The chromosphere 2008

Philip Judge, *HAO, NCAR*

PLATE X

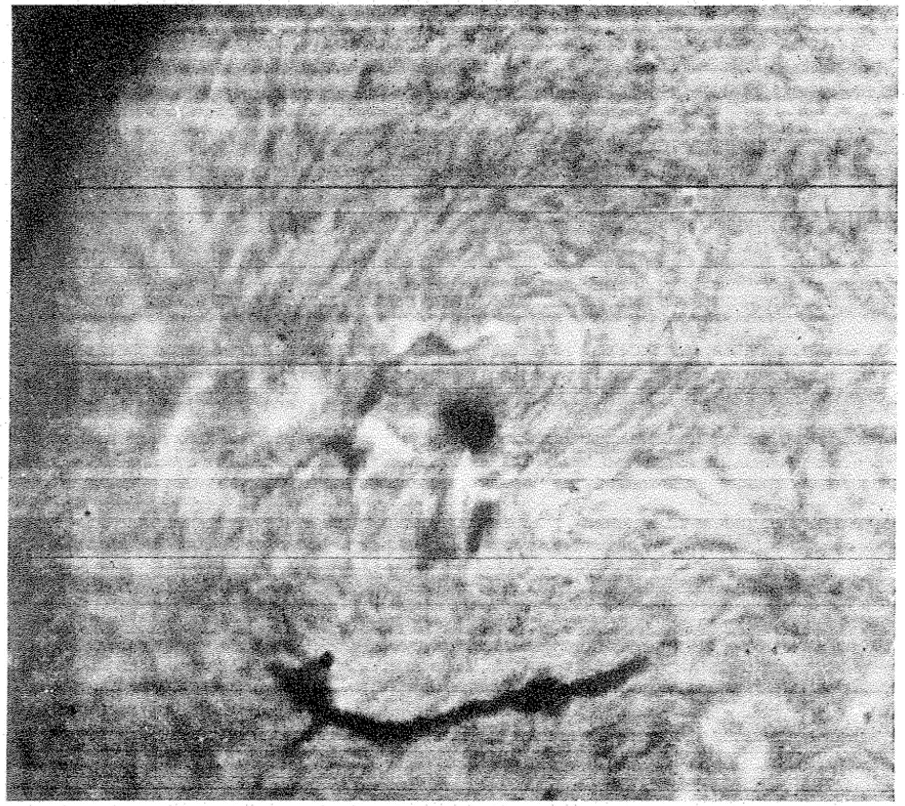
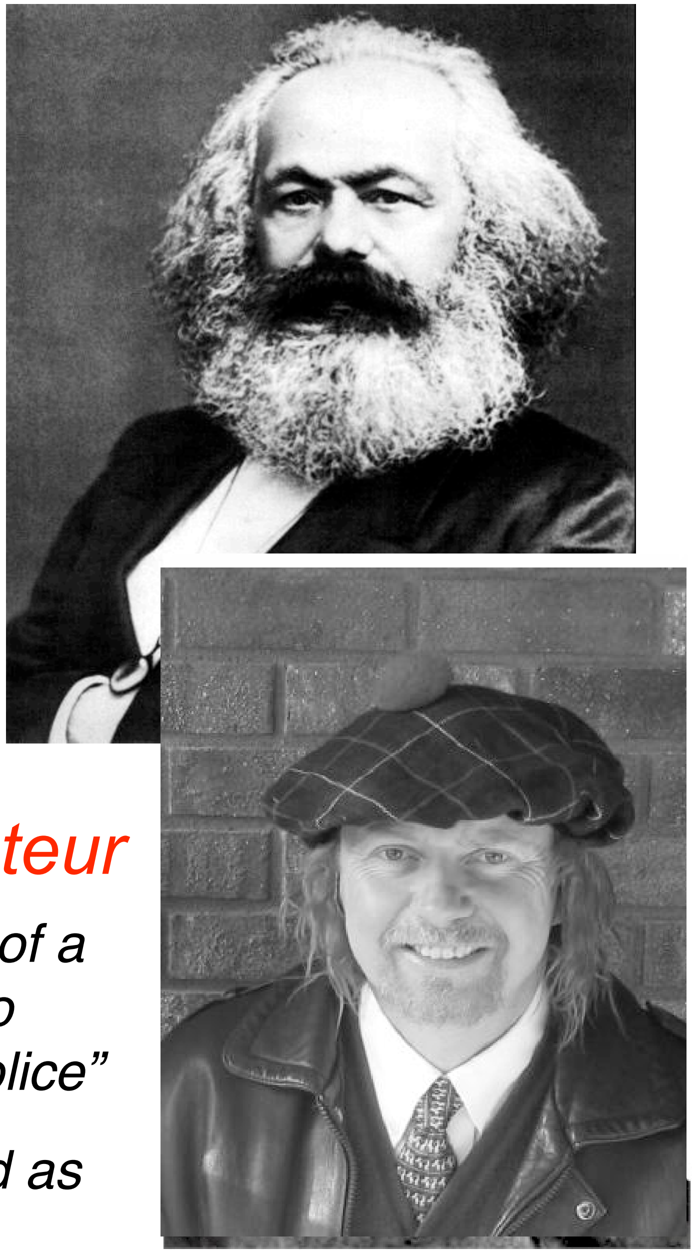


FIG. 1.—SUN-SPOT AND HYDROGEN ($H\alpha$) FLOCCULI
1908, May 29, 4^h 26^m P. M. Scale: Sun's Diameter = 0.3 Meter

1908



Agent Provocateur

"By 1908, Azef was playing a double role of a revolutionary assassin and police spy who received 1000 rubles a month from the police"

"later ...Azef lived with a singer and worked as a corset salesman and stock speculator"

NCAR

December 2008

ESSL

the chromosphere
primary observational characteristics

- eclipse Hα emission above the photosphere 1800s
- Ca II network emission, plages 1900s
  - correlated with photospheric magnetic fields 1950s
- UV radiation 1950s
- fine structure (Hα network, fibrils, spicules) Secchi 1870s,..
- dynamics (spicules, oscillations,...) 1960s

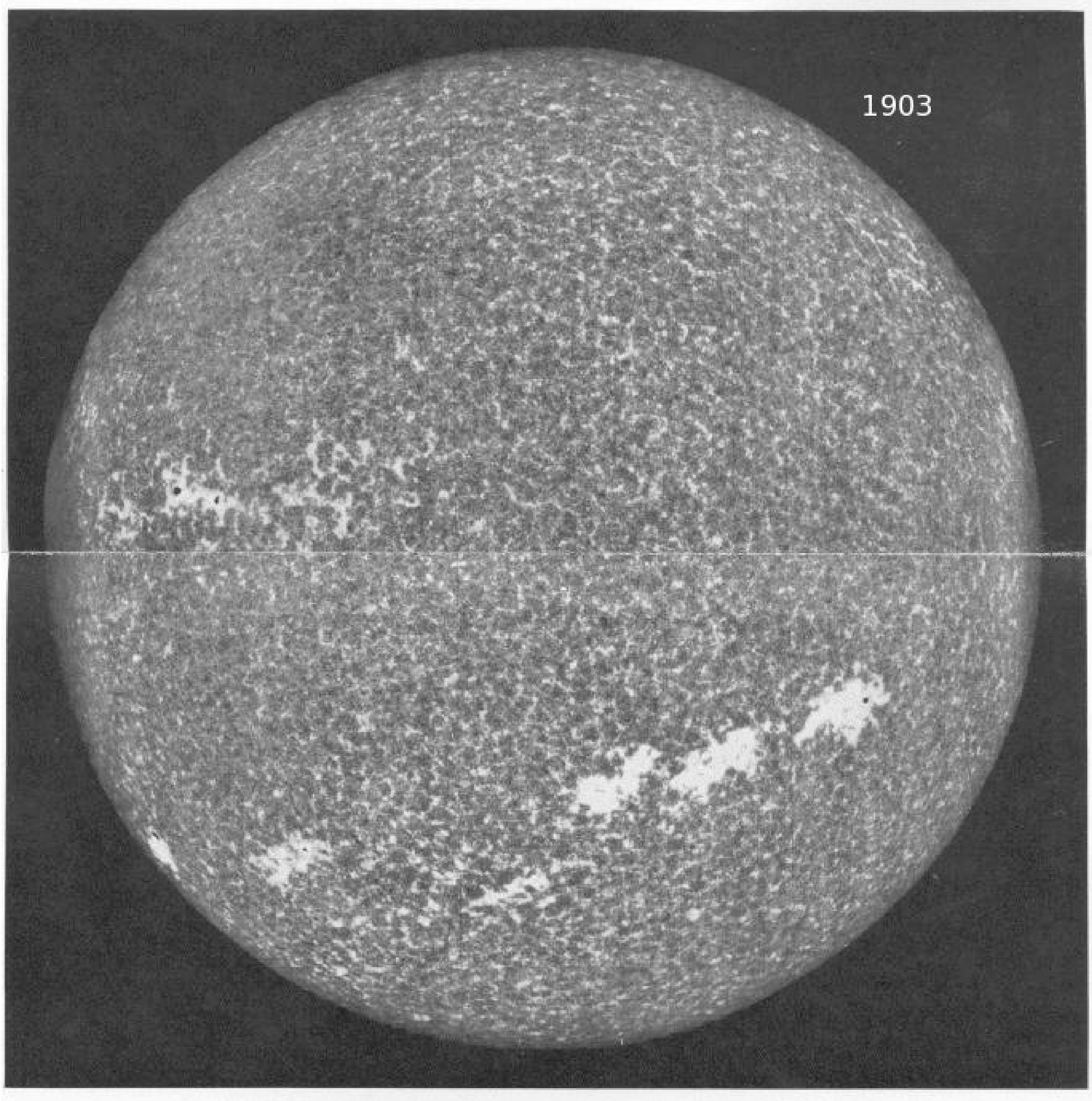
Why is the Sun obliged to do this?

the Sun

- no magnetic field:
  - convection, turbulence, atmospheric waves
  - global (p-) modes
  - weak, stochastic chromosphere
  - no corona (almost)
- with magnetic field:
  - ?

what is supergranulation?

➞observationally driven problem



The Sun, Showing the Calcium Flocculi (H_2 Level). 1903, August 12, $8^h\ 52^m$. C. S. T.

(Scale of Original Negative.)

(See p. 41.)

$\lambda/\Delta\lambda \geq 40{,}000$

chromospheres

- present in all stars with surface convection
  1960s

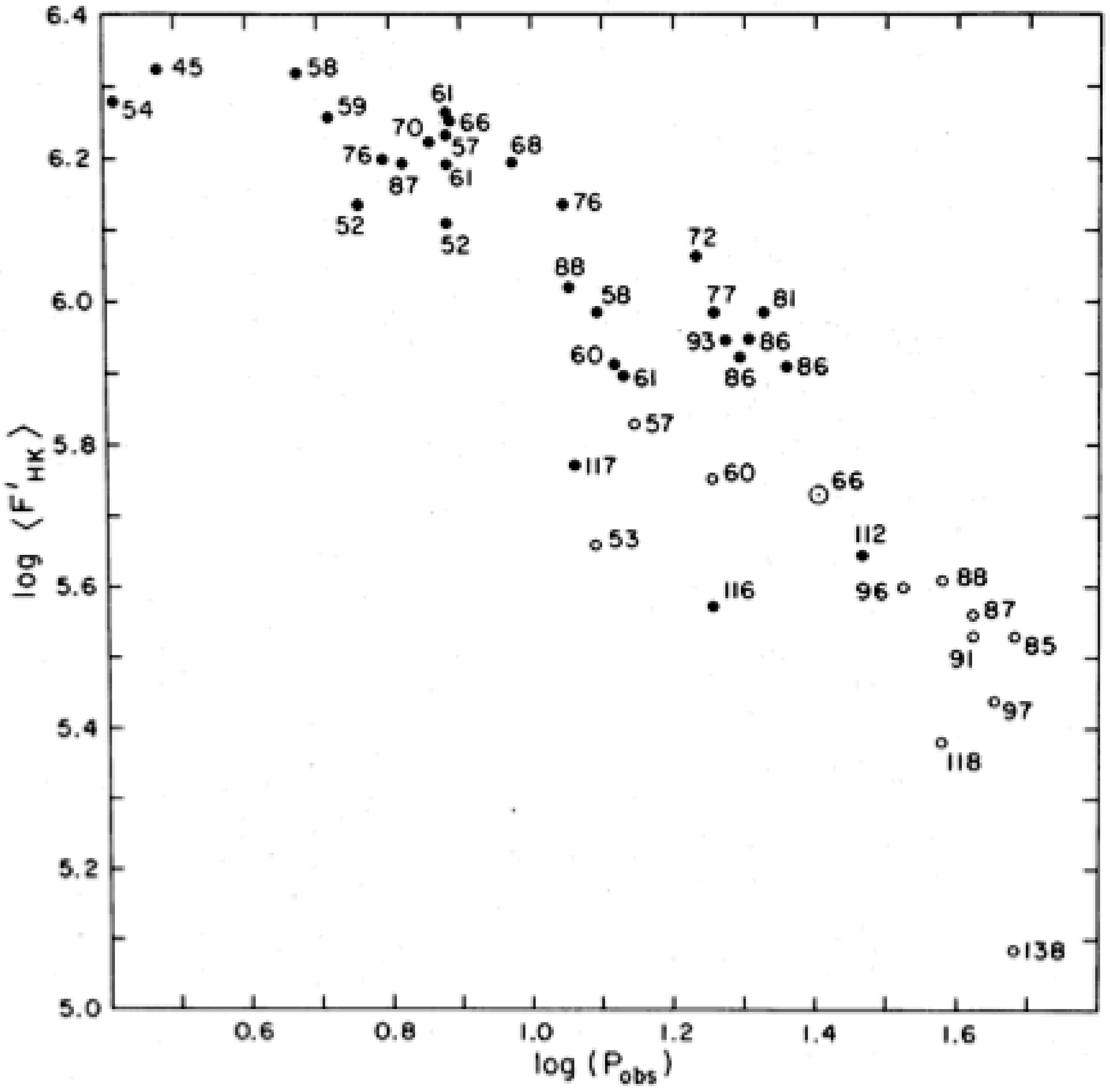


FIG. 4.—The mean chromospheric flux $\langle F'_{HK}\rangle = \sigma T_{eff}^{4}\langle R'_{HK}\rangle$ vs. rotation period P_{obs}. Labels give $100(B-V)$

the Sun is not alone

the chromosphere:
derived physical characteristics

- stratified: spans 9 pressure scale heights
- requires 30-100x as much power as the corona
- usually contains plasma $\beta=1$ surface
- Progress
  - internetwork dynamics
  - type I spicules identified, explained
- Open questions
  - magnetic heating, force balance, spicule (type II)
  - connections chrom.-TR-corona

SKYLAB data - VAL thermal models, average stratification

THE SOLAR H AND K LINES 187

$\lambda/\Delta\lambda \approx 10{,}000$

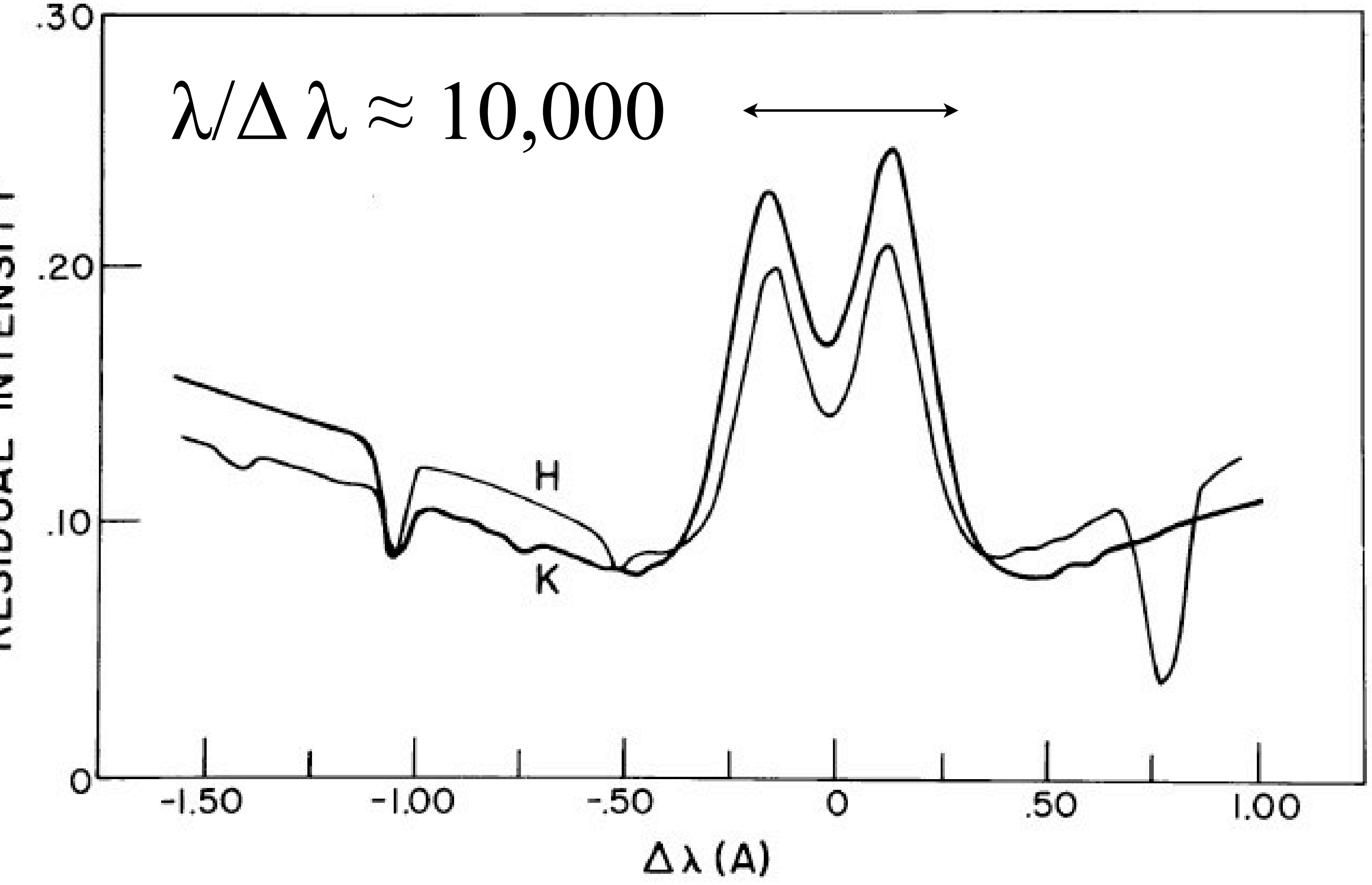
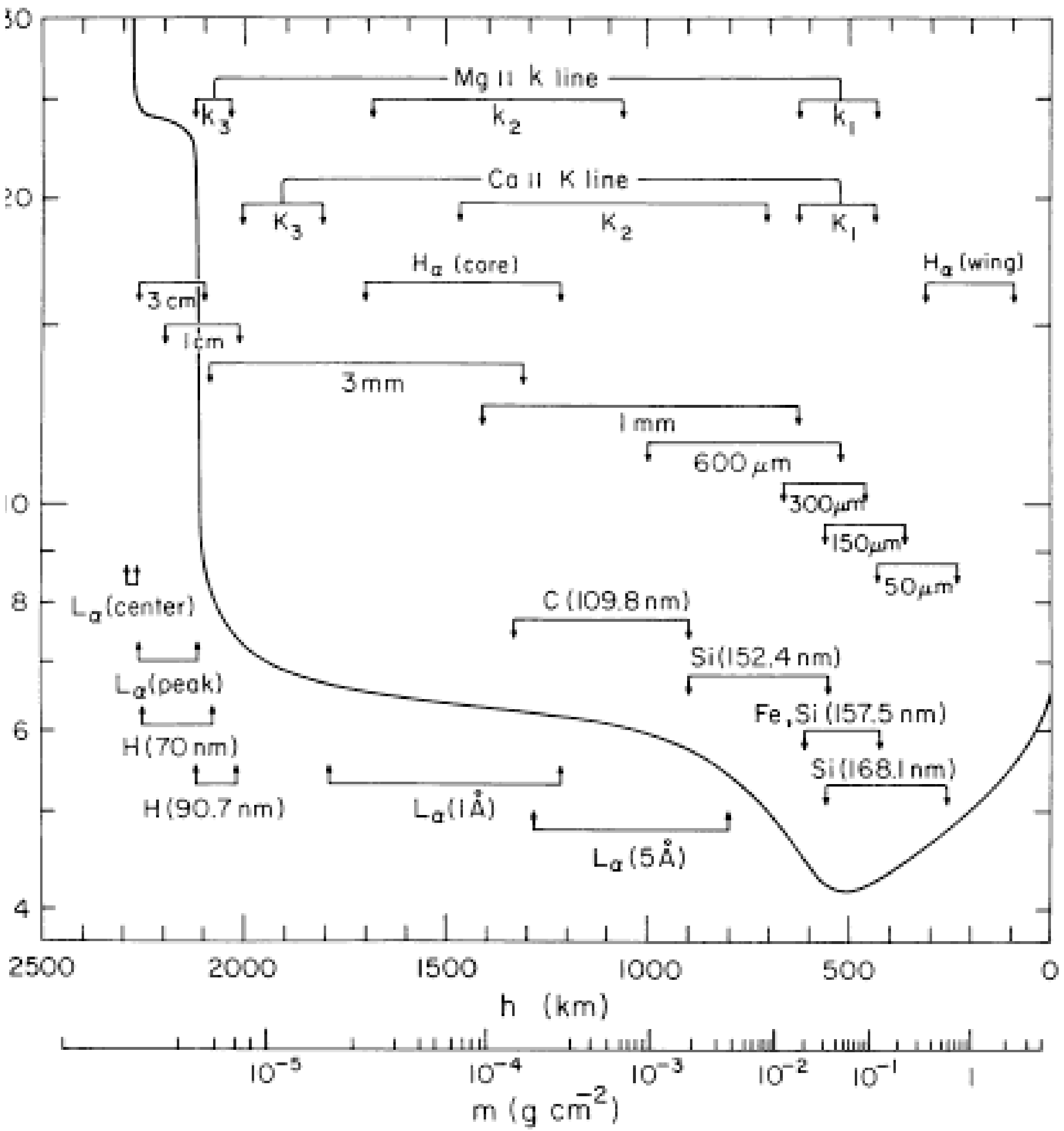


FIG. 5 — Low-spatial resolution residual intensities of the H and K lines for plage region at $\mu = 0.78$ as obtained by Linsky (1970). The K line is ystematically brighter than the H line throughout the core and $r(K_3)/r(H_3)$ = 1.20 ± 0.03.

QUIET SUN EUV BRIGHTNESS COMPONENTS

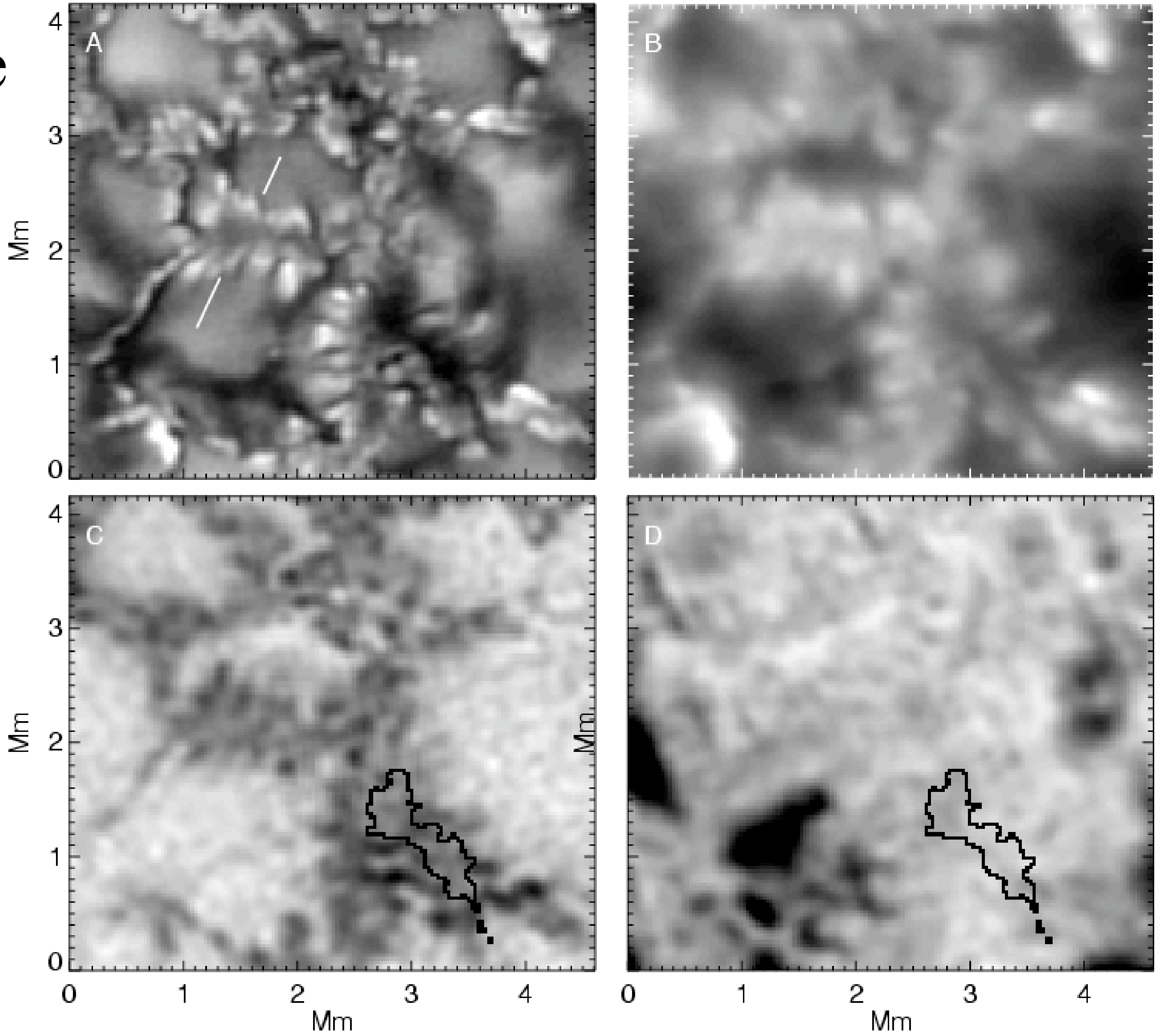


Heroic reference work of vital importance, 1981

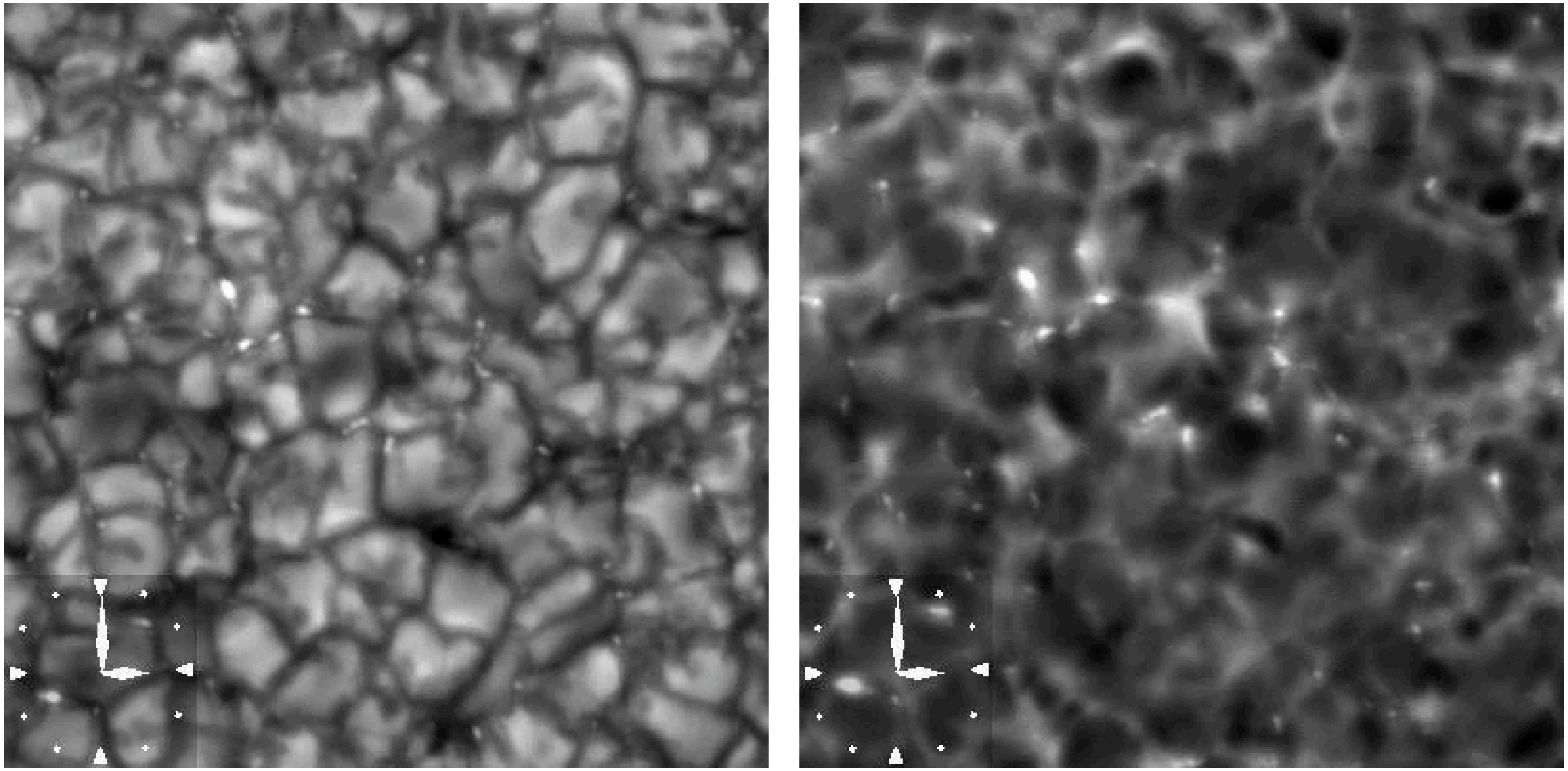
some observations

SST data: Berger et al 2004 A&A

- photosphere plage
  - A. G-band
  - B. Ca II H 3Å, $\lambda/\Delta\lambda \approx 1{,}300$
  - C. magnetogram
  - D. Ni I doppler
- fluted sheets, tubes rare
- *more time for wave/mag. field interactions*



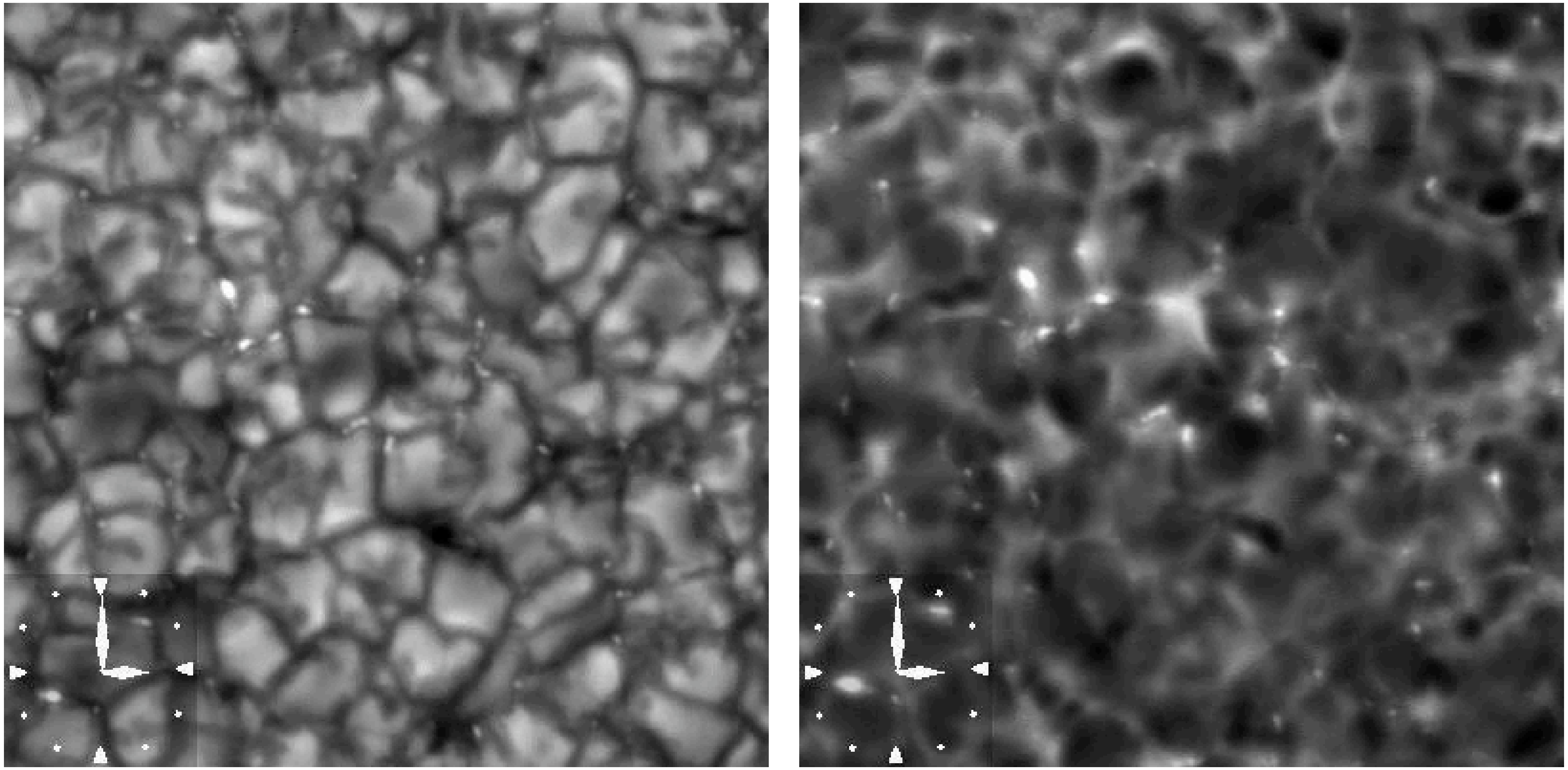
Hinode photosphere



G band

Calcium II

Hinode disk chromosphere



- Ca II H 2.2Å, $\lambda/\Delta\lambda \approx 1{,}800$
- need $\lambda/\Delta\lambda \geq 18{,}000$ (Reardon et al 2008)
- oh dear...

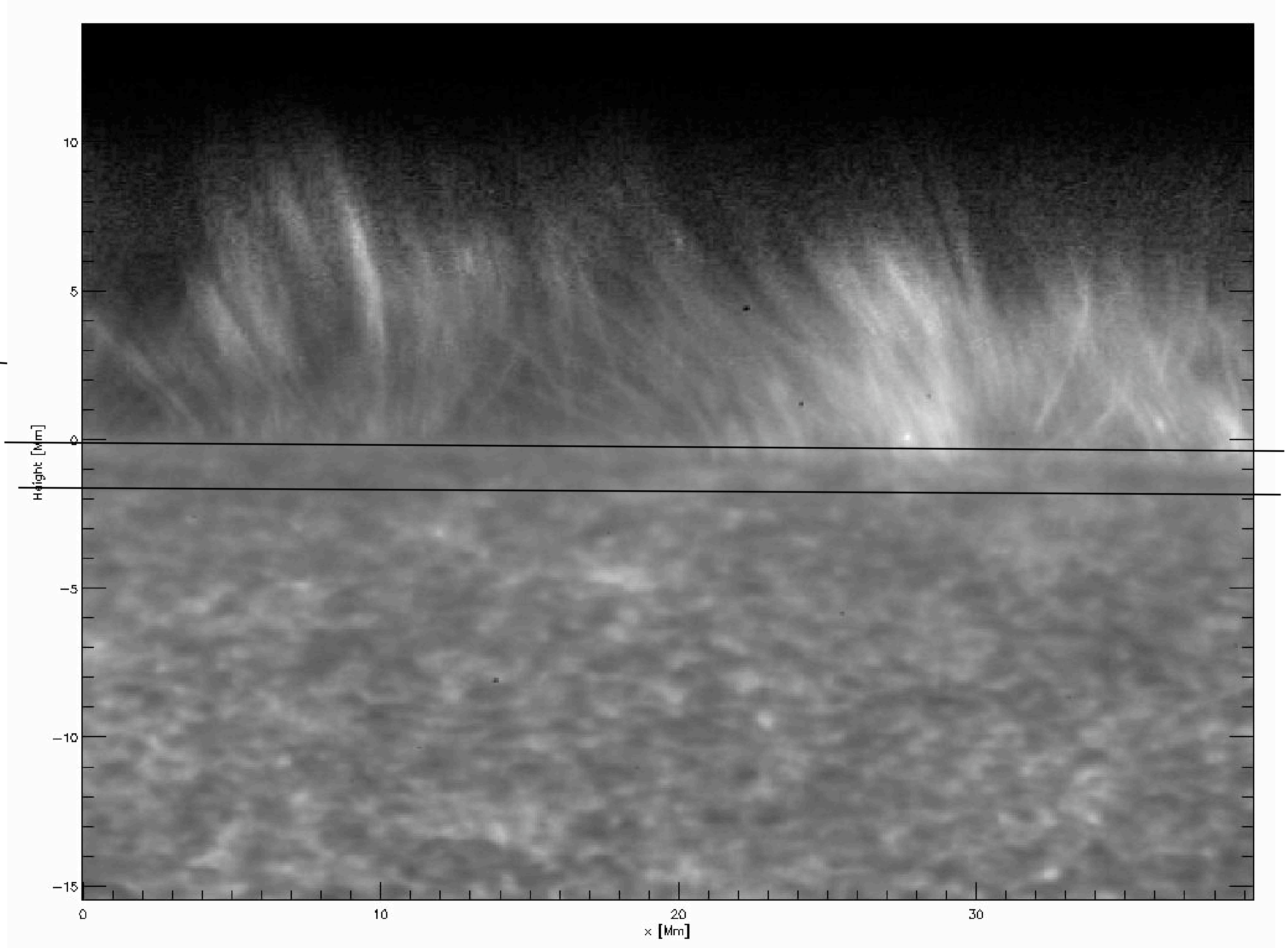
Hinode limb chromosphere

- Ca II (radial filter to enhance spicules, M. Carlsson)

spicules *arise from within* the chromosphere

stratified VAL chromosphere 1.5Mm only

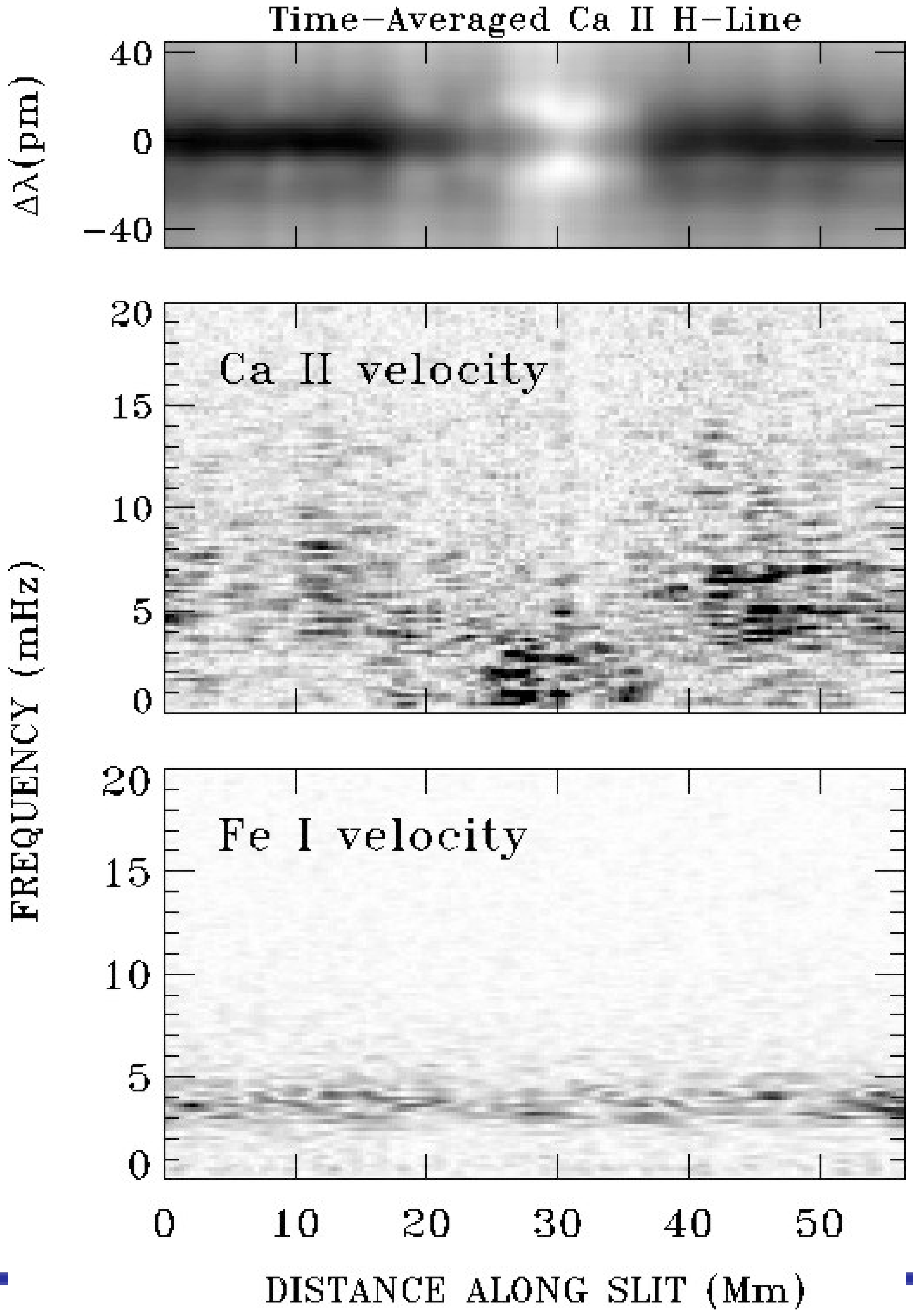
fast dynamics (on disk see McIntosh & de Pontieu)



Ca II H 2.2Å, $\lambda/\Delta\lambda \approx 1,800$

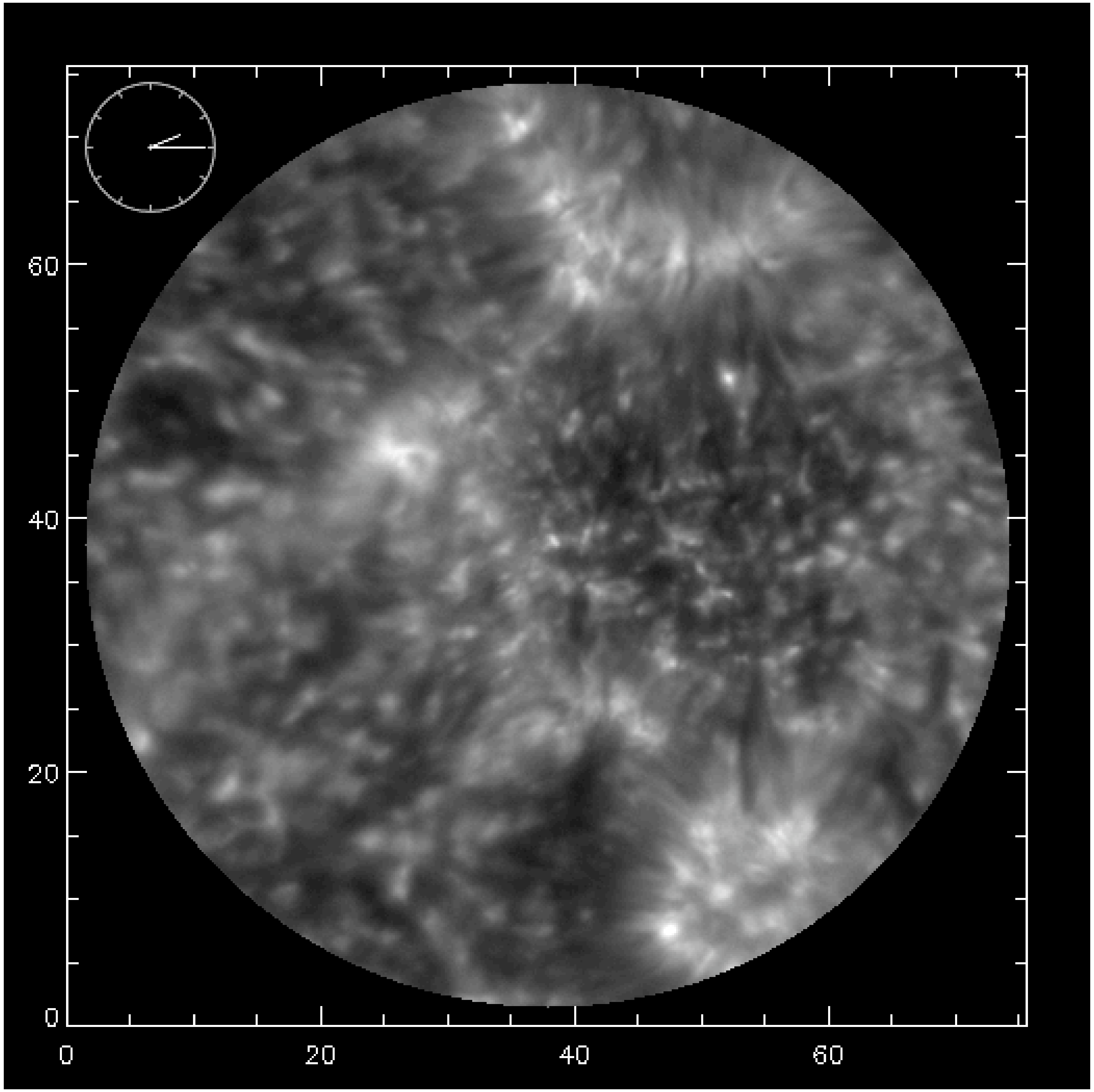
dynamics: ground-based Ca II

- Lites, Rutten, Kalkofen 1993
  - Ca II H $\lambda/\Delta\lambda \approx 200{,}000$
  - CI: 3min
  - NB: ≥5min: *slow*
- wave crossing time for NB
  - $l/c_s \approx 5\ (l/3\text{Mm})$ min
- *NB* structure lives >> this
- (sub)sonic motions
- *magnetostatic equilibrium not unreasonable*



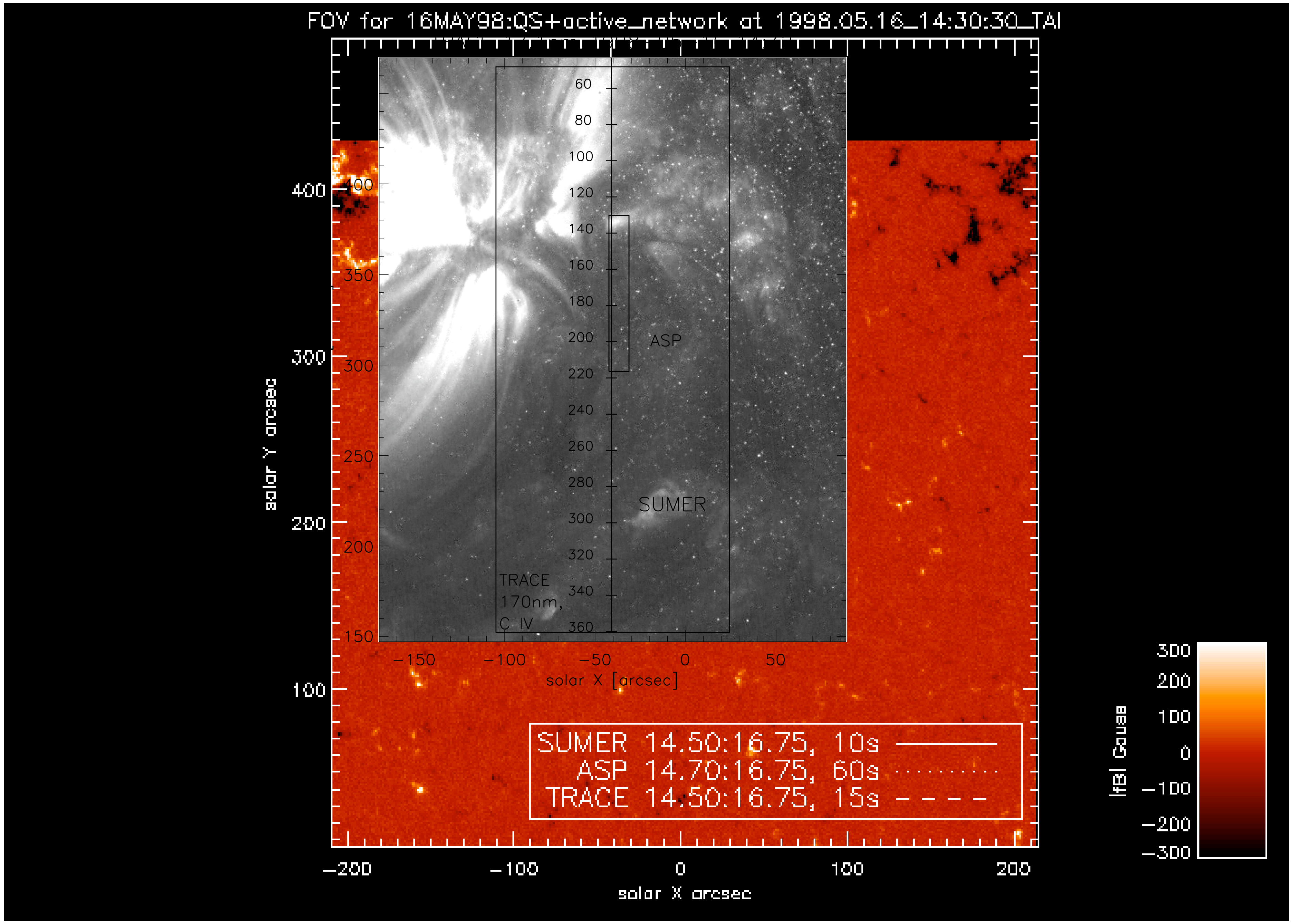
dynamics: IBIS Ca II IR triplet
QS chromosphere

- Cauzzi et al 2007
- λ/Δ λ ≈ 100,000
- line core
- network vs internetwork



Photosphere-chromosphere-transition region

- Unpublished ASP/TRACE/SOHO data (JOP72)
  - Judge, Lites, Tarbell
  - unique slit alignments
- dynamics



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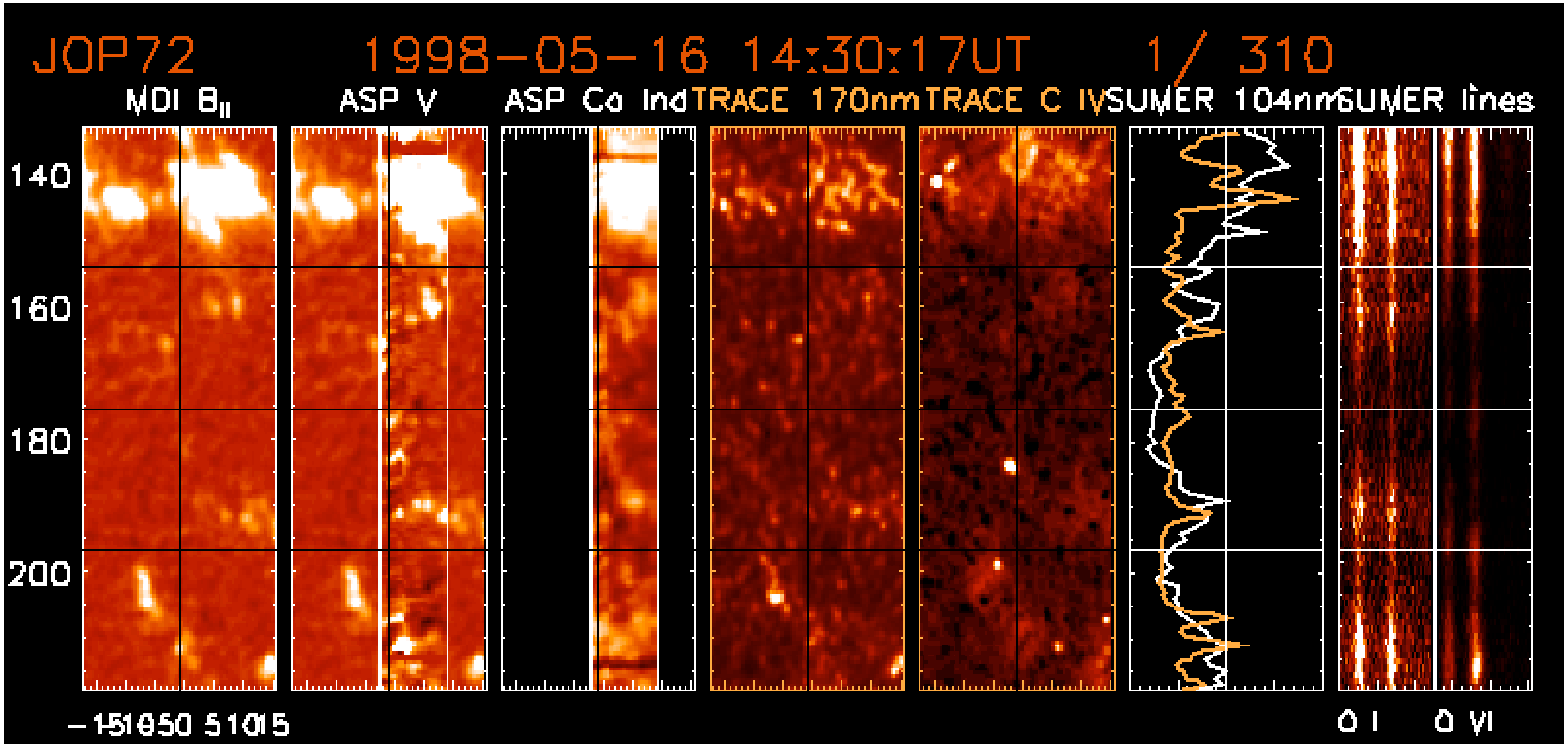
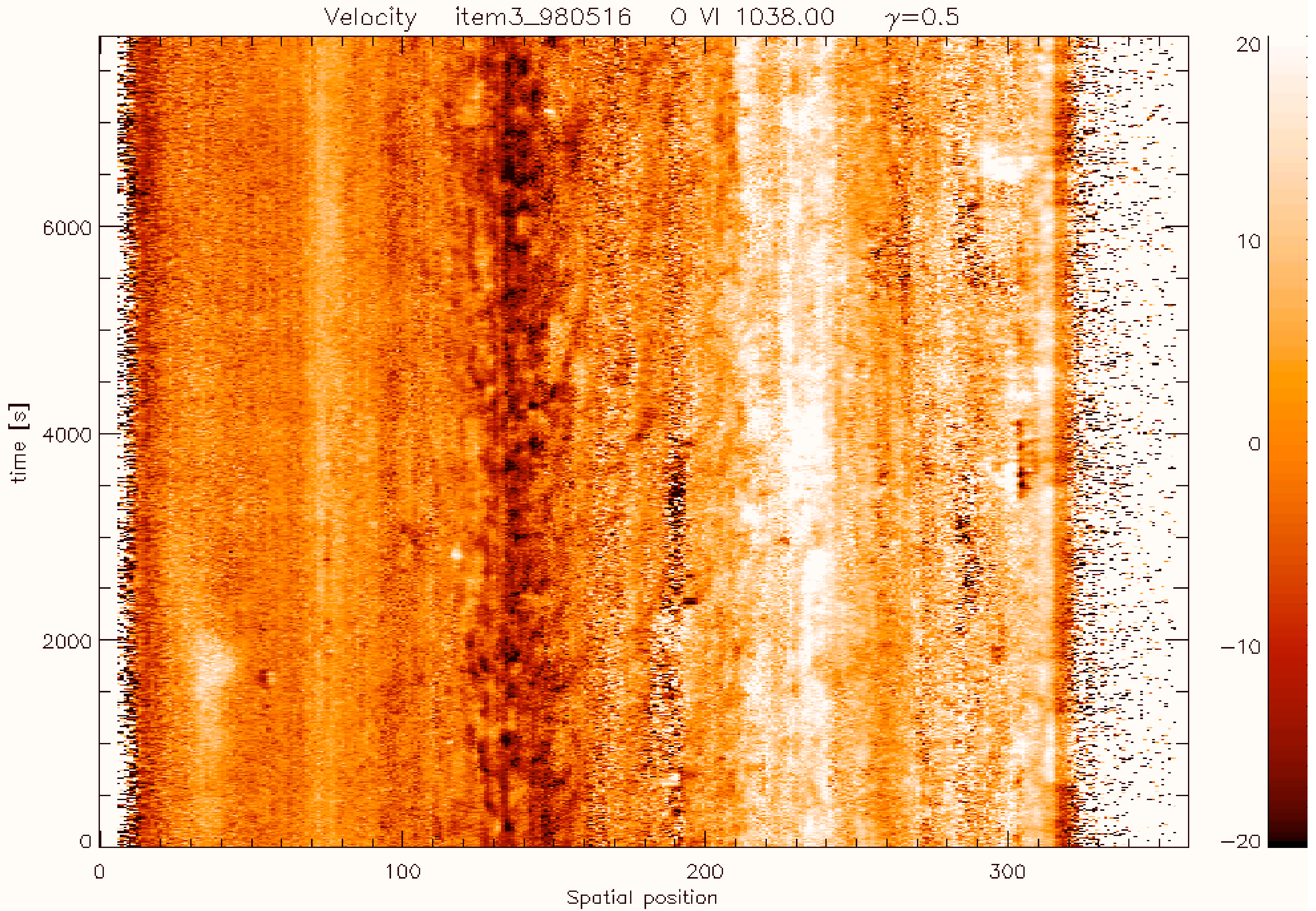
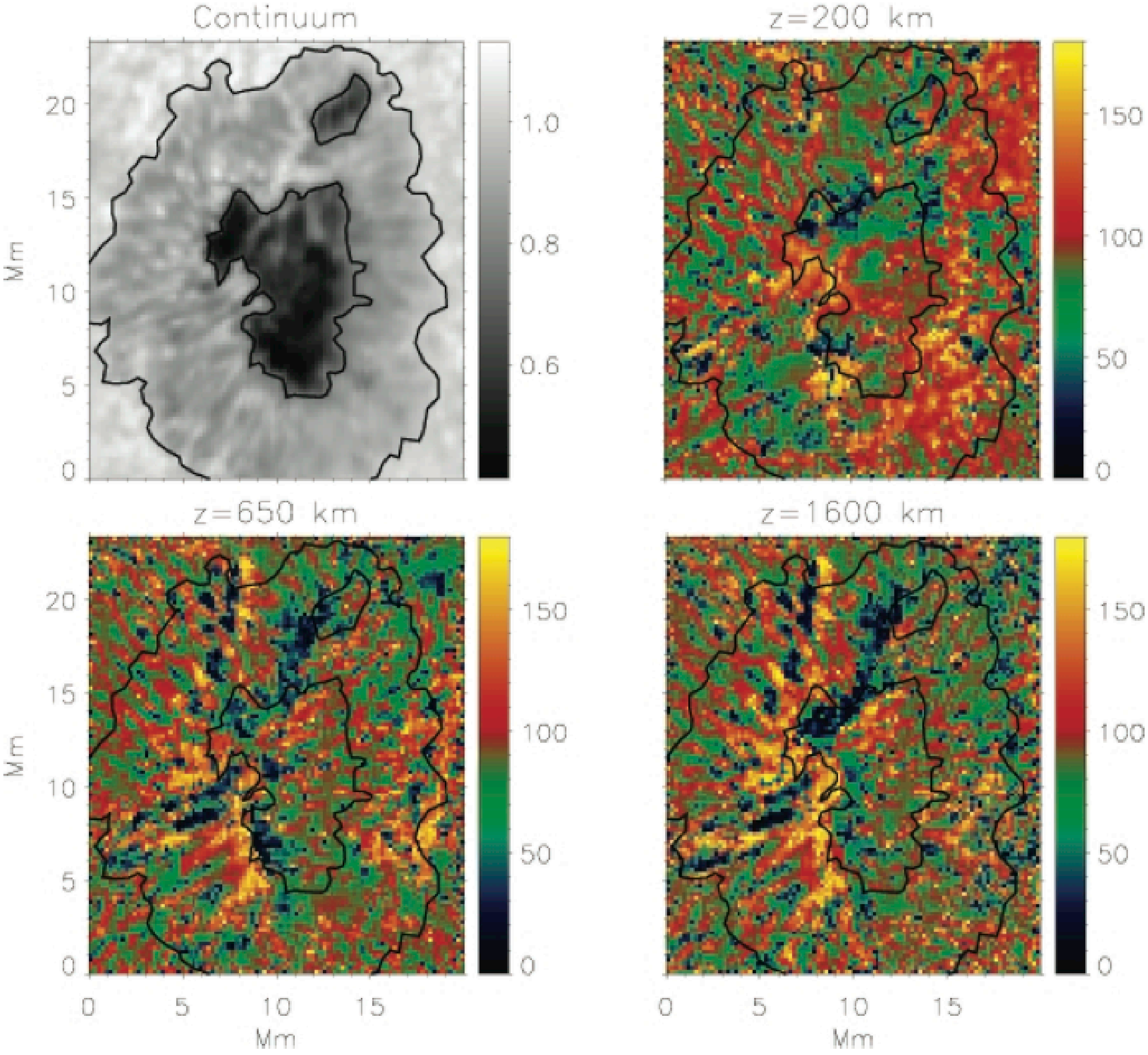



Velocity item3_980516 O VI 1038.00 γ=0.5
time [s]
6000
4000
2000
0
0
100
200
300
Spatial position
20
10
0
−10
−20

some thoughts on magnetic heating

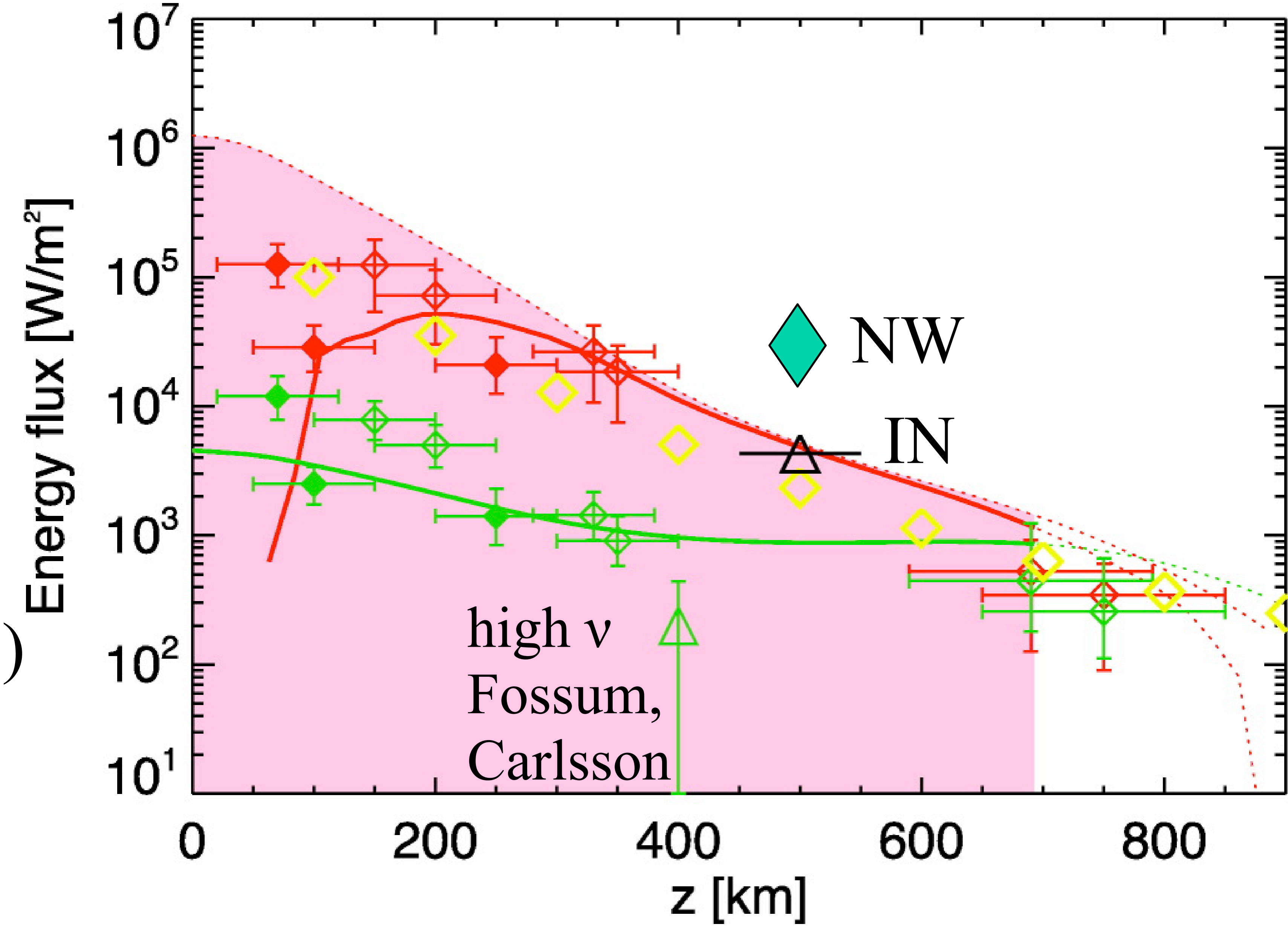
steady currents

- Navarro 2005(SPINOR)
- small spot
- consistency checks- credible
- heating:*steady current systems not dominant*
- **j×B ≠0**



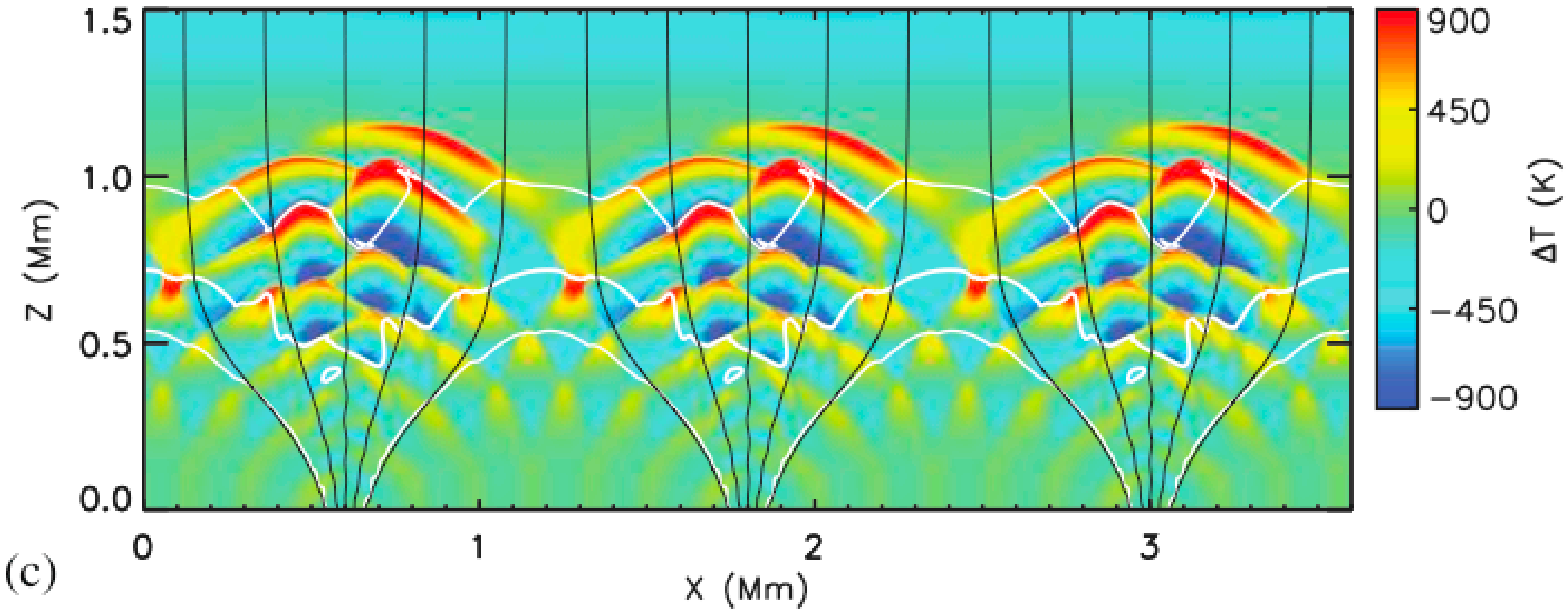
gravity waves and magnetic network

- IBIS obs. +simulations(Straus et al. 2008)
  - source of energy for NW chromosphere?
- *But*
  - NW requires a few $\times 10^4$ W m^{-2} (VAL F, P)
  - average gravity wave 5×10^3 W m^{-2} (VAL A,B)
  - if important, gravity waves must dump a lot of energy in NW
  - coupling efficiency?



exploring MHD wave heating (single fluid)

- large literature
- little direct observational support
  - (high frequencies look like “turbulence”)
- typically (e.g. Hasan & Van Ballegooijen 2008)
  - MHD waves in/around field concentrations (tubes, sheets)
  - high frequencies (40 mHz: shorter simulation times)
  - *dissipation* is via conversion to slow modes which shock



chromosphere as a partially ionized plasma

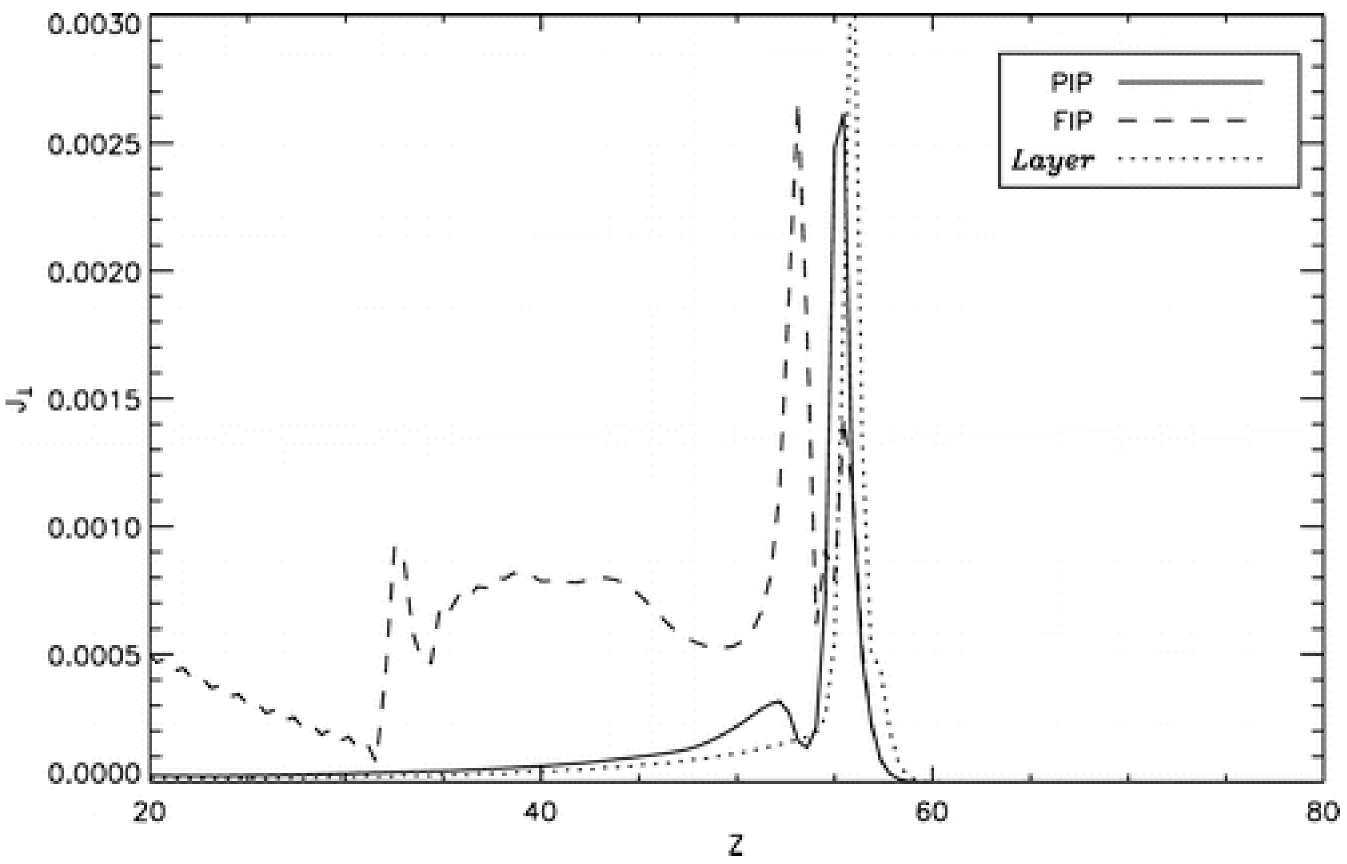
- partial ioniz^{n} ⇒ 3-fluid *frictional dissipation, heating*
- efficient damping by ion-neutral collisions
- Kinetic theory (Braginskii 1965)
  - $Q_{fr} = \mathbf{j}.\mathbf{E} = j^2/\sigma + (\xi_n\, \mathbf{j}\times\mathbf{B} - \mathbf{G})^2/\alpha_n,$ $\mathbf{G} = \xi_n \nabla p - \nabla p_n$
  - "ambipolar diffusion"/star formation (1950s Schlüter, Cowling)
- $\mathbf{G} = \mathbf{0}$ ⇒ "Cowling conductivity" $\sigma_\perp^*$
  - $Q_{fr} = j_{\parallel}^2/\sigma + j_\perp^2/\sigma_\perp^*$ $\sigma/\sigma_\perp^* = 1 + 2\,\xi_n\, \omega_e\tau_e\, \omega_i\tau_i,$ $>>1$
  - ⇒ *rapid dissipation of* $\mathbf{j}_\perp$
  - Goodman & colleagues: wave heating
  - Arber & colleagues: flux emergence

Chromospheric dissipation of $\mathbf{j}_\perp$

- Braginskii (1965): certain motions (**G**...) dissipate $\mathbf{j}_\perp$
  - Alfvén, fast modes, dynamic situations where $\nabla p - \rho \mathbf{g} + \mathbf{j} \times \mathbf{B} \neq \mathbf{0}$
- **Not** slow modes, slow dynamics **(cf.** Goodman 2000)
- So, at coronal lower boundary, chromosphere makes:
  - $\mathbf{j}_\perp \sim 0$; $\mathbf{j} \times \mathbf{B} \sim 0$
  - **weaker Alfvén/fast modes**

*Flux emergence: Arber, Haynes & Leake (2007) based upon Cowling's conductivity (**G=0**):*

Plot of the magnitude of $j_\perp$ as a function of height along the line $x = y = 0$ for all three resistivity models at $t = 160$.



*...radical effect on **j** and flux emergence process*

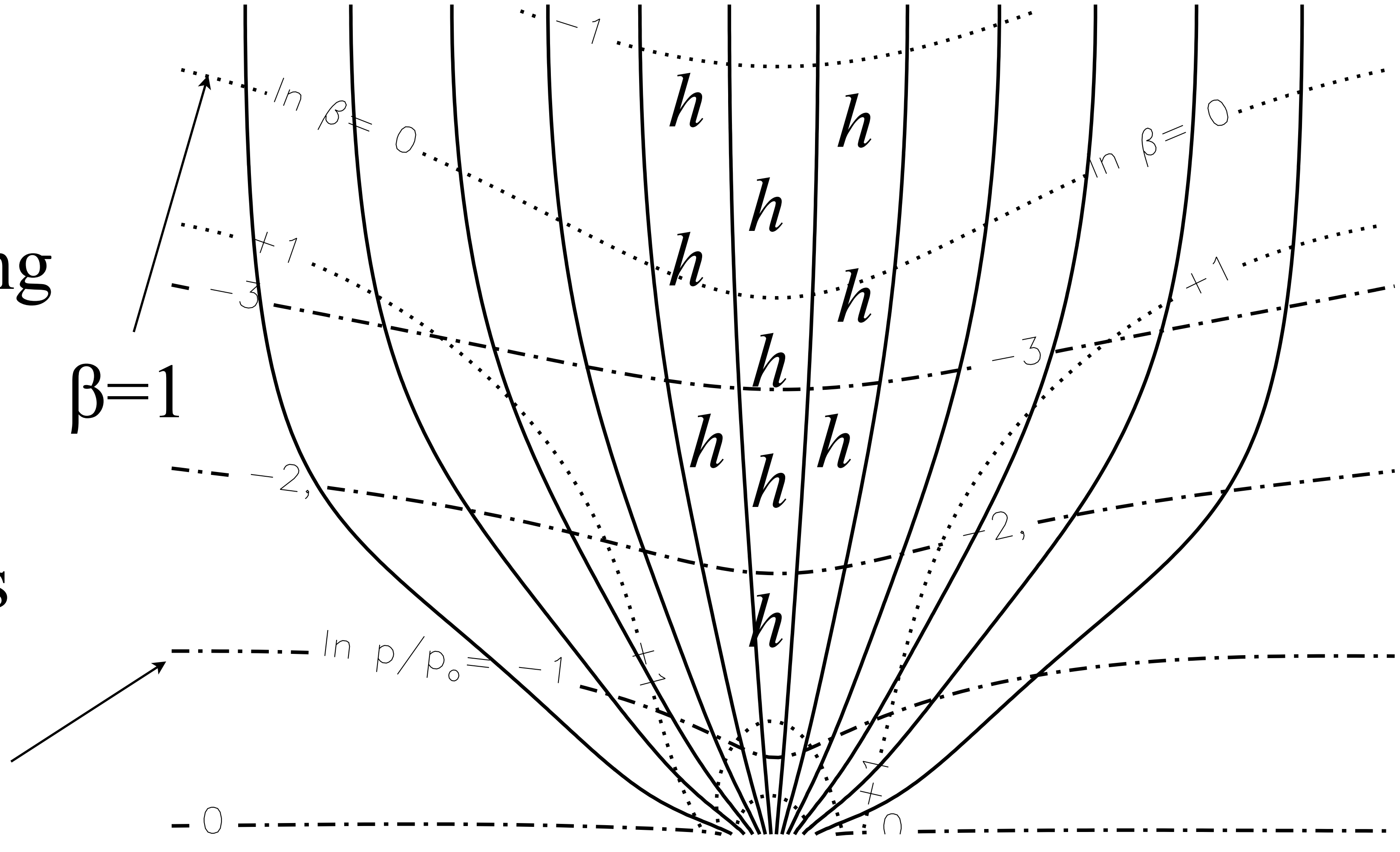
chromosphere as a partially ionized plasma II

- $\sigma_\perp^*$ is some steps removed from σ (kinetic theory)
  - case **G** $\neq$ **0:** $\sigma_\perp^*$ incorrect!
  - one must simultaneously determine the nature of $\mathbf{j}_\perp$ (cf. E-region electrojet) from the dynamics
- Fontenla (2005, 2008 A+A)
  - for length scales >100 km (few mHz waves),
  - $Q_{fr} = \mathbf{j}.\mathbf{E}$ too small, invokes instability (Farley-Buneman)
  - need neutral component velocity > ion acoustic velocity

Conundrum

force and energy imbalance?

- VAL models require high *P* where *B* is high (marked "*h*")
- Magnetostatic models require low *P* where *B* is high
- proposals:
  - Wilson depression
  - fast heating, cooling
  - z-pinch
- Is there a problem?
  - better observations



β=1

isobars

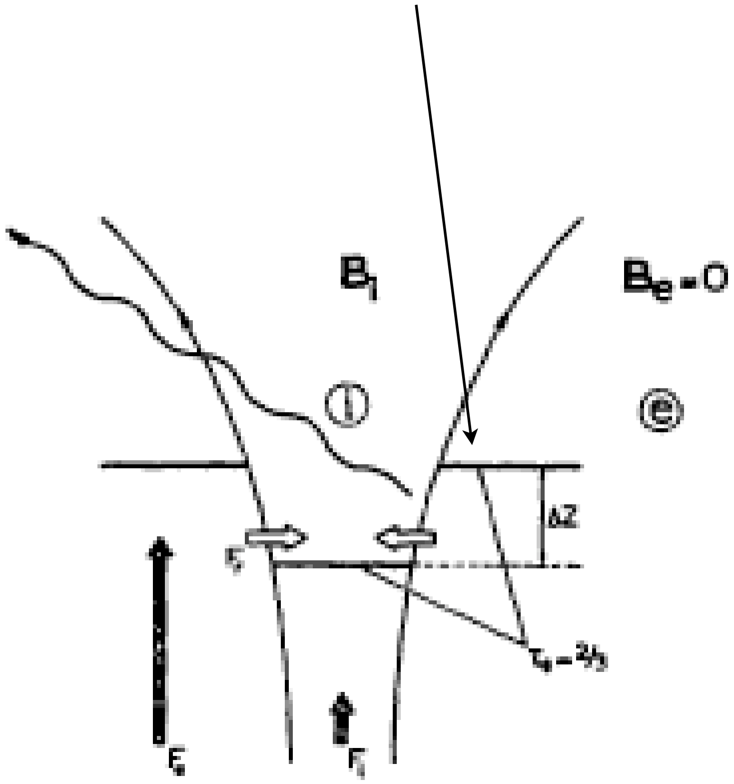
"CI"

"NB"

Solanki, Steiner & Uitenbroek (1991)

- photosphere in NB lower than CI (“Wilson *anxiety*”, ΔZ)
- $dP/dz = - \rho g$ invariant with $z \rightarrow z + constant$
- move entire NB atmosphere ↓
  - satisfy horizontal pressure equilibrium
  - get same *vertical* emergent intensity

  Problems?



- VAL F/A requires >2 scale heights *anxiety*,
- *but model F* is from 5”x5” observations
- probably >3? scale heights needed, “depression”
- is NB observed to be “deeper” than CI?
- (consistent with 3D MHD models?)

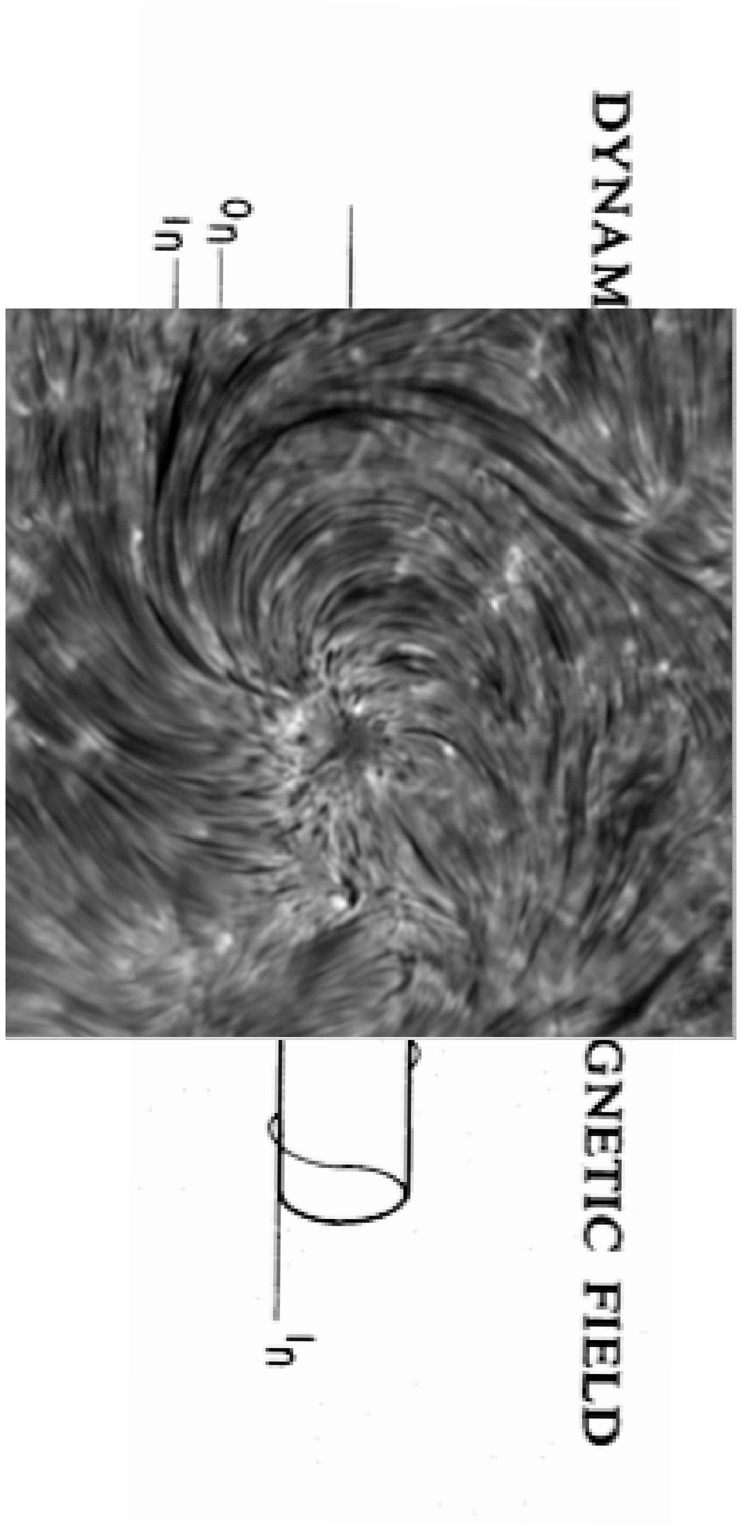
Increase NB brightness, but without increasing pressure

- Radiative cooling time 90 sec (Anderson & Athay 1989)
- perturbations of *P* travel ~10 km/s (high β fast+slow modes)
  - NB→CI travel time ≥ 300 sec
  - probably refracted downwards (nb WKB?)
- shocks present in simulations (Schaffenberger et al 2005)
- so, bursts of heat on time scales << 300 sec lead to pressure pulses which may refract and *will radiate energy before arriving at NB/CI boundary*
- no direct observational evidence for or against, but
  - this may also be a possible thermal source for *spicules*

Lorentz force: z-pinch?

- Steiner et al (1986), twisted flux tubes
  - in asymptotic region (merged field)
    - *Instability* when $B_\varphi/B_z > \sqrt{f}$,
      f =photos. fill factor of B
    - *$\sqrt{f} \approx 0.1$ in quiet Sun*
    - radial tube expansion by 10: $B_\varphi/B_z = 1$
      - *may be sufficient?*
    - dynamics after instability not known

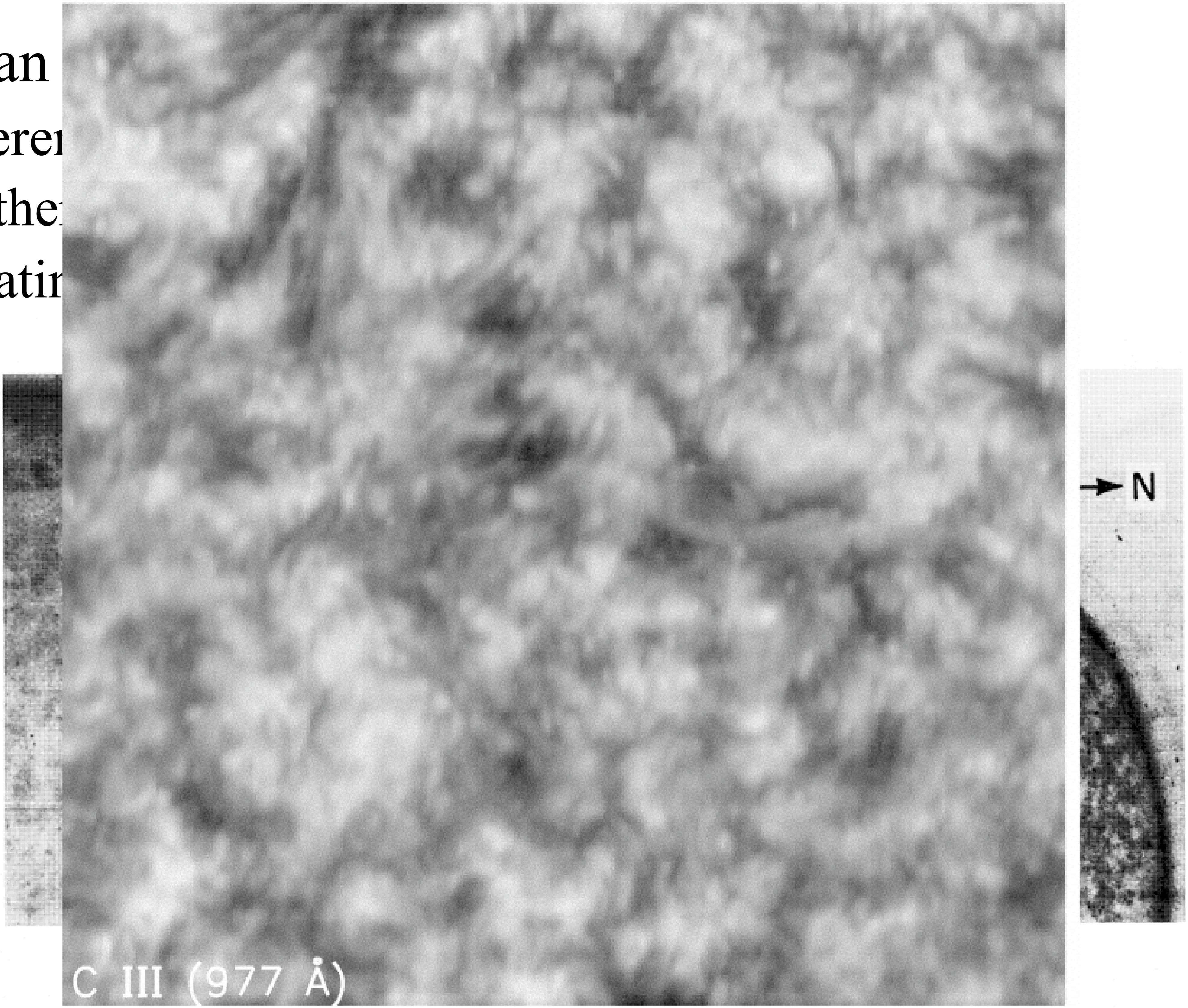
- *possibly a magnetic source for spicules II*



chromosphere - corona thermal interface

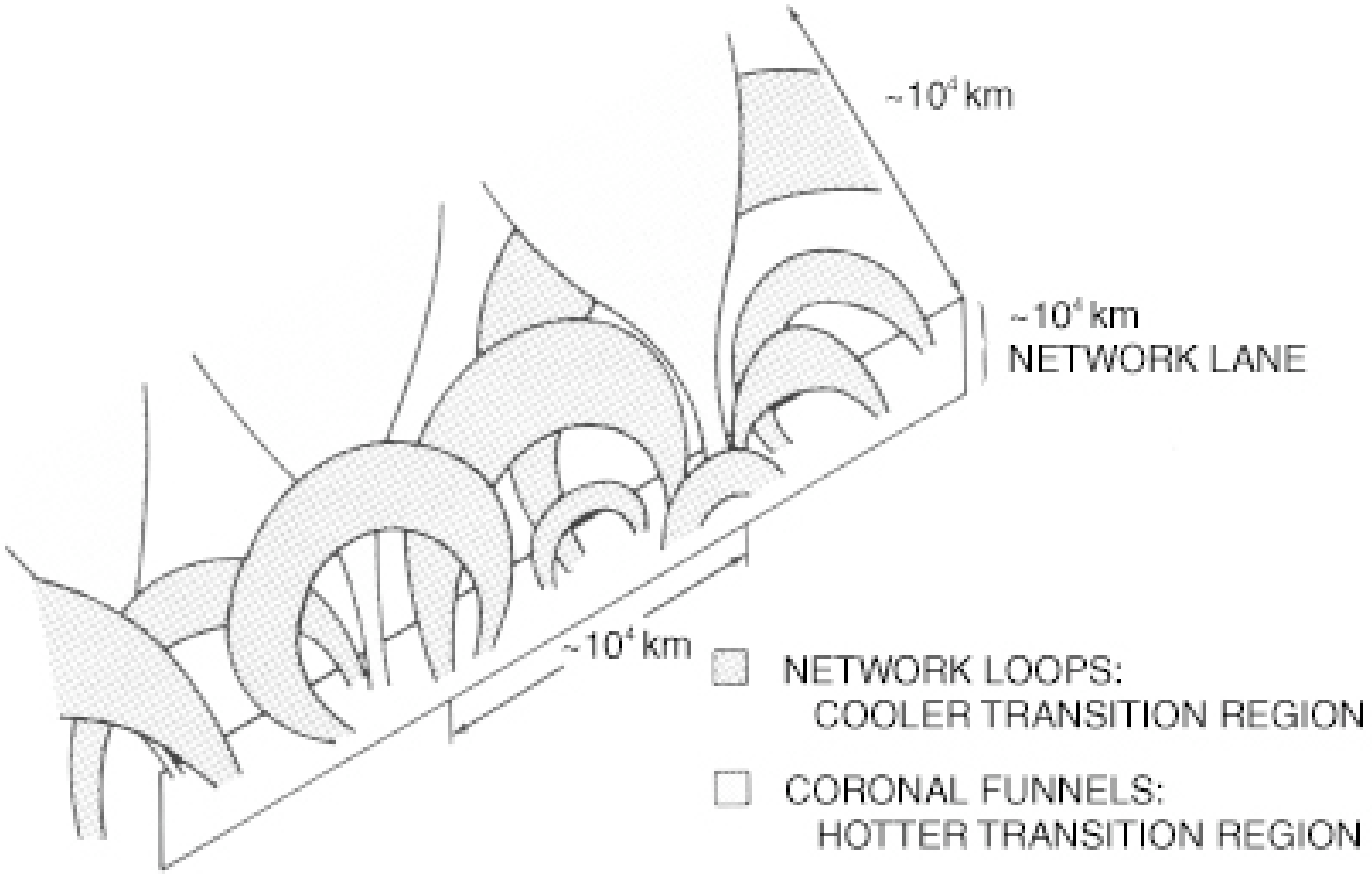
The problem- observations

- Feldman
  - differe
  - TR the
  - radiati



Dowdy et al. (1986)

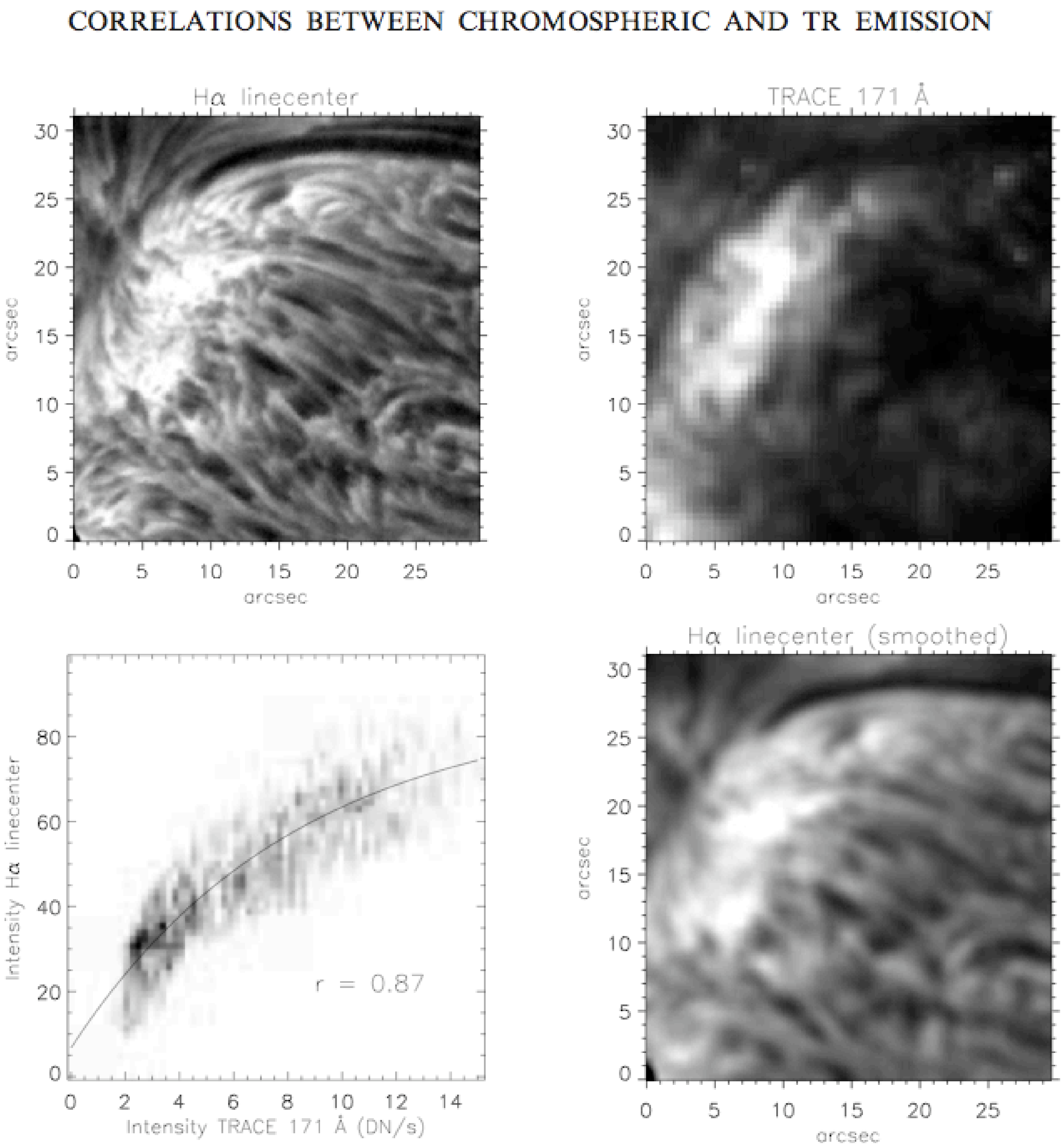
- Mixed polarity within network boundaries
- tries to explain “UFS”
- indeed these are thermally and magnetically separate entities



Depontieu et al 2003: TRACE/SST data

Yet...

Significant correlations exist between the Hα chromospheric intensity and the low corona


CORRELATIONS BETWEEN CHROMOSPHERIC AND TR EMISSION

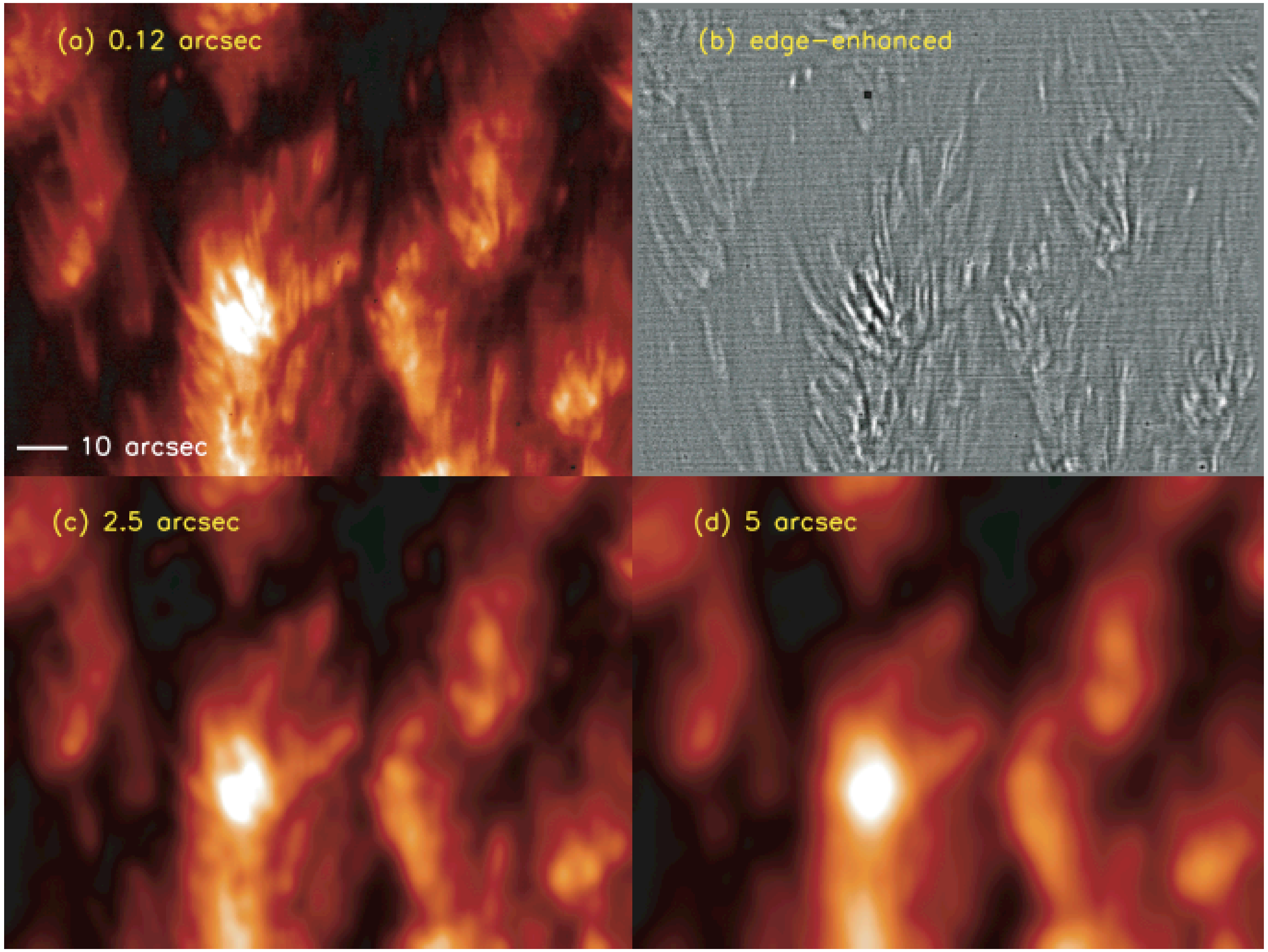
Questions concerning cool loops

- Cool loops are considered by most a viable explanation, but
- where does the 10^6 erg cm^{-2} s^{-1} conductive flux go?
- Is it merely a coincidence that the lower TR radiates about 10^6 erg cm^{-2} s^{-1}?
- Why should the cool loop distribution make the upper (conductive) and lower (cool loop) TR be correlated, at least on scales > a few Mm?
- are they stable (Cally & Robb 1991)?
- where are the tell-tale magnetic footpoints?
- …

Judge & Centeno (2008)

- VAULT Lα data vs. KPNO magnetic data
  - supplemented by Hinode SP vector polarimetry
- Prompted by Patsourakos et al (2007)
  - We noted something “odd” about proposed cool loops
  - large-scale alignment of Lα threads

Patsourakos et al:



KPVT+POTL FIELDS+VAULT
active network

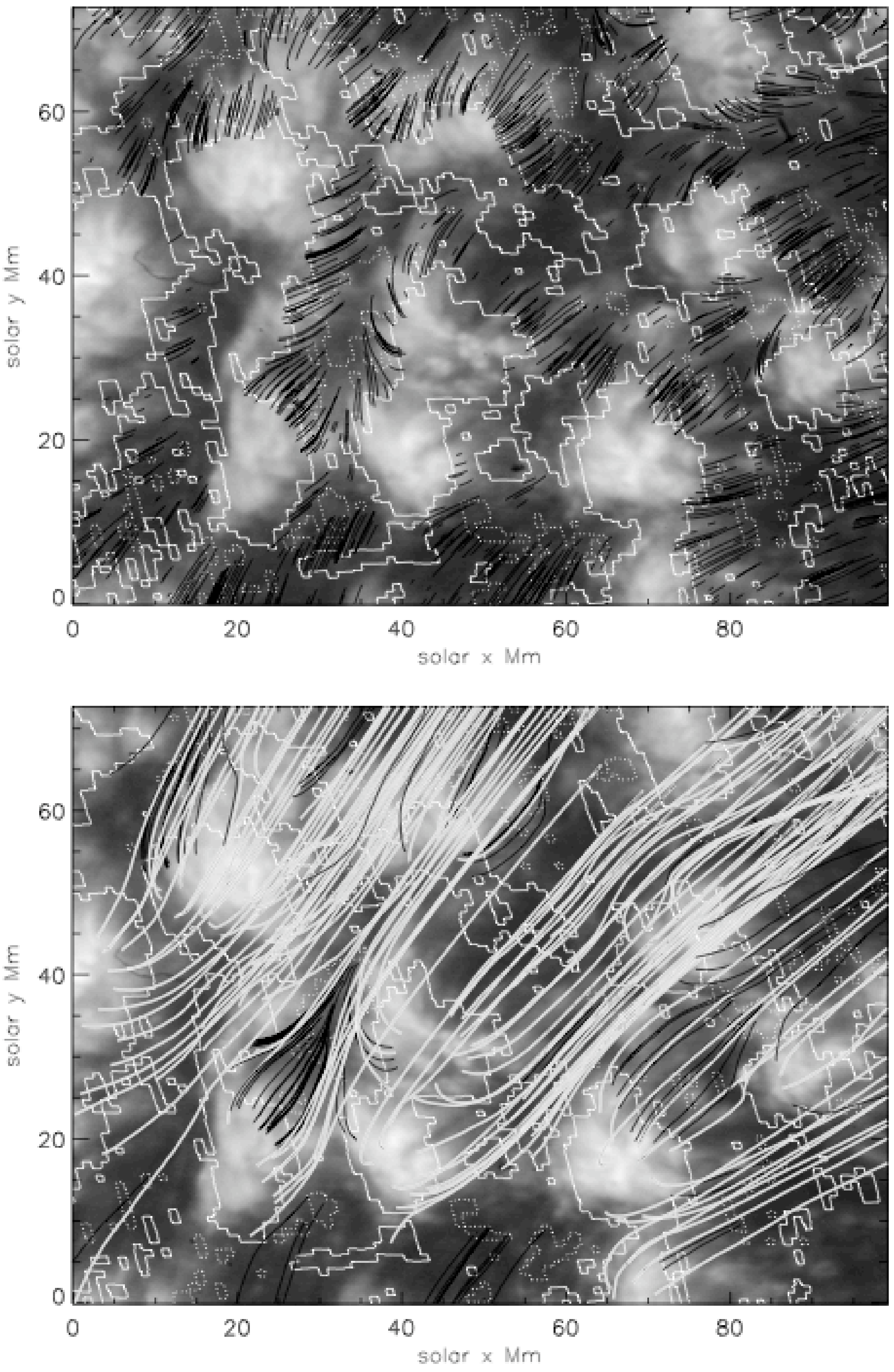
Black=low-lying loops (h<5Mm)
Gray= long

Stability requires that low- lying loops are possibly cool, but higher loops must be hot

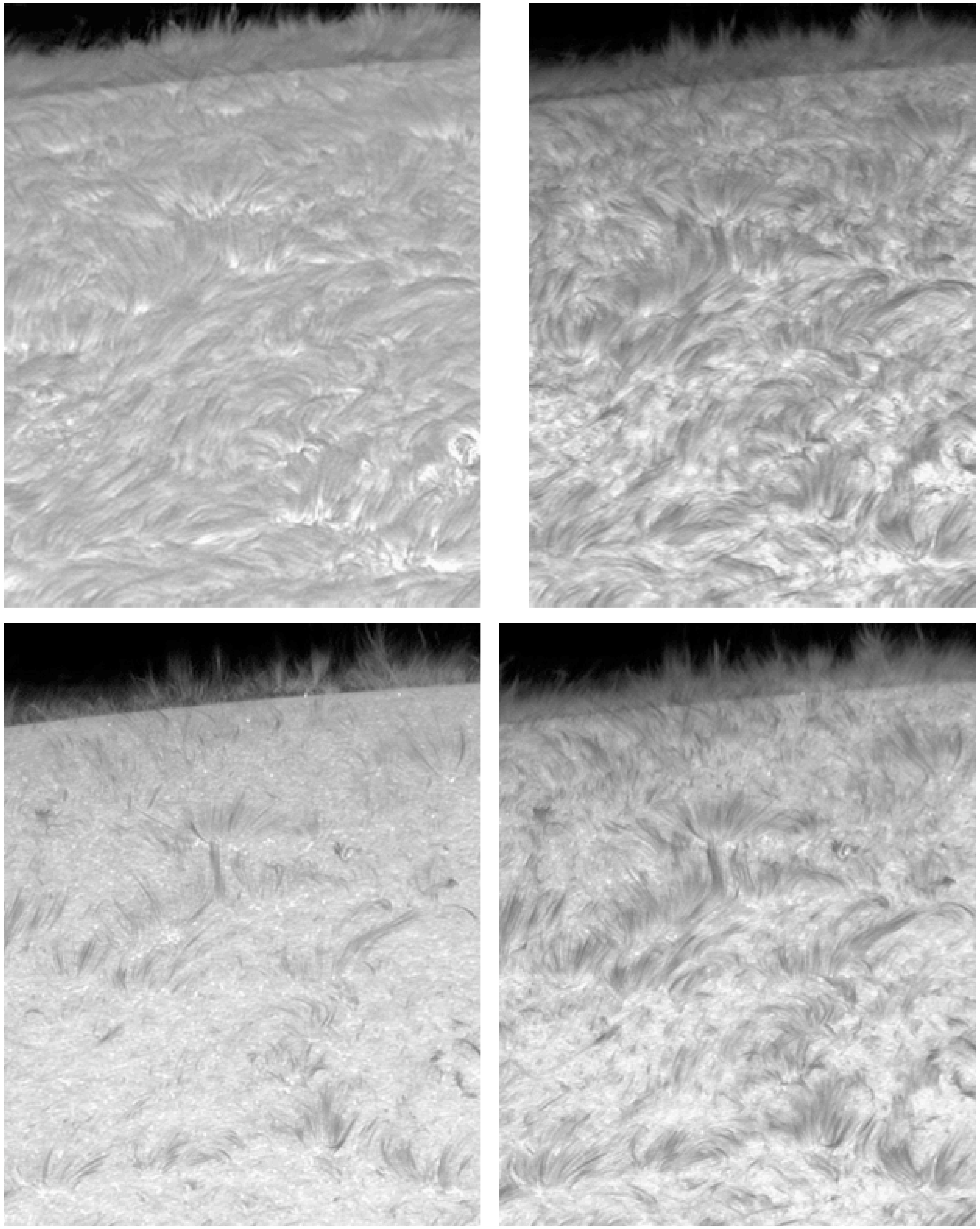
Most $L\alpha$ emission originates from the base of hot, coronal loops

Some may arise from cool loops, but not commonly in active network

Cannot appeal to “unresolved (salt +pepper)fields”- $L\alpha$ emission forms above h=0.8 Mm. “Loops” with footpoints separated by 1” can’t reach these heights



Spicules, fibrils..



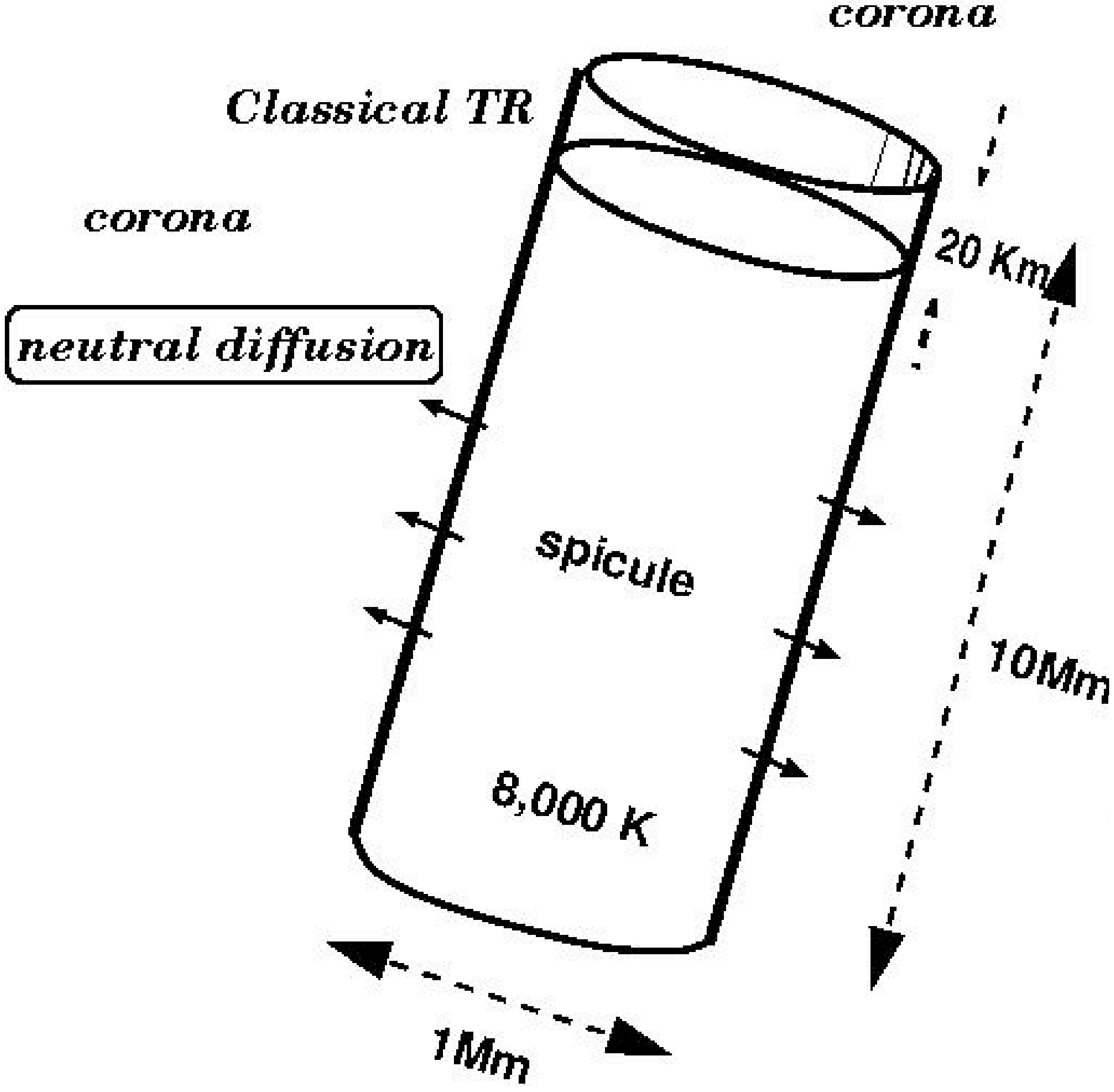
- base of the corona is a non-planar thermal boundary
- e.g., DOT Hα (Rutten 2007) clockwise 0, -0.4, -0.6,-0.8 Å:

consider α in

curl $\mathbf{B} = \alpha\mathbf{B}$ for photosphere

and coronal base

Judge (2008) ApJL 683, 87-90
“spicule” → cross field diffusion→ TR radiation



Initial corona			
T_h	K	10^6	
n_h	cm^{-3}	8.0×10^8	
n_p, n_e	cm^{-3}	4.0×10^8	
p	cm^{-3}	1.1×10^{-1}	
B	G	10	
β		2.8×10^{-2}	
ω_p	s^{-1}	9.6×10^4	
r_{gyro}	km	1.5×10^{-3}	
τ_{pp}	s	1.6	$n_p^{-1}T^{+3/2}$
$\omega_p\tau_{pp}$		1.5×10^5	
τ_{ee}	s	5.0×10^{-2}	$n_e^{-1}T^{3/2}$
chromospheric tube			
T_c	K	8.0×10^3	
$\overline{v}$	$\mathrm{km\ s}^{-1}$	13	$T^{1/2}$
n_c	cm^{-3}	10^{11}	
τ_{nn}	s	1.4×10^{-2}	$n_n^{-1}T^{-1/2}$

5 moment equations of motion including diffusive fluxes

$\omega\tau \gg 1$: across the field, can ignore heat flux, thermal force, diffusion of ions:

$$\frac{\partial n_s}{\partial t} + \frac{\partial}{\partial x}\{n_s u_s + d_s^n\} = \frac{\delta n_s}{\delta t}, \tag{1}$$

$$m_s \frac{\partial n_s u_s}{\partial t} + \frac{\partial}{\partial x}\left\{m_s n_s u_s^2 + p_s + d_s^M\right\} + F = \frac{\delta M_s}{\delta t}, \tag{2}$$

$$\frac{\partial E_s}{\partial t} + \frac{\partial}{\partial x}\left\{u(E_s + p_s) + d_s^E\right\} = \frac{\delta E_s}{\delta t} + Q - L. \tag{3}$$

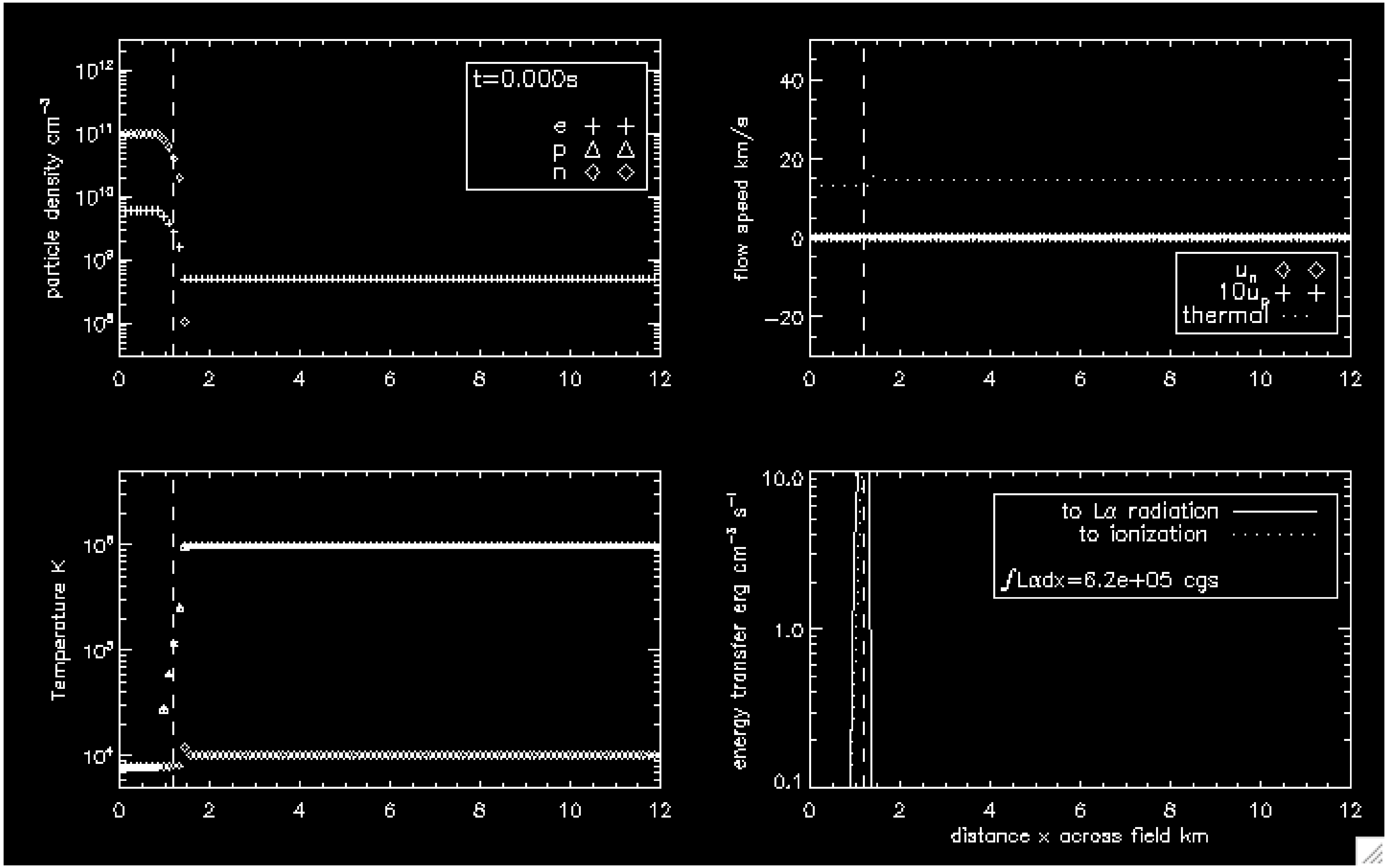
$$d_s^n \approx -\frac{1}{3}\lambda_s \frac{\partial}{\partial x}\{n_s(x)\overline{v}_s(x)\} \qquad \text{(diffusive fluxes)}$$

- when d_s^i, $\frac{\delta}{\delta t}$, Q L are 0, => Euler for s
- λ = mean free path, $\overline{v}_s(x) = \sqrt{\frac{8kT_s}{\pi m_s}}$, $E_s = \frac{3}{2}n_s k T_s + \frac{1}{2}m_s n_s u_s^2$, $p_s = n_s k T_s$
- $\frac{\delta X_s}{\delta t}$, non-linear collisions for species s (Schunk 1977).
- Solve for n_s, u_s, T_s from a given initial state.

Results: model Lα ~0.1x observed using only local coronal heat

1D 3-fluid calculation of cross-field diffusion from a cool flux tube into coronal plasma

no field aligned conduction



calculations with different coronal *n*, *T*: non-linear relationship between Lα and coronal emission

Judge (2008)

- calculations for Lα are promising, (also Lβ, He I 584)
  - this is the hardest line to explain, others may follow?
- cross-field diffusion of neutrals might solve the 40+ yr problem of energy balance in extended structures in the lower TR
- chromosphere supplies the mass, corona the energy
  - cool loops don't explain active network (Judge & Centeno 2008)
  - "UFS" in this new picture is thermally connected to the corona

- needed
  - 2D calculations including field-aligned conduction and dynamics
  - observations of the chromosphere/corona interface in relation to magnetic field

chromosphere as the coronal base

To understand the corona we must understand what is under Gold’s line... *is single-fluid MHD adequate*?

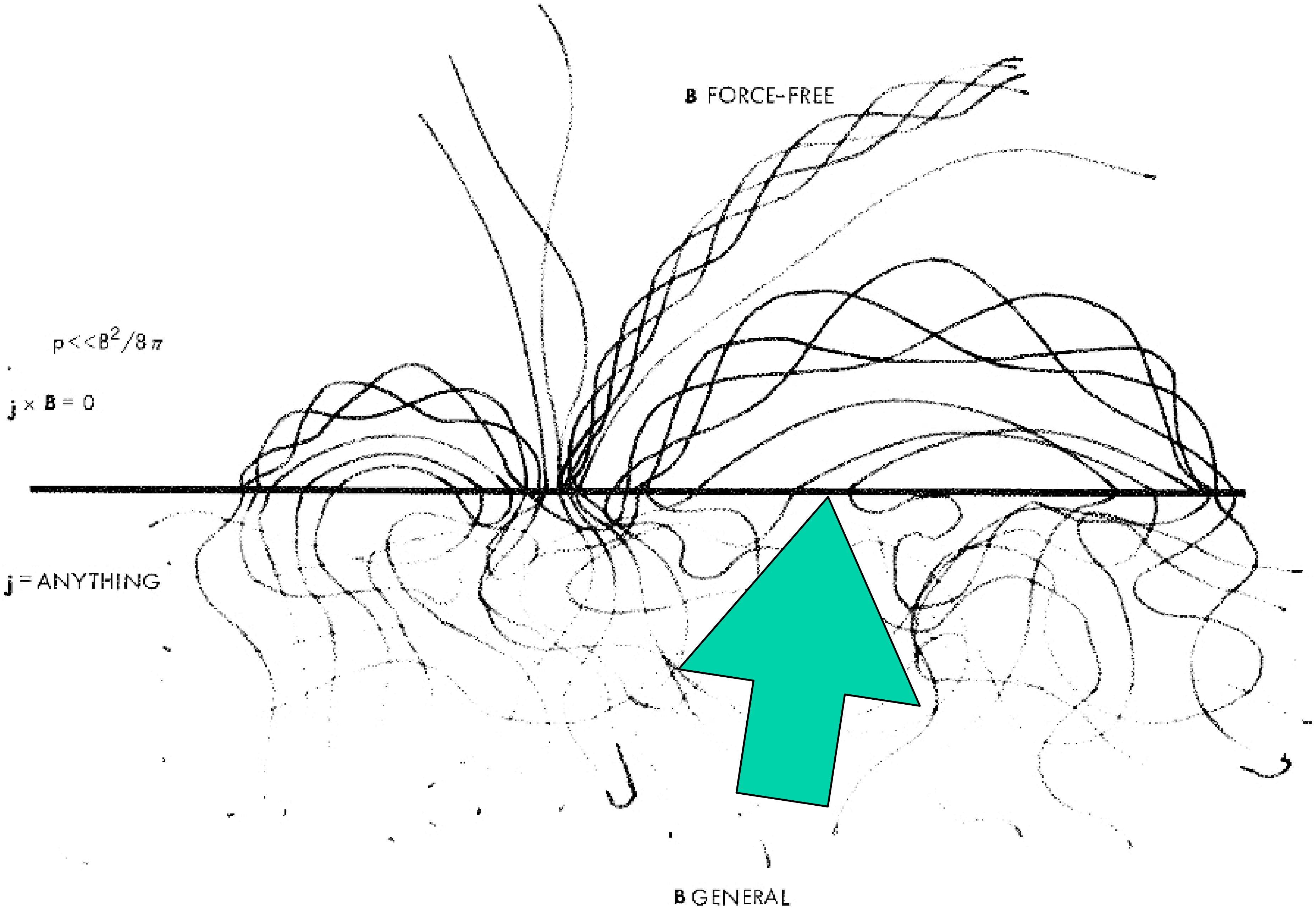


FIGURE 44–2. Magnetic field in a turbulent conducting medium. The fluid pressure is assumed large compared with magnetic forces below the dividing plane and small above it.

390

DOT and TRACE: 9 Jul 2005
(A.G. de Wijn, R. J. Rutten)

photosphere
chromosphere
corona

coronal structure
already present
in the
chromosphere

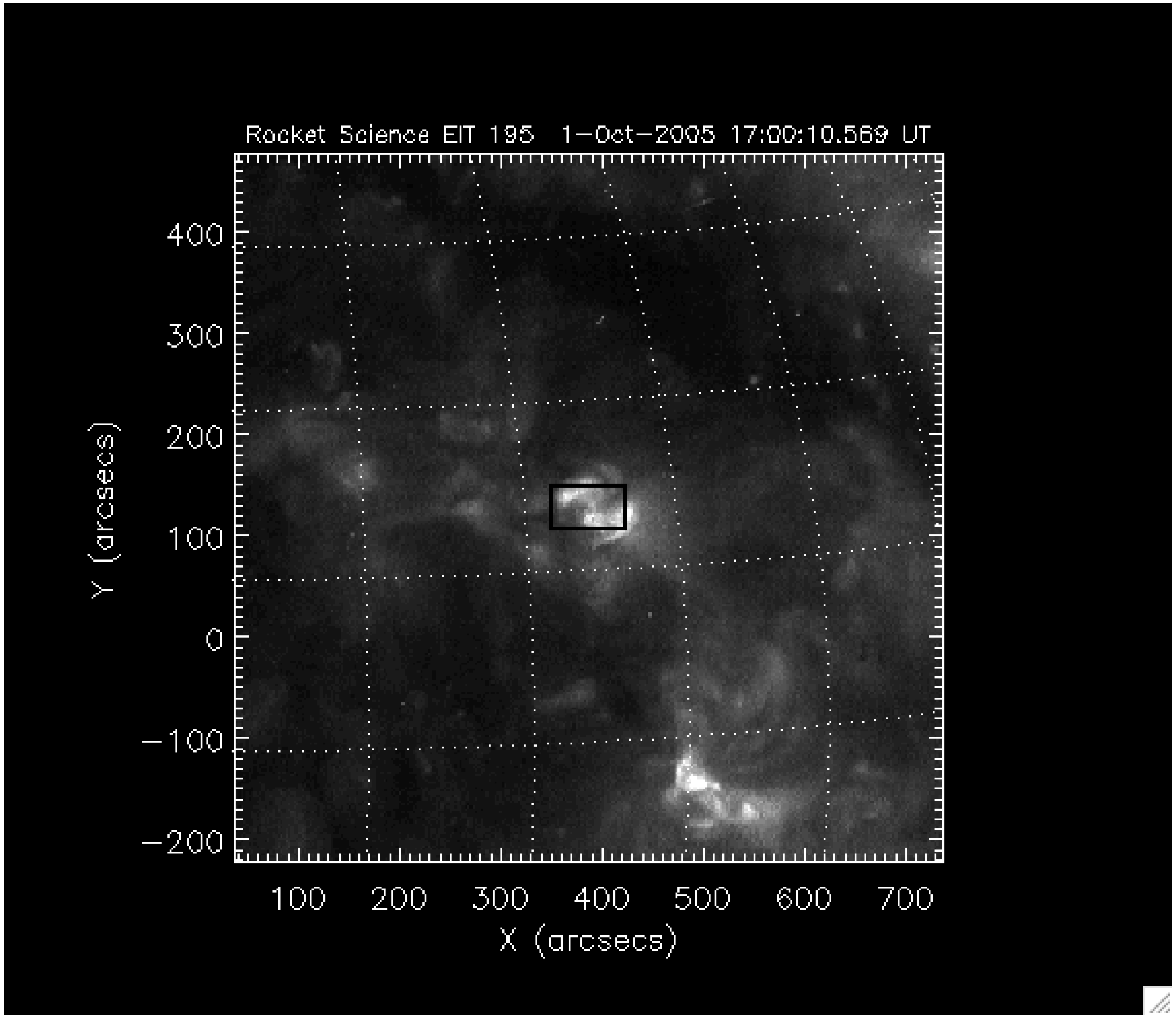
Chromosphere vs. photosphere as the coronal boundary

- is the lower boundary for the corona
  - modulates flow of mass, momentum, energy and magnetic field into the corona
  - implicit mass reservoir in coronal loop scaling laws
- **$\mathbf{j}_\perp \rightarrow$ small** at coronal base, for 2 reasons
  - force balance traversing 9 scale heights
    - $|\mathbf{j}\times\mathbf{B}| \rightarrow \boldsymbol{\beta}\, B^2/2\mu$ above $\beta=1$
  - frictional dissipation of $\mathbf{j}_\perp$
- **$\alpha(r) \rightarrow$? at the coronal base:** coronal current sheets (Parker)

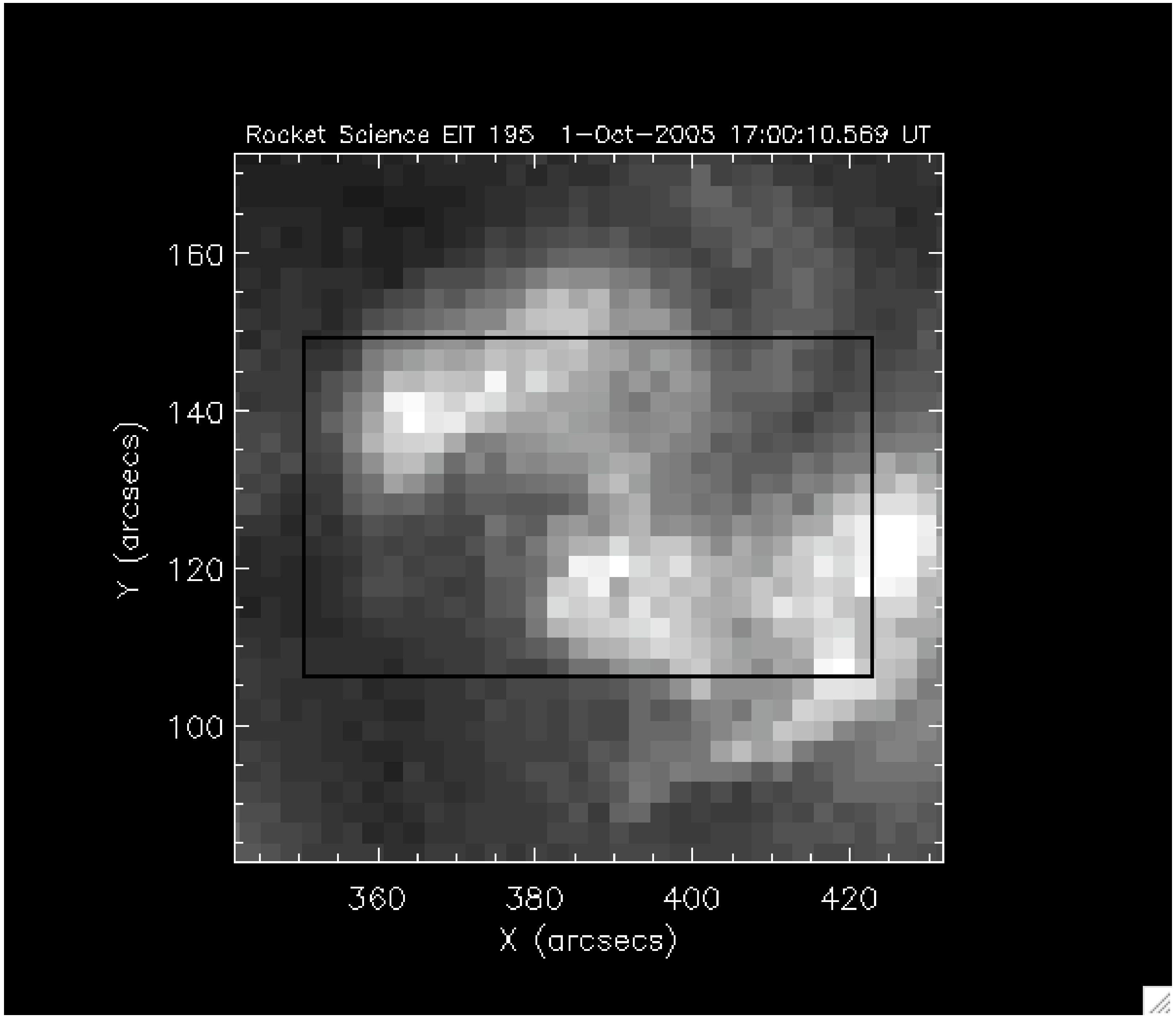
magnetic interface observations:

an example

Small AR, pores



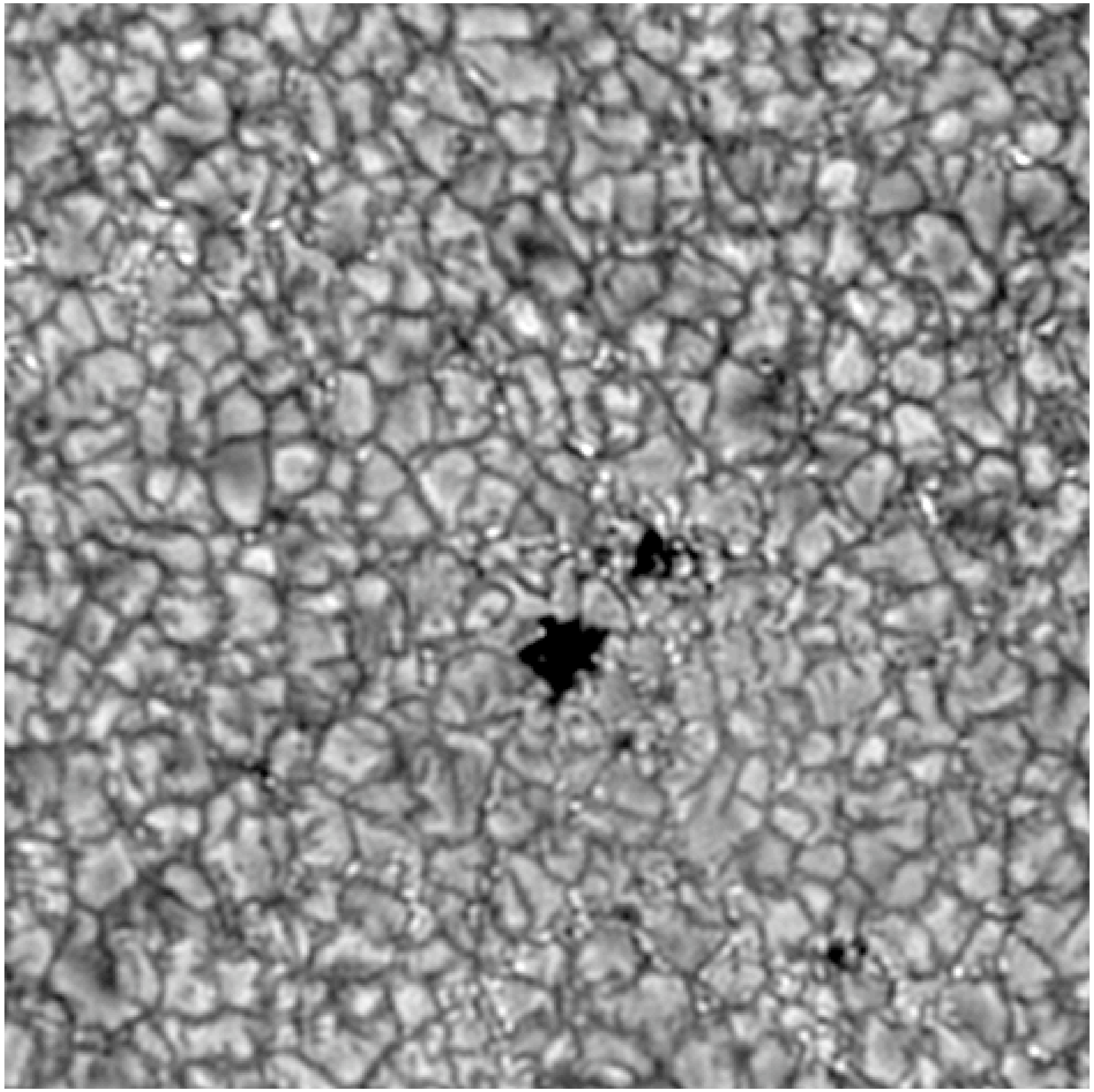
Small AR, pores: closer view



Chromosphere as seen with IBIS

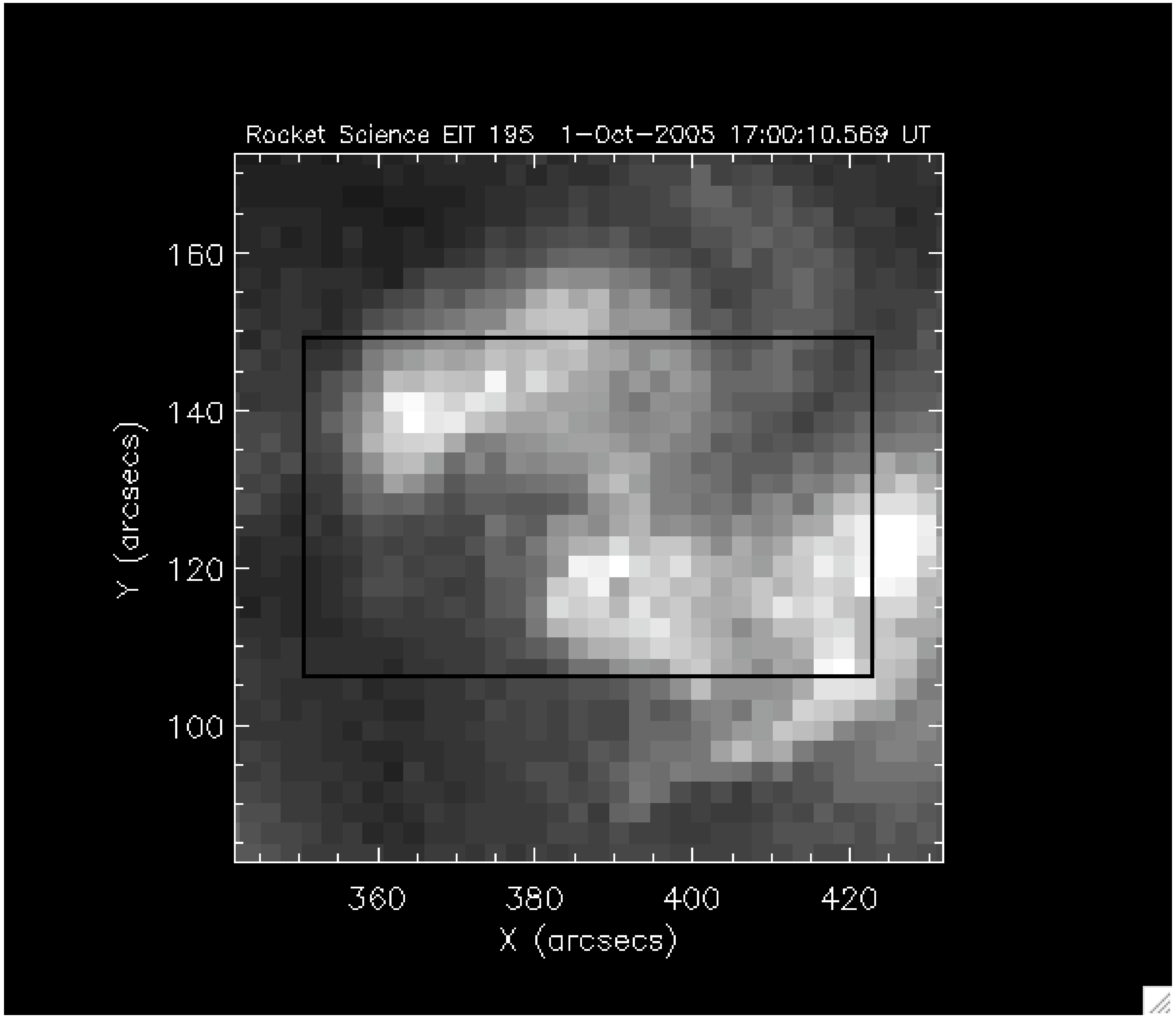
- Ca II 854.2 nm
- samples many pressure scale heights

- base of corona is very different from photosphere



G. Cauzzi et al 2008, A+A

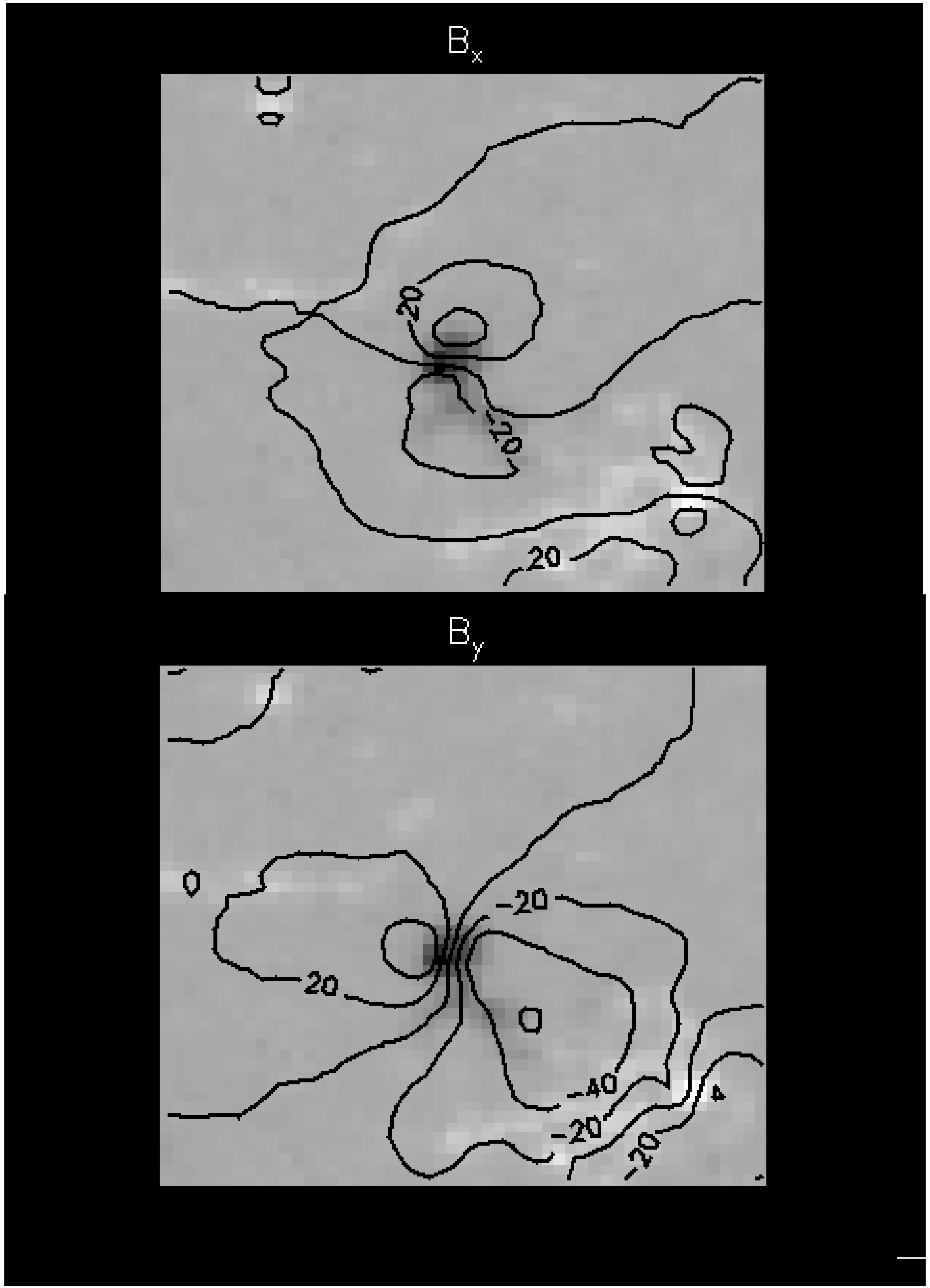
Small AR, pores: high resoution photosphere and chromosphere



detailed study of IBIS data: G. Cauzzi et al 2008, A+A

Differences between potential and constant α photospheric fields

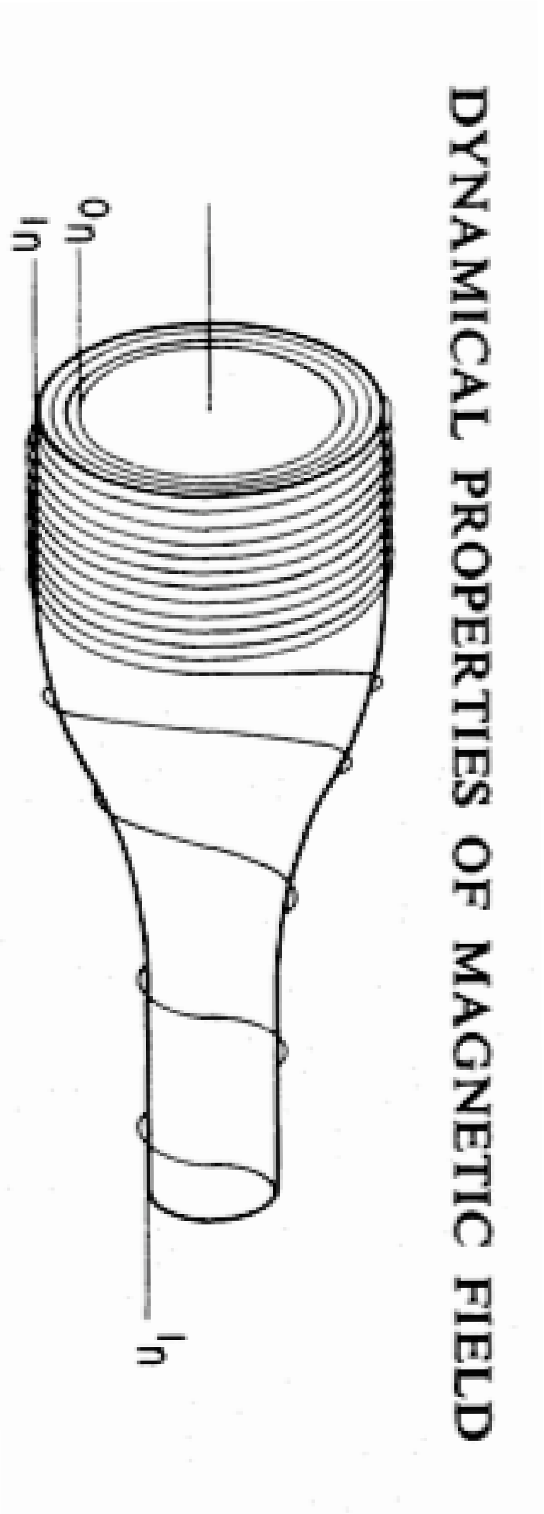
- IBIS morphology⇒ transverse fields differ by ~20-40G
- Hinode 630.2 sensitivity B_T(app) Lites et al (2008) ApJ **672**, 1237
  - 40 Mx $\mathrm{cm}^{-2}\,\mathrm{px}^{-1}$ (normal map)
  - 20 Mx $\mathrm{cm}^{-2}\,\mathrm{px}^{-1}$ (deep map)
- Hinode can study photospheric vs chromospheric electrical currents, forced ➔ force free transition!
- Total ÷ potential energy:
  - 2 (chromosphere)
  - 5-10 (corona)

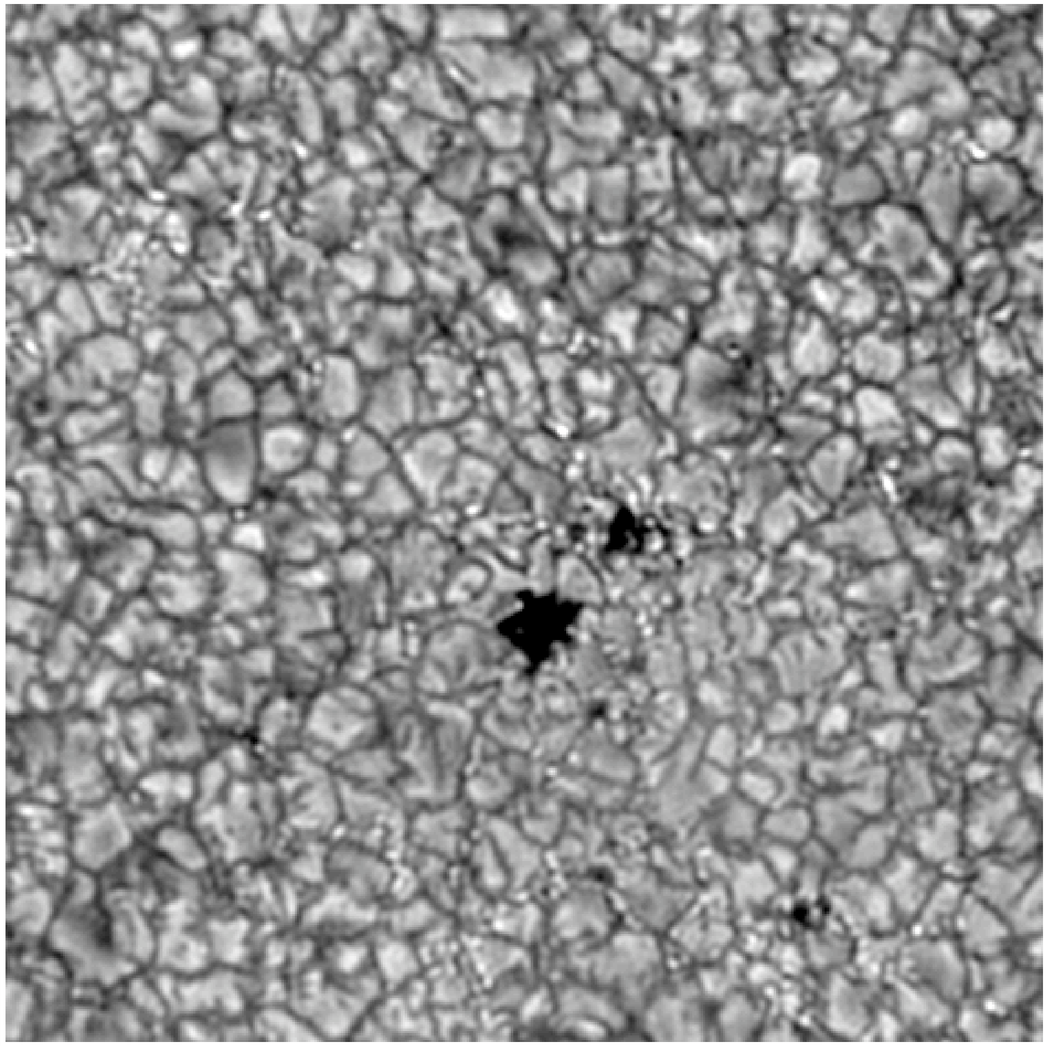


the future:
imaging spectroscopy/
spectropolarimetry

twist/electrical currents revealed in the chromosphere!

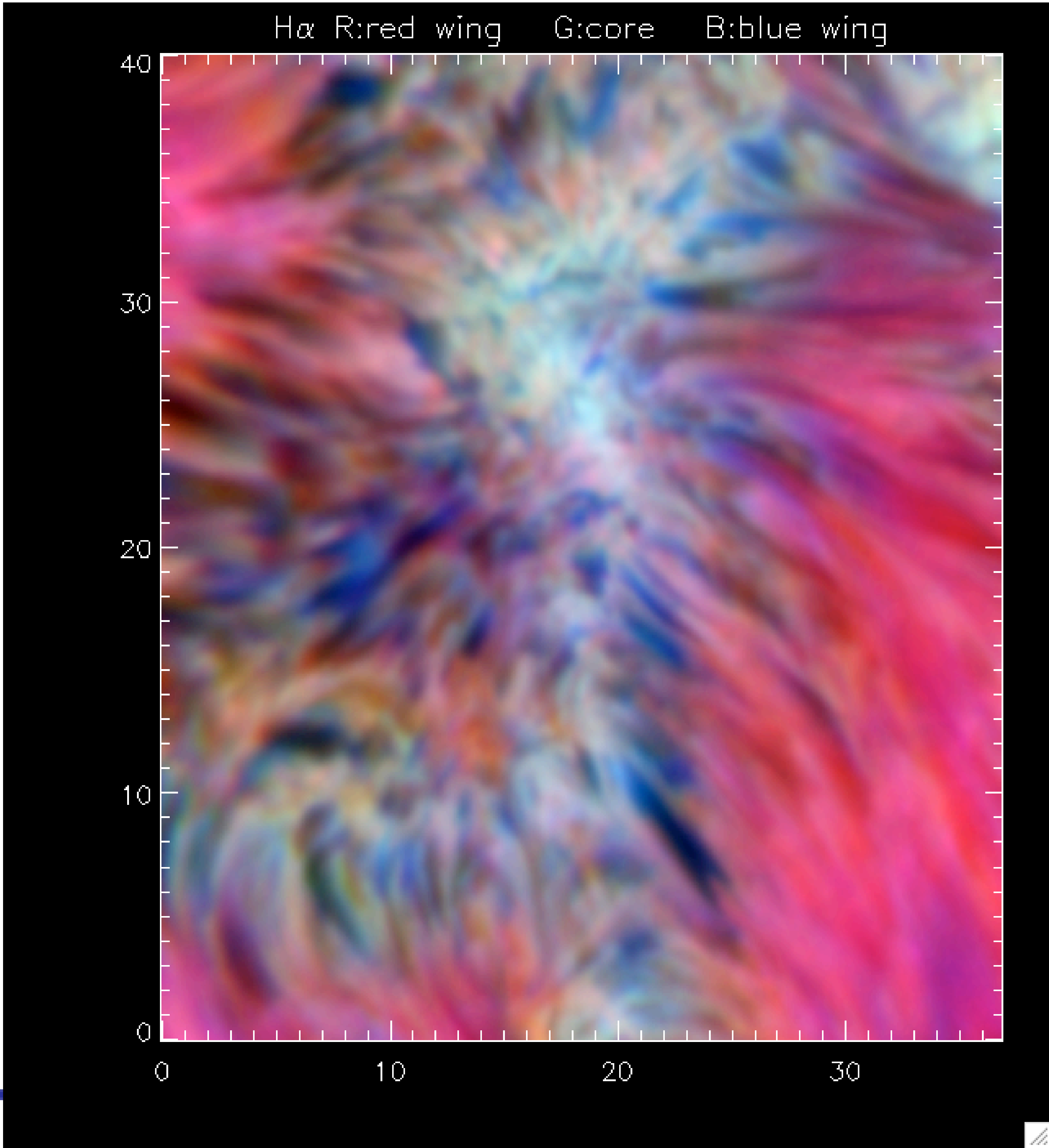
- IBIS again: clear $B_\varphi \Rightarrow j_z$
- Hinode rotating spicules
- Parker (1974):
  - B_φ/B_z *increases with* z





IBIS Fe I 6302, Ca II IR IQUV, Hα I

- joint IBIS/ Hinode/Trace
- 20 May 2008
- pore/network



Conclusions

- the magnetic chromosphere remains poorly understood
- the Sun undergoes the awkward transition from forced **$\beta>1$** to force-free **$\beta<1$** there: **$j\times B \rightarrow 0$ at the coronal base**
- magnetic free energy → chromospheric, heat, radiation, spicules?
  - dissipation of **$j_\perp$: $j\times B \rightarrow 0$,**
  - **$\alpha(r) \rightarrow$? at the coronal base:** Parker's current sheets
  - observed chromospheric losses might arise from **$j_\perp.E$? (friction)**
- spicules/fibrils+neutral diffusion+coronal heat
  - finally explains the lower transition region?
- **meaningful** photos./chromos. polarimetry is here and is needed to
  - understand basic MHD physics (e.g. Pietarila & colleagues)
  - understand magnetism at the coronal base (e.g. Wiegelmann, Schrijver)
- 3-fluid MHD models are needed to assess chromospheric processes and hence coronal base conditions