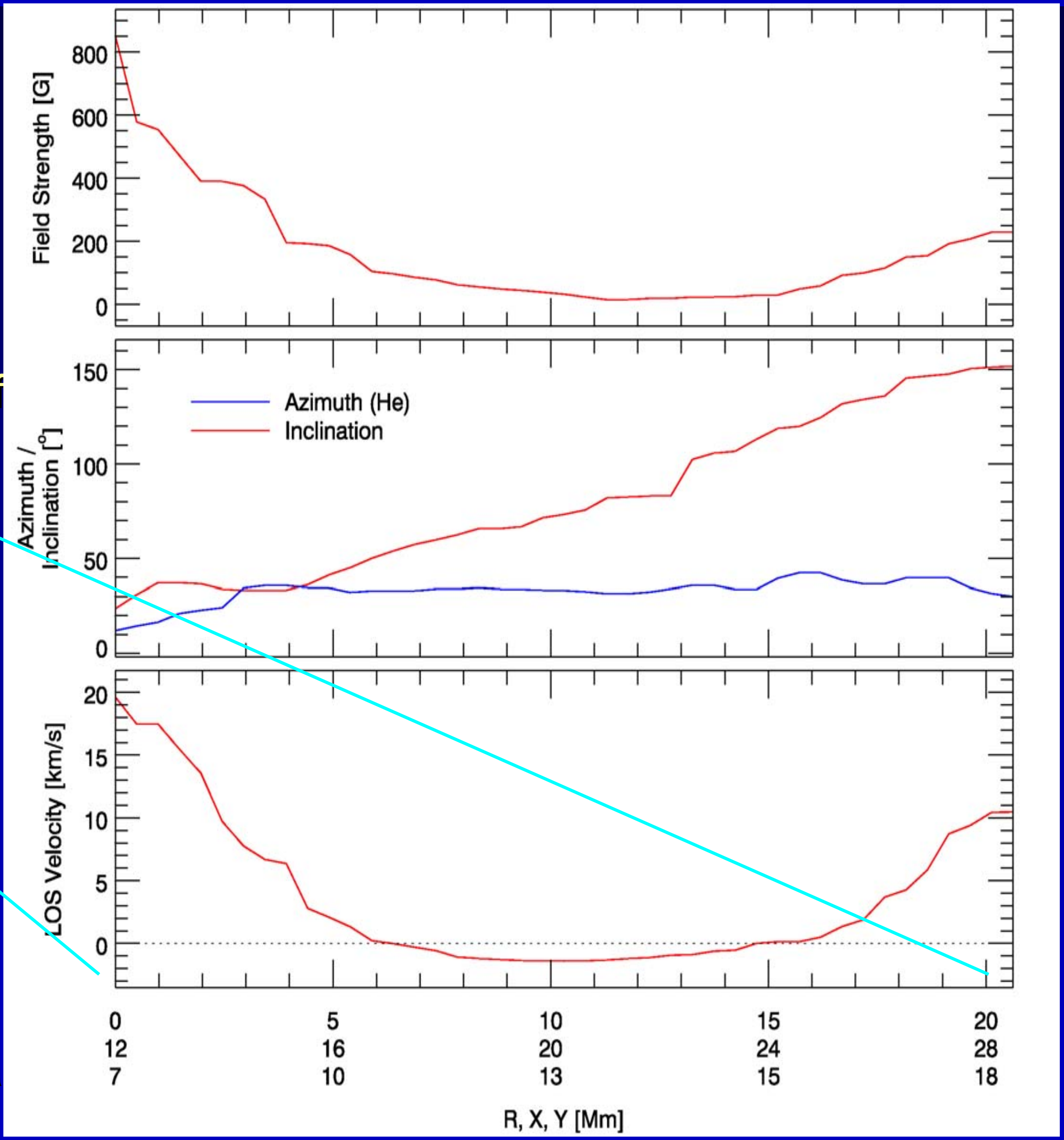
LOS-velocity



Loop tracing in chromosphere

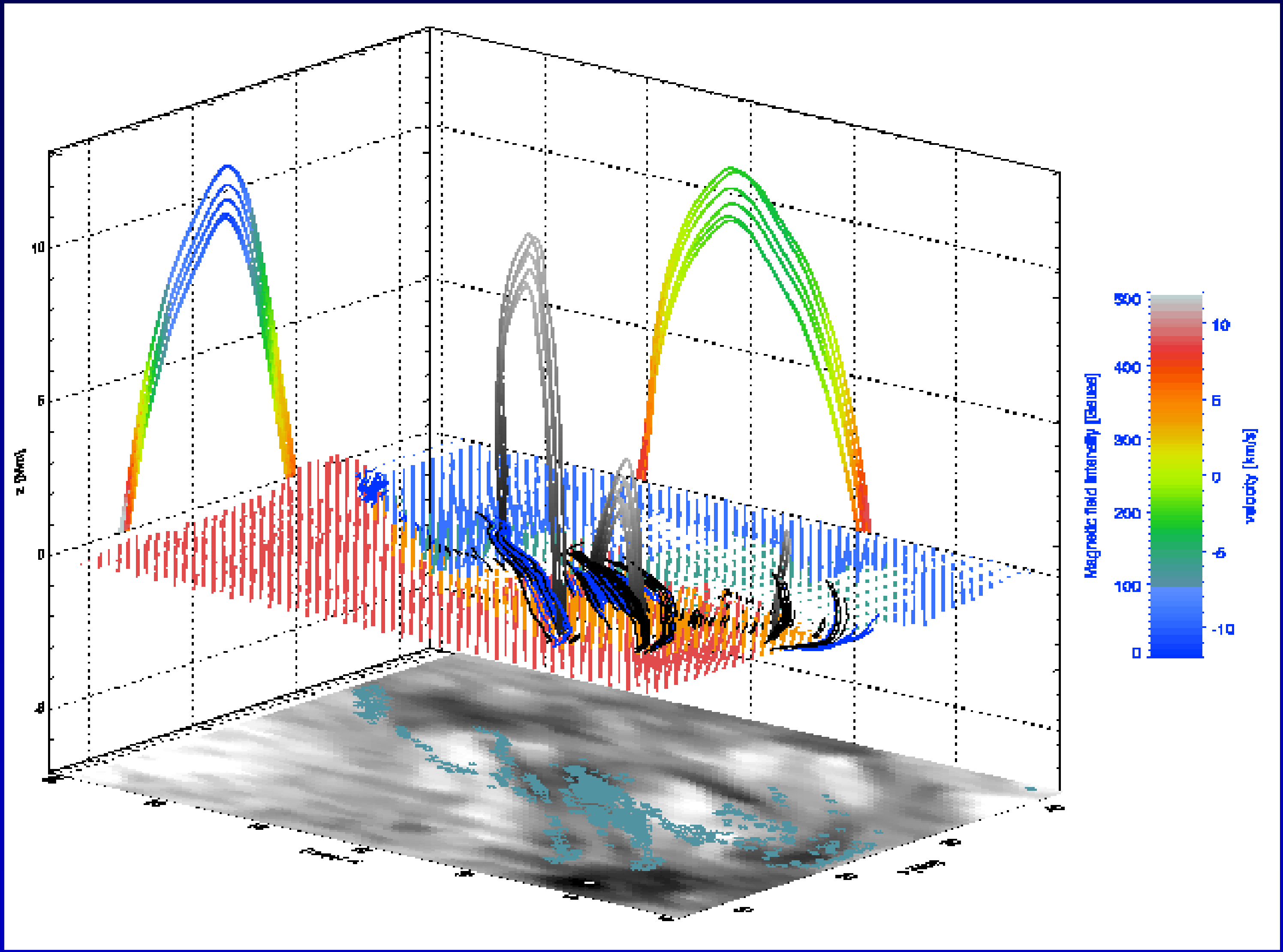


- start at random pixel
- connect to neighboring pixel using azimuth
- continue if pixel matches (direction, mag. field gradient)



parameters of a “typical” loop

3D Chromosphere



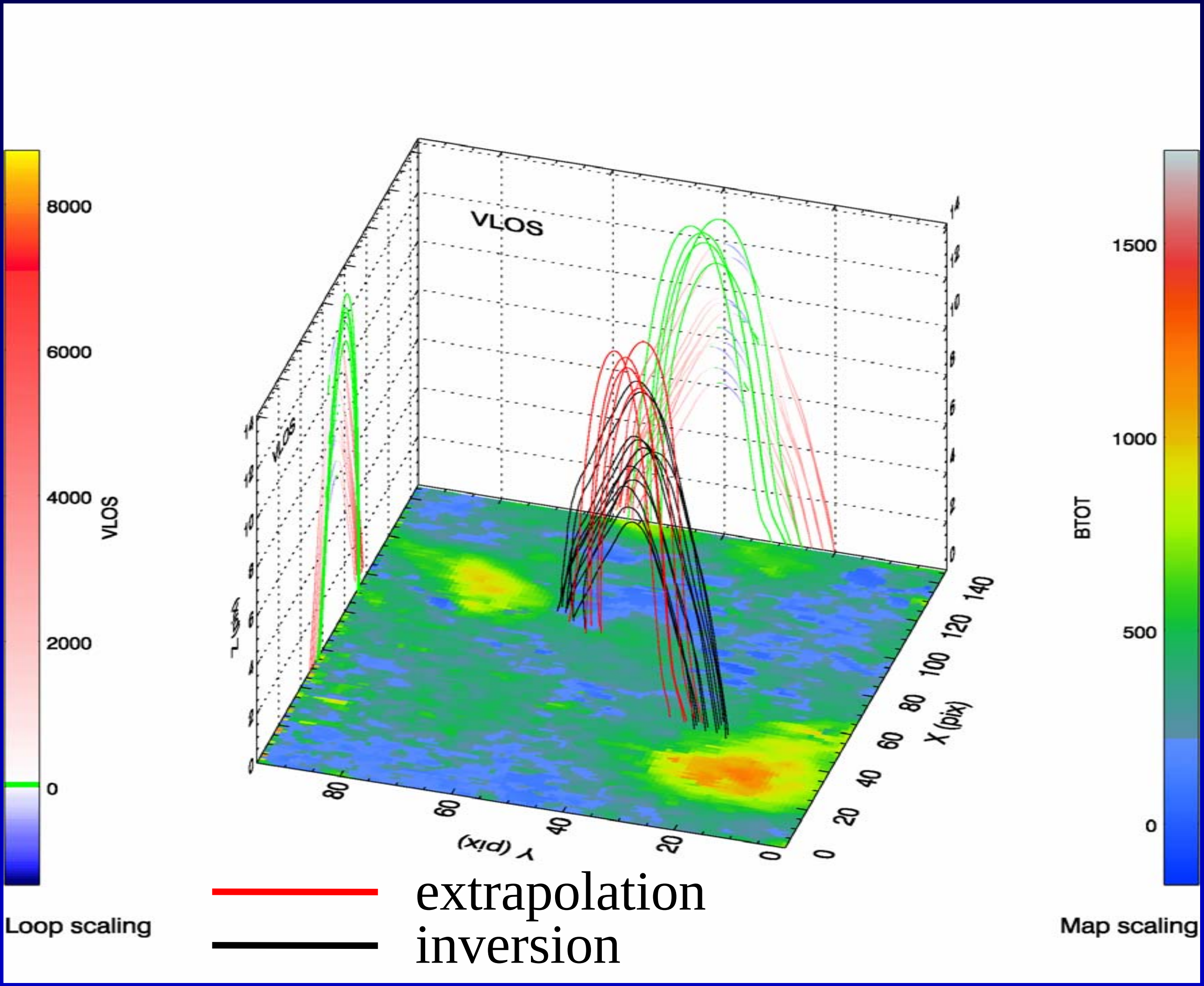
Comparison with Extrapolations

(T. Wiegelmann, 2003)

used map:
photospheric field obtained from inversion of Si-line

force free field:

$$\nabla \times \vec{B} = \alpha B$$



Wiegelmann (next talk + P.49)

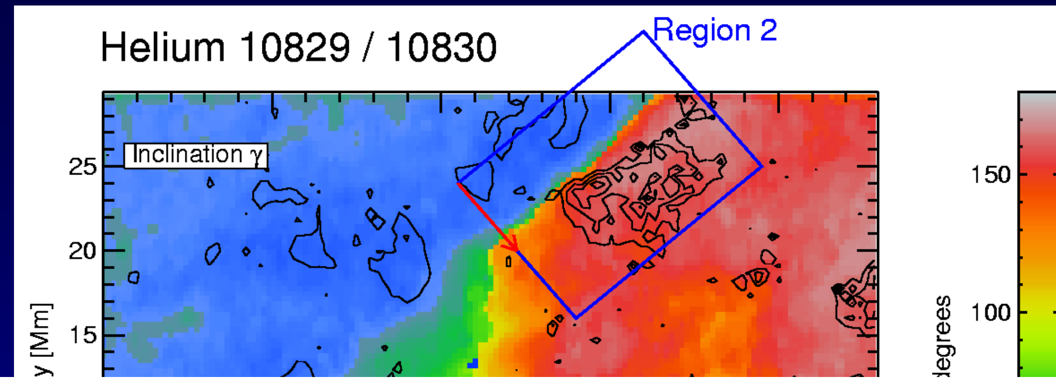
Current Sheet

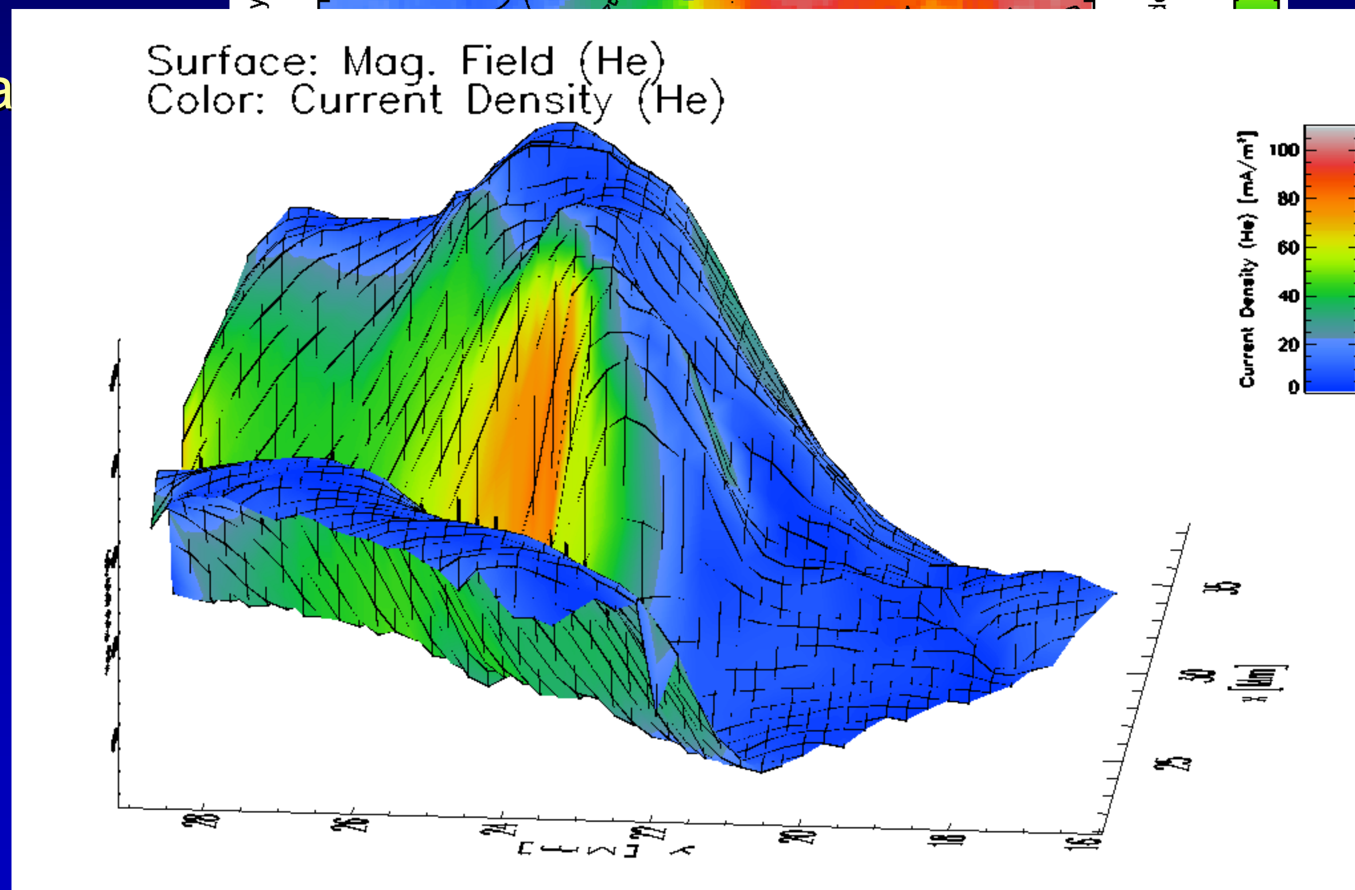
- opposite polarity fields separated by < 4 pixels
- narrow valley (< 2Mm) where B < 50 G

➔ electric current ‖ surfa

Ampère's Law:

$$j_{min} = 90 \text{ mA/m}^2$$





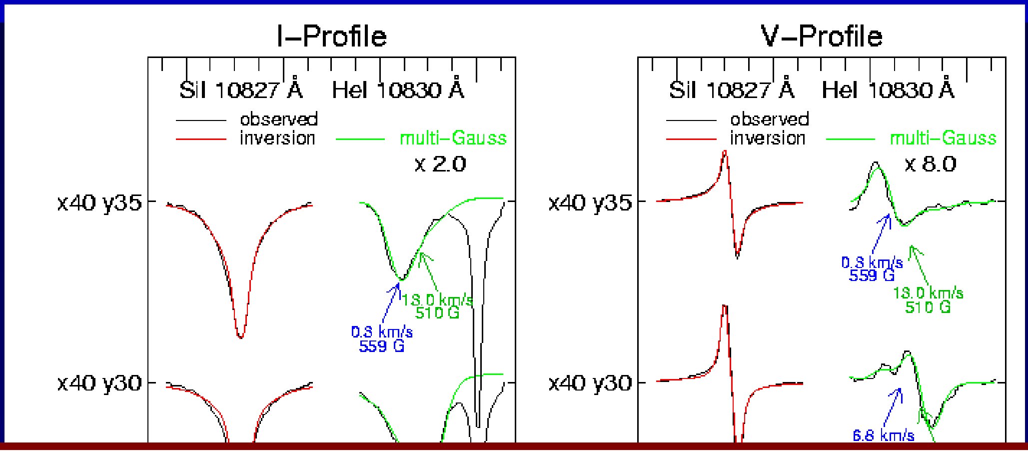
current sheet can continuously convert magnetic flux into heat and plasma kinetic energy

several C-Class events reported for NOAA 9451 on May 13 2001

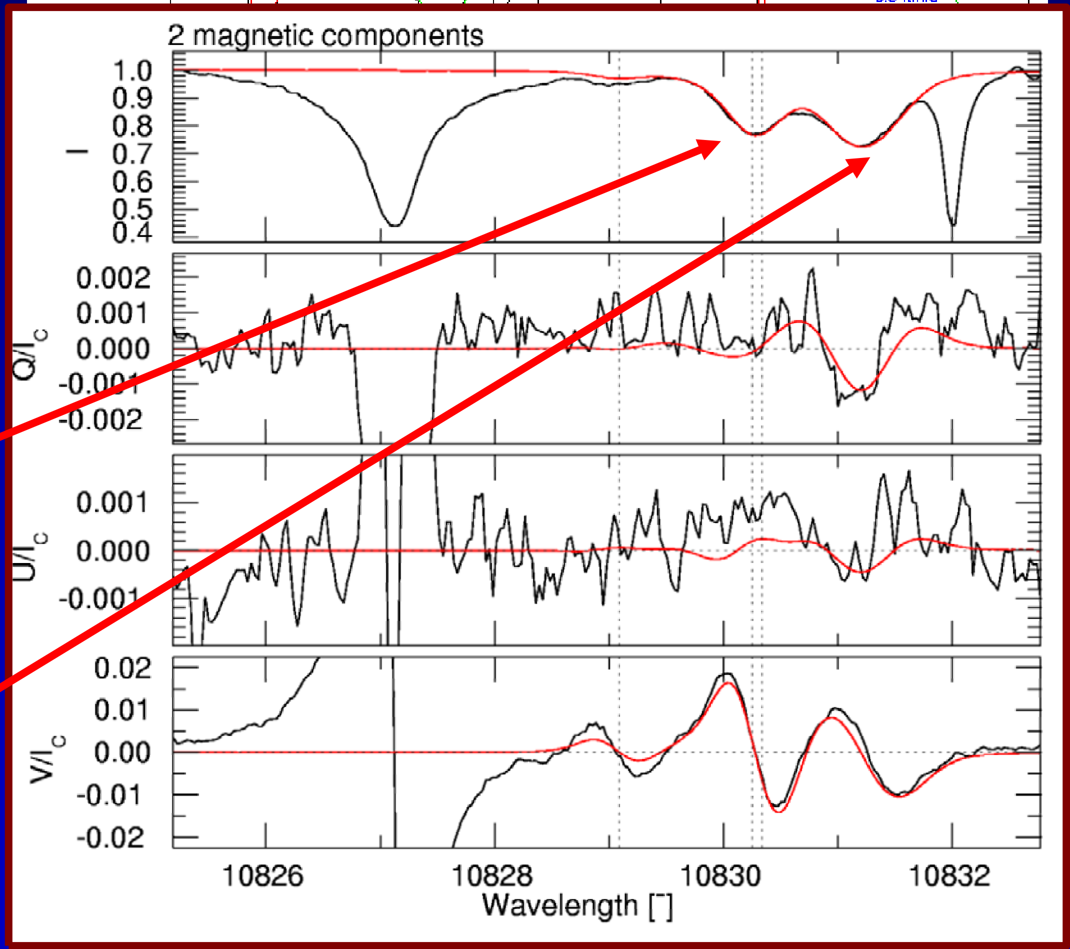
Solanki, Nature 2003

2-component Downflows

very common feature: downflows of up to 60 km/s
(see poster Aznar Cuadrado, P.02)



He 1083 inversion + genetic algorithm (PIKAIA):
allows the retrieval of magnetic field vector for slow and fast component

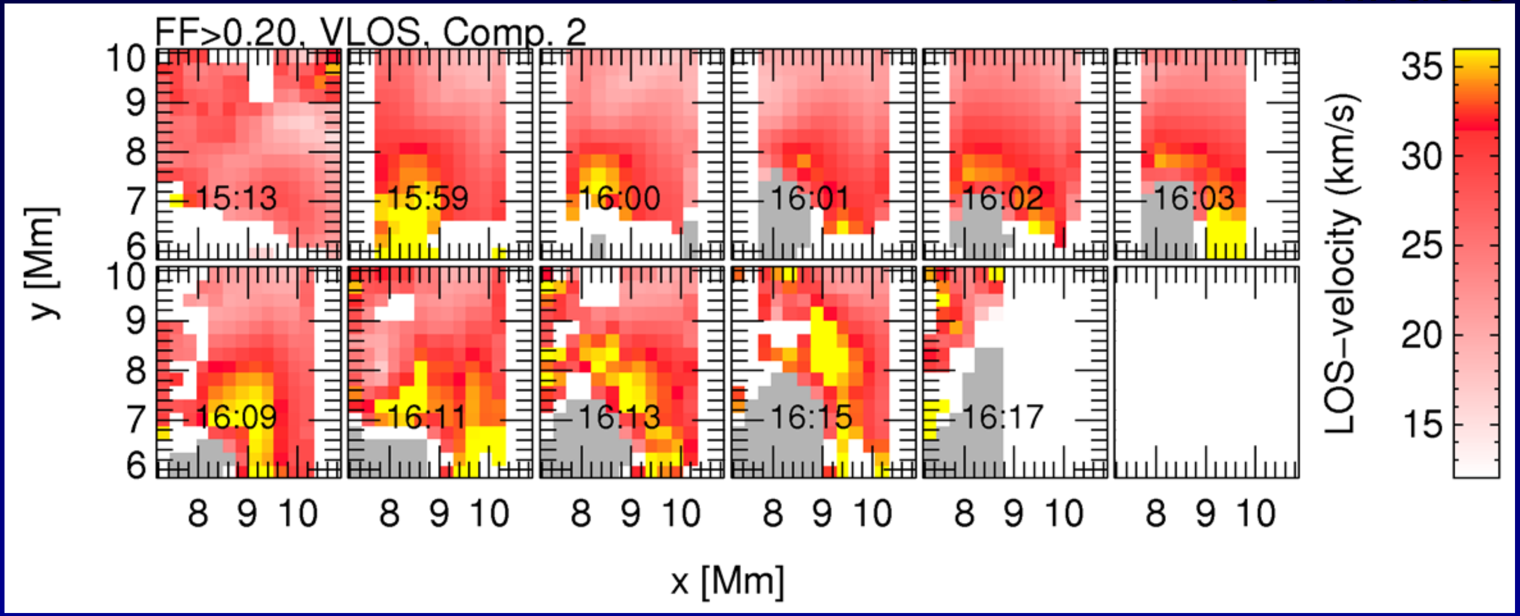


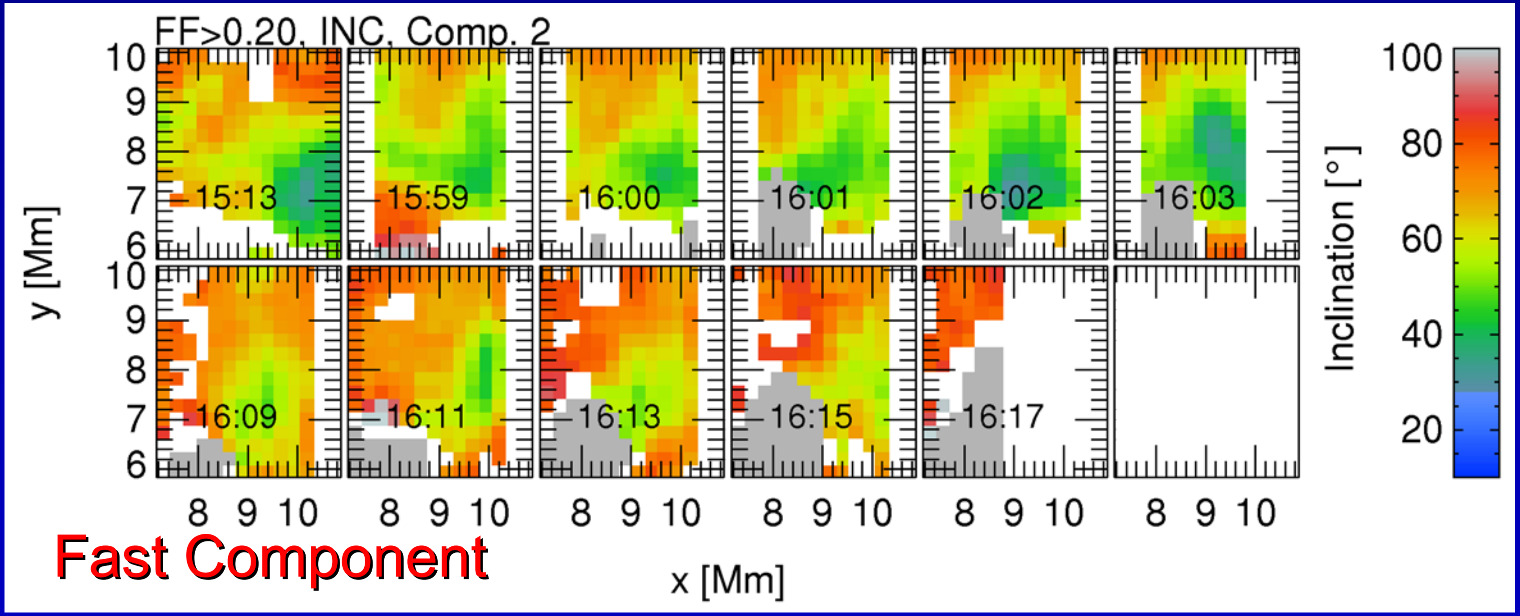
Slow Component:			
VLOS	B	Incl.	Azim.
-620 m/s	520 G	33°	-14°

Fast Component:			
VLOS	B	Incl.	Azim.
24900 m/s	730 G	67°	10°

Downflows: Temporal Evolution

~70 minutes





➔ uncombed chromosphere!!

Outlook

- Chromosphere contains huge variety of magnetic structures
- key for better understanding: vector magnetic field
- promising methods:
  - extrapolations
  - Hanle / Zeeman polarimetry (multi-wavelength, high S/N):
    sensitive to very low magnetic fields
    full magnetic vector
  - mm / sub-mm (ALMA):
    allows the analysis of hot & cool gas simultaneously
  - atmospheric seismology