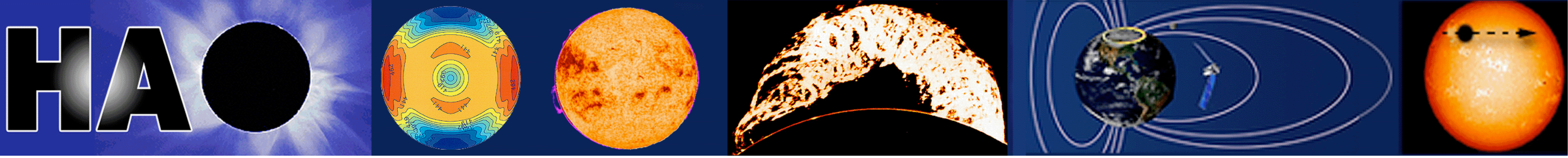


Physics of the chromosphere and the lower coronal boundary conditions

Philip Judge
HAO, NCAR, Boulder CO USA

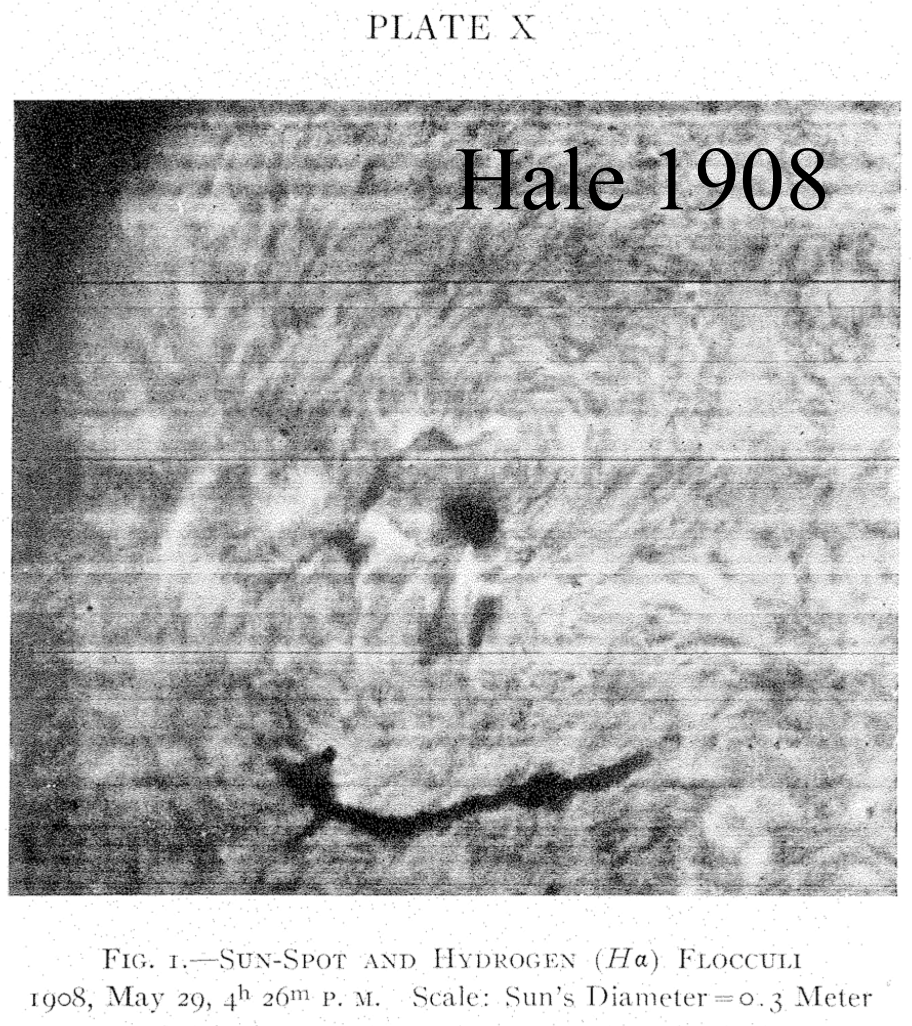


PLATE X

Hale 1908

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

December 2008

the chromosphere: interface between photosphere and corona

- partially ionized: thermostat
- stratified: spans 9 pressure scale heights
- so it usually contains plasma β=1 surface
  - forced at the base
  - force-free at the top
- requires 30-100x as much power as the corona
- 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

Gold (1964)

- chromosphere occupies thick black line
- 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

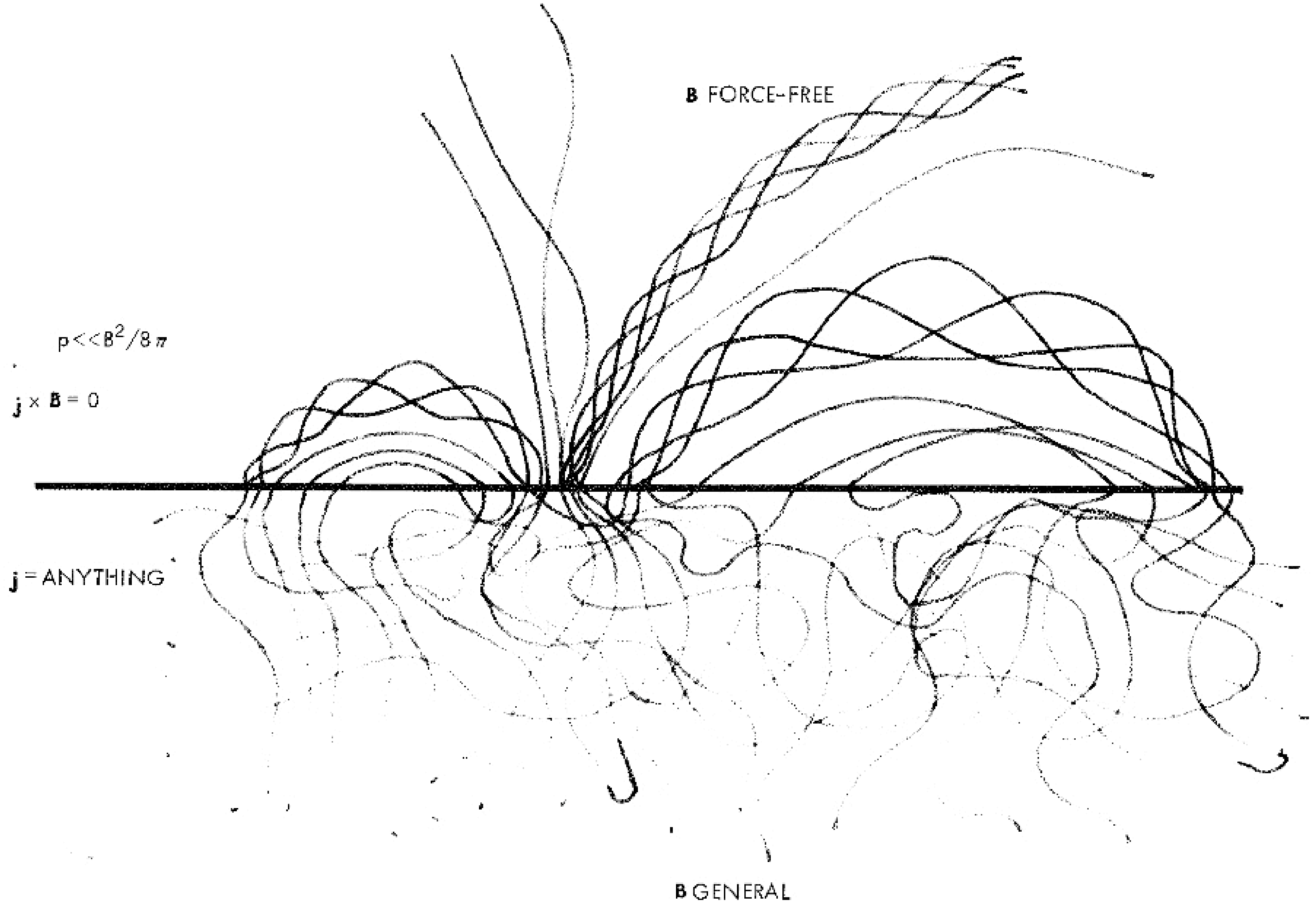
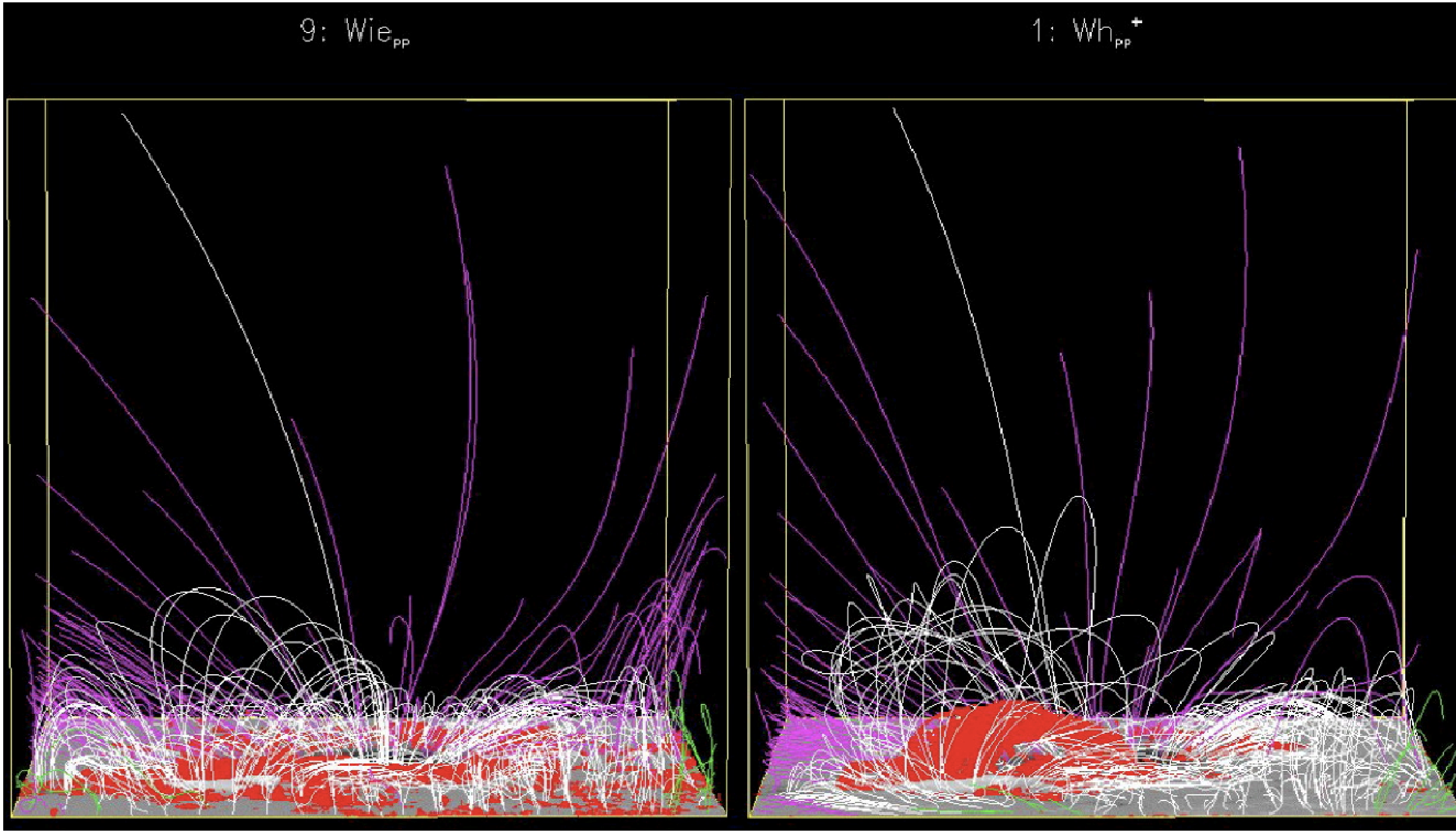


FIGURE 44–2. Magnetic field in a turbulent conducting medium. The fluid pressure is assumed large compared with magnetic forces below the dividing plane and small above it.

390

nlff field extrapolation (Schrijver et al 2008)

red:
current



force free extrapolations from photospheric vector polarimetry. Photospheric boundary is *not* force-free...

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

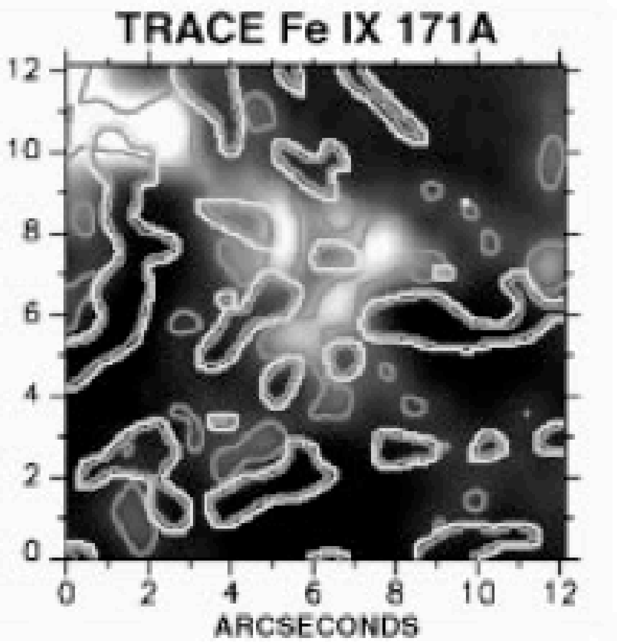
photosphere
- forced

top of
chromosphere,
corona
- force free

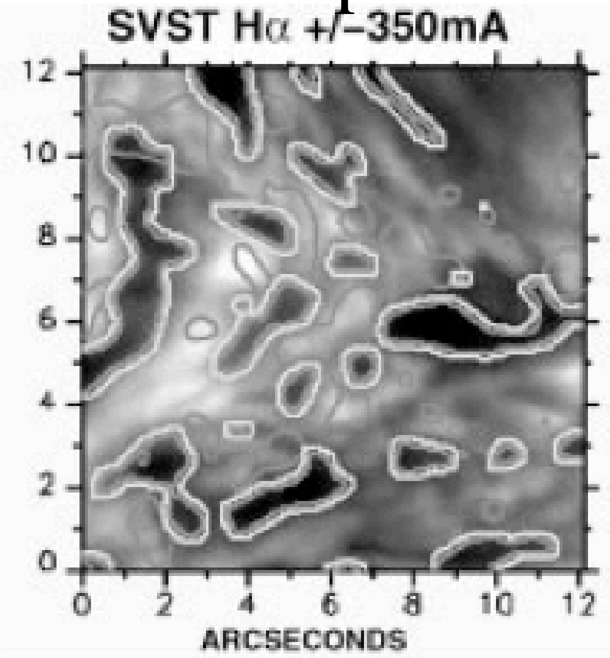
failure to trace magnetic field lines through the solar atmosphere

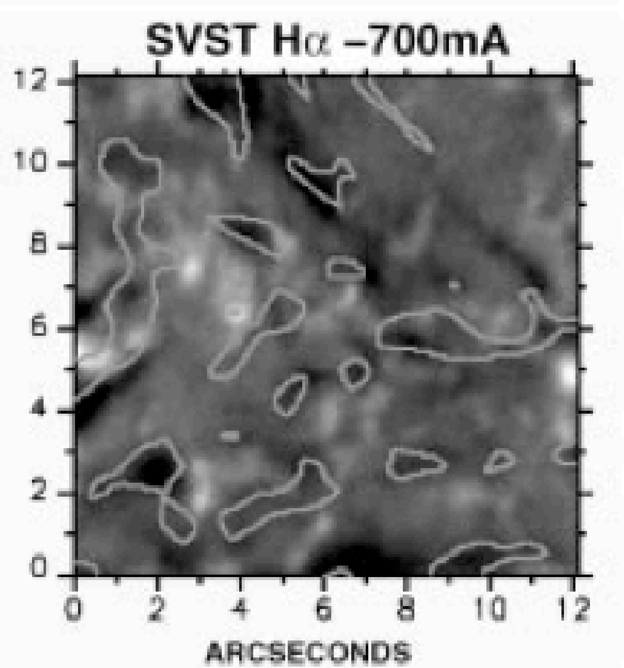
- high plasma conductivity allows tracing of field lines using
  - photospheric observations (polarimetry, proxies)
  - coronal threads
- TRACE & other missions failed to do this
- why?- chromosphere

lower corona

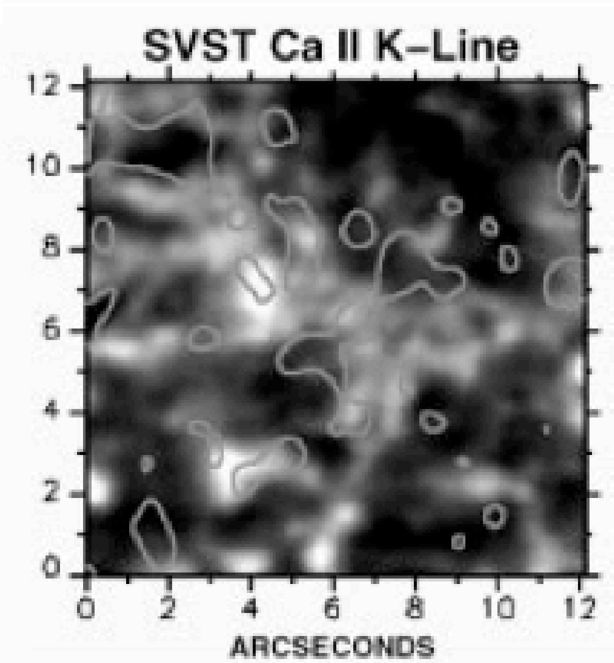

TRACE Fe IX 171A

upper chromosphere


SVST Hα +/−350mA


SVST Hα −700mA

upper chromosphere


SVST Ca II K–Line

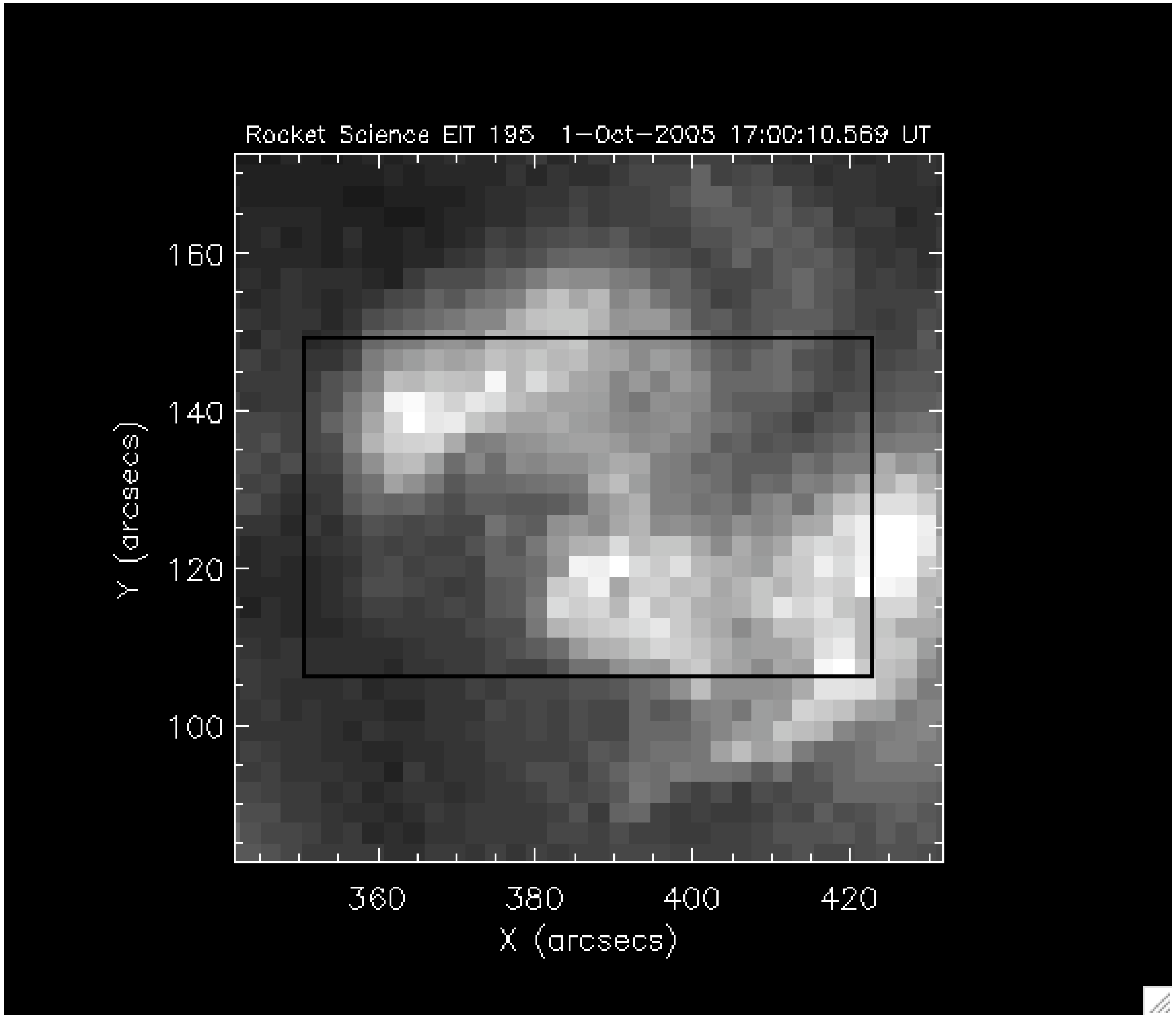
magnetic elements + reverse granulation

De Pontieu et al. 1999
“moss”

magnetic interface observations:

an example

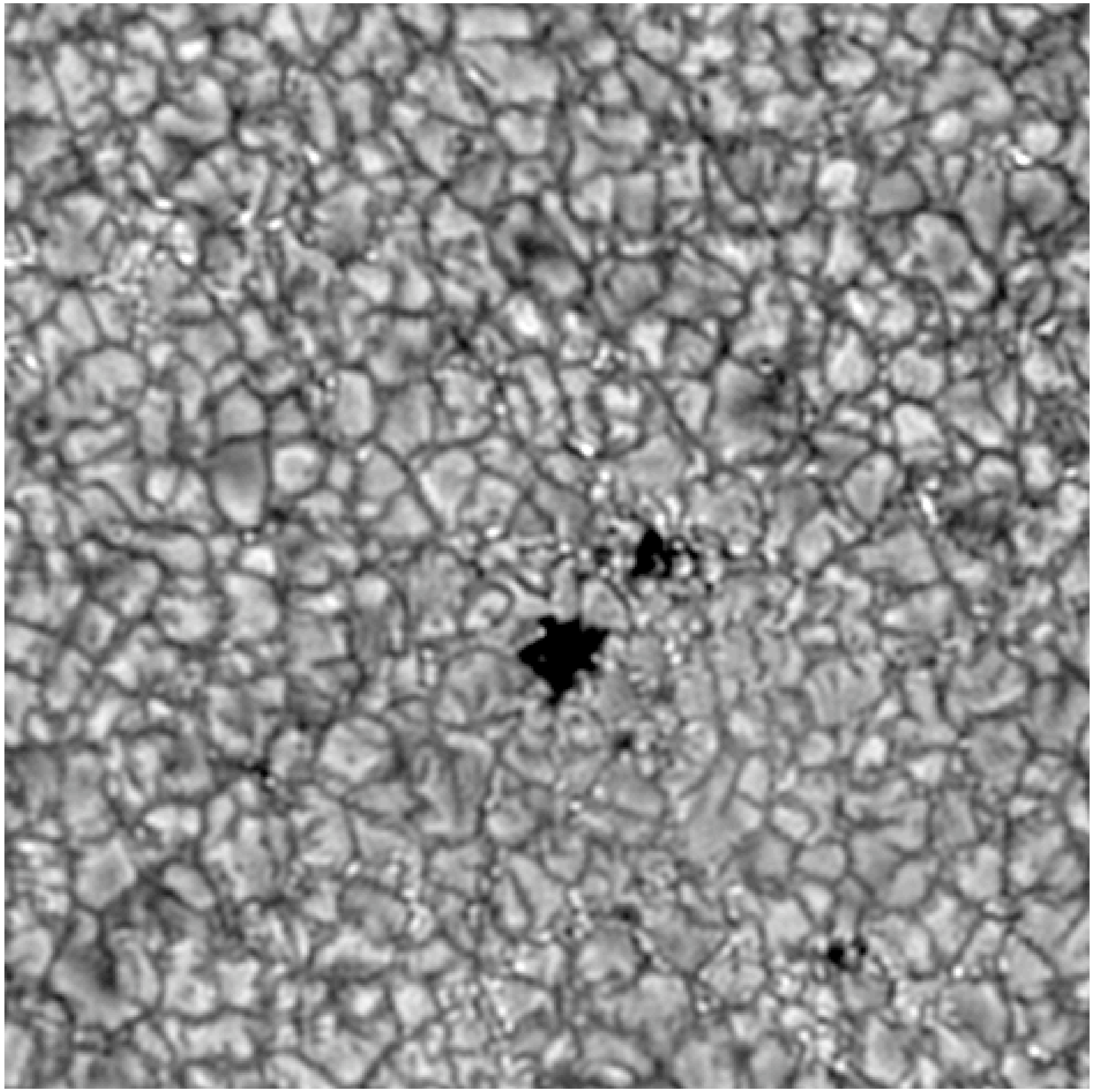
Small AR, pores



Chromosphere as seen with IBIS

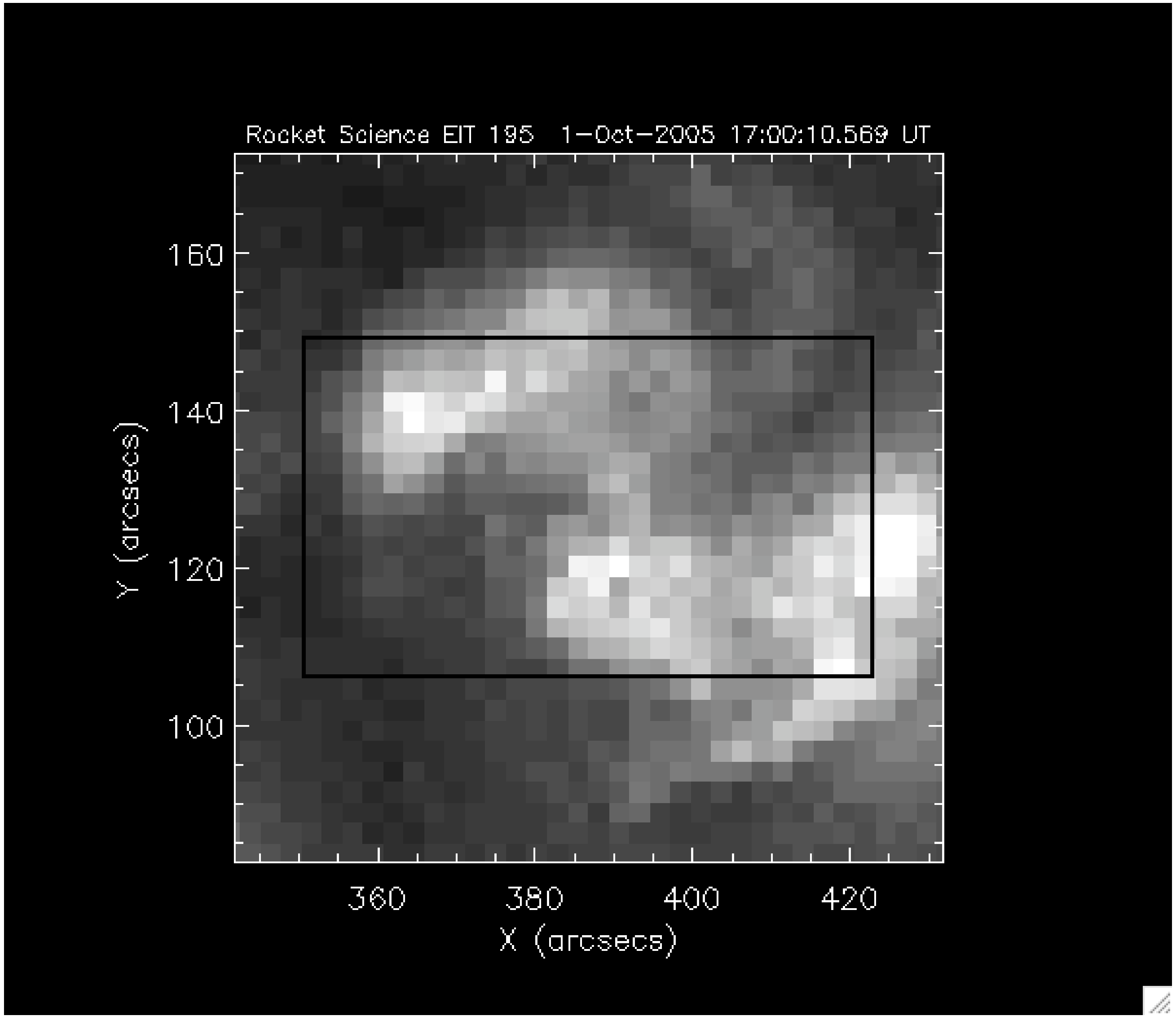
- Ca II 854.2 nm
- samples many pressure scale heights
- high resolution
  - resolution ≈ 0.3” (DST limit 0.24”)
  - (FOV 40”×40”)

base of corona is very different from photosphere



G. Cauzzi et al 2008, A+A

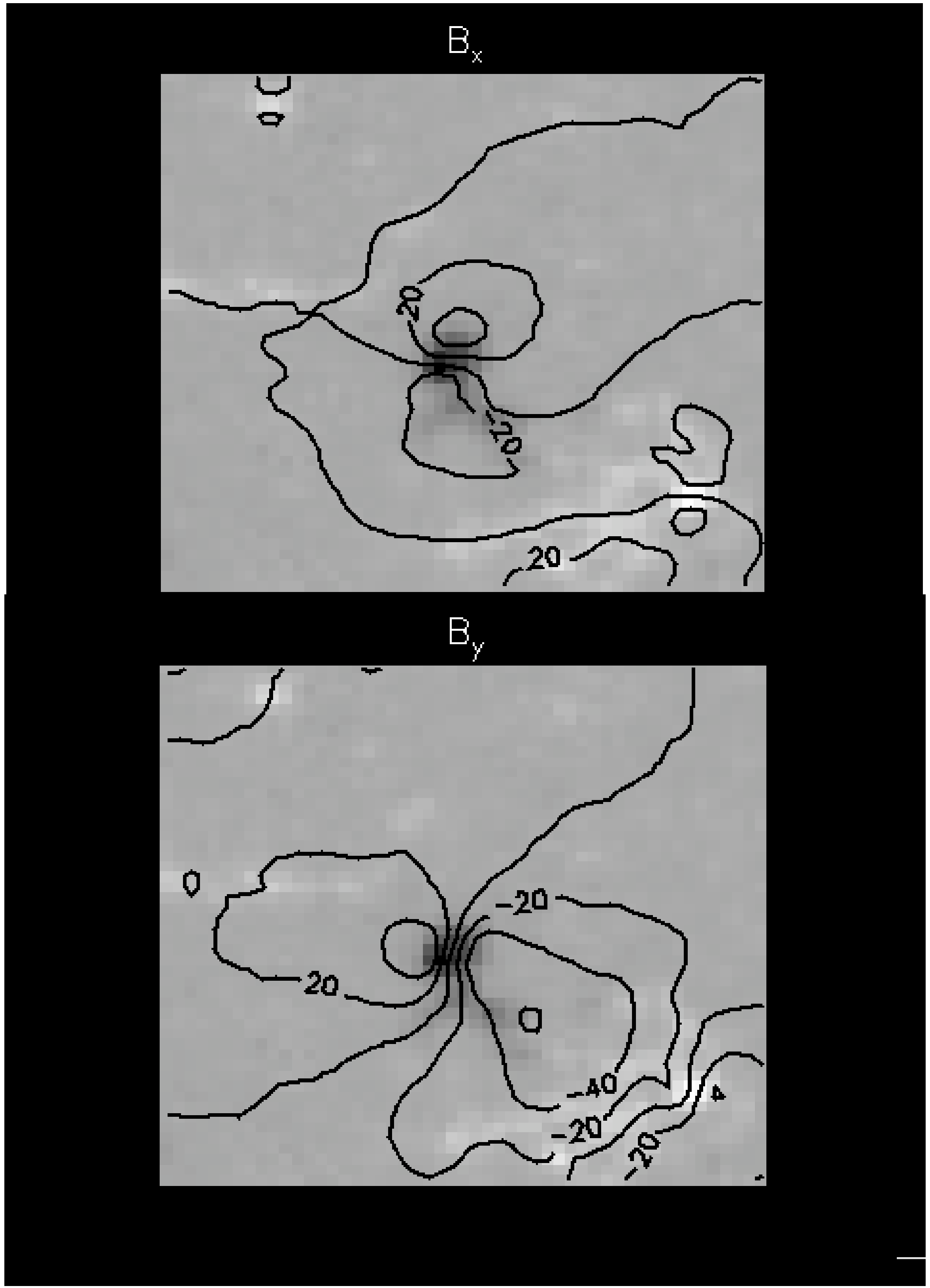
Small AR, pores:
including the chromosphere



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

Differences between potential and constant α photospheric fields

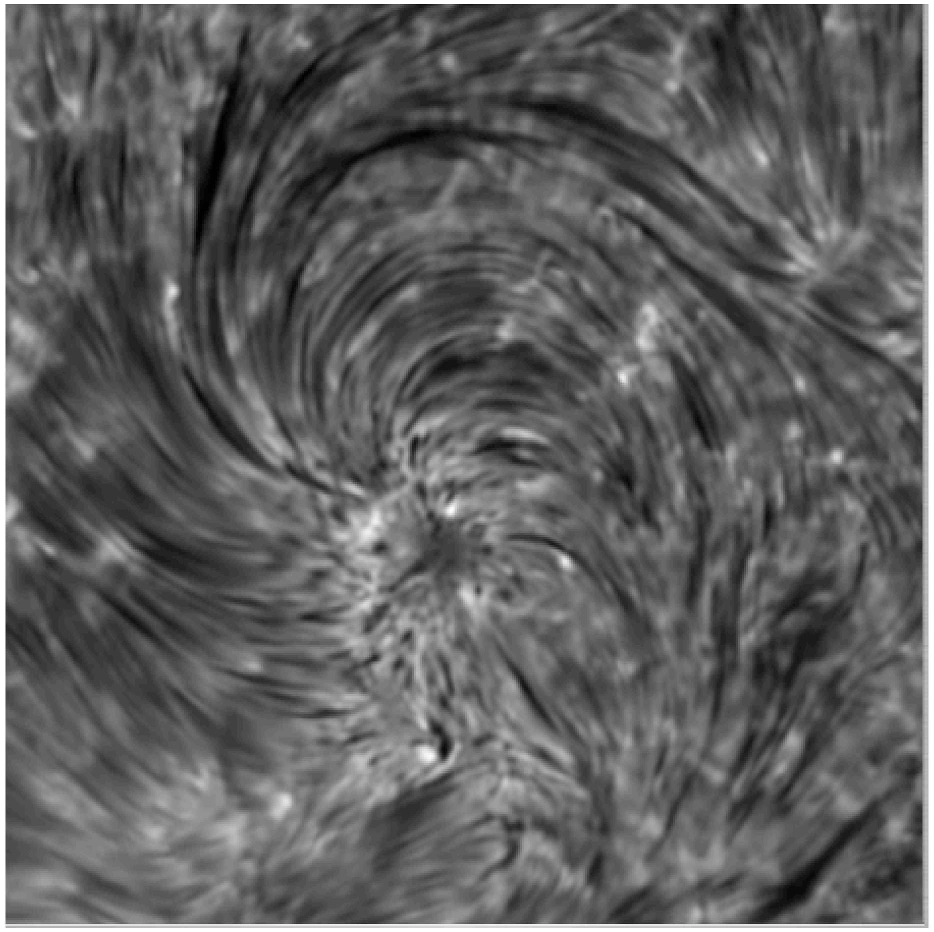
- IBIS morphology⇒ transverse fields differ by ~20-60G
- Hinode photospheric 630.2 sensitivity B_T(app) Lites et al (2008) ApJ **672**, 1237
  - 40 Mx cm^{-2} px^{-1} (normal map)
- current instruments can be used to study the forced ➔ force-free transition
  - chromospheric electrodynamics



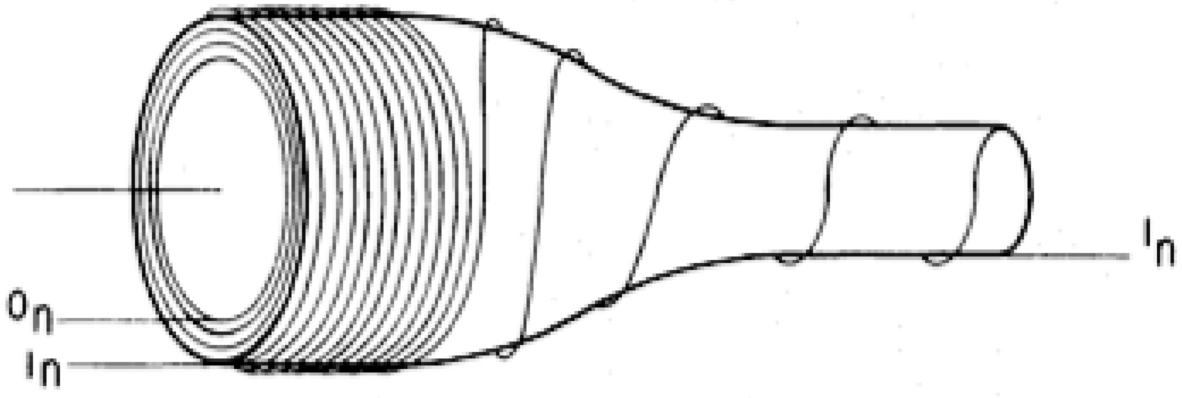
Note: twist/ electrical currents can be easier to detect in the chromosphere!

- IBIS fibrils reveal a clear $B_\varphi \Rightarrow j_z$
- also Hinode rotating spicules

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



DYNAMICAL PROPERTIES OF MAGNETIC FIELD



magnetic interface
physical considerations

chromosphere as a partially ionized plasma

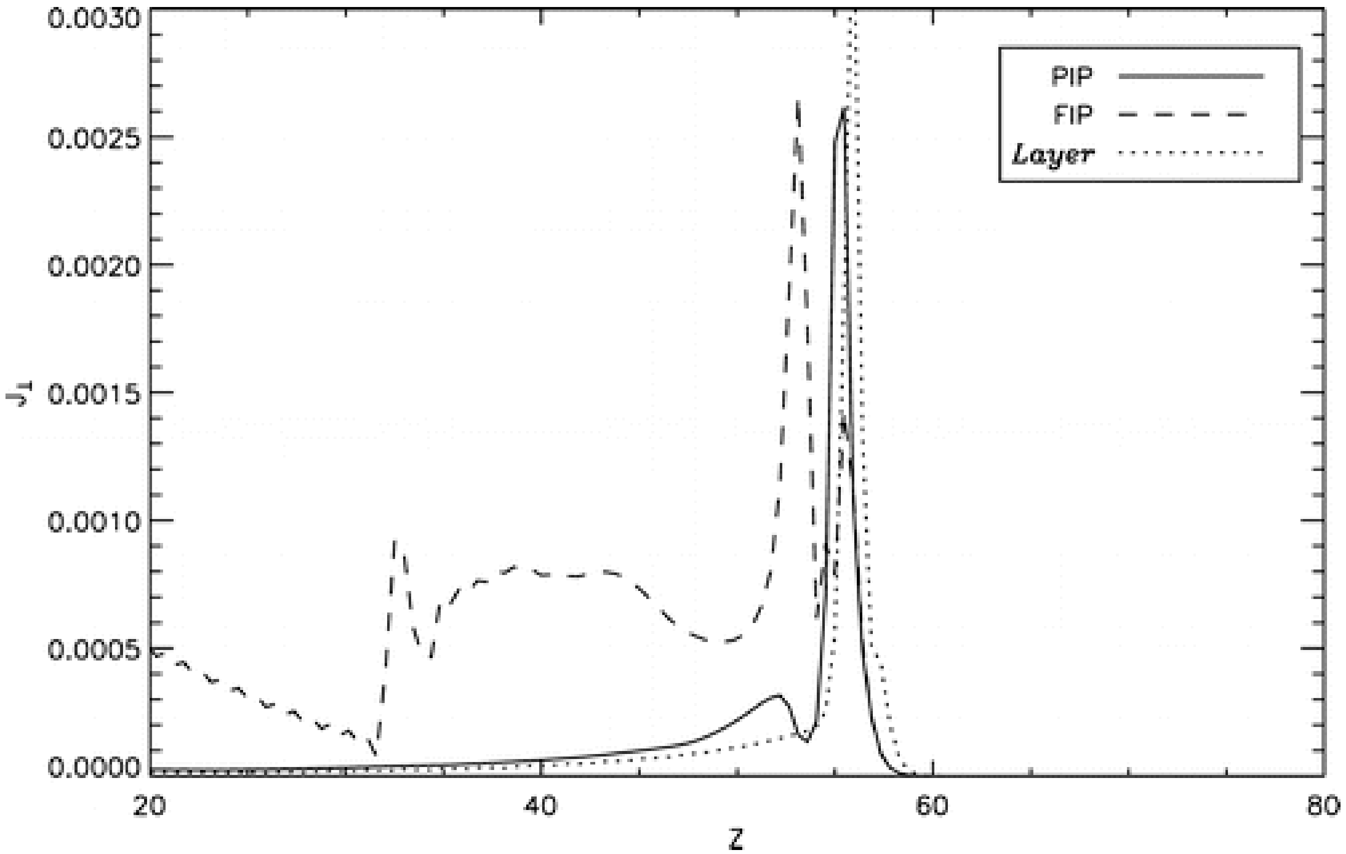
- partial ioniz^{n} ⇒ 3-fluid *frictional dissipation, heating*
- efficient damping by ion-neutral collisions
- Kinetic theory (Braginskii 1965)
  - $Q_{fr} = \mathbf{j}.\mathbf{E} = j^2/\sigma + (\xi_n\, \mathbf{j}\times\mathbf{B} - \mathbf{G})^2/\alpha_n,$ $\mathbf{G} = \xi_n \nabla p - \nabla p_n$
  - "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 $\nabla p - \rho \mathbf{g} + \mathbf{j}\times\mathbf{B} \neq 0$
- **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 $\mathbf{G} \neq \mathbf{0}$: $\sigma_\perp^*$ incorrect!
  - one must consistently 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

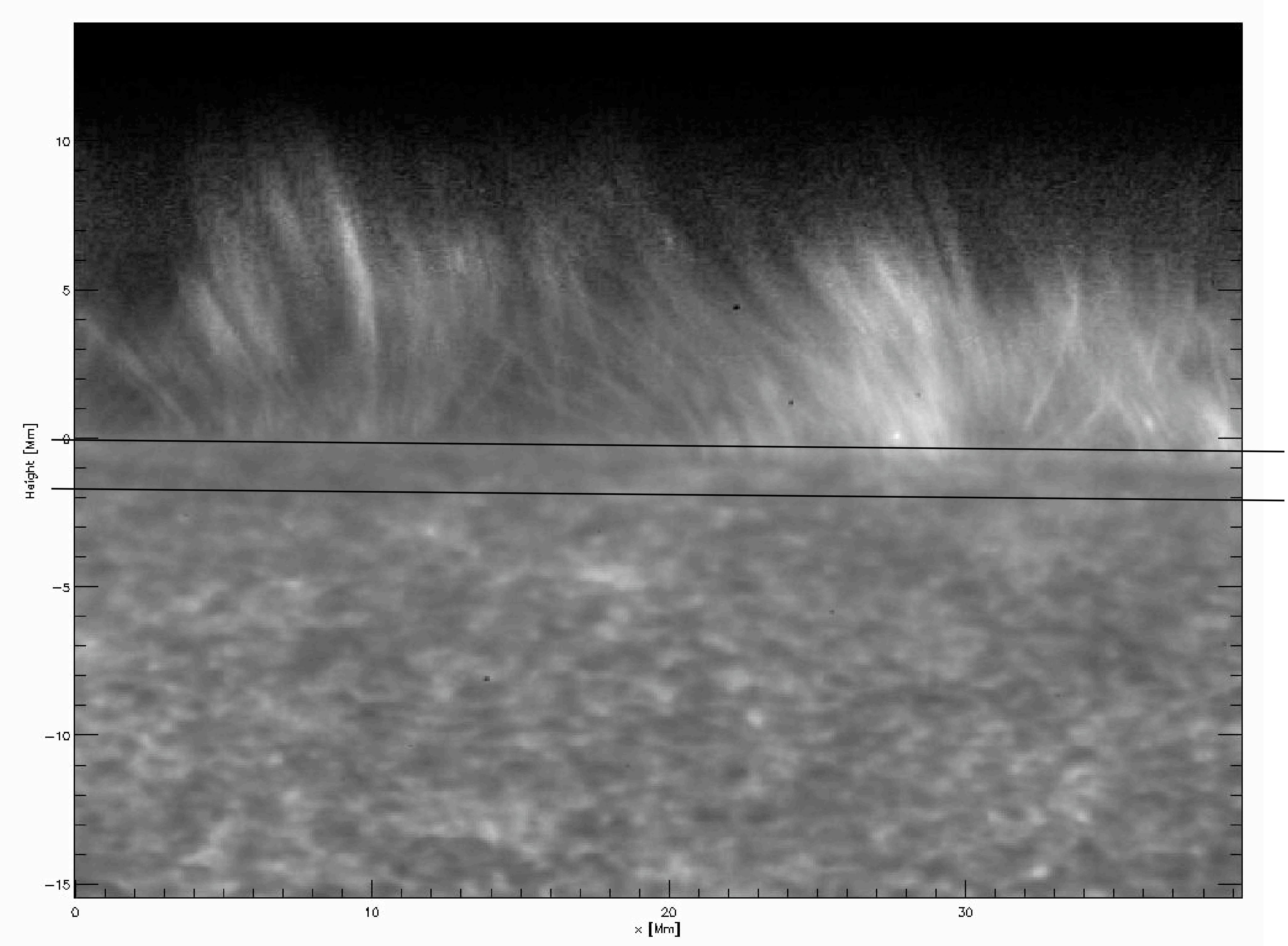
thermal interface

non-planar interface: Hinode spicules

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

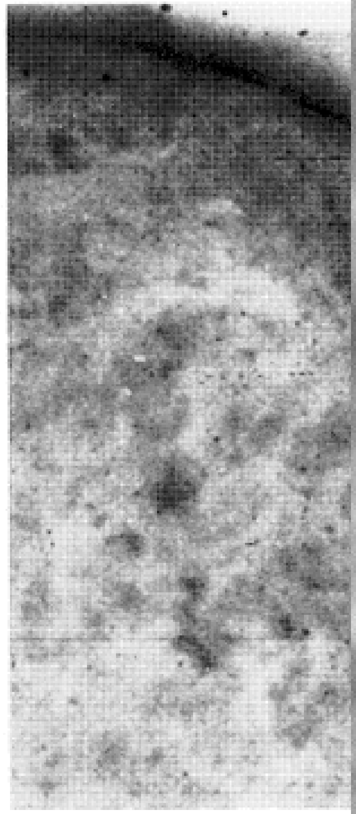
nb.
stratified VAL
chromosphere
1.5Mm only ↕

spicules are
produced by the
chromosphere

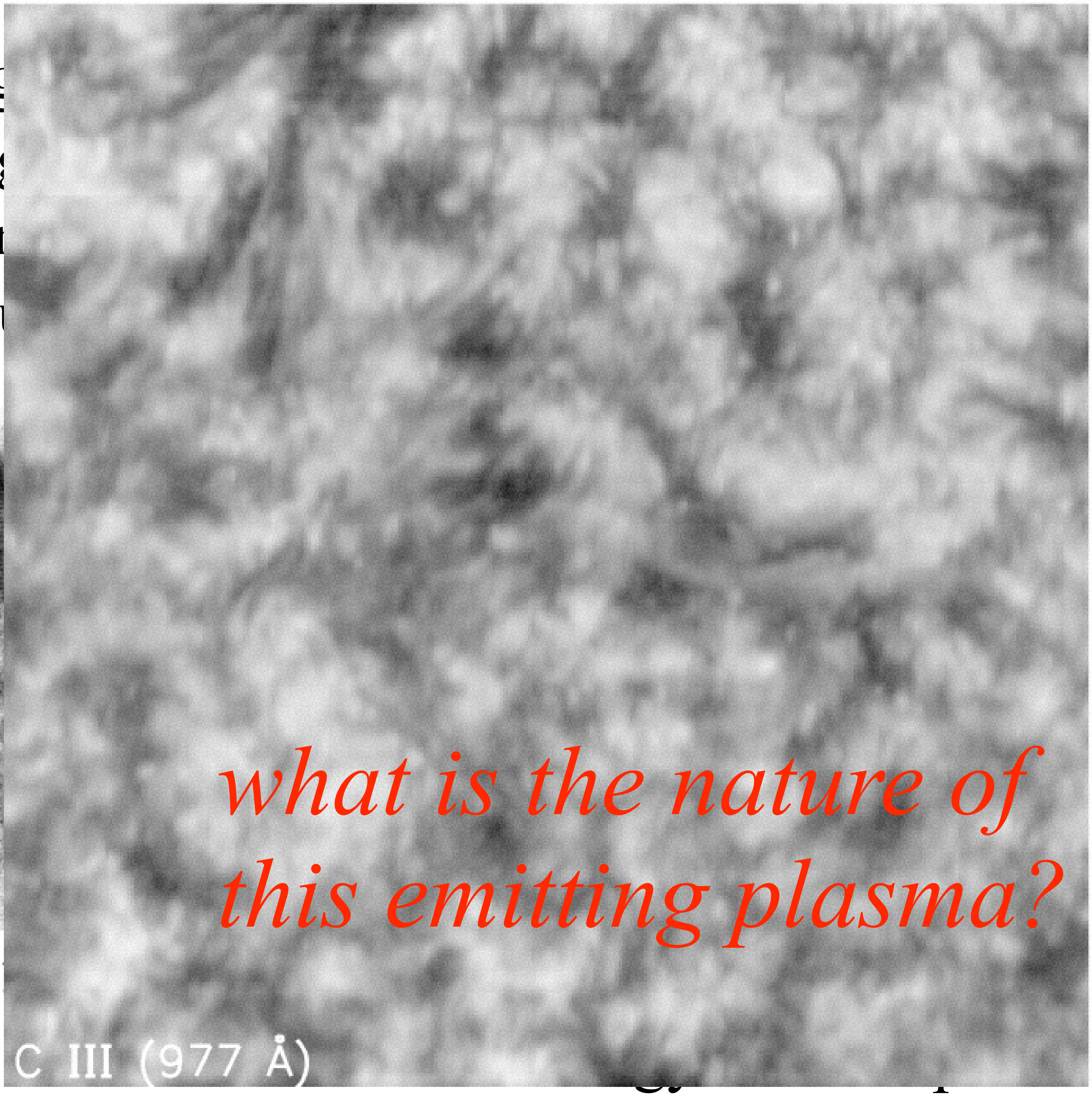


non-planar interface: transition region-corona

- Feldman and colleag
  - different morpholo
  - TR thermally, magn
  - radiating entity = “u



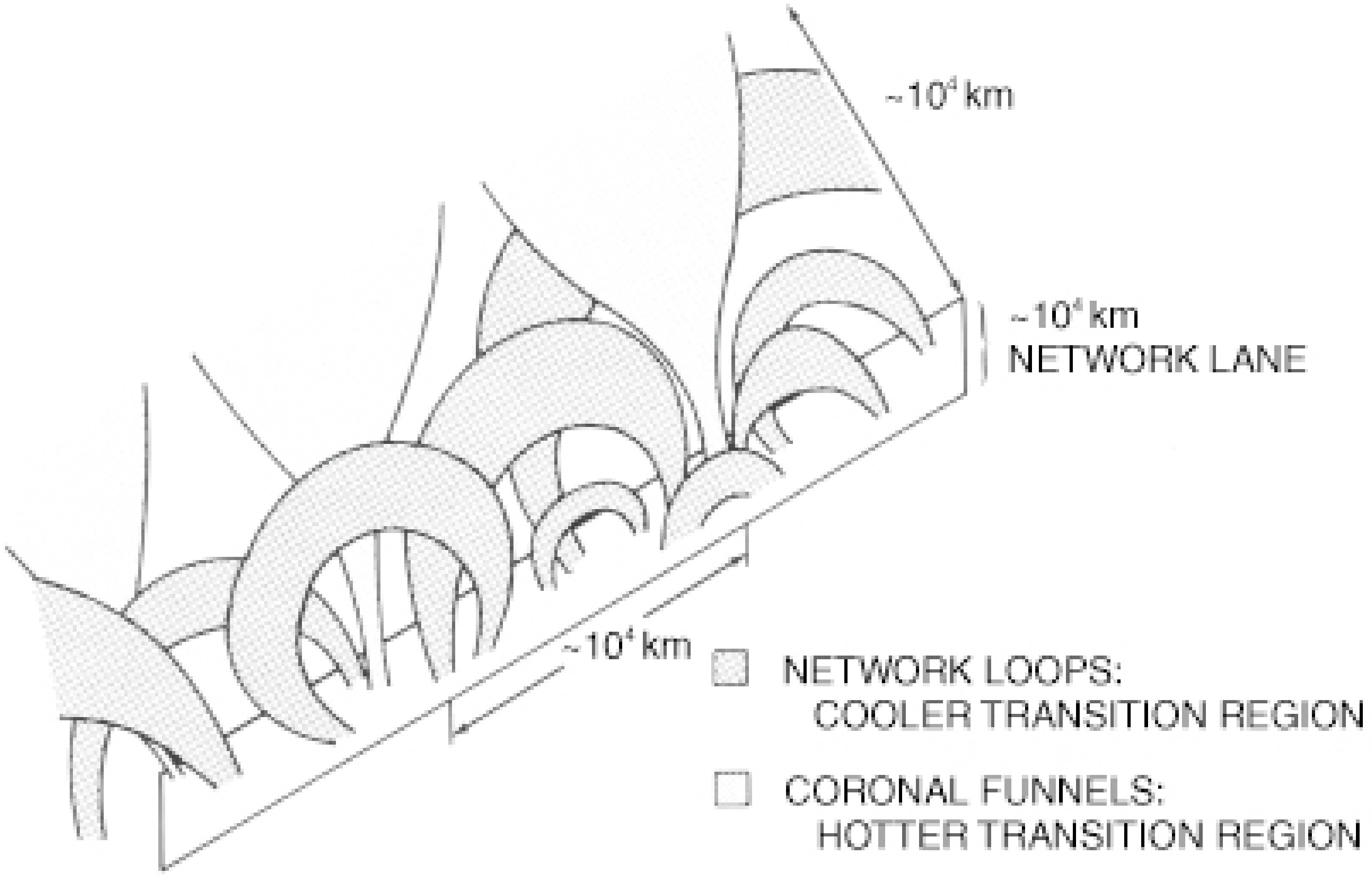
Mg I



what is the nature of this emitting plasma?

Dowdy et al. (1986)

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

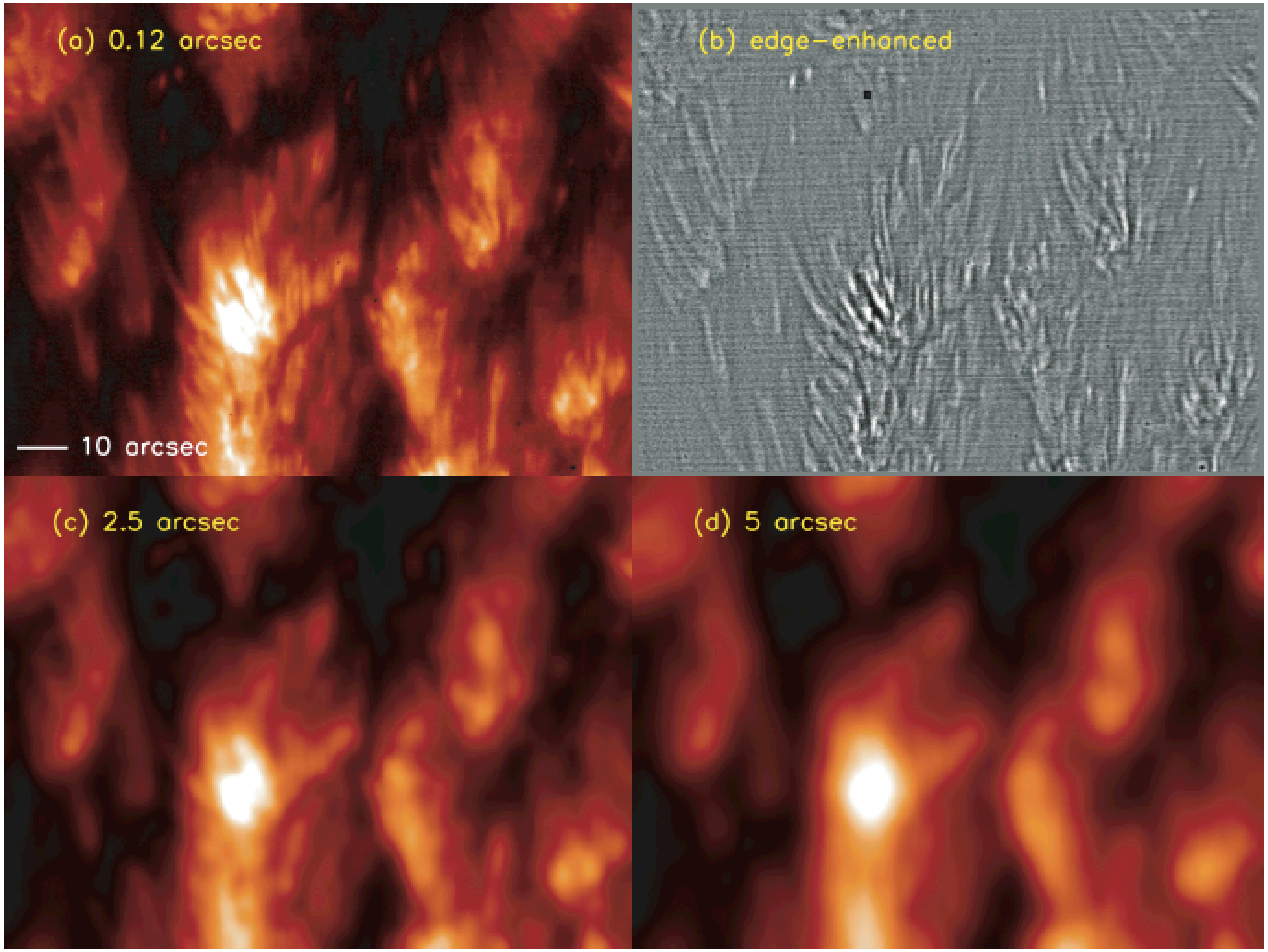


Questions: stability; footpoint magnetic fields; fate of downward conductive energy flux,...

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

Potential fields:

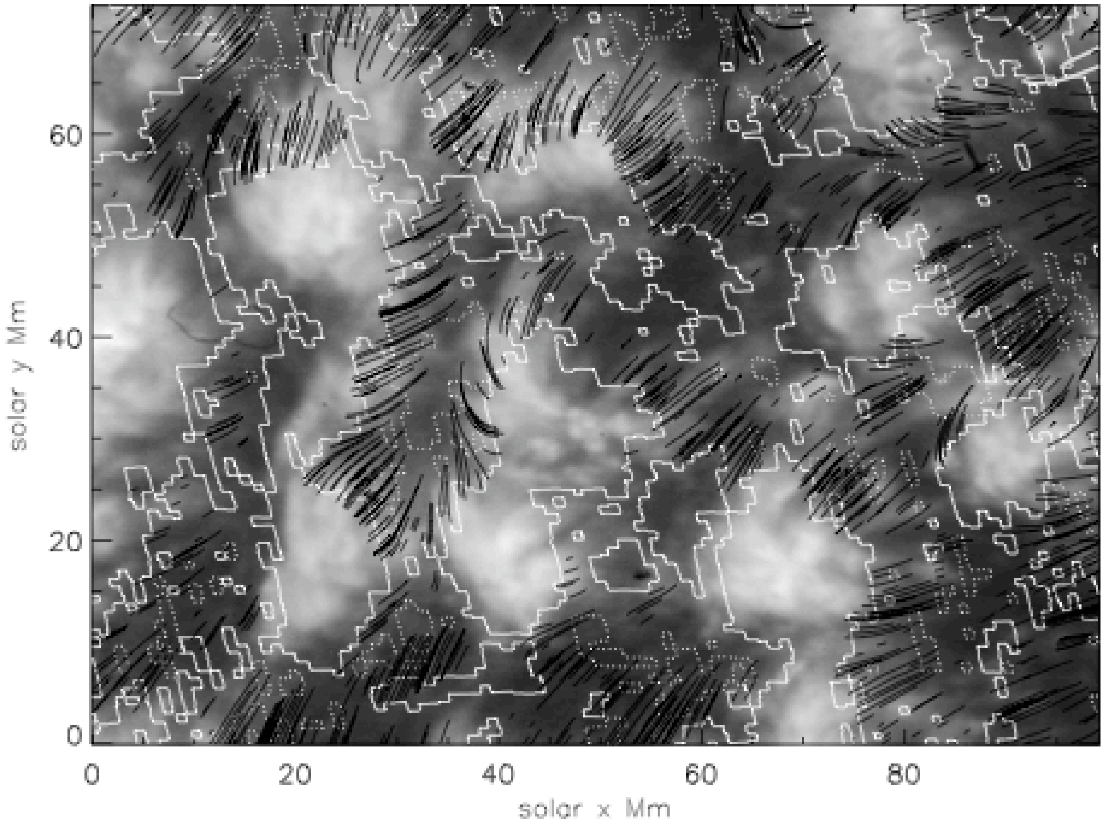
Black=low loops (h<5Mm)
Gray= higher

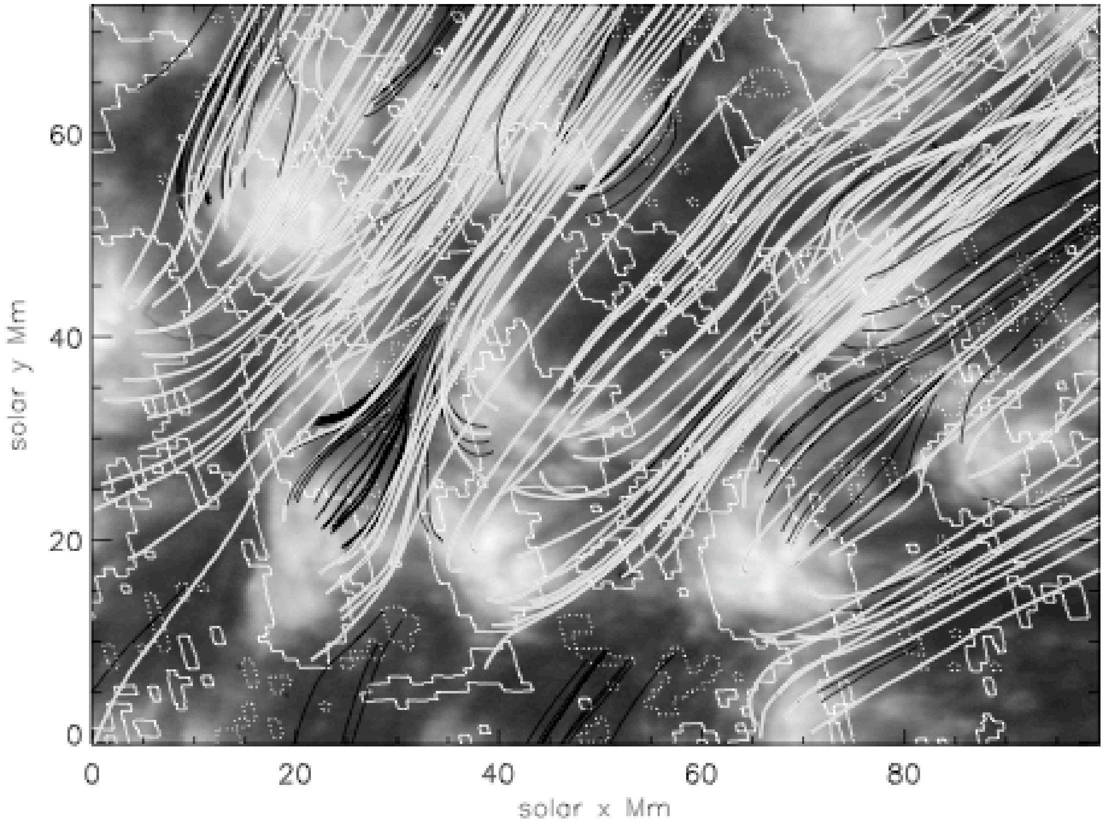
Non potential fields are generally higher

Stability requires that higher loops be hot

Most Lα emission originates from the base of hot, coronal loops

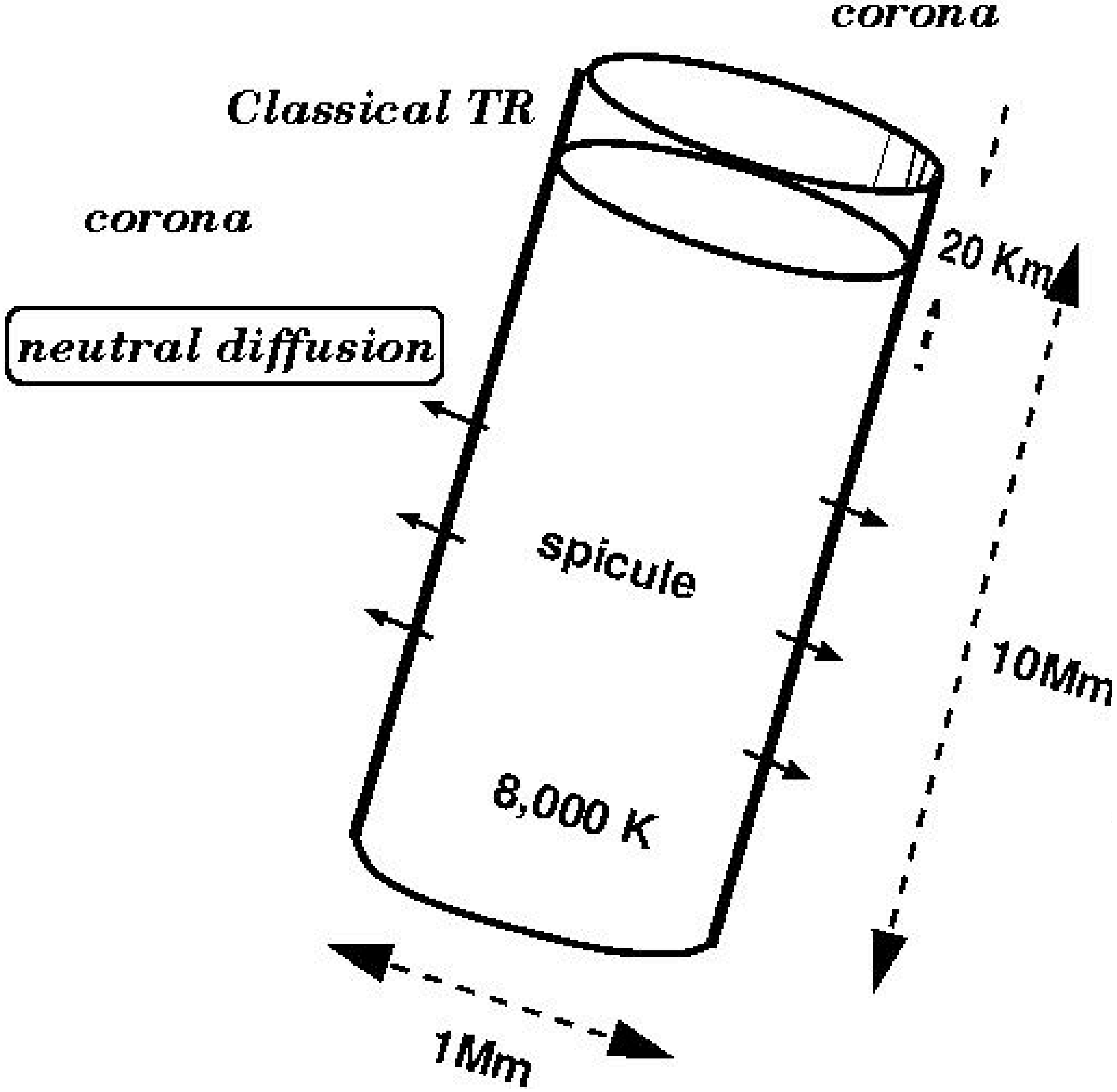
Unresolved mixed polarity fields don't work. Lα emission forms above h=0.8 Mm. Loops with footpoints separated by ≤1" cannot reach these heights

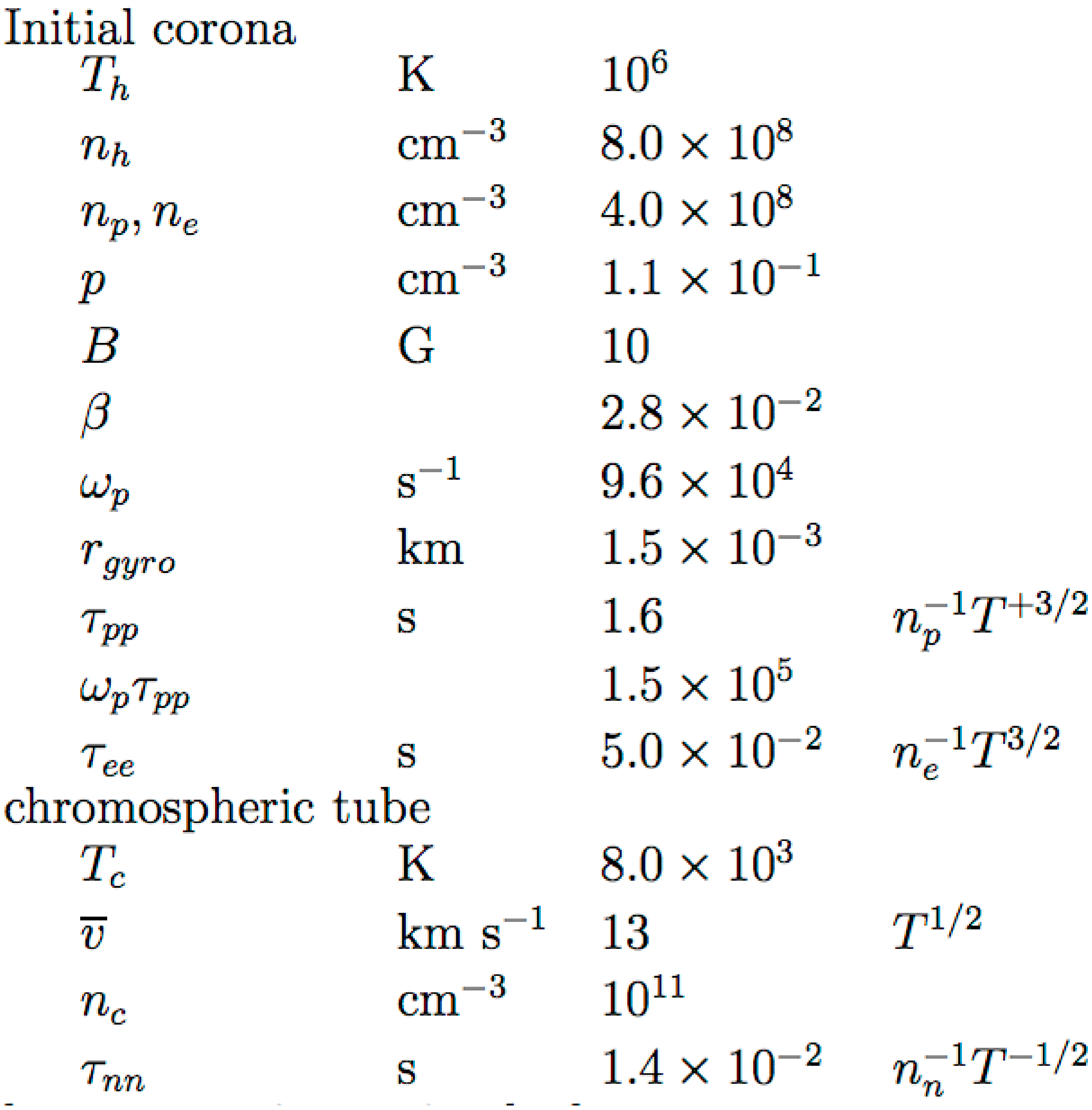




Judge (2008) ApJL 683, 87-90:
is there a simple explanation for the network transition region without appealing to cool loops?

“spicule” → cross field diffusion→ TR radiation



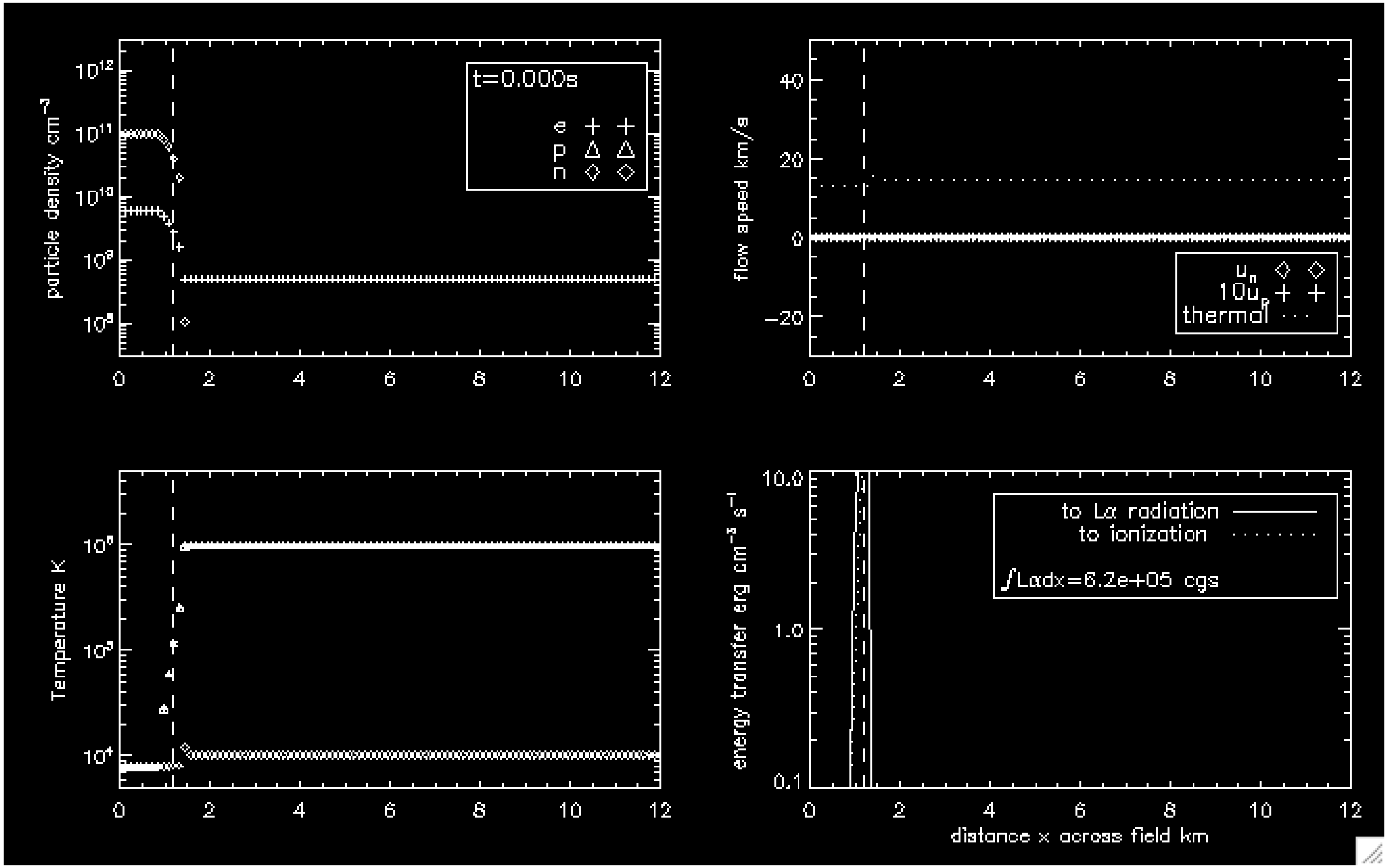


Initial corona			
T_h	K	10^6	
n_h	cm^{-3}	8.0×10^8	
n_p, n_e	cm^{-3}	4.0×10^8	
p	cm^{-3}	1.1×10^{-1}	
B	G	10	
β		2.8×10^{-2}	
ω_p	s^{-1}	9.6×10^4	
r_{gyro}	km	1.5×10^{-3}	
τ_{pp}	s	1.6	$n_p^{-1} T^{+3/2}$
$\omega_p \tau_{pp}$		1.5×10^5	
τ_{ee}	s	5.0×10^{-2}	$n_e^{-1} T^{3/2}$
chromospheric tube			
T_c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

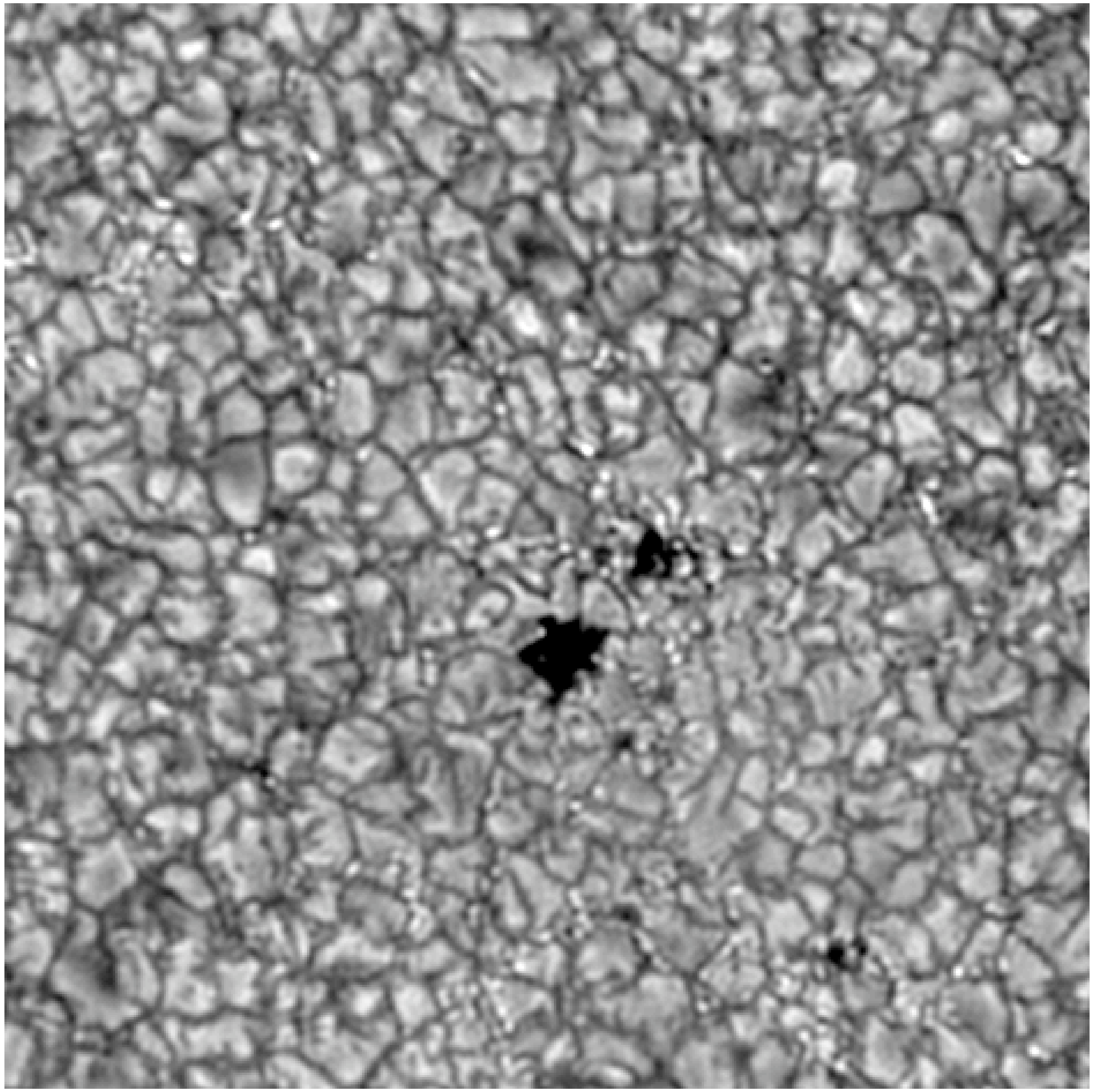
Judge (2008)

- chromosphere supplies the (neutral) mass, corona the energy
  - "UFS" in this new picture is thermally connected to the corona
  - calculations for Lα are promising, (also Lβ, He I 584)
- cross-field diffusion of neutrals might solve the 40+ yr problem of energy balance in extended structures in the lower TR
- 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

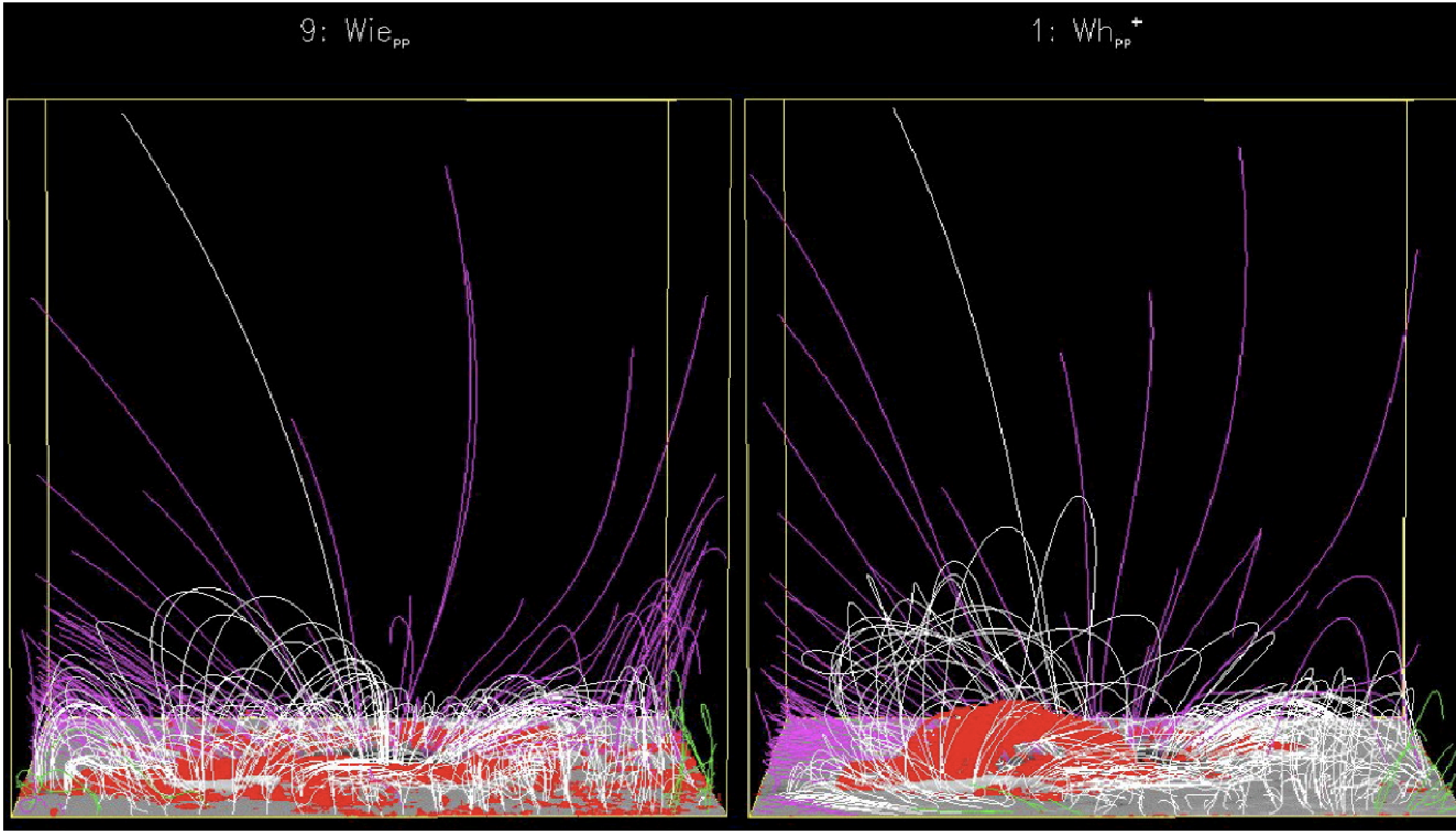
the need for sub-arcsec imaging spectroscopy/ spectropolarimetry at the coronal base

- to map low β magnetic structure
  - ≤1” angular resolution
  - ≥ 30”×30” FOV
- to get dynamics
  - < 30s (spicules..)
- ground-based:
  - spectropolarimetry
  - Ca II, He I, H I,...
  - chromosphere only
- space (UV)
  - spectroscopy
  - chrom+TR+corona



nlff field extrapolation (Schrijver et al 2008)

red:
current



new chromospheric **B** constraints (including e.g., just fibrils) can provide boundary conditions compatible with the calculations

To understand the corona we must study what is under Gold’s line

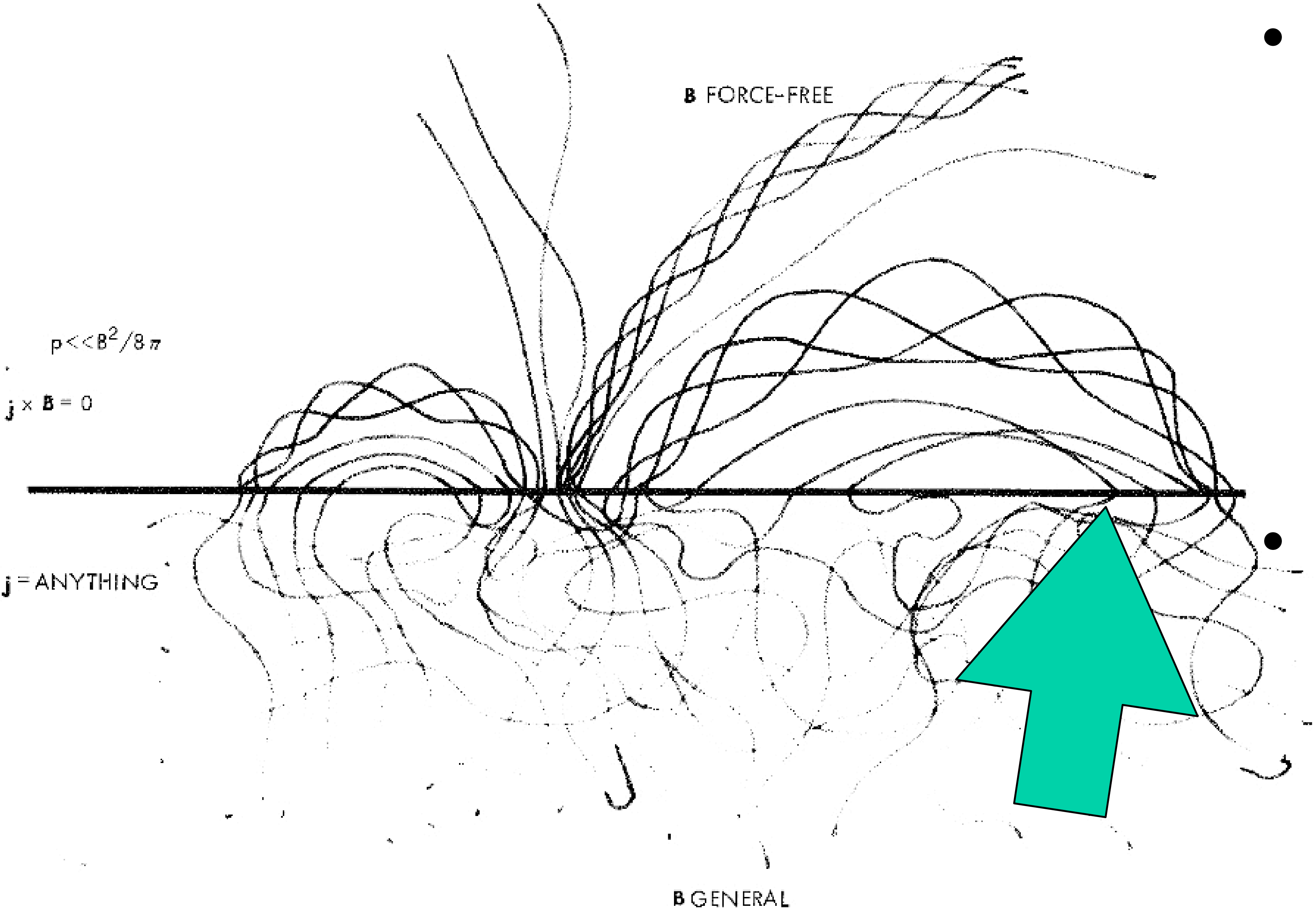


FIGURE 44–2. Magnetic field in a turbulent conducting medium. The fluid pressure is assumed large compared with magnetic forces below the dividing plane and small above it.

390

- understand mass, momentum, free energy transport across chromosphere
    - *single fluid MHD OK?*
- obtain much better boundary conditions on the corona
    - magnetic
    - thermodynamic
- *ground+space data required*