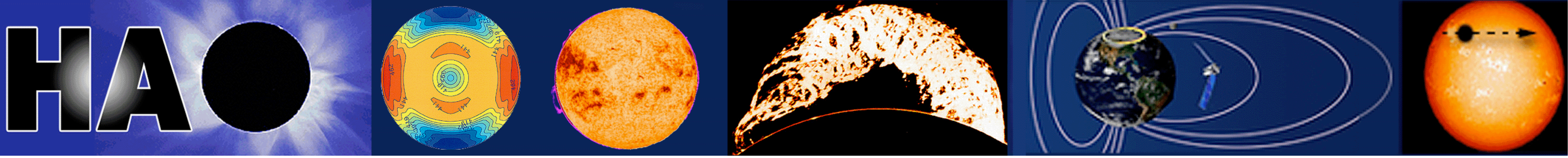


The photosphere/corona interface: new perspectives

Philip Judge + R. Centeno, M. Kubo, B. Lites, S. McIntosh, A. G. de Wijn, HAO; G. Cauzzi, K. Reardon, Arcetri; A. Tritschler, H. Uitenbroek NSO

re-visiting some physical issues

old vs. new perspectives

magnetic interface

thermal interface

September 2008

PLATE X

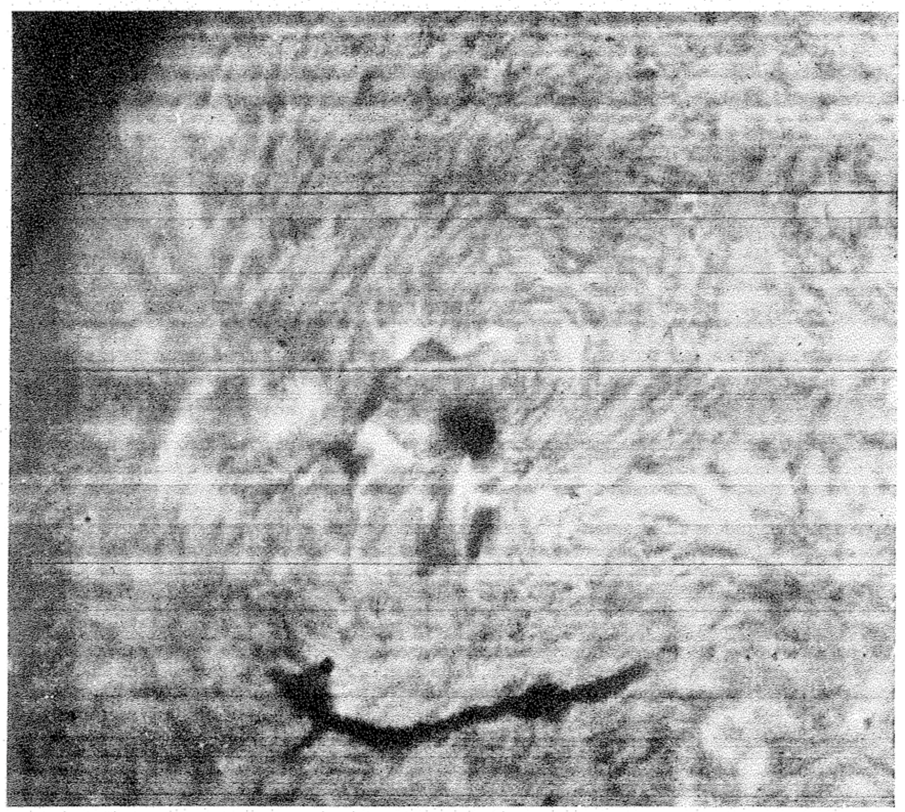


FIG. 1.—SUN-SPOT AND HYDROGEN ($H\alpha$) FLOCCULI
1908, May 29, 4h 26m P. M. Scale: Sun's Diameter = 0.3 Meter

NCAR

ESSL

the chromosphere

- stratified: spans 9 pressure scale heights
- requires 30-100x as much power as the corona
- usually contains plasma β=1 surface
- 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
- yet
  - "chromosphere Hinode" search reveals 1/3 of "corona Hinode" publications
  - chromosphere is an "ignore-o-sphere"?
  - "too complicated"?

Example of "old" perspectives
SKYLAB data - VAL thermal models

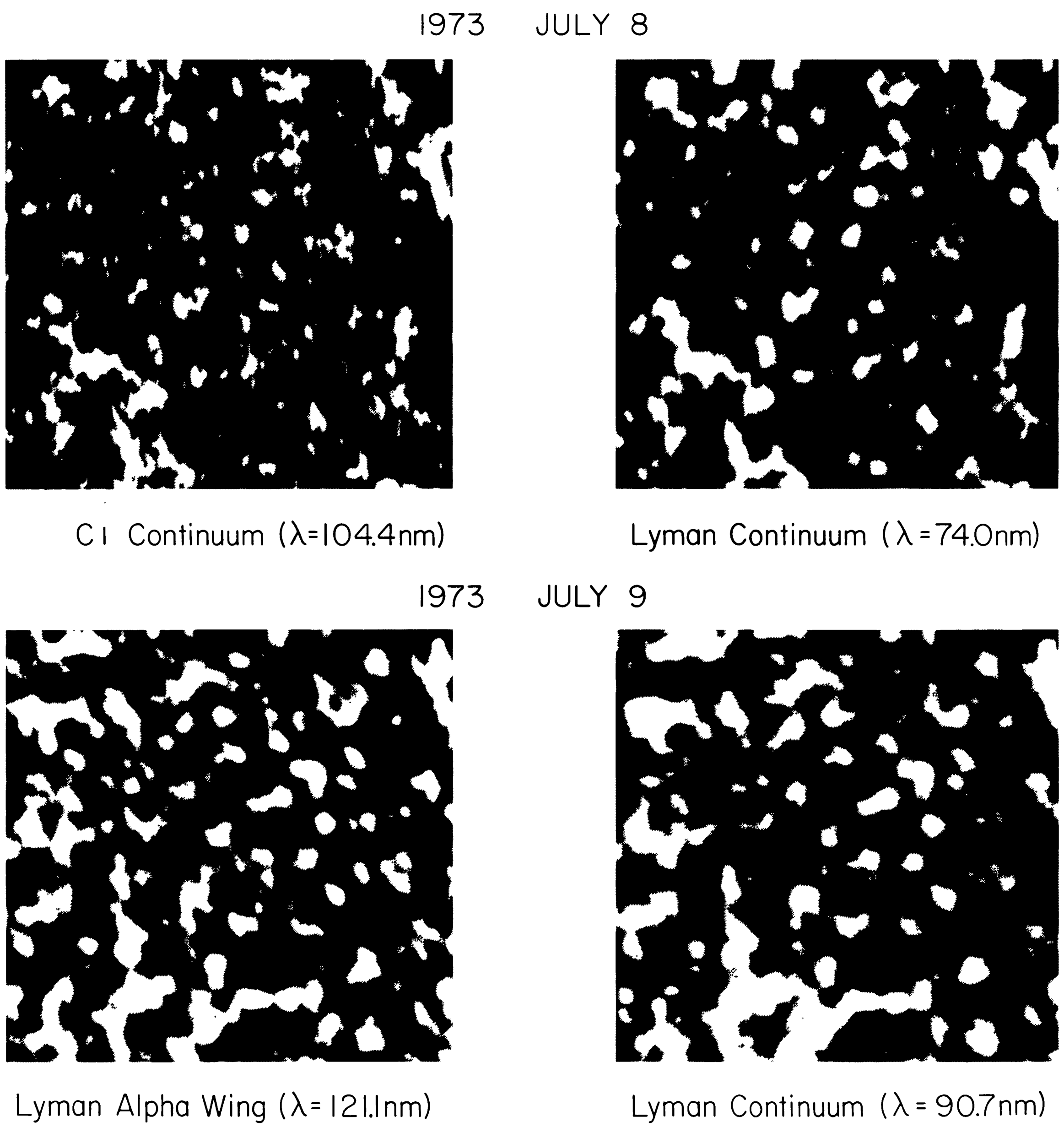
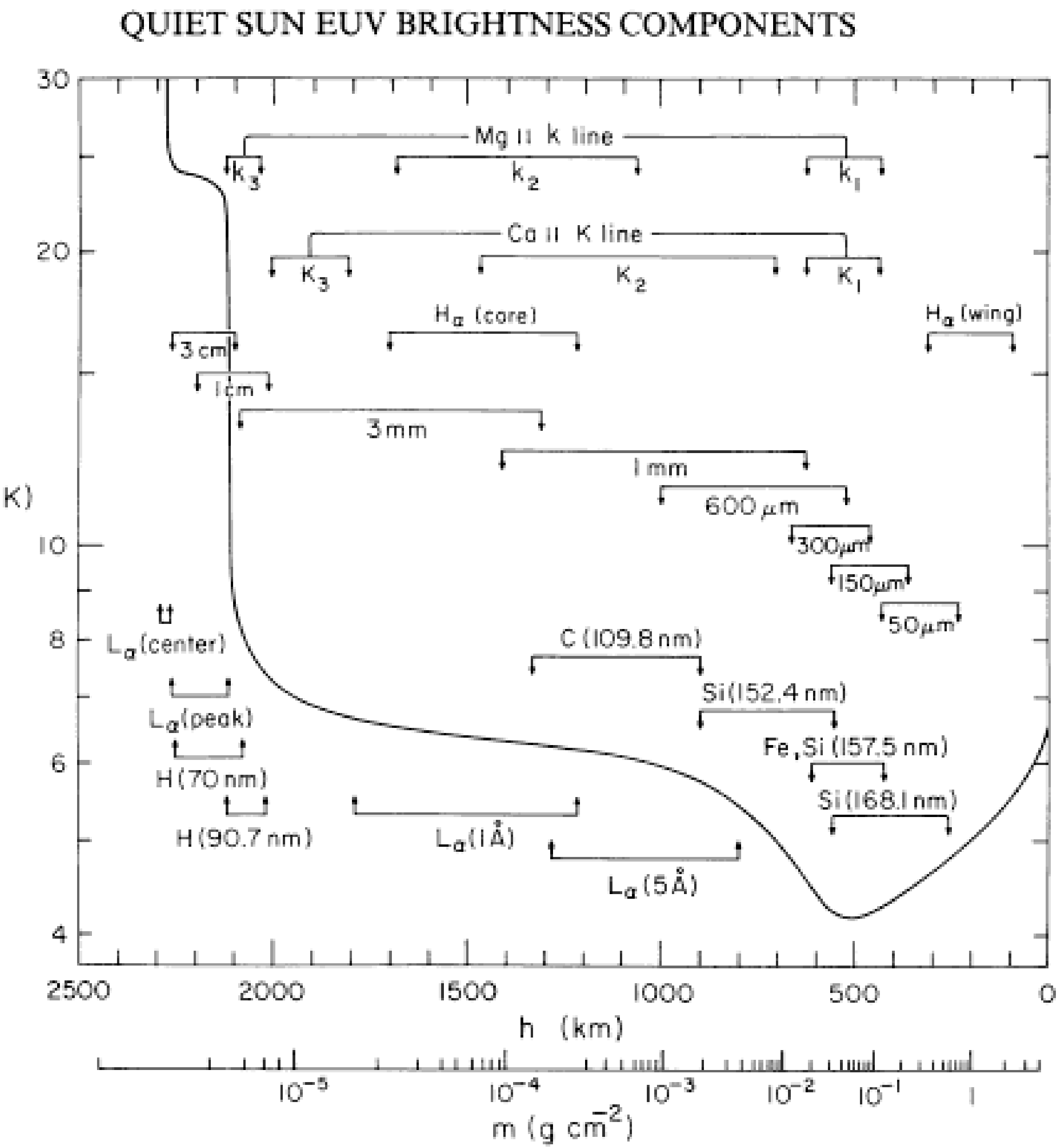


FIG. 6.—*Skylab* spectroheliograms of two 5′×5′ areas of the solar surface, at wavelengths 104.4 and 74 nm (*above*) and wavelengths 121.1 and 90.7 nm (*below*).

VERNAZZA *et al.* (*see* page 647)

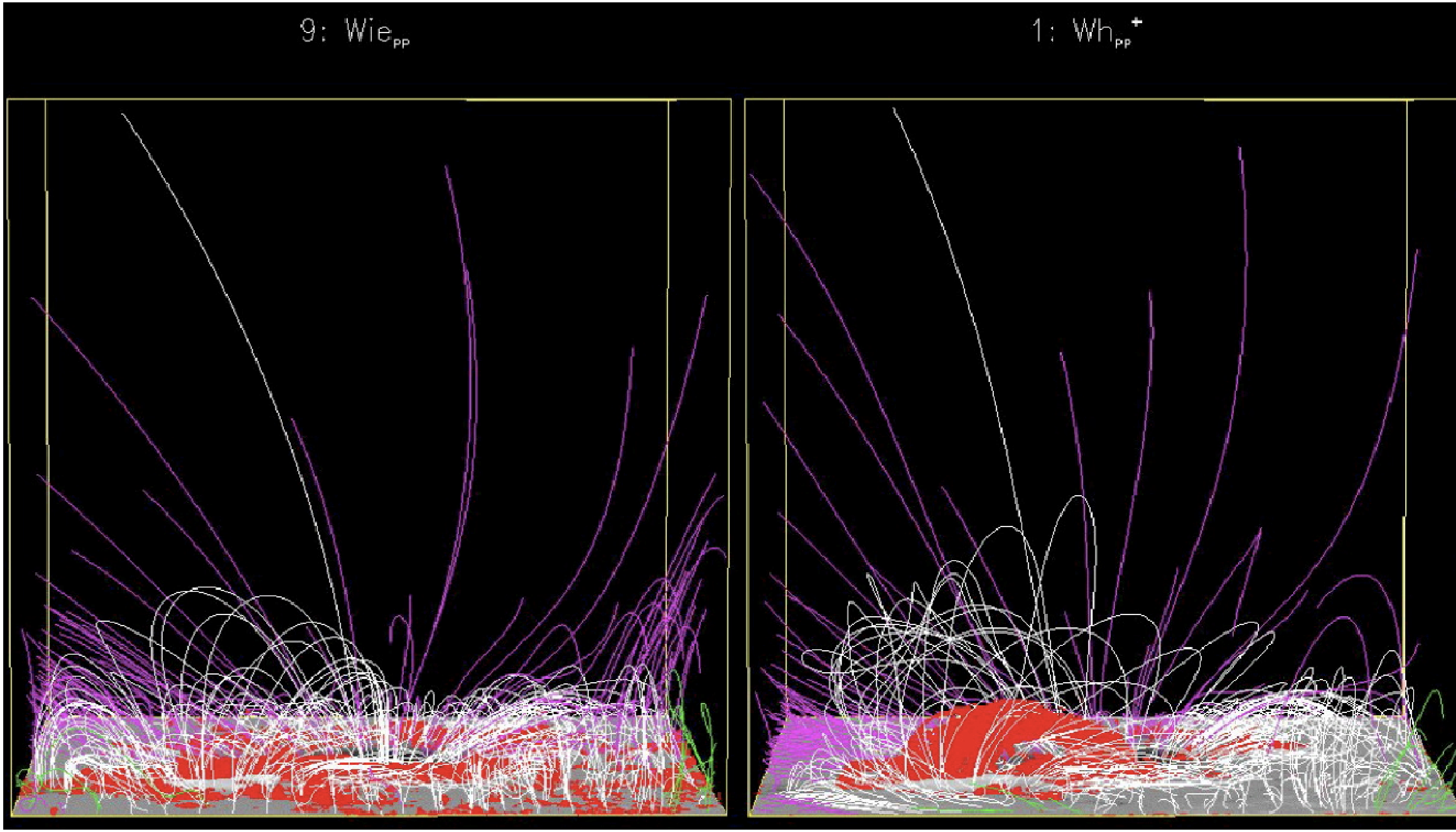
1D
RT
nLTE
HSE
PRD
...



Heroic reference work of vital importance, 1981

Recent(!) example of "old" perspectives nlff field extrapolation (Schrijver et al 2008)

red: current



Hinode SP photospheric vector polarimetry, no chromospheric data (nb. Low & Flyer 2007)

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

photosphere
chromosphere
corona

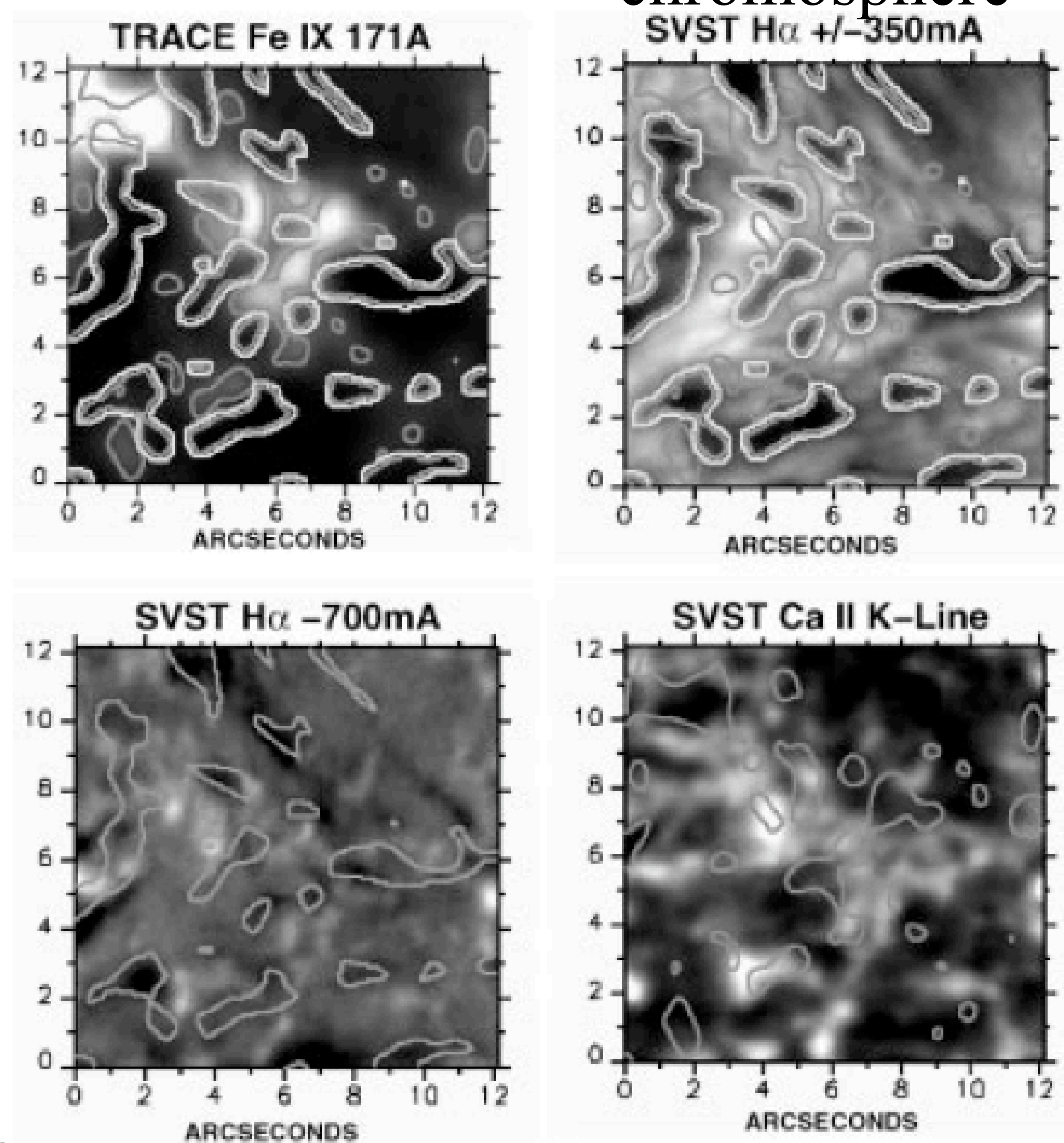
magnetic interface

Magnetism and the solar atmosphere

- measure ***B*** where possible
- high plasma conductivity- "trace field lines" from photosphere to corona
- TRACE & other missions failed to do this
- why?- chromosphere

lower corona

upper chromosphere



upper chromosphere

magnetic elements + reverse granulation

De Pontieu et al. 1999
"moss"

Gold (1964)

- consider potential and f-f fields in upper half
- the electro-dynamics of the chromosphere is critical to the supply of magnetic free energy into the corona.
- traditionally it is treated as in the figure

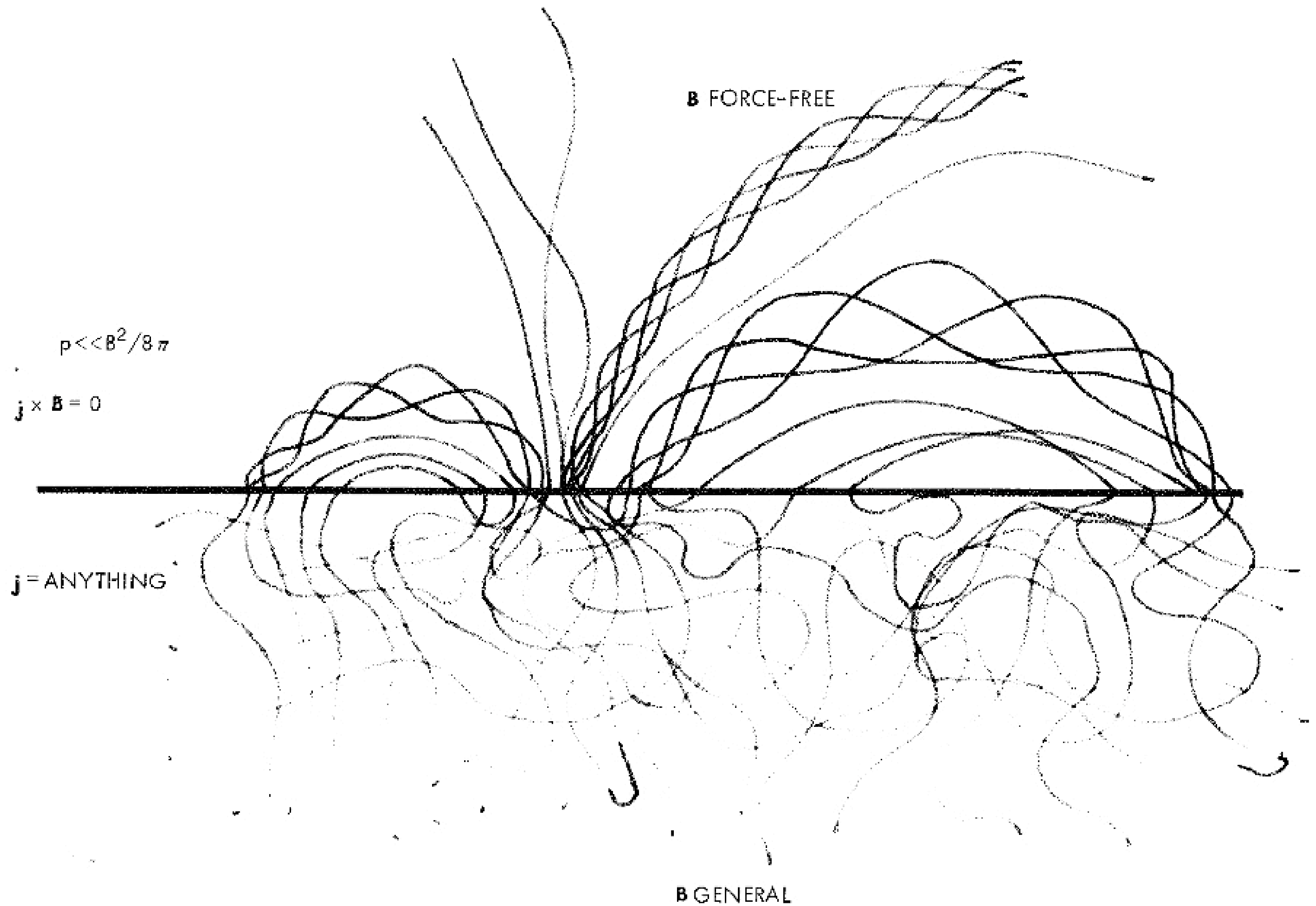


FIGURE 44–2. Magnetic field in a turbulent conducting medium. The fluid pressure is assumed large compared with magnetic forces below the dividing plane and small above it.

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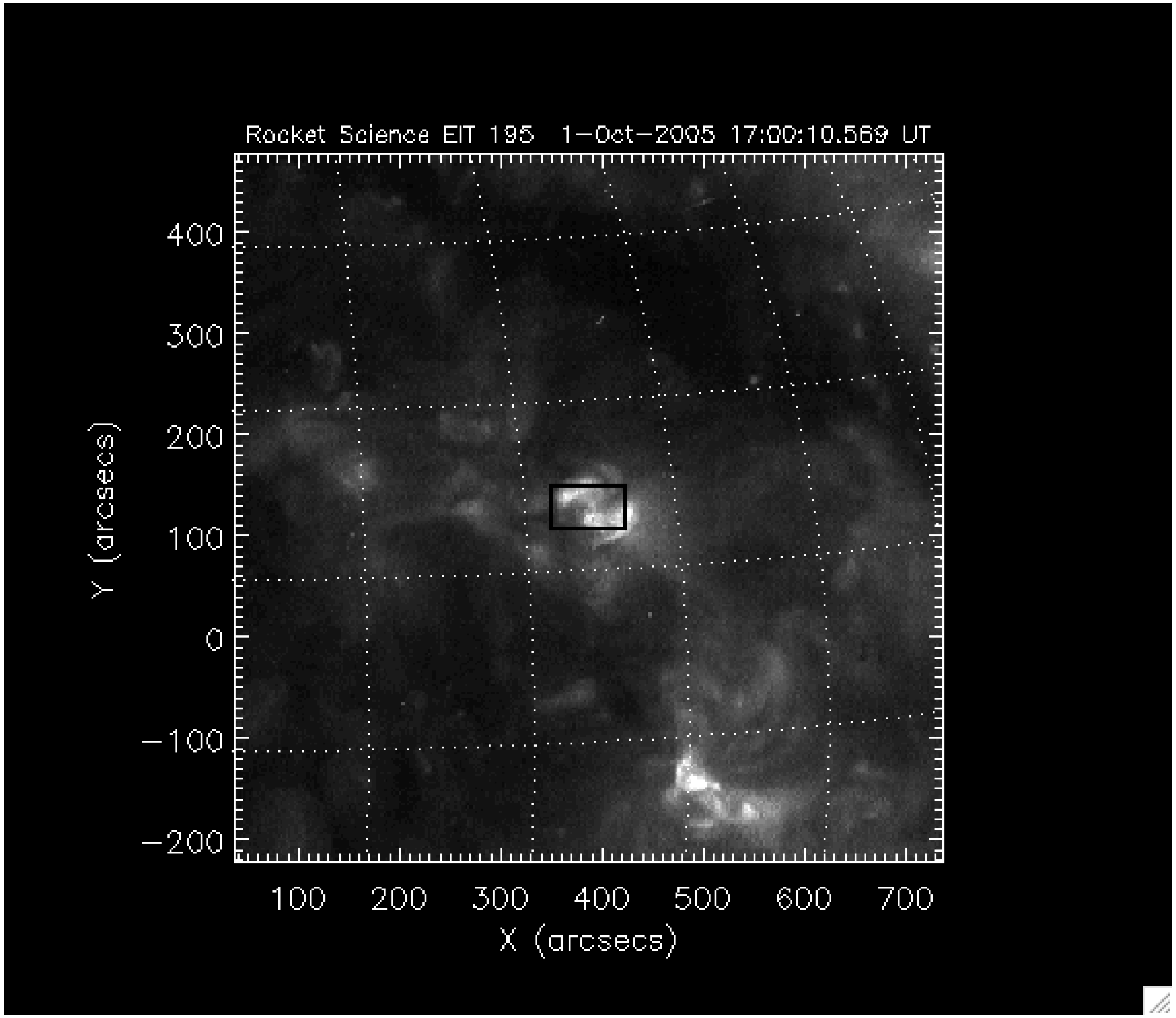
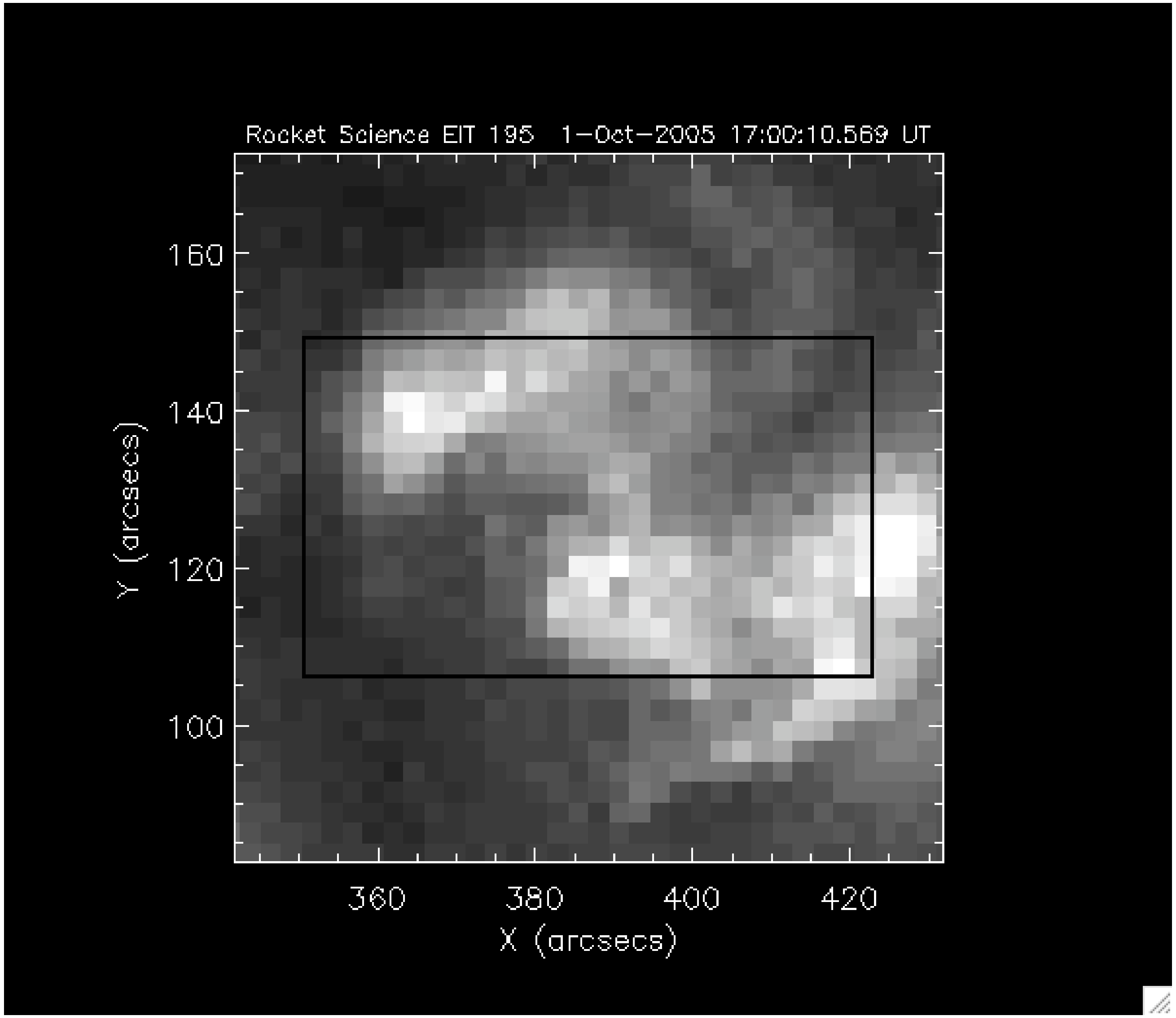
magnetic interface observations:
an example

Small AR, pores

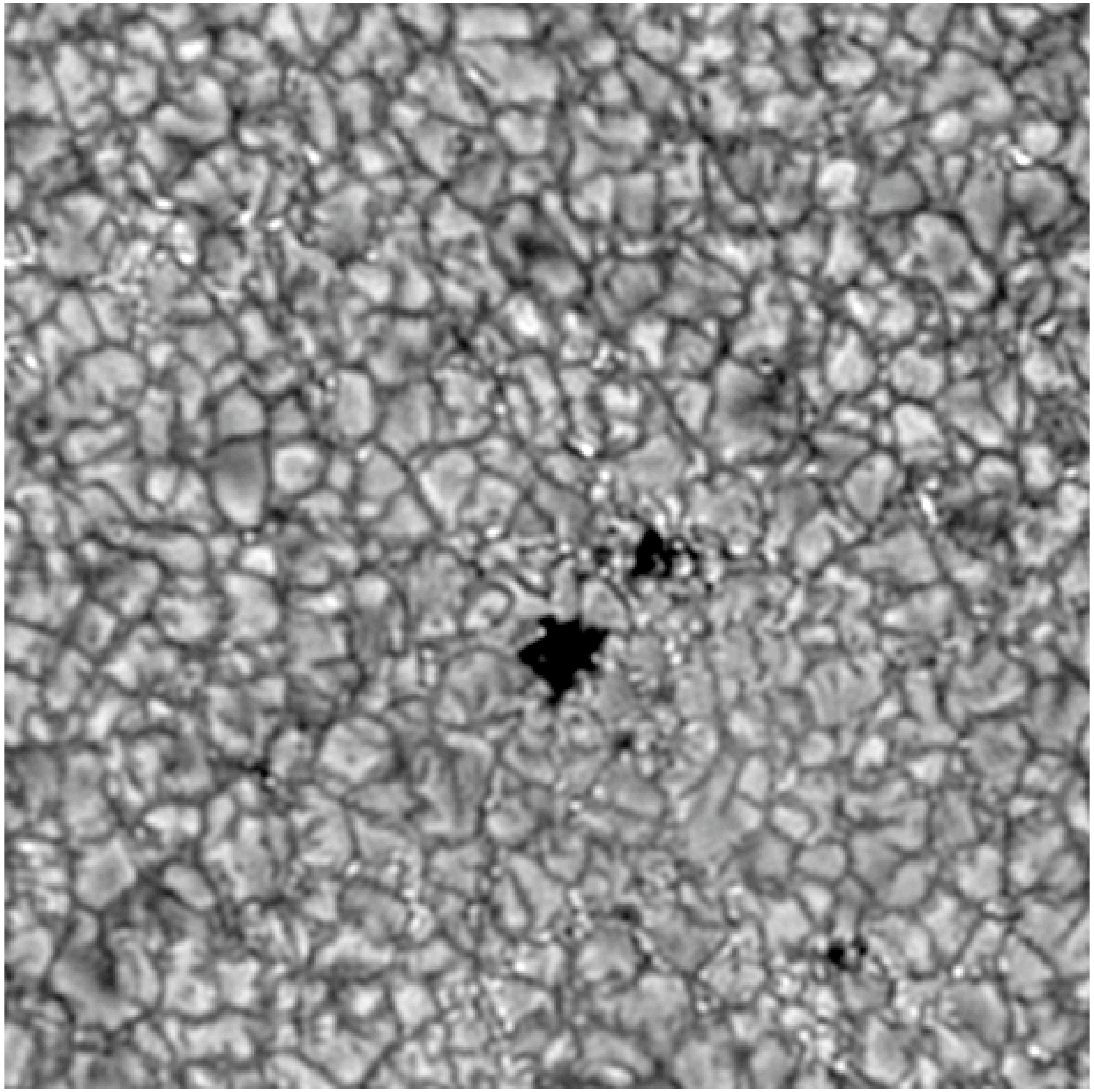


Small AR, pores: closer view



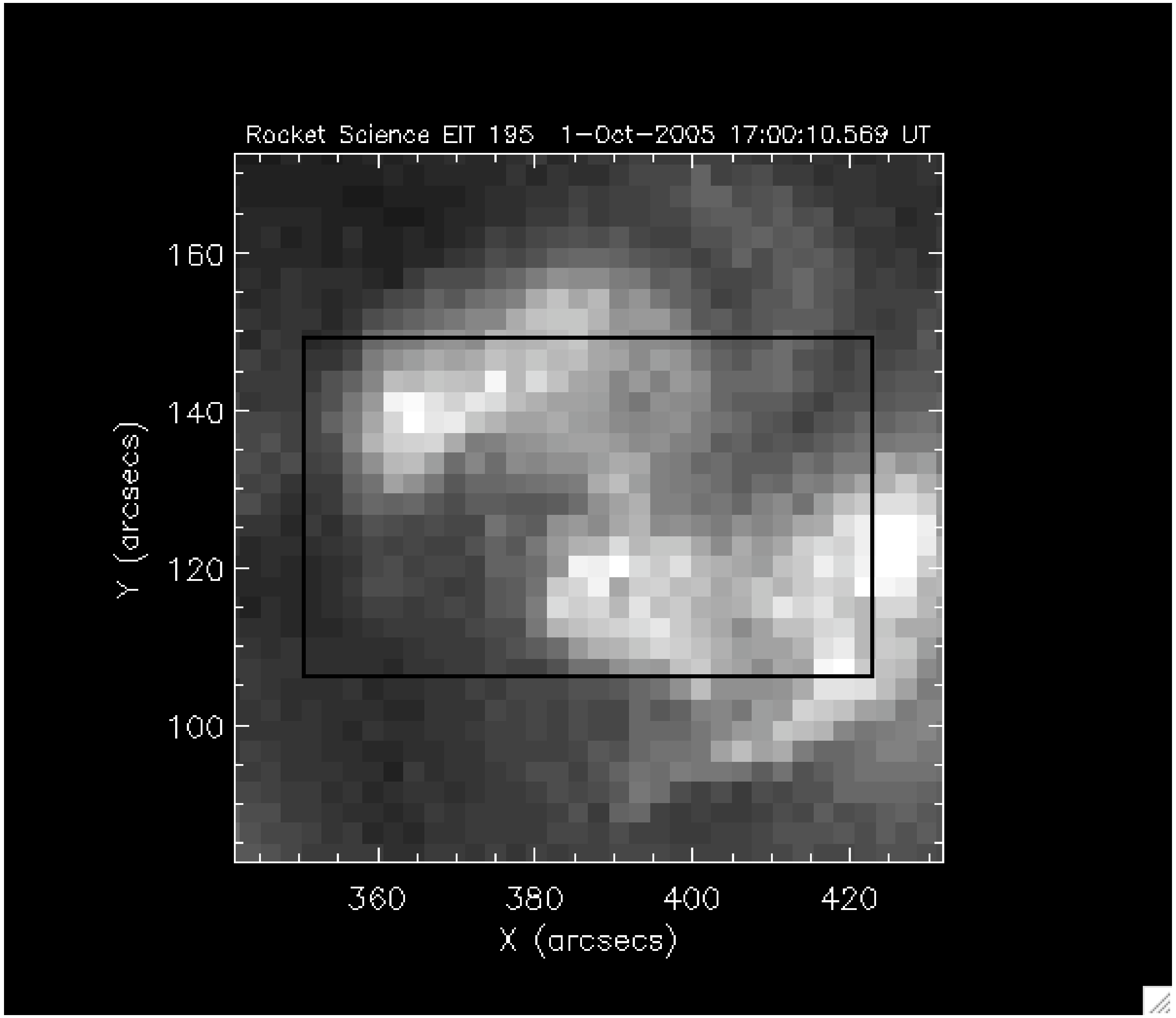
Chromosphere as seen with IBIS

- 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

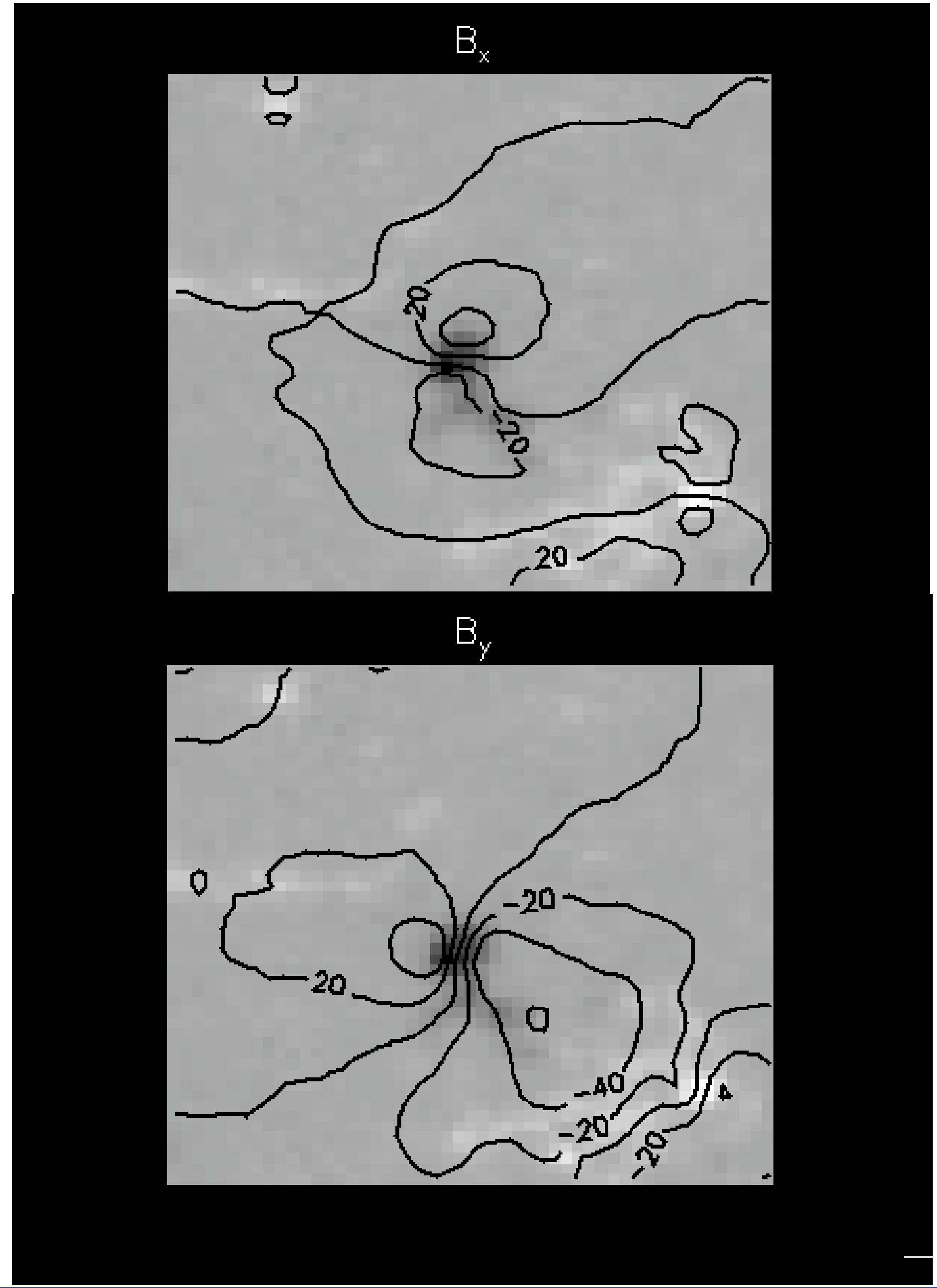
Small AR, pores: high resoution photosphere and chromosphere



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 cm^{-2} px^{-1} (normal map)
  - 20 Mx cm^{-2} px^{-1} (deep map)
- Hinode can study photospheric vs chromospheric electrical currents, forced ➔ force free transition!
- Total ÷ potential energy:
  - 2 (chromosphere)
  - 5-10 (corona)



Hale 1908: 100 years on

PLATE X

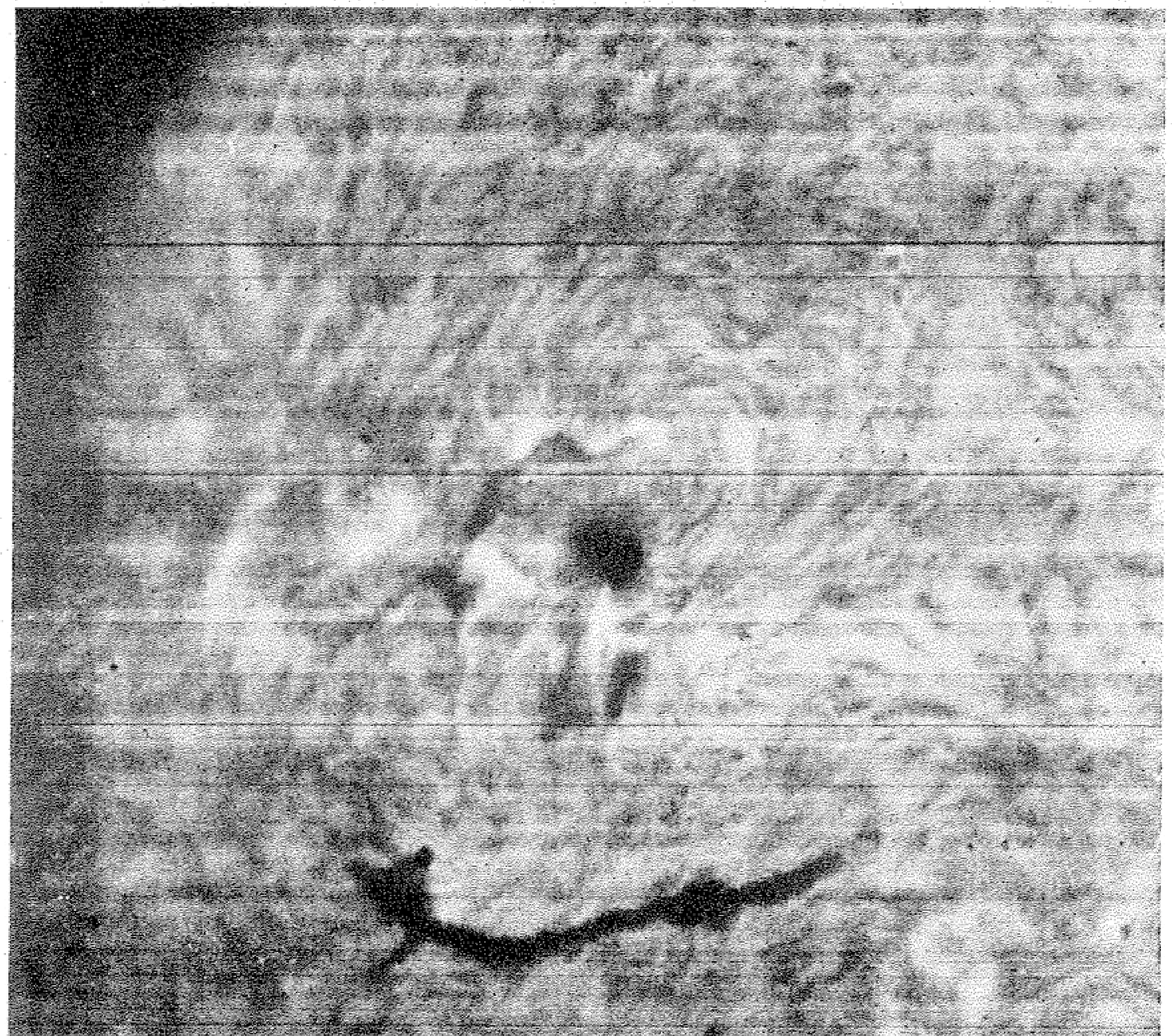


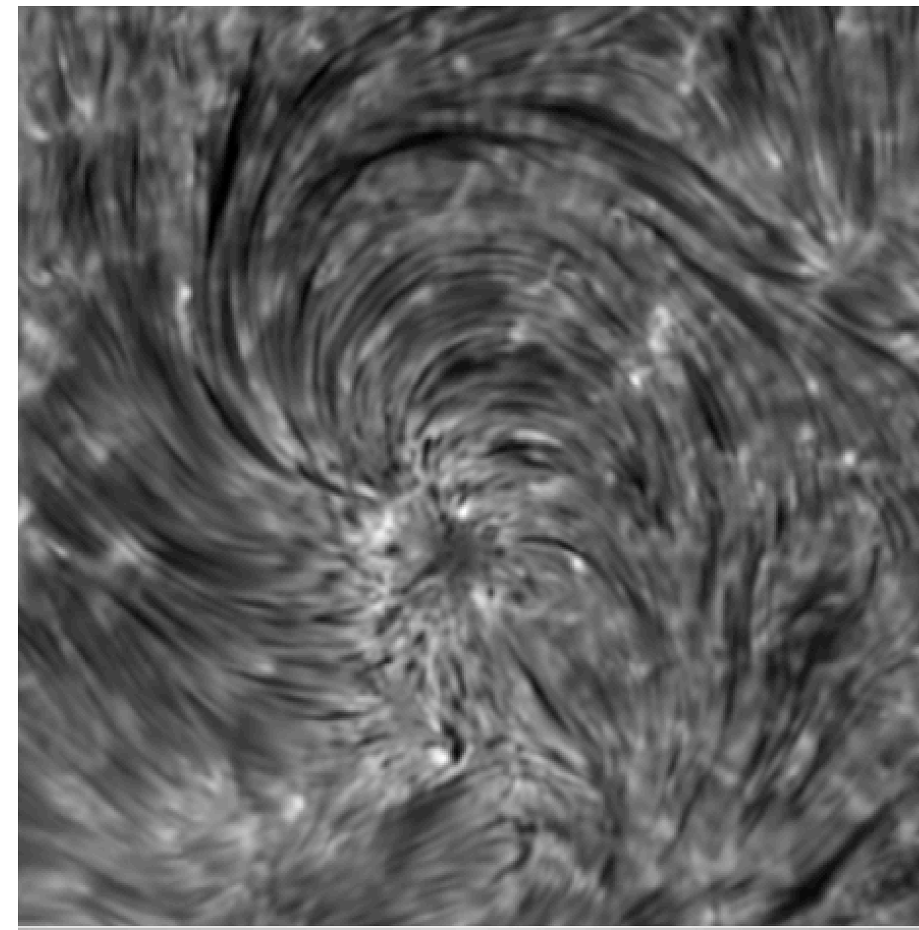
FIG. 1.—SUN-SPOT AND HYDROGEN ($H\alpha$) FLOCCULI
1908, May 29, 4^h 26^m P. M. Scale: Sun's Diameter = 0.3 Meter

Inspiration for much work generically called "chromospheric fine structure"

magnetic interface
physical considerations

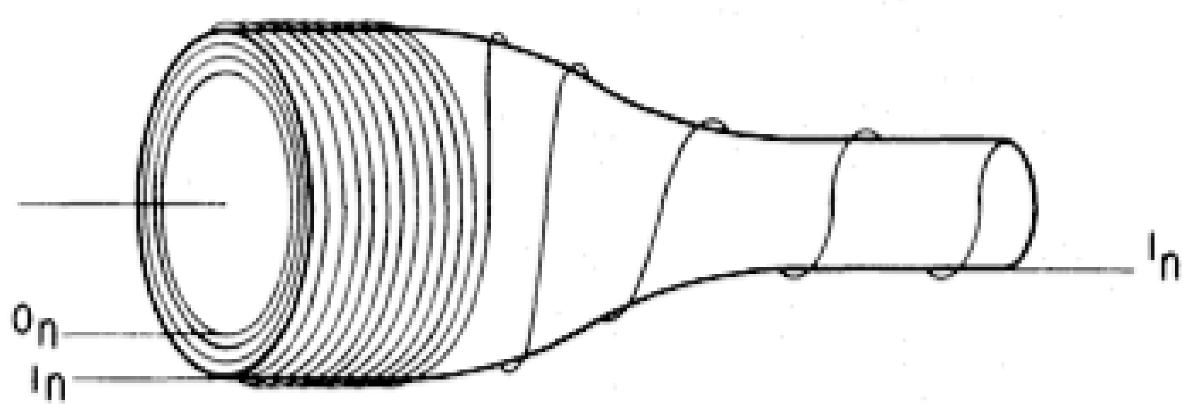
Note: twist/ electrical currents can be easier to detect in the chromosphere!

- IBIS again: clear $B_\varphi \Rightarrow j_z$
- Hinode rotating spicules
- ang. mom. conservation around tubes
- Knölker et. al. (1988)- tube stability requires rotating flow



- Parker (1974): B_φ/B_z *increases with z*

DYNAMICAL PROPERTIES OF MAGNETIC FIELD



Chromosphere vs. photosphere as the coronal boundary

- chromosphere spans 9 scale heights
- $\Rightarrow$ chromosphere usually contains β=1 surface
  - $|\mathbf{j}\times\mathbf{B}| \rightarrow \boldsymbol{\beta}\, B^2/2\mu$ above β=1 **$\mathbf{j}_\perp \rightarrow$ small**
- partial ioniz$^n \Rightarrow$ 3-fluid frictional dissipation, heating
  - $Q_{fr} = j^2/\sigma + (\xi_n\, \mathbf{j}\times\mathbf{B} - \mathbf{G})^2/\alpha_n$, $\mathbf{G} = \xi_n \nabla p - \nabla p_n$
  - "ambipolar diffusion"/star formation (1950s Schlüter, Cowling)
- case $\mathbf{G} = \mathbf{0} \Rightarrow$ "Cowling conductivity" $\sigma_\perp^*$ (Arber & cohorts)
  - $Q_{fr} = j_{\|}^2/\sigma + j_\perp^2/\sigma_\perp^*$ $\sigma/\sigma_\perp^* = 1 + 2\, \xi_n\, \varpi_e\tau_e\, \varpi_i\tau_i >> 1$
  - $\Rightarrow$ dissipation of $\mathbf{j}_\perp$. *Explains why IBIS nearly f-f?*
- NOTE: $\sigma_\perp^*$ is some steps removed from σ (kinetic theory)
  - case $\mathbf{G} \neq \mathbf{0}$: $\sigma_\perp^*$ incorrect!
  - one must simultaneously determine the nature of $\mathbf{j}_\perp$ (cf. E-region electrojet) from the dynamics

HAO

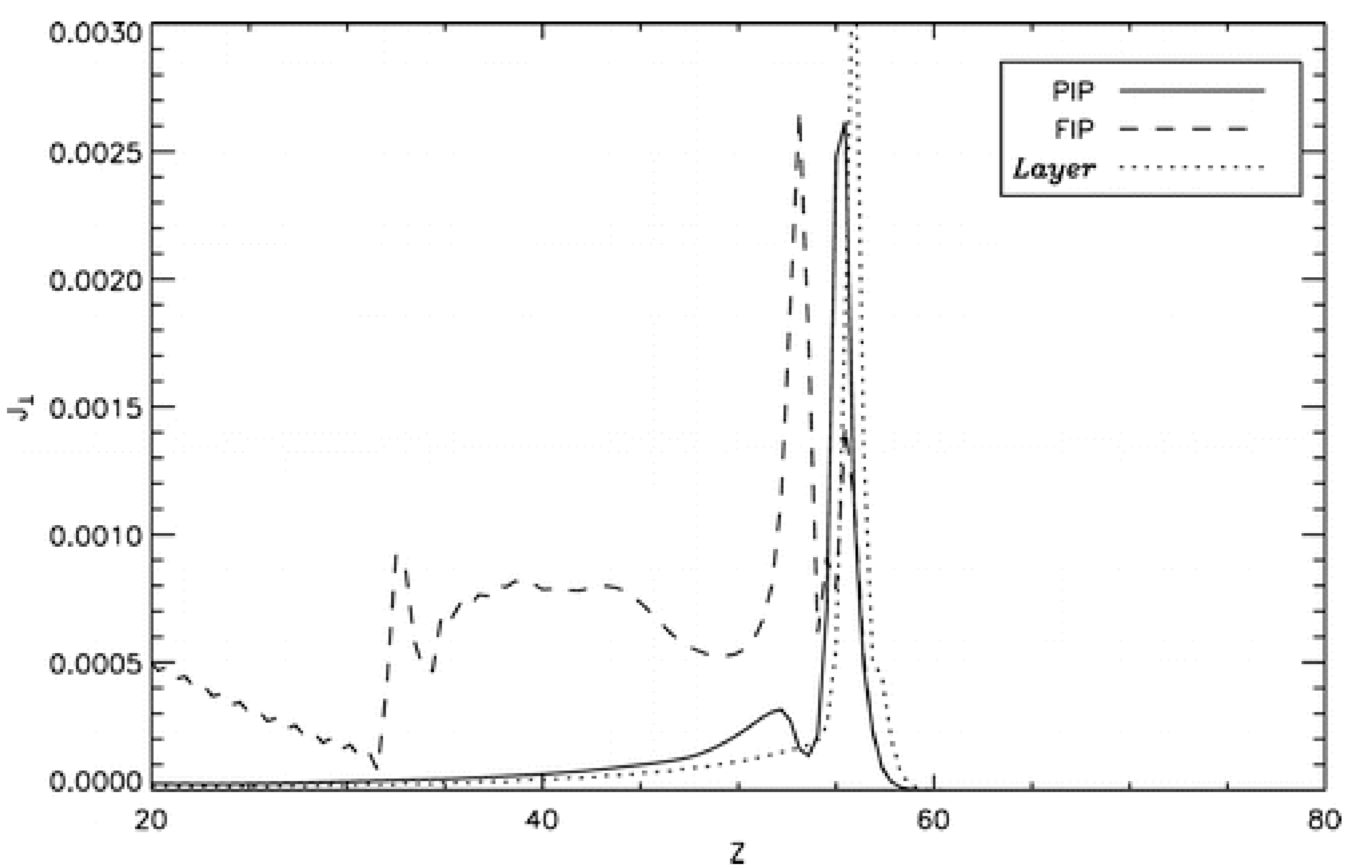
Chromosphere tends to "filter out" $j_\perp$: coronal base magnetic field → force-free

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

(Parker current sheets..)

*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 $t = 160$.

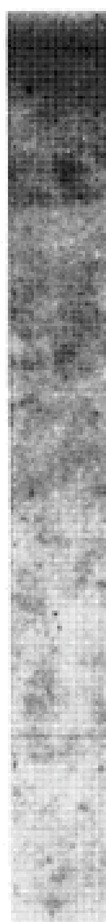


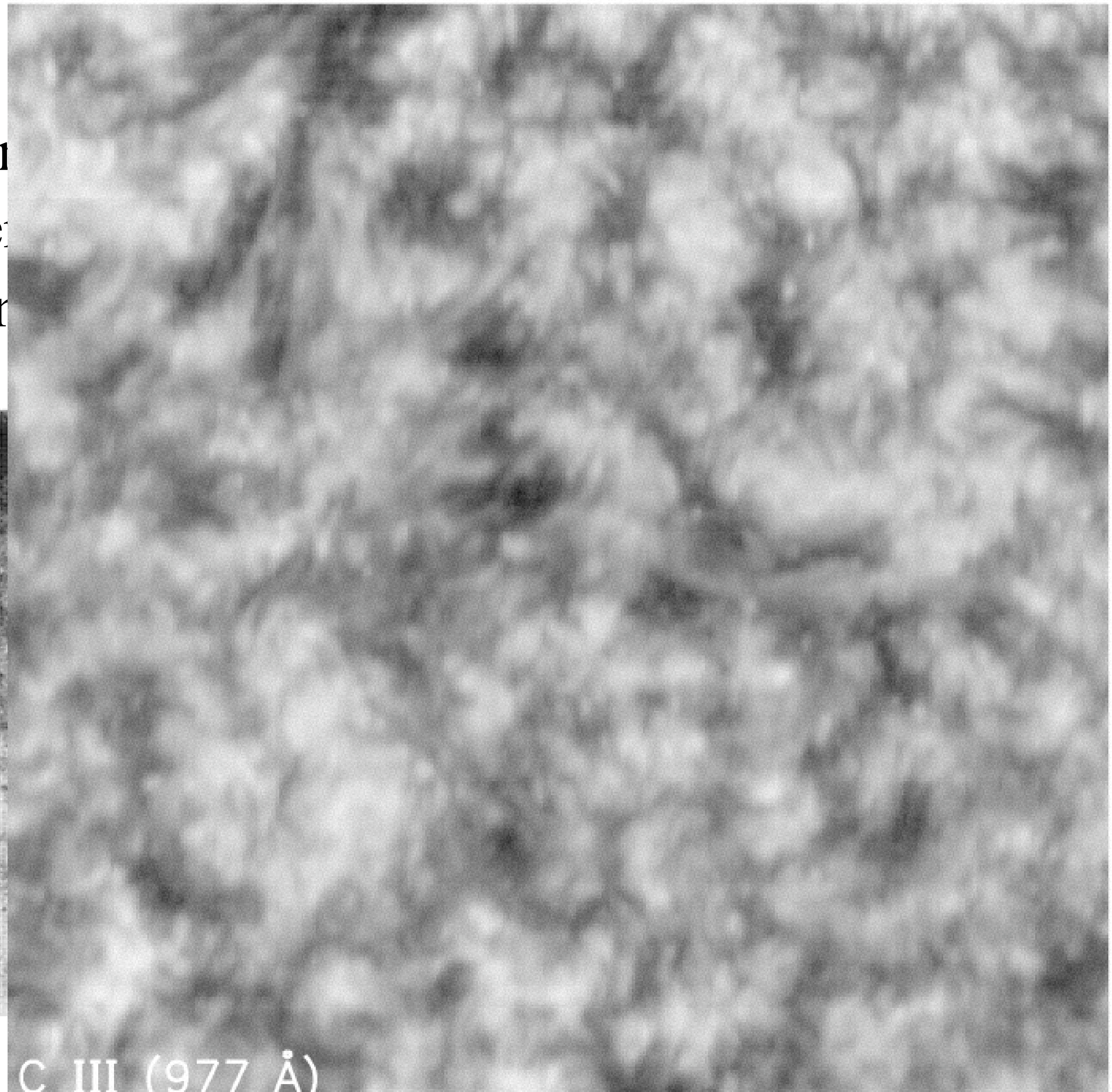
...radical effect on flux emergence process

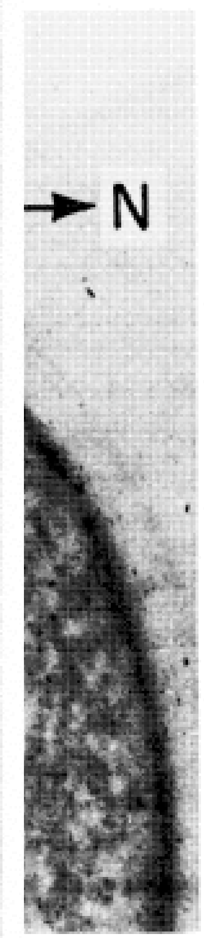
thermal interface

The problem- observations

- Feldman
  - differen
  - TR the
  - radiatin

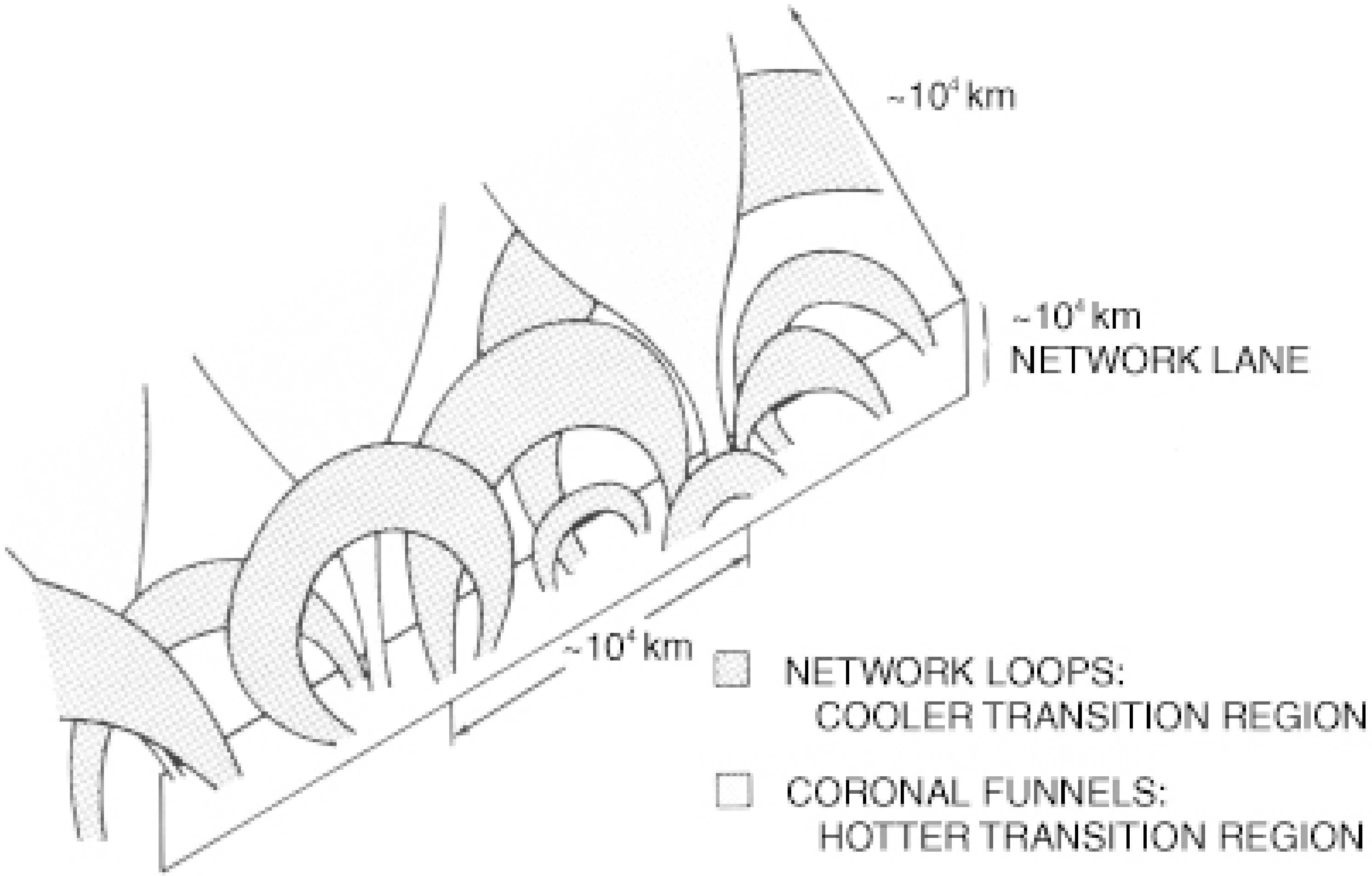




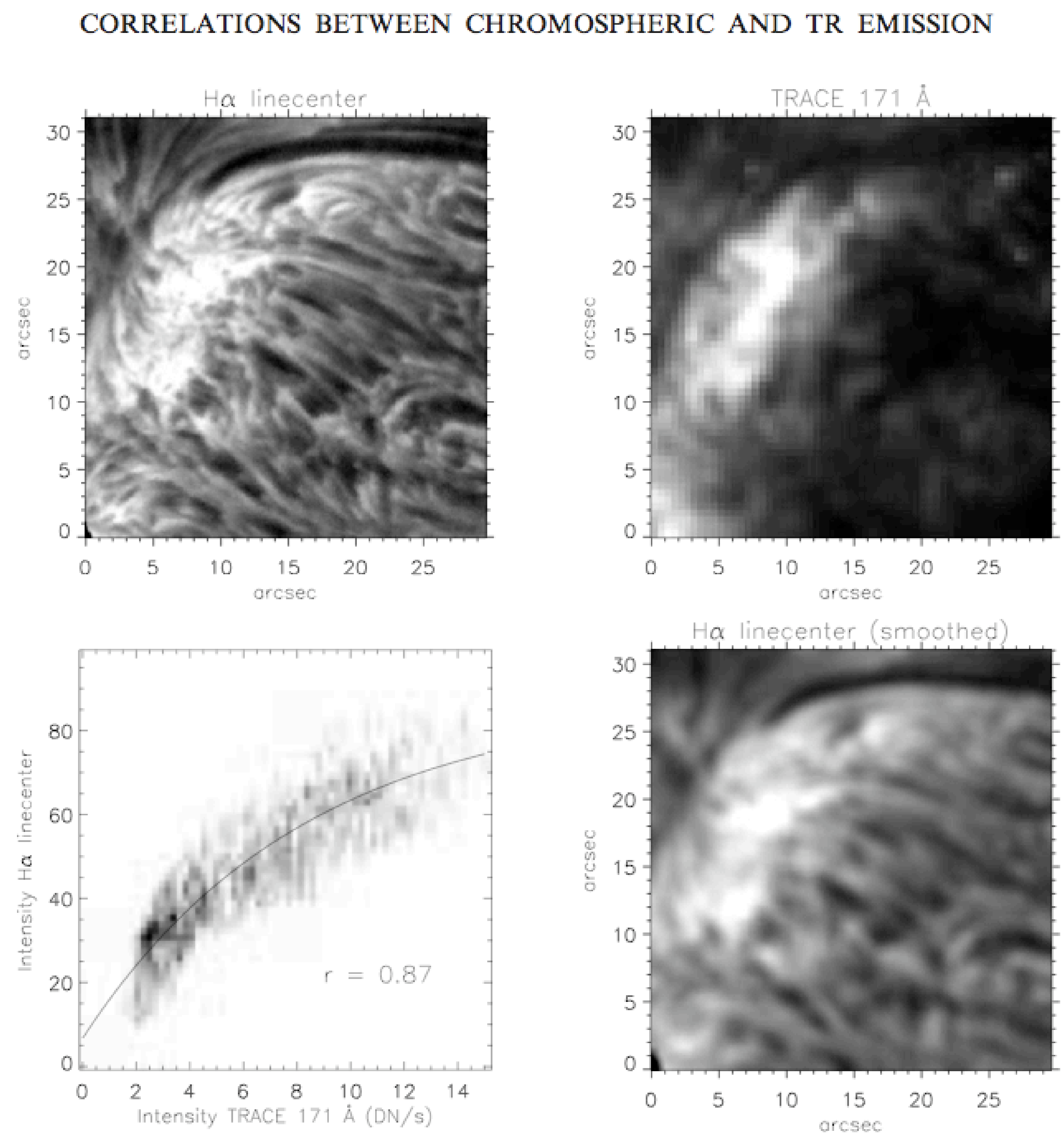


Dowdy et al. (1986)

- 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

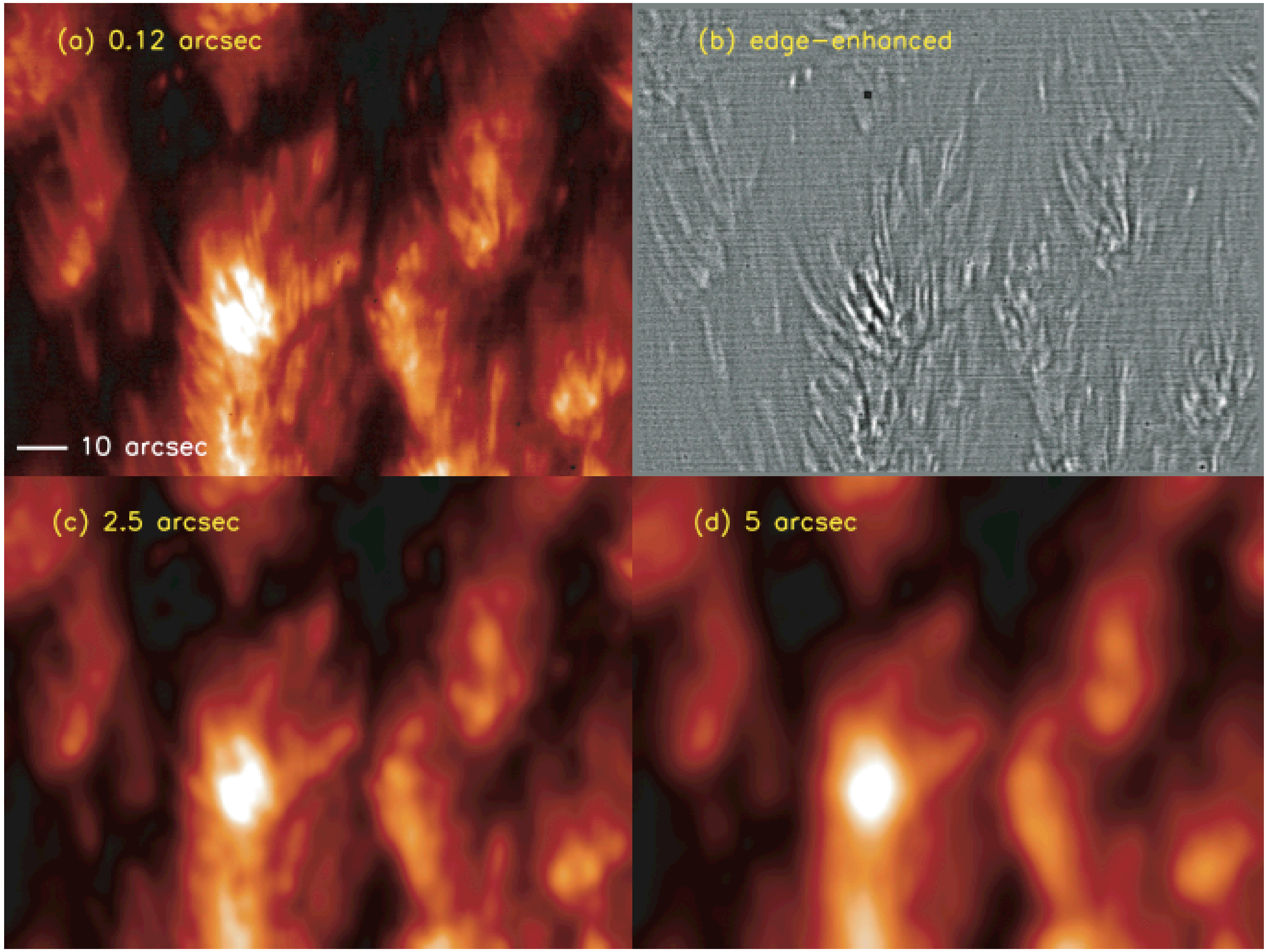
Questions concerning cool loops

- 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

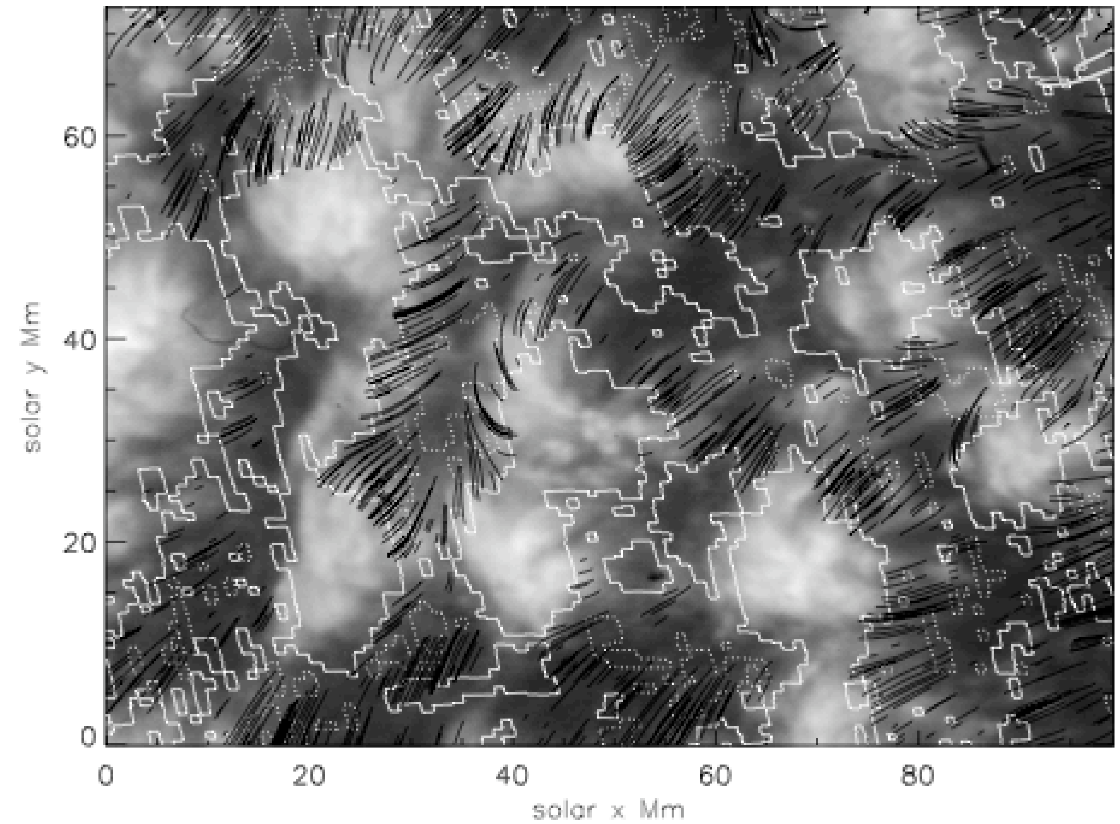
Black=low-lying loops (h<5Mm)
Gray= long

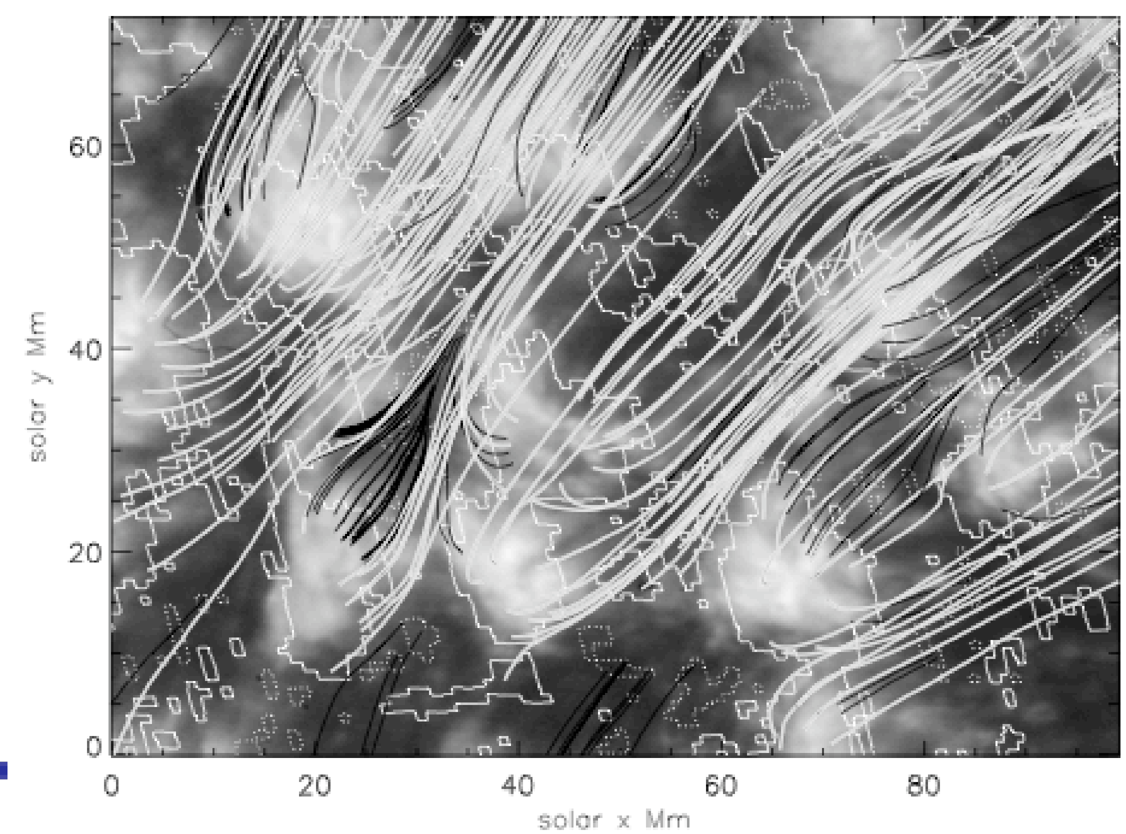
Stability requires that low- lying loops are possibly cool, but higher loops must be hot

Most Lα 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"- Lα emission forms above h=0.8 Mm. "Loops" with footpoints separated by 1" can't reach these heights





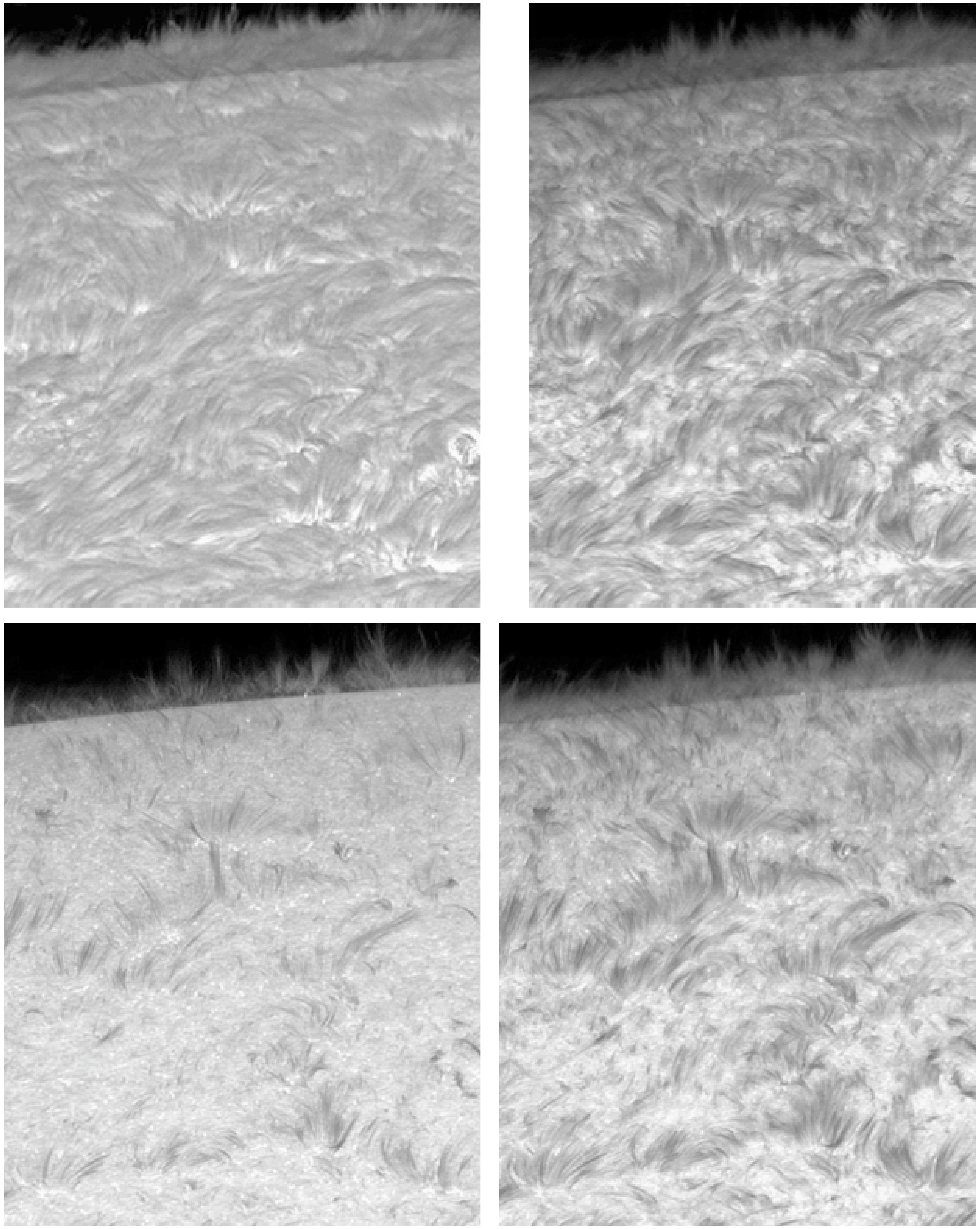
Spicules, fibrils..

- 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

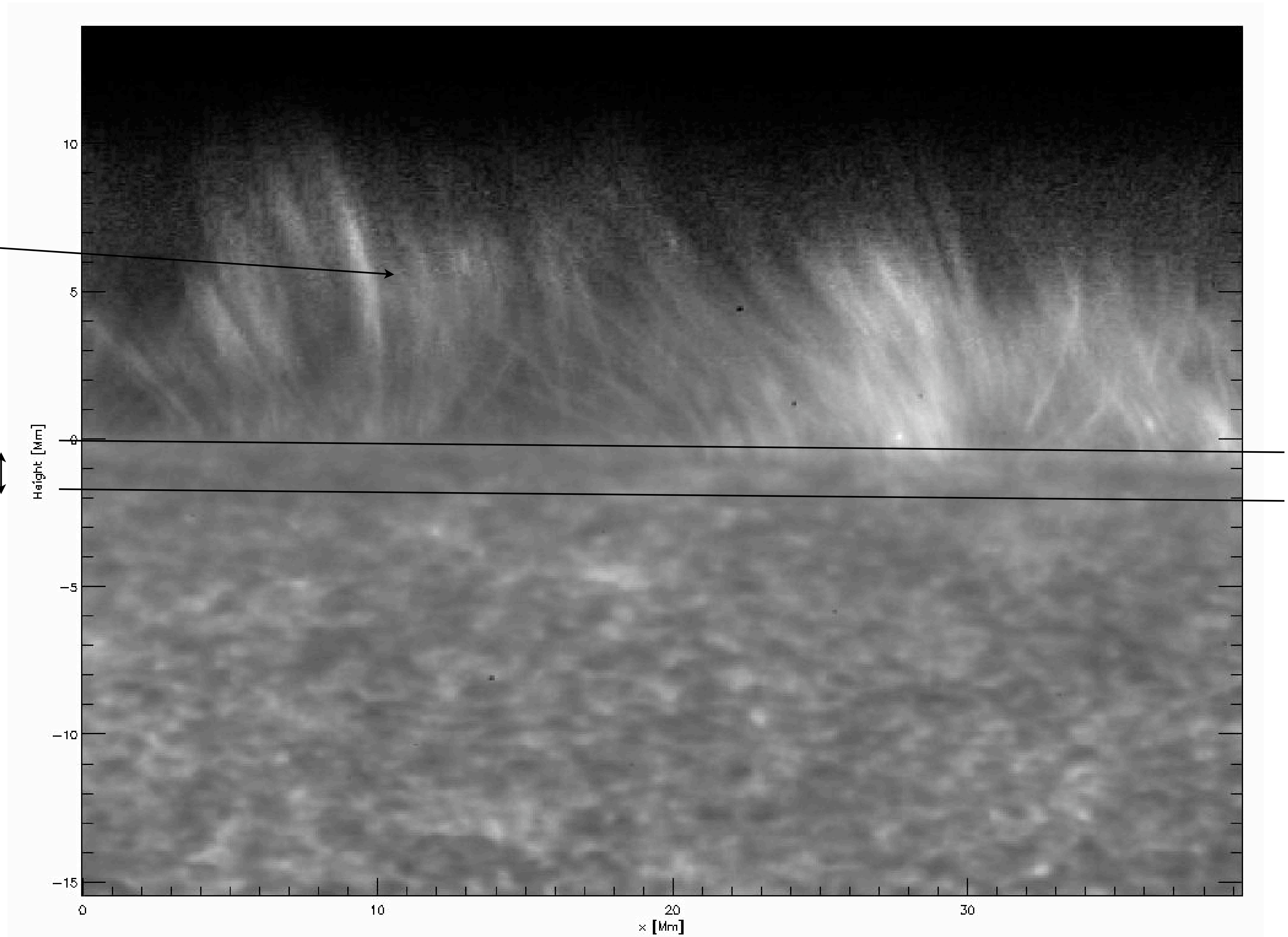


Hinode spicules

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

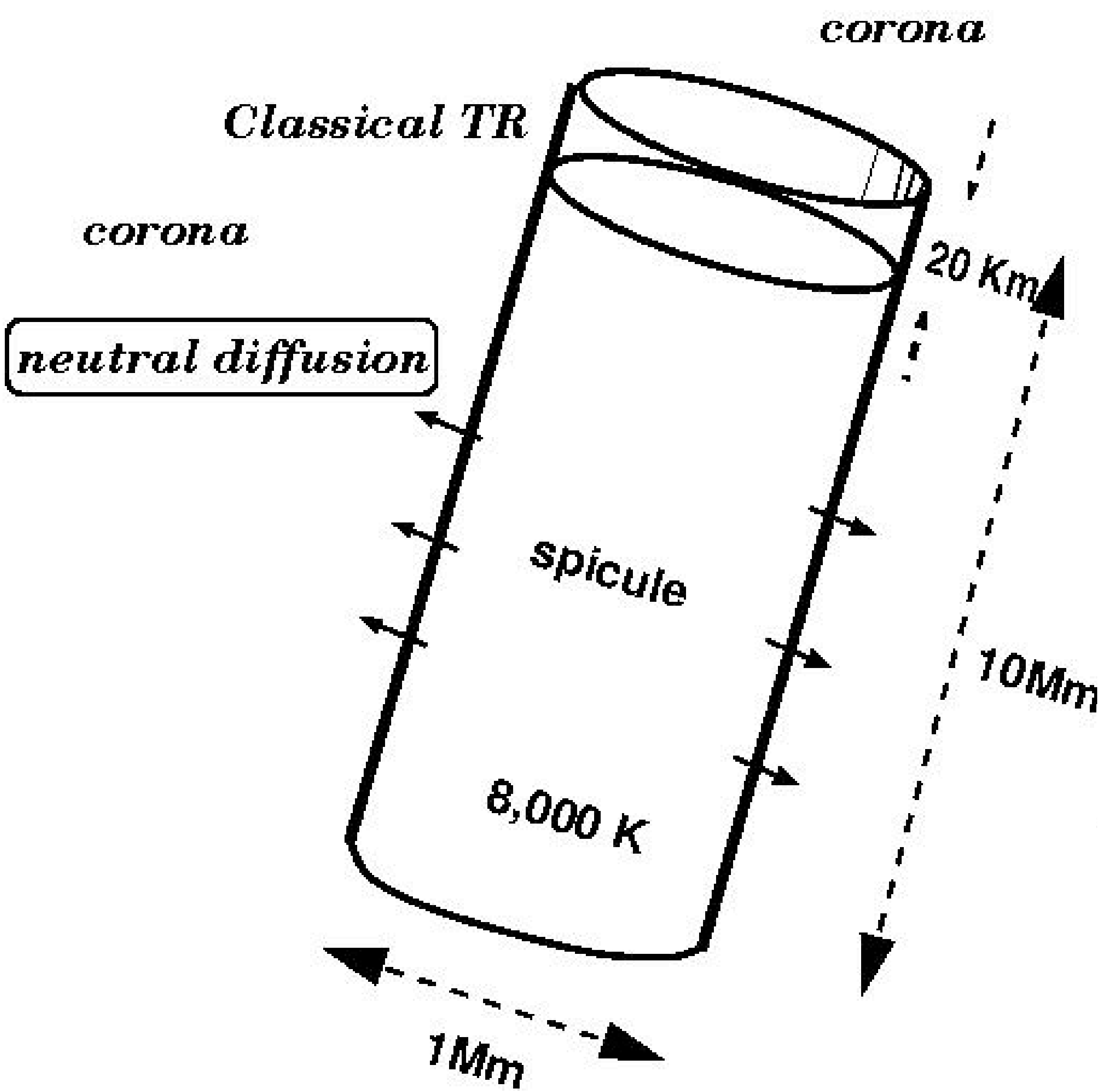
spicules *arise from within* the chromo-sphere

stratified VAL chromosphere 1.5Mm only



Judge (2008) ApJL 683, 87-90

"spicule" → cross field diffusion→ TR radiation

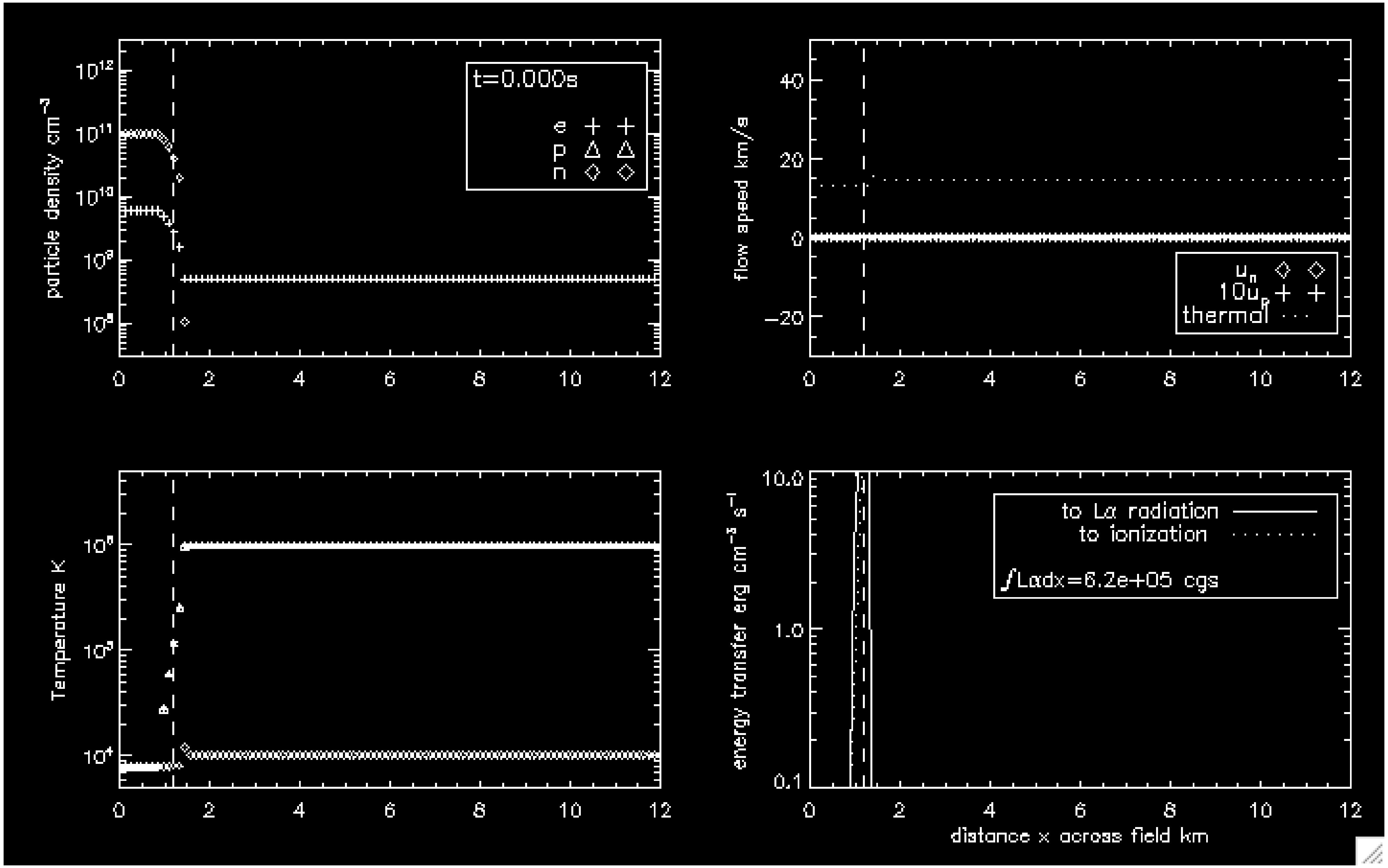


Initial corona			
T_h	K	10^6	
n_h	cm^{-3}	8.0×10^8	
n_p, n_e	cm^{-3}	4.0×10^8	
p	cm^{-3}	1.1×10^{-1}	
B	G	10	
β		2.8×10^{-2}	
ω_p	s^{-1}	9.6×10^4	
r_{gyro}	km	1.5×10^{-3}	
τ_{pp}	s	1.6	$n_p^{-1} T^{+3/2}$
$\omega_p \tau_{pp}$		1.5×10^5	
τ_{ee}	s	5.0×10^{-2}	$n_e^{-1} T^{3/2}$
chromospheric tube			
T_c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

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

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 and radiation
  - 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 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 how chromospheric processes influence the coronal base conditions (e.g., validity of Cowling's $\sigma_\perp^*$)

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.

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