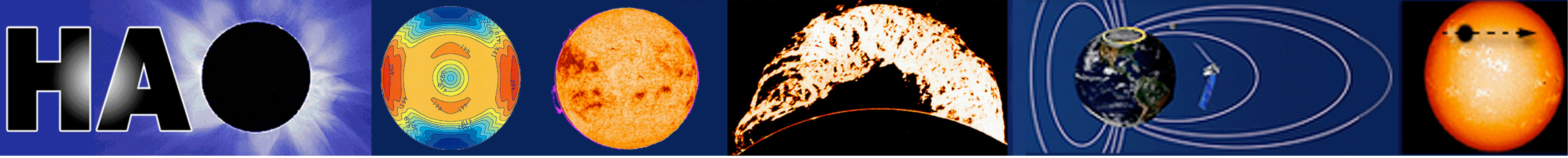


The chromosphere: why should anyone care?

Philip Judge, *HAO, NCAR*

PLATE X

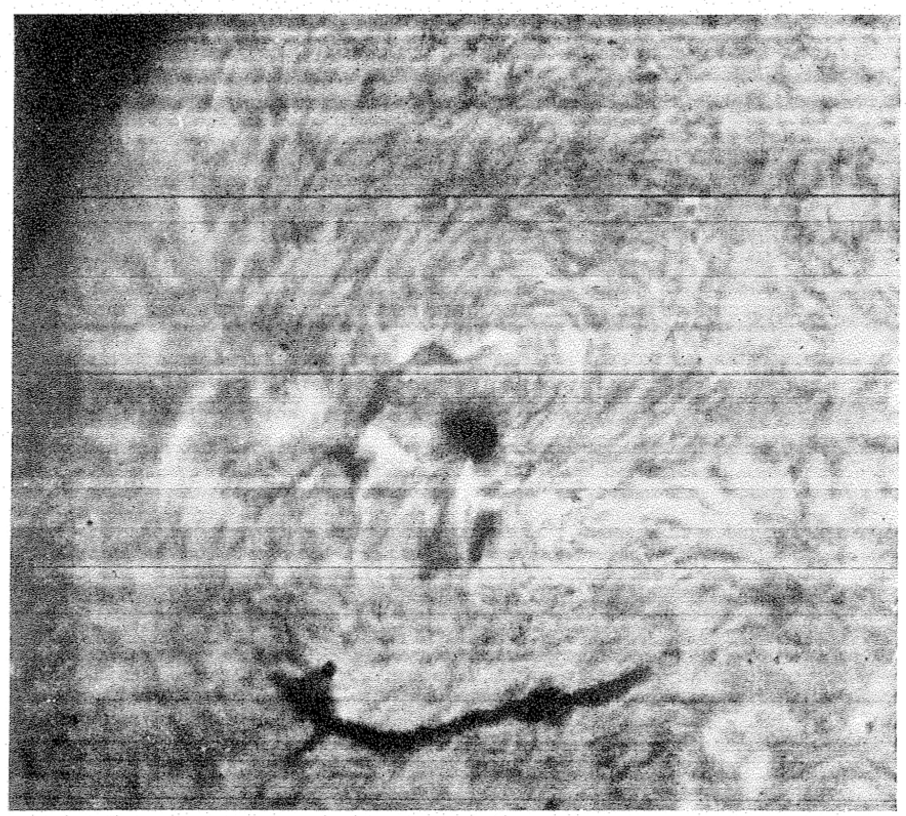


FIG. 1.—SUN-SPOT AND HYDROGEN ($H\alpha$) FLOCCULI
1908, May 29, 4^h 26^m P. M. Scale: Sun's Diameter = 0.3 Meter

chromosphere:
~ $10^{-12} M_\odot$
~ 1000 Mt. Everests

Papers 2000- Jul 09 (ADS abstracts)

All	934495	
Stars	147621	
Galaxies	118824	
Cosmology	61145	
Corona	18192	
Photosphere	8746	
Planetary nebula	4601	
Chromosphere	4510	0.48%
Dark matter	2066	
(Solanki)	400	

NCAR

September 2009

ESSL

the chromosphere
primary observed characteristics

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

Reason 1: we don't understand why the Sun is obliged to do this (from first principles)

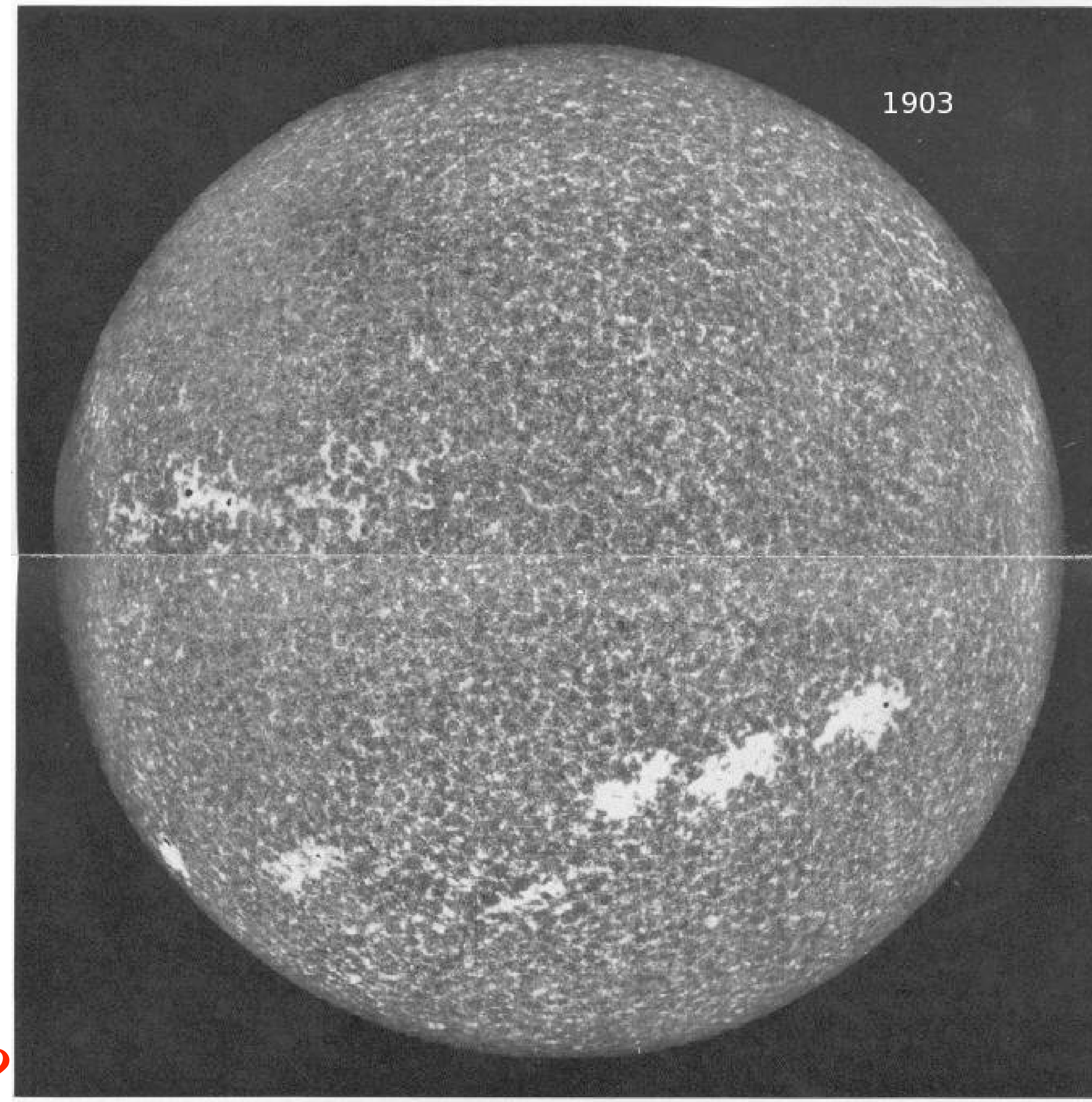
Reason 2: variable UV influences the heliosphere

HAO

example: the Sun's network

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

what is supergranulation?



S

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.)

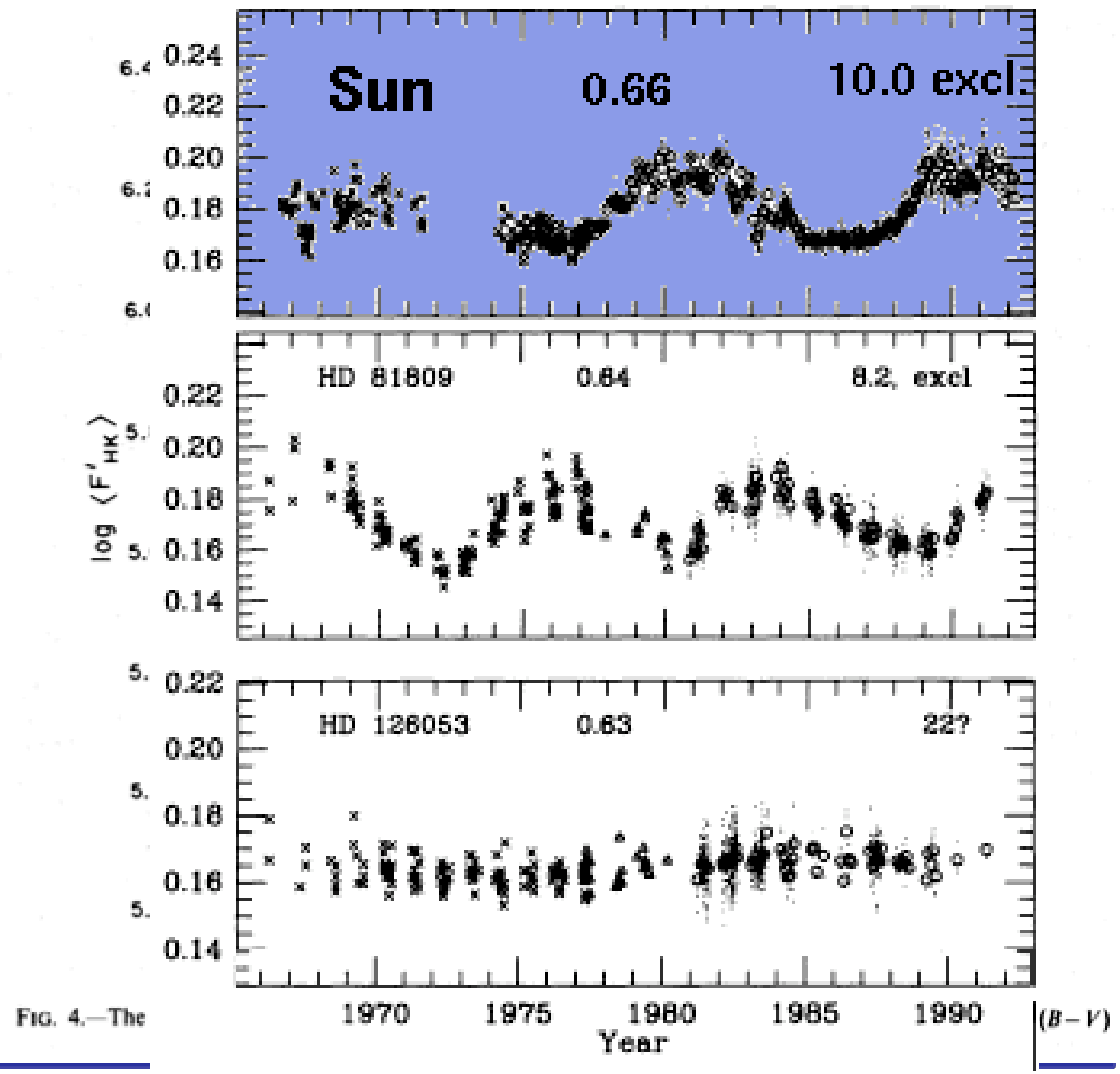
$\lambda/\Delta\lambda \geq 40{,}000$

chromospheres

- present in all stars with surface convection 1960s

Reason 3: the Sun is not alone

Reason 4: stellar magnetism and dynamos



main physical characteristics

- stratified: spans 9 pressure scale heights
- requires 30-100x as much power as the corona
- nLTE, partially ionized, (magnetized) plasma
- usually contains plasma β=1 surface

Progress

internetwork dynamics

type I spicules identified, explained

Reason 5: Open questions

magnetic heating, force balance, spicules (type II)

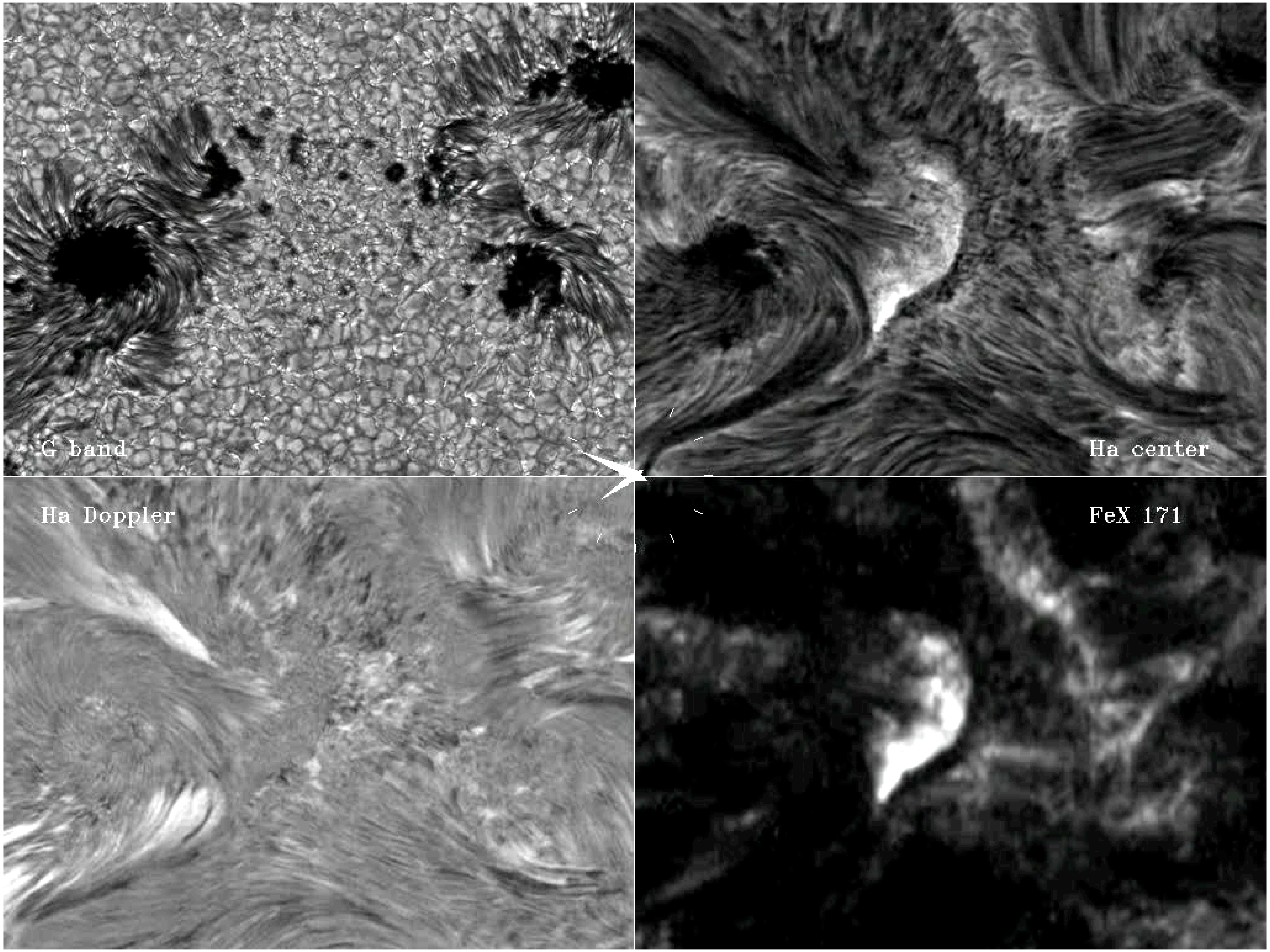
connections chromosphere-TR-corona, ...

energizing the corona

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

photosphere
chromosphere
corona

coronal structure already present in the chromosphere



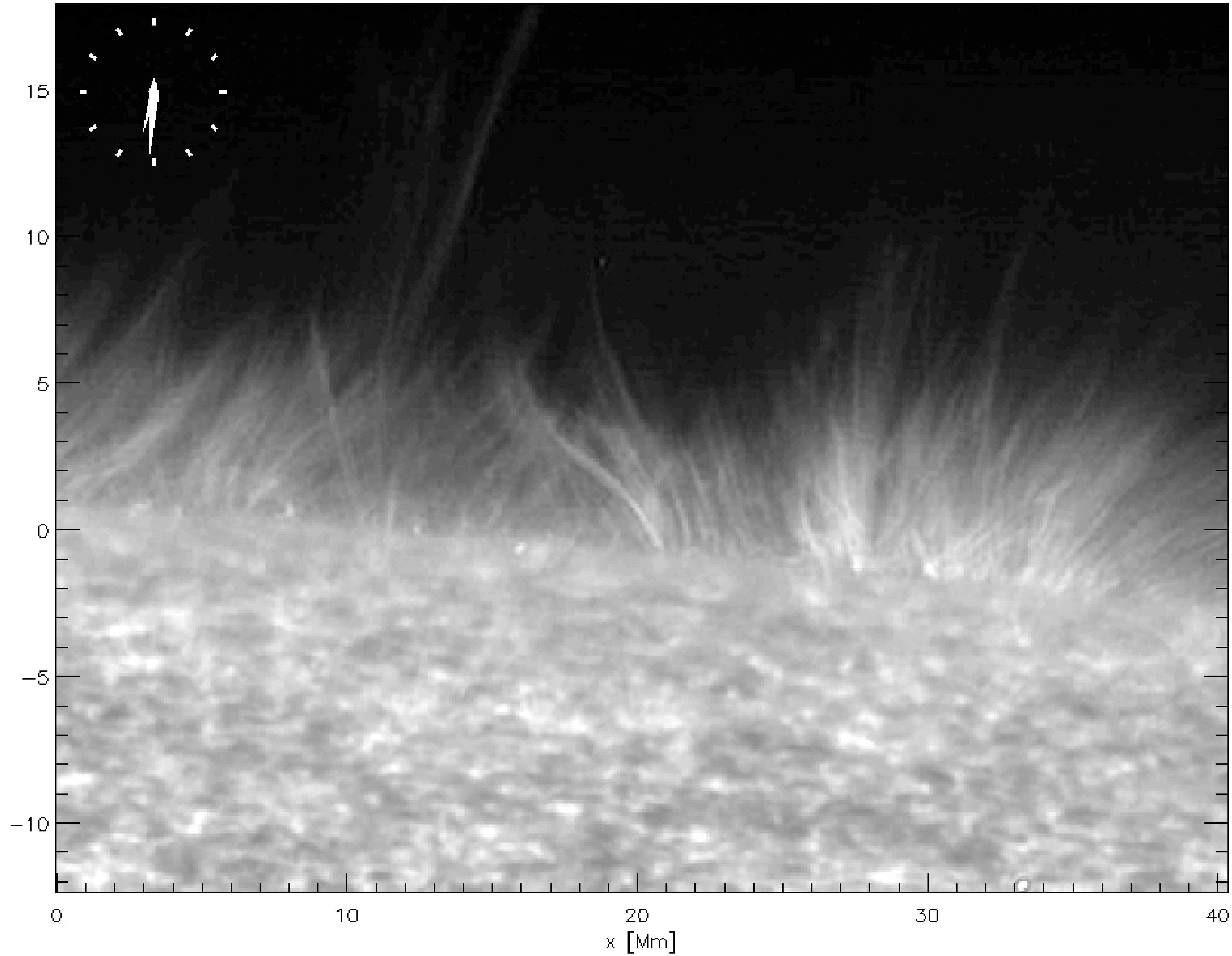
spicules

Hinode Ca II

- bright tracers of dynamic mag- netism within the corona

- complex thermal interface with the corona

- mass supply



The awkward β≳1 transition occurs within the chromosphere

Gold (1964).

stratification makes this transition geometrically thin

that is not the whole story...

yet the chromosphere is often so-treated

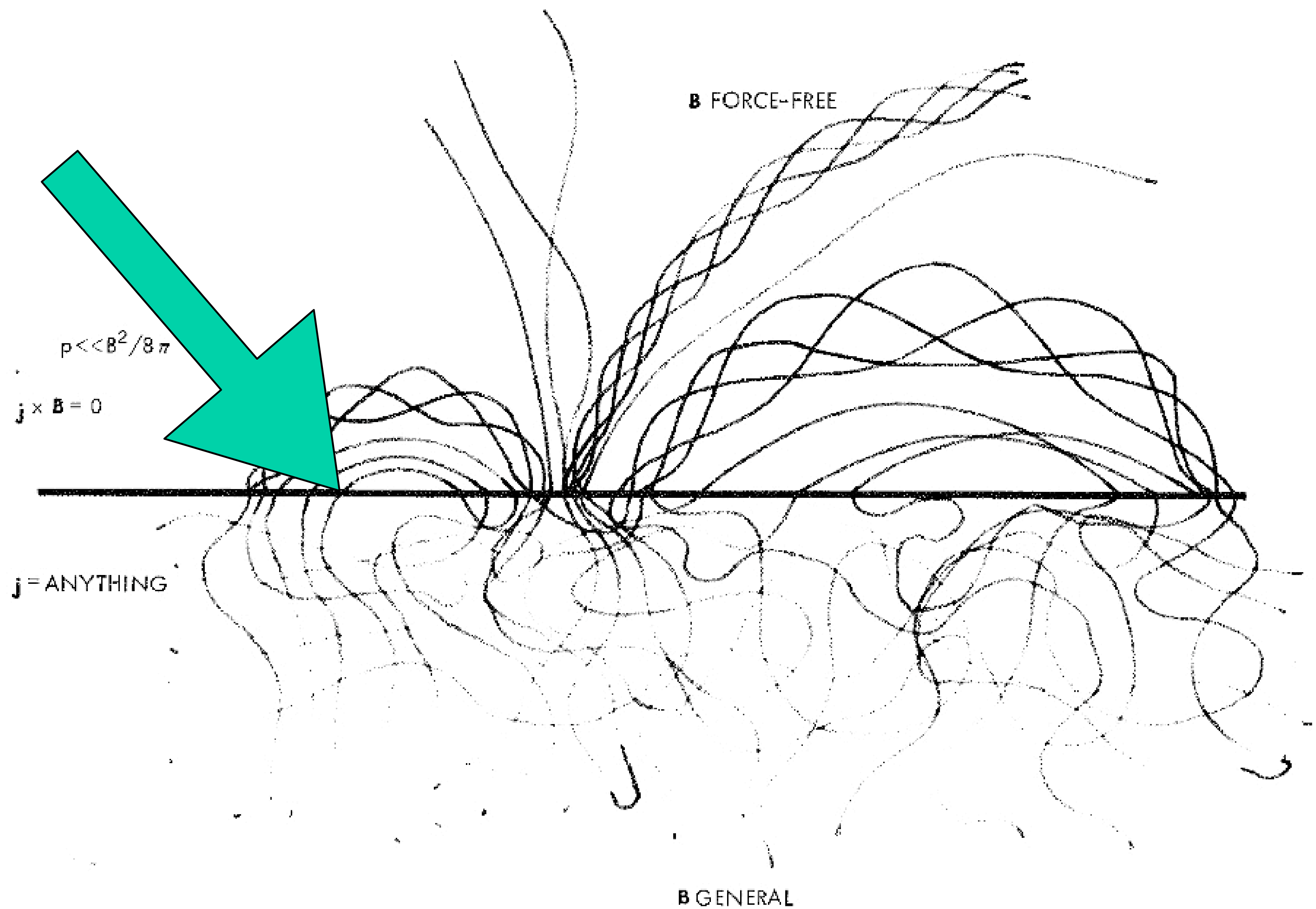


FIGURE 44-2. Magnetic field in a turbulent conducting medium. The fluid pressure is assumed large compared with magnetic forces below the dividing plane and small above it.

let us recall the virial result of Chandrasekhar (1961):

$$\int_V \boldsymbol{r} \cdot [(\nabla \times \boldsymbol{B}) \times \boldsymbol{B}] dV$$

$$= \int_V \tfrac{1}{2} B^2 \, dV + \int_{\partial V} [(\boldsymbol{B} \cdot \boldsymbol{r})\boldsymbol{B} - \tfrac{1}{2} B^2 \boldsymbol{r}] \cdot d\boldsymbol{s} \,, \quad (22)$$

given in standard notation. If the field $\boldsymbol{B}$ is force-free in a volume V, the left-hand side vanishes and the total energy is determined uniquely by the surface vector field,

Reason 6: coronal magnetic free energy can be derived from measurements of magnetic fields at the base in force-free plasma

HAO

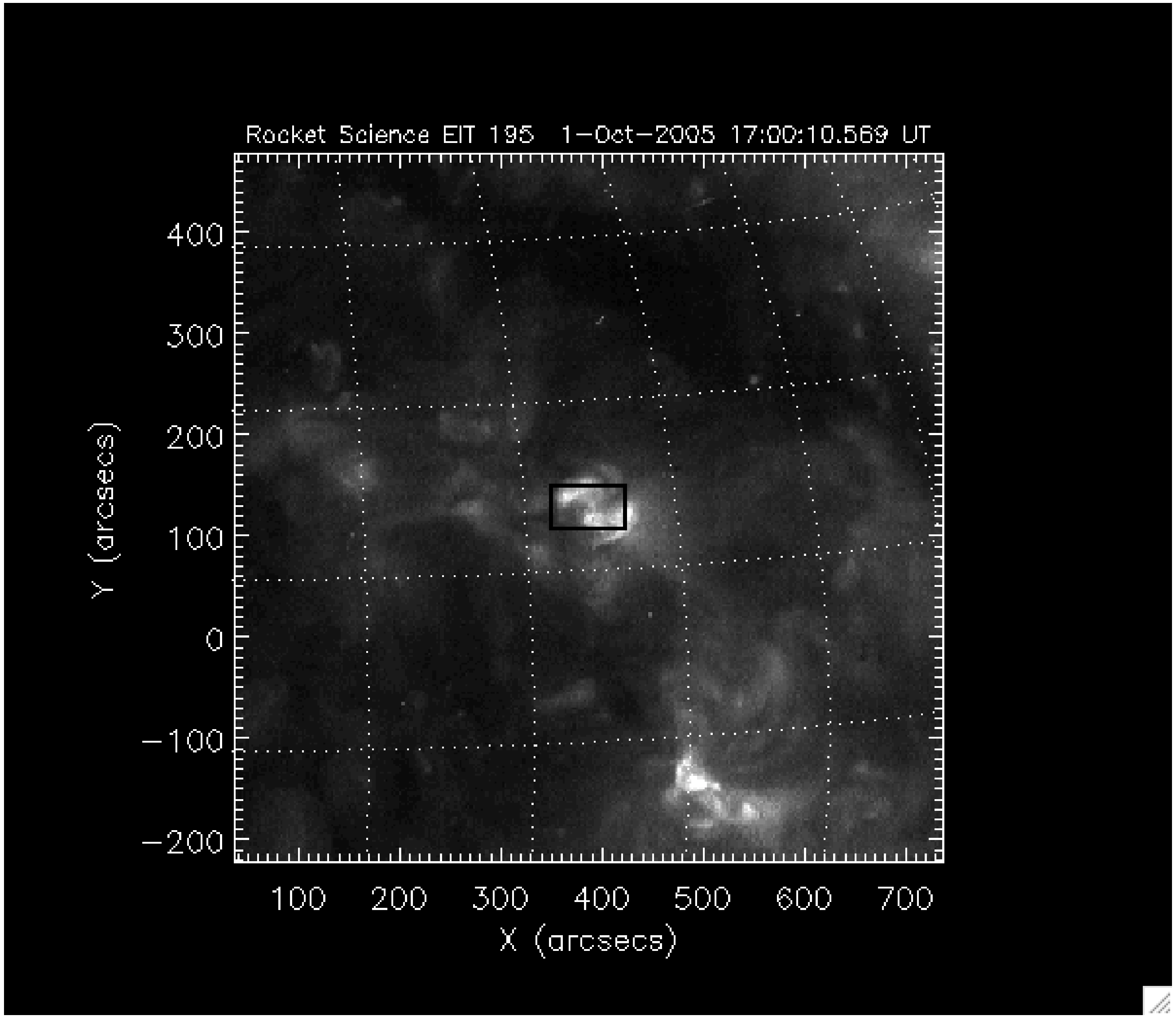
Chromosphere vs. photosphere as the coronal boundary

- Obviously the chromosphere is the coronal base
  - it modulates flow of mass, momentum, energy and magnetic field into the corona
  - it is the implicit mass reservoir in "coronal loop scaling laws"
- **it makes $j_\perp$ small** in the corona, 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 **$j_\perp$ due to ion-neutral collisions**
- **$\alpha(r) \rightarrow$? at the coronal base:** coronal current sheets (Parker)

Reason 7: the chromosphere actively sets the boundary conditions for the corona and its evolution

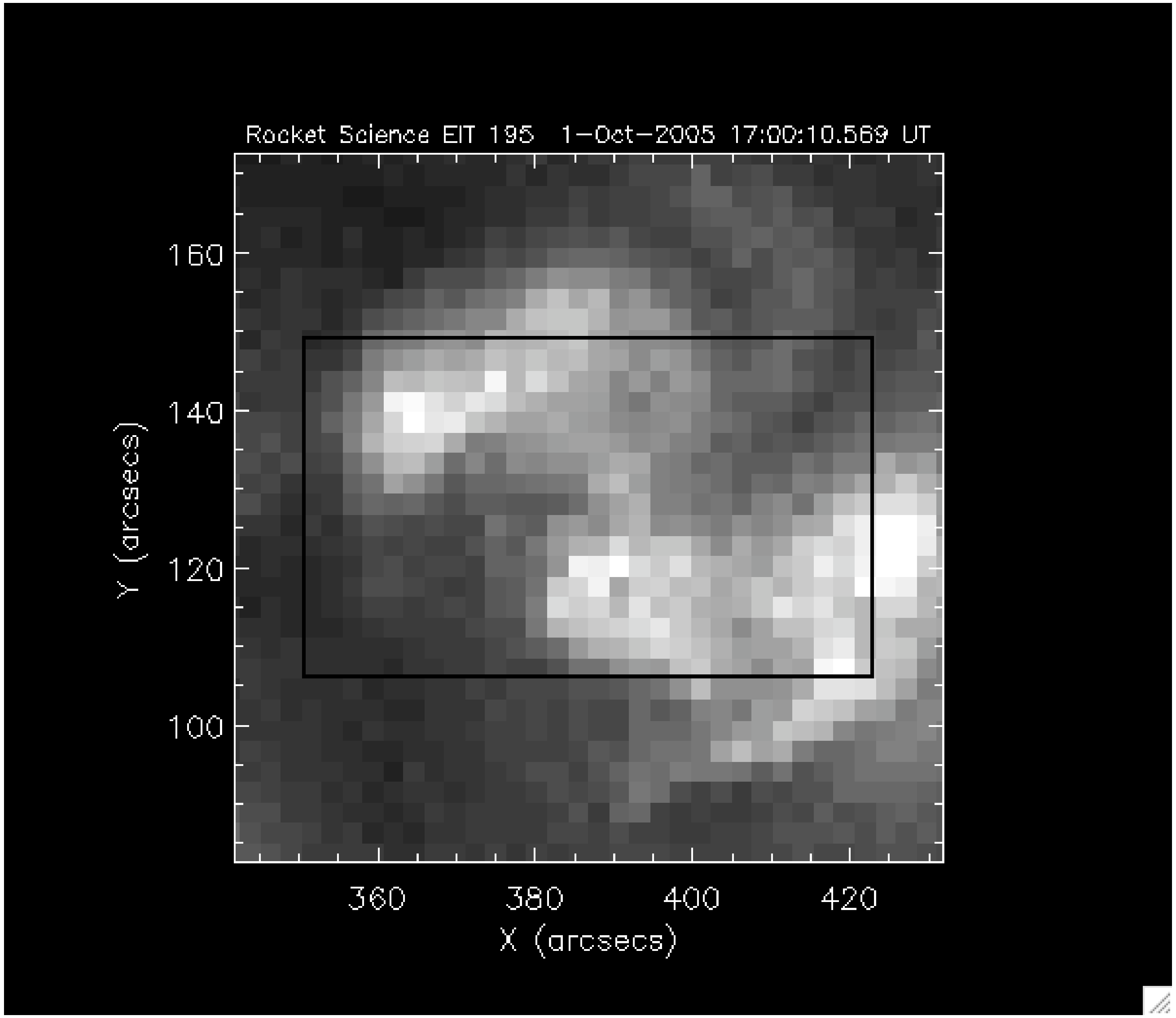
HAO

Example



Rocket Science EIT 195 1-Oct-2005 17:00:10.569 UT
400
300
200
100
0
−100
−200
Y (arcsecs)
100
200
300
400
500
600
700
X (arcsecs)

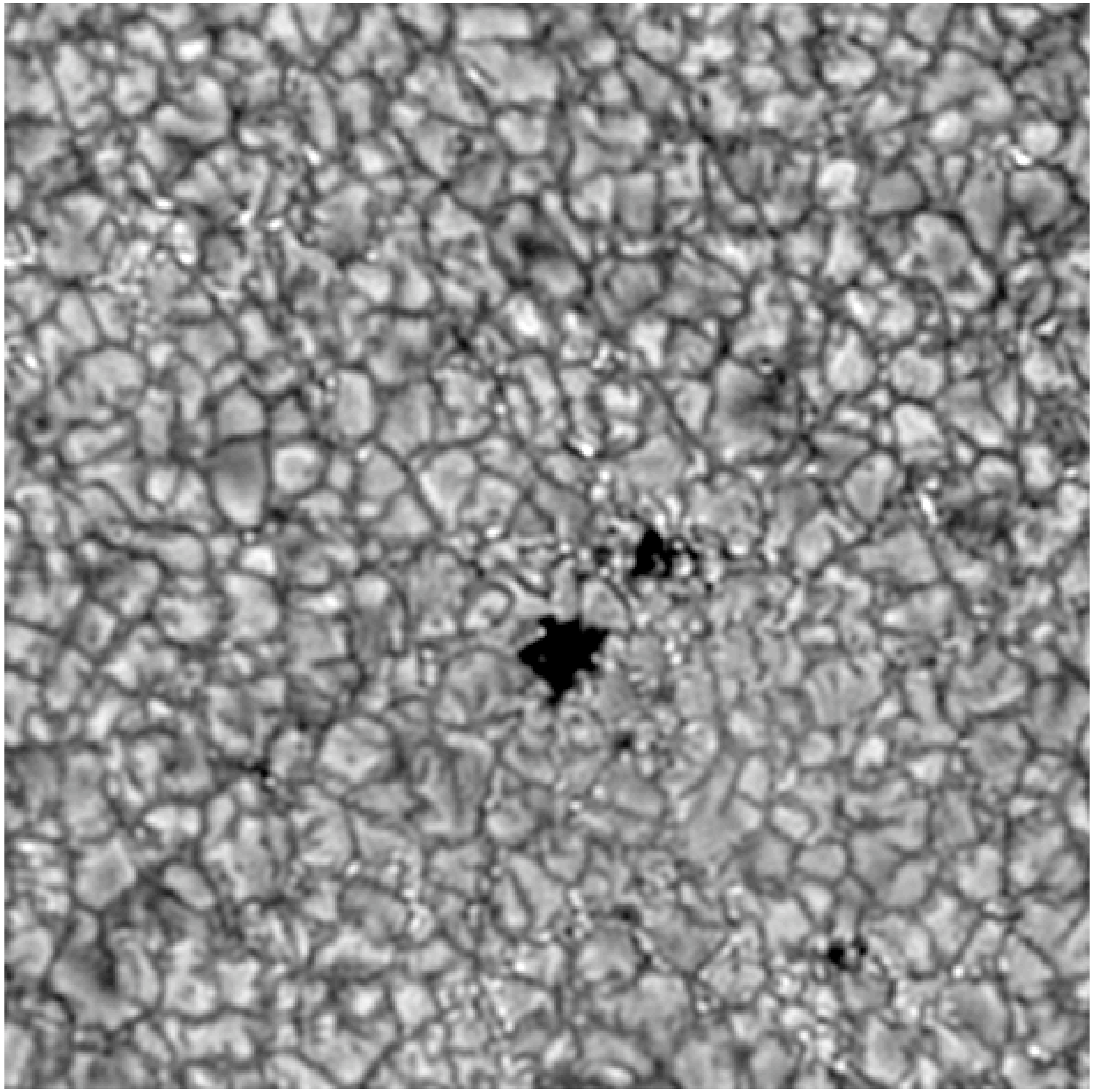
a closer view



Box=IBIS FOV

the photosphere and chromosphere as seen by IBIS

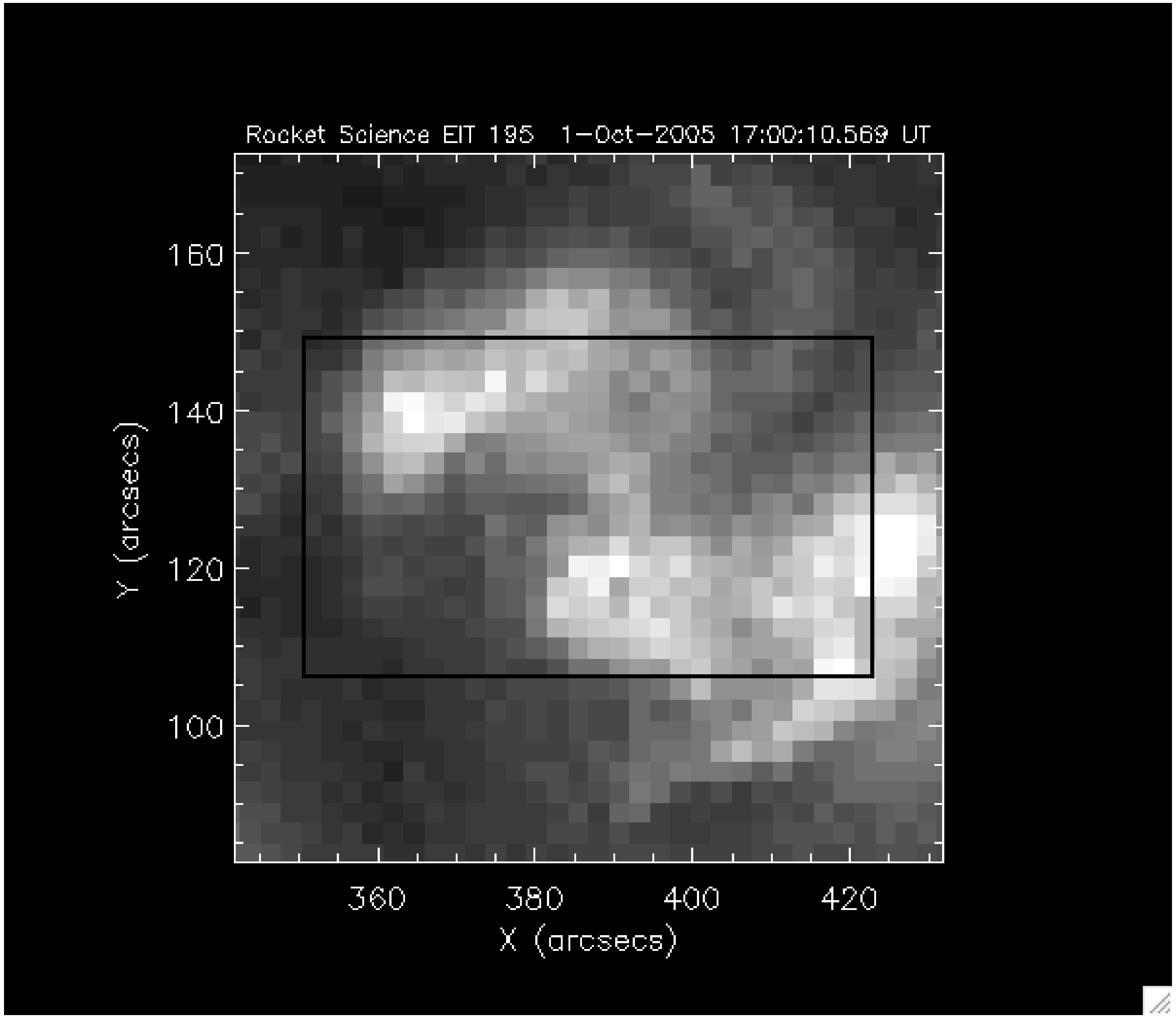
- Ca II 854.2 nm
- samples many pressure scale heights
- through this “very thin” layer



G. Cauzzi et al 2008, A+A

yet base of corona is very different from photosphere!

photosphere - chromosphere - corona and field extrapolations

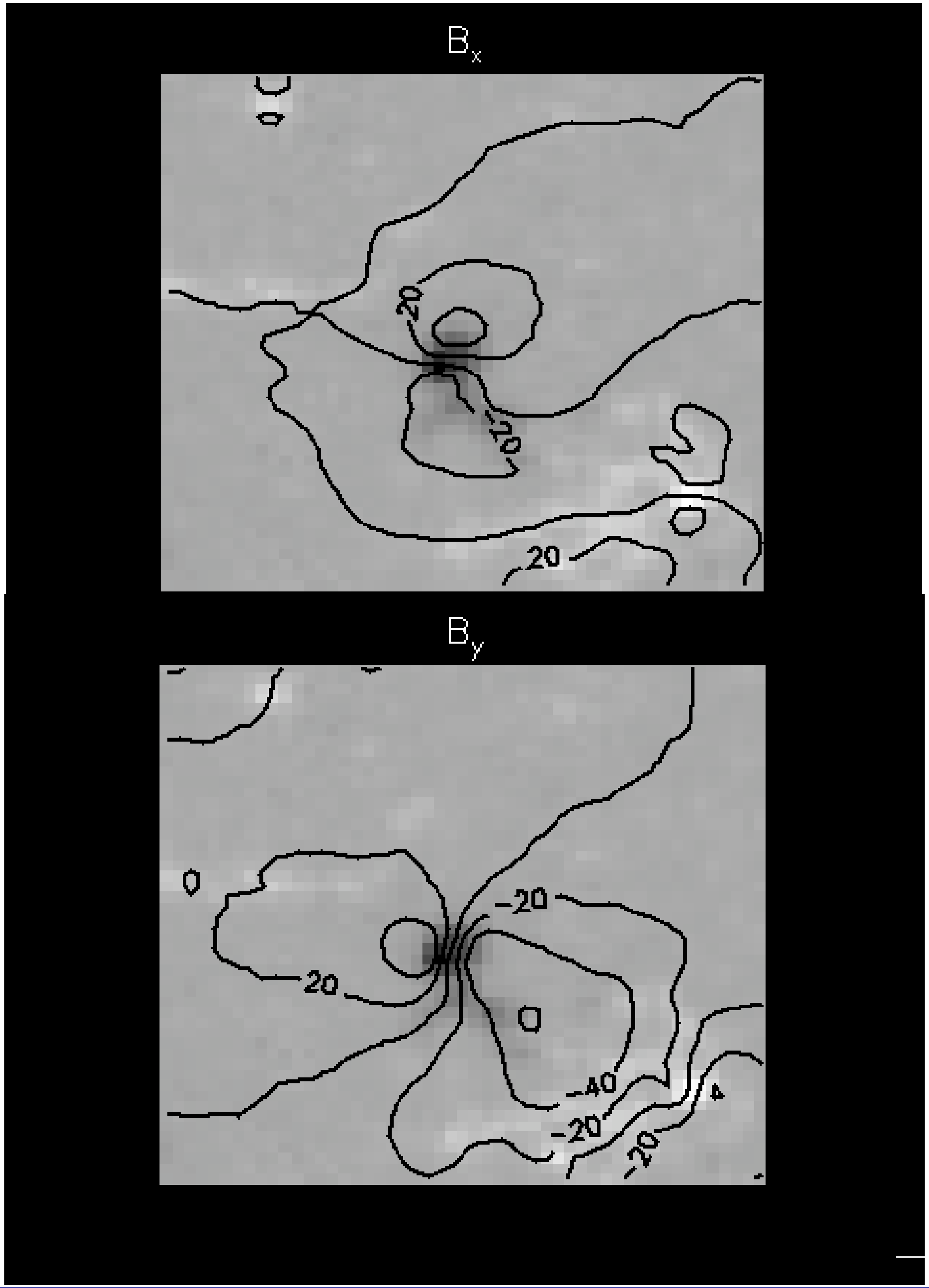


α=constant does not fit morphology- hence current sheets exist

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 *barely* detect transverse fields implied by chromospheric morphology

Reason 8: chromospheric fibrils covering surface clearly sense non-potential magnetic energy



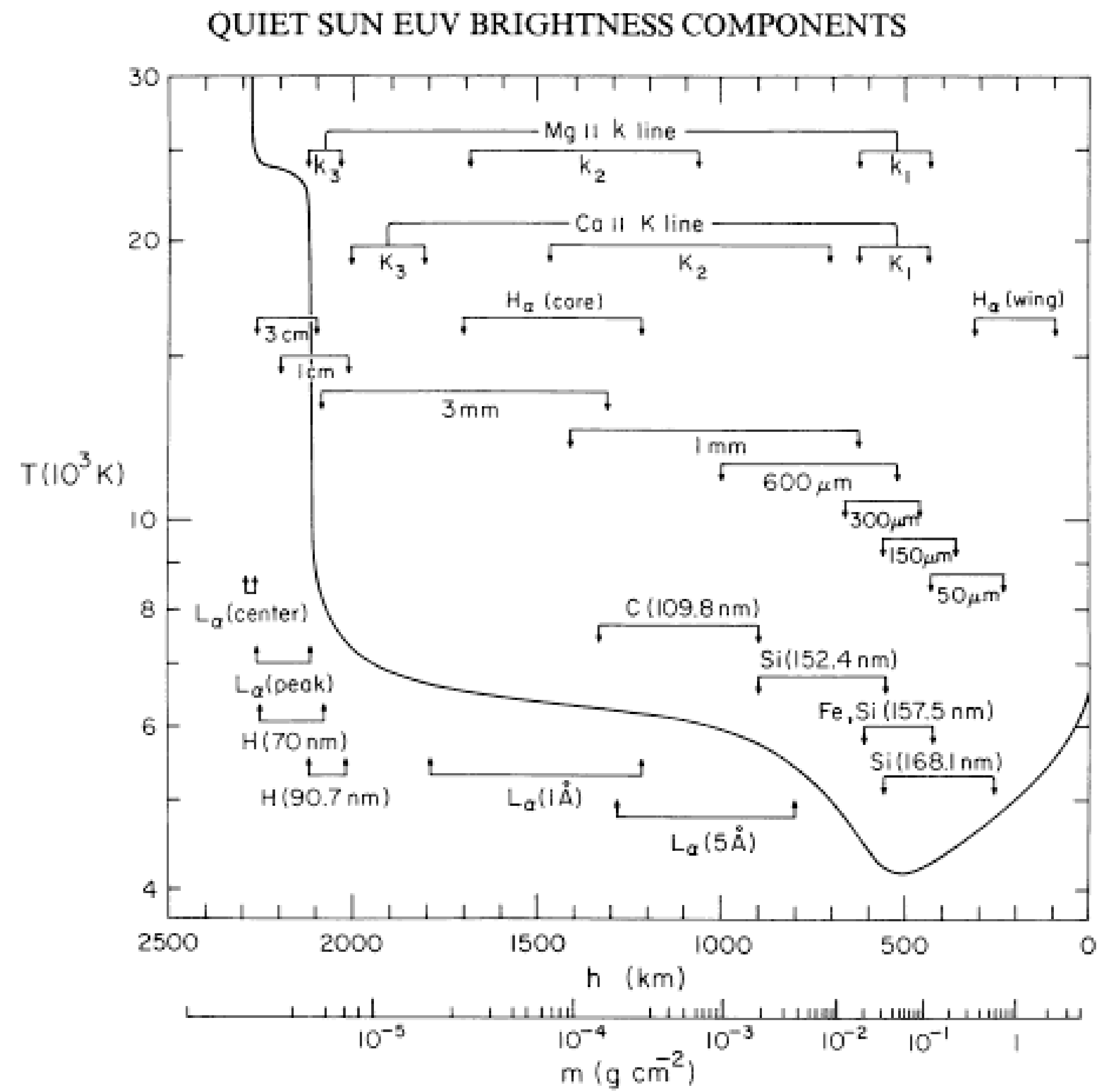
The chromosphere is interesting all by itself

- ➔ Limb vs disk chromosphere
- ➔ Force imbalance in the network chromosphere?
- ➔ Basic physics of partially ionized magnetized plasmas
- ➔ Origin of transition region emission
- ➔ As a target for *imaging spectropolarimetry*

where is the chromosphere at the limb?

“disk chromosphere”

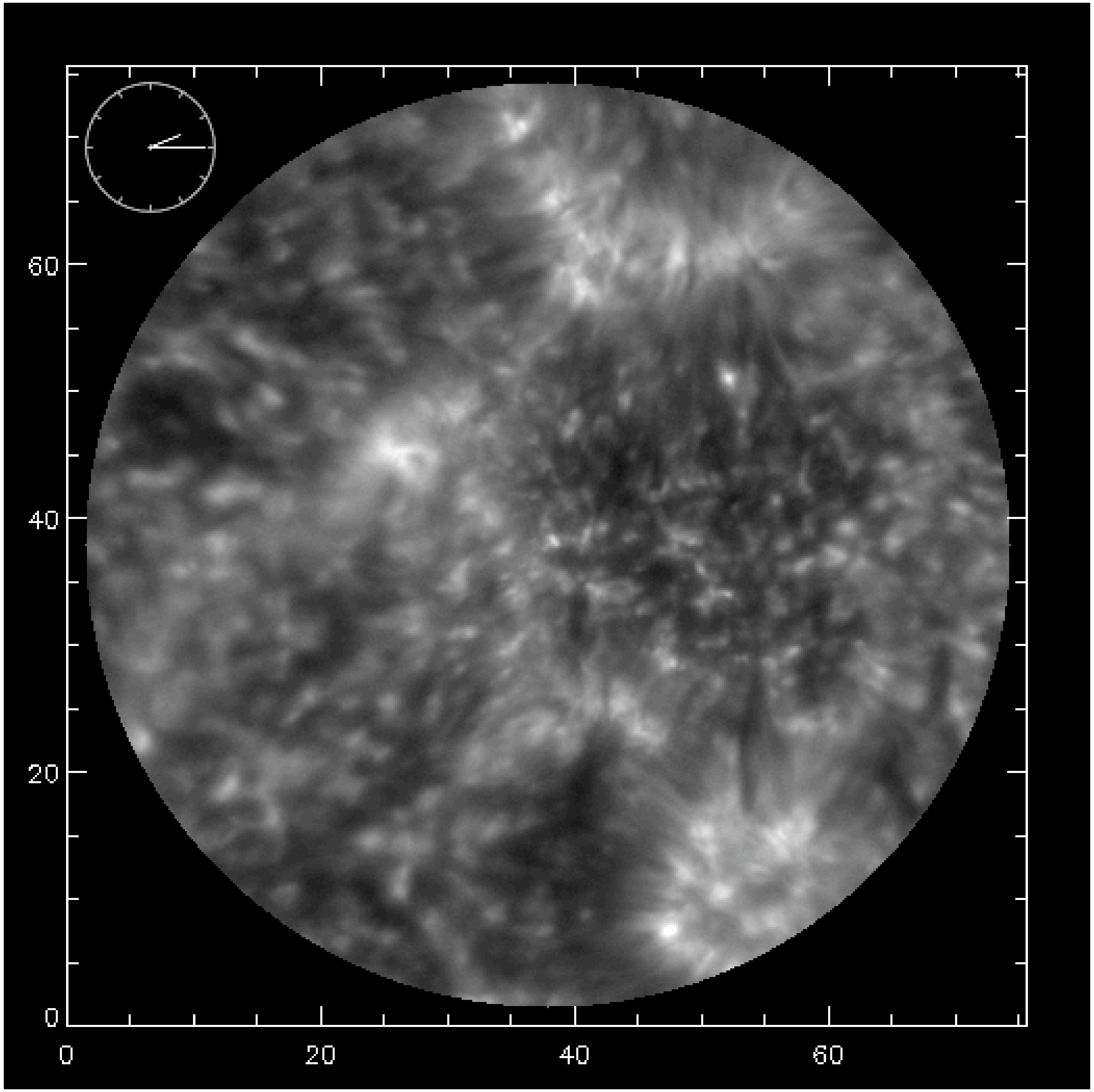
- UV/EUV: HSRA, VAL, FAL,…
- hydrostatic
  - => not credible?
- consider-
  - eclipse data (flash)
  - subsonic motions
  - oscillation data
  - …
- gross stratification is sound
  - P(corona)=10^{-5} P(photosphere)
  - type I spicule models



chromosphere spans 1.5-2 Mm

dynamics: IBIS Ca II IR triplet
QS chromosphere

- Cauzzi et al 2007
- $\lambda/\Delta\lambda \approx 100{,}000$
- line core
- network vs internetwork



Ca II H QS chromosphere

Lites et al 1993

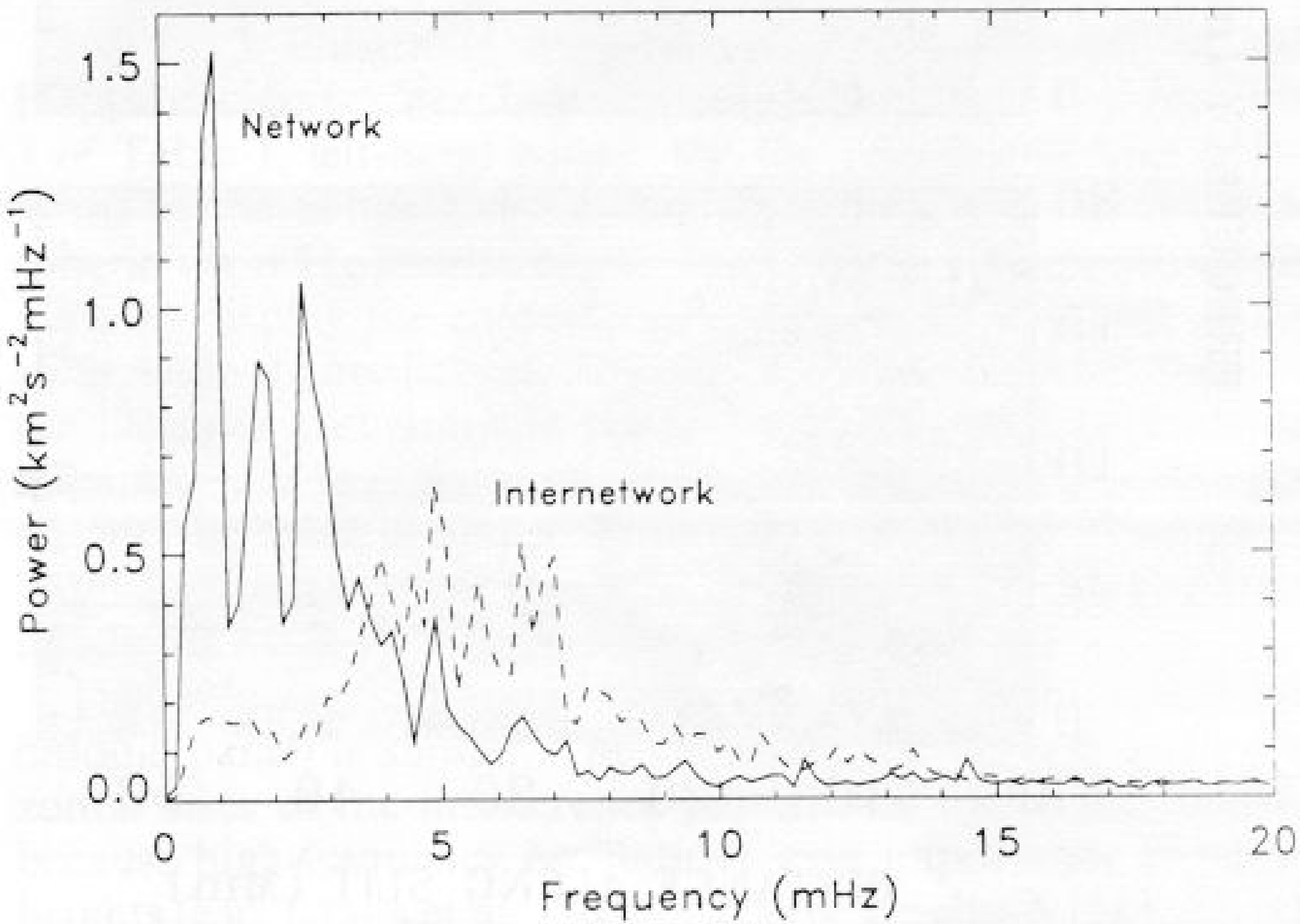
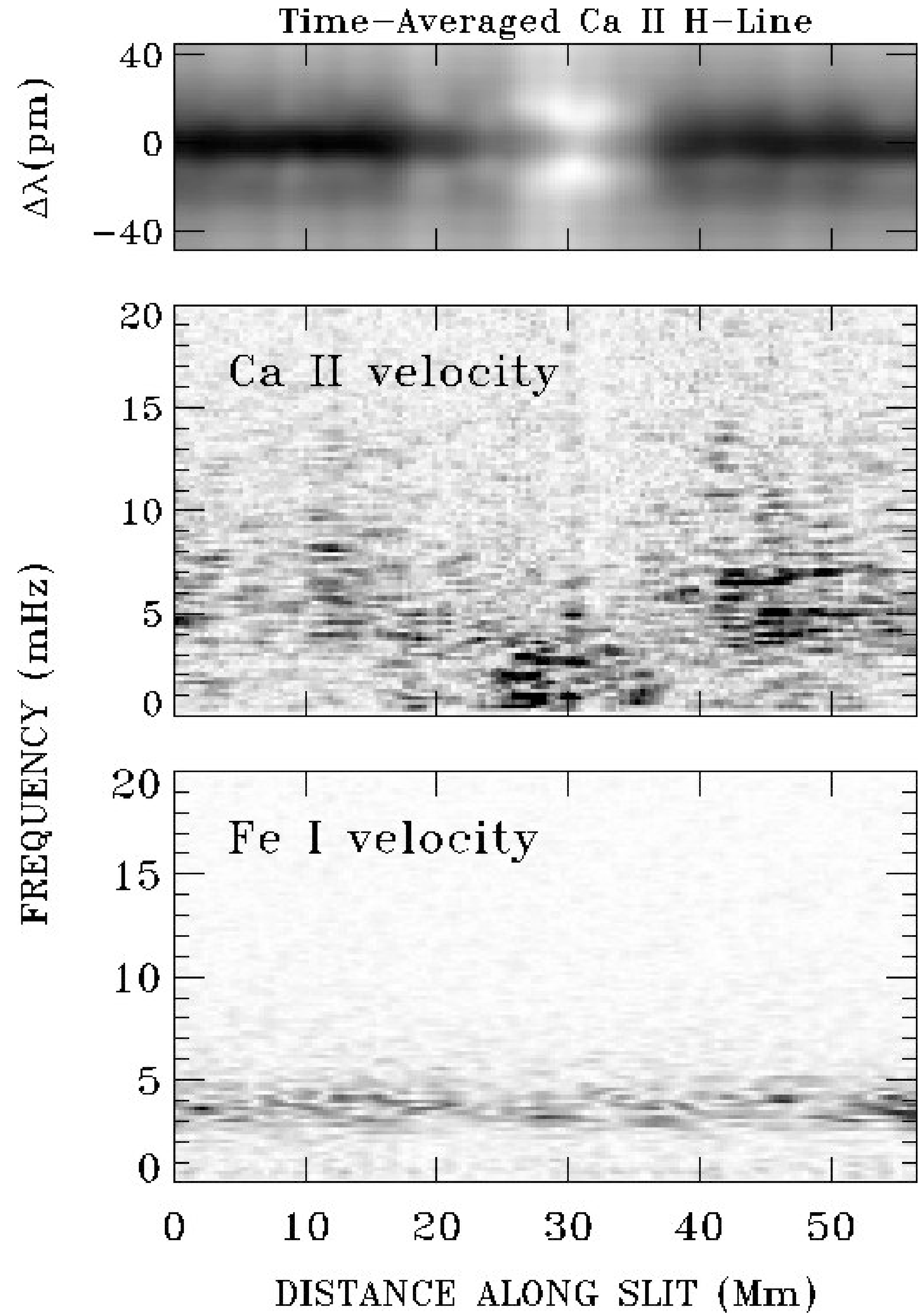


FIG. 6.—Velocity power spectra are shown for the Ca II H_3 excursions, with separate spatial averaging over the network (*solid curve*) and internetwork (*dashed curve*) regions along the slit.

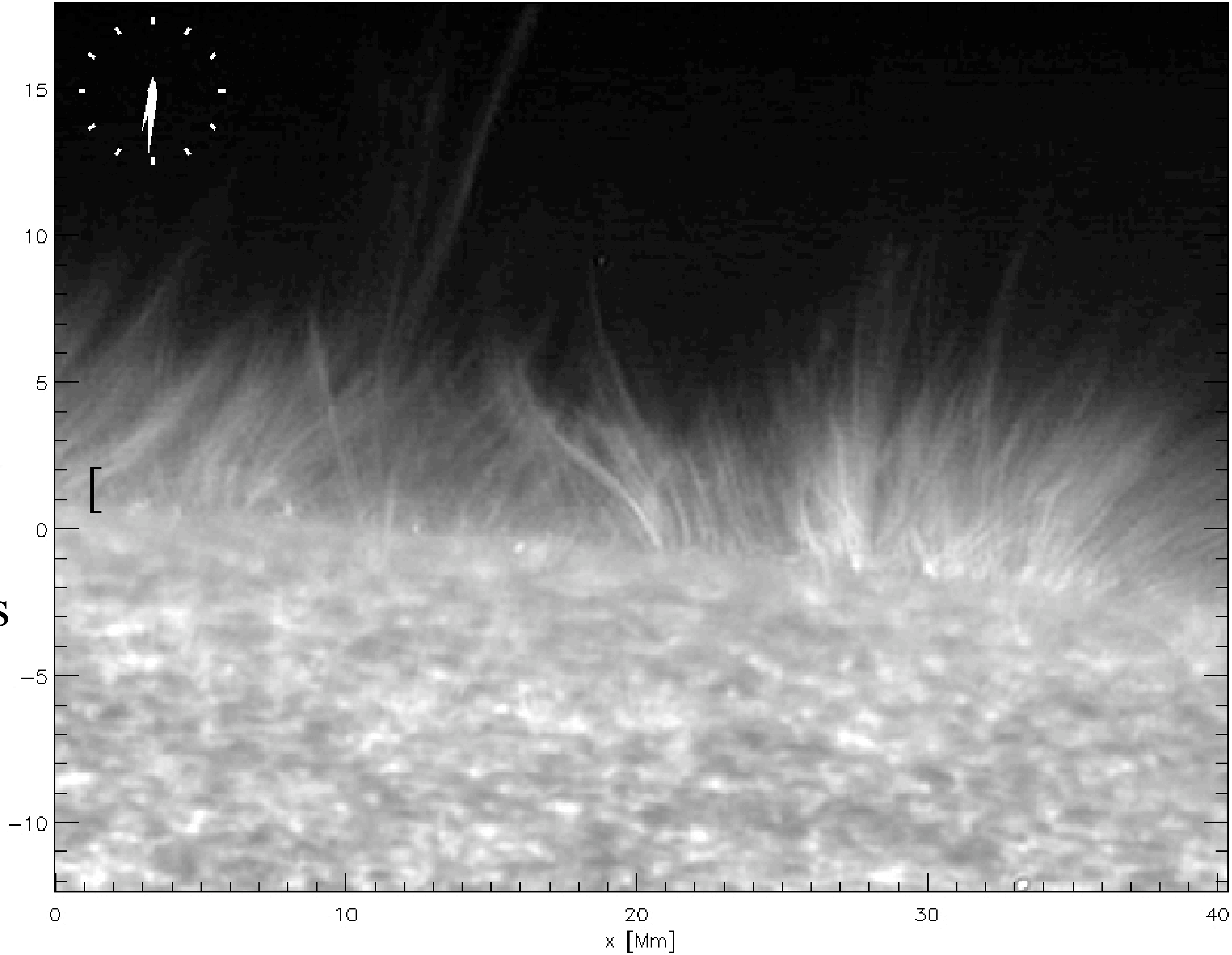


where is it?

Hinode Ca II H
h=0: blue continuum @ disk center.
Bjølseth 2008

Disk chromosphere

Type II spicules *appear* to originate fully fledged from photosphere!



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

chromosphere=spicules?

A Tale of Two Spicules: The Impact of Spicules on the Magnetic Chromosphere*

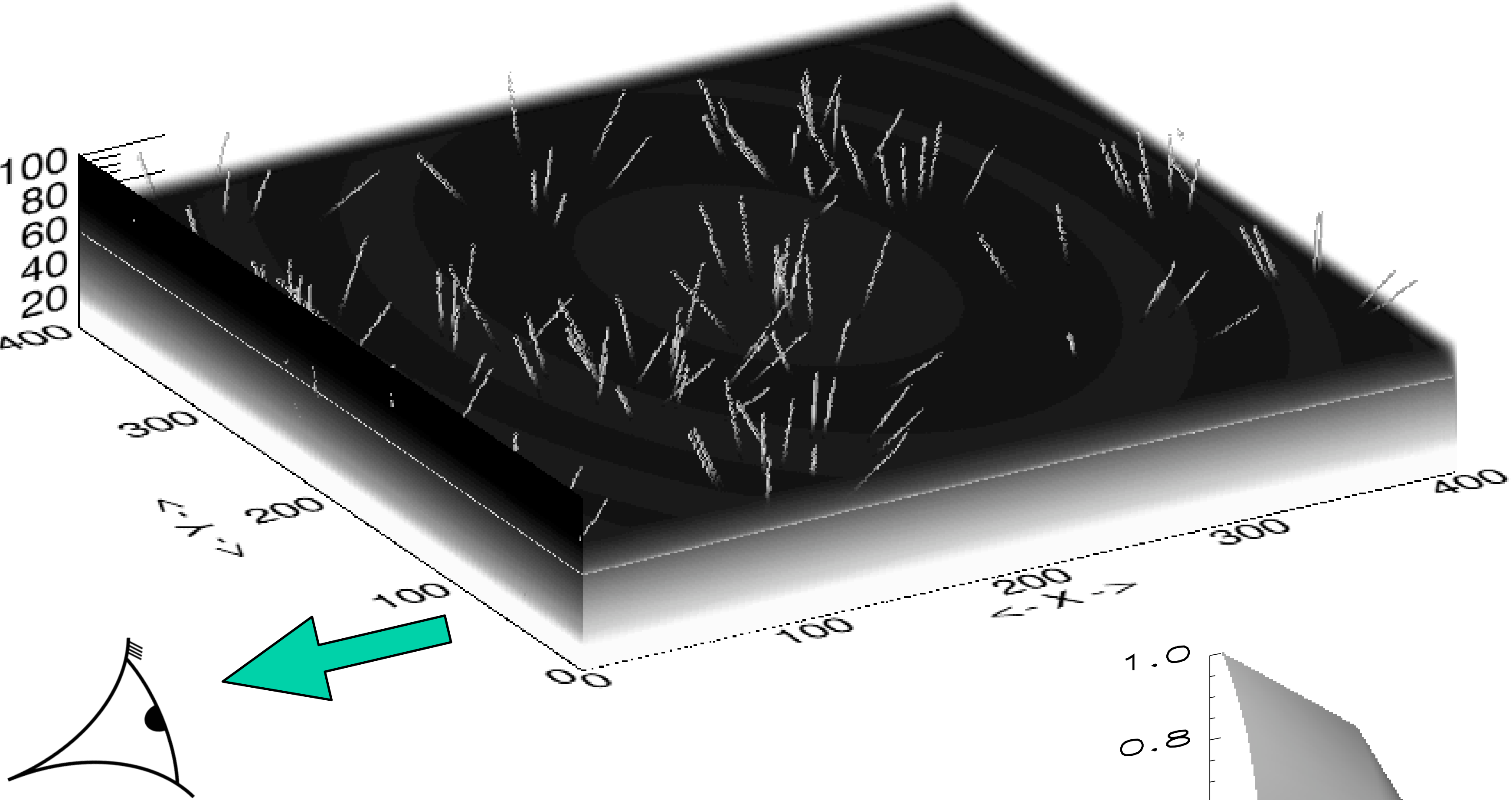
Bart DE PONTIEU,[1] Scott MCINTOSH,[2,3] Viggo H. HANSTEEN,[4,1] Mats CARLSSON,[4] Carolus J. SCHRIJVER,[1] Theodore D. TARBELL,[1] Alan M. TITLE,[1] Richard A. SHINE,[1] Yoshinori SUEMATSU,[5] Saku TSUNETA,[5] Yukio KATSUKAWA,[5] Kiyoshi ICHIMOTO,[5] Toshifumi SHIMIZU,[6] and Shin'ichi NAGATA[7]

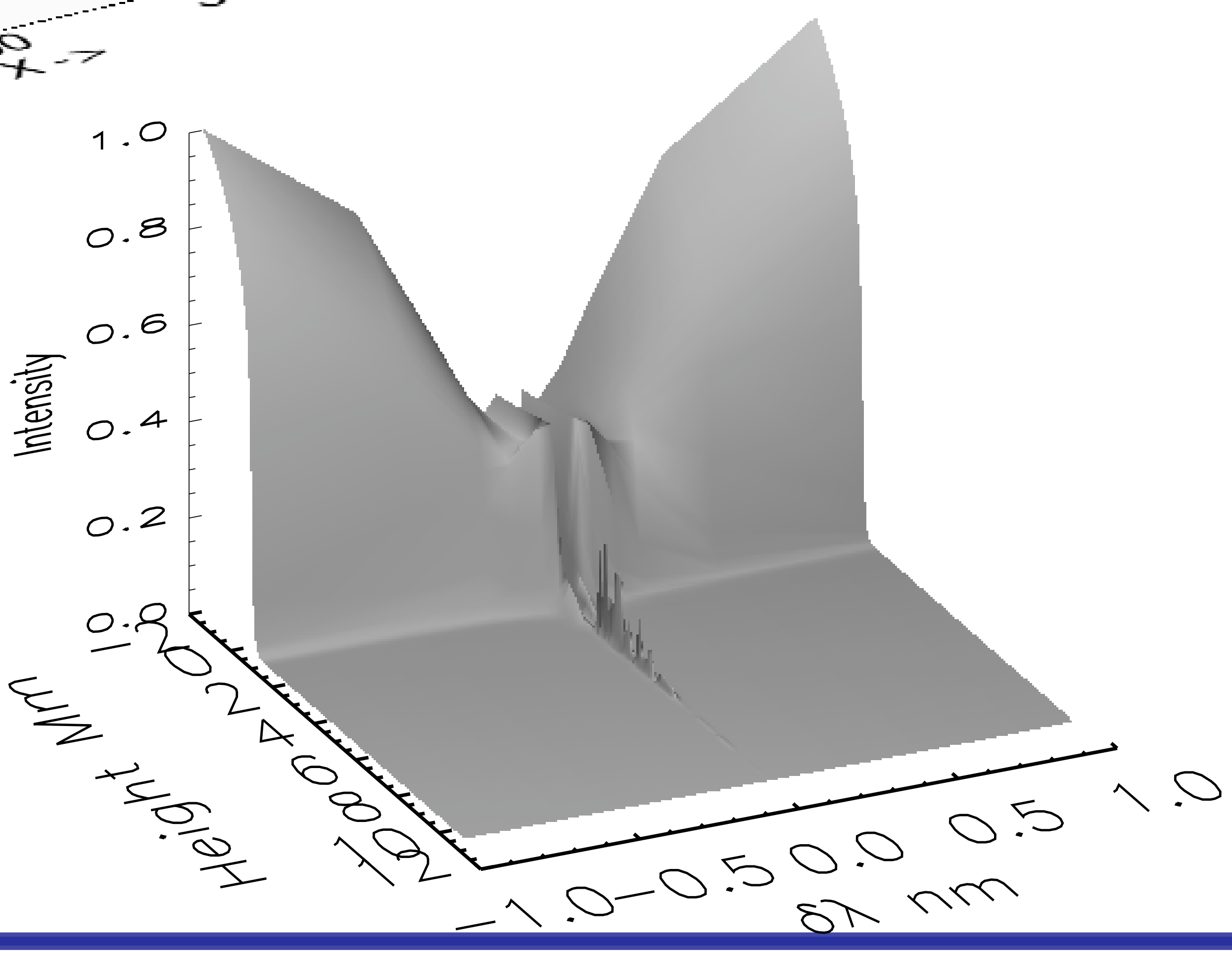
Abstract

We use high-resolution observations of the Sun in Ca II H (3968 Å) from the Solar Optical Telescope on Hinode to show that there are at least two types of spicules that dominate the structure of the magnetic solar chromosphere. Both types are tied to the relentless magnetoconvective driving in the photosphere, but have very different dynamic properties. "Type-I" spicules are driven by shock waves that form when global oscillations and convective flows leak into the upper atmosphere along magnetic field lines on 3–7 minute timescales. "Type-II" spicules are much more dynamic: they form rapidly (in $\sim 10\,\mathrm{s}$), are very thin (≤ 200 km wide), have lifetimes of 10–150 s (at any one height), and seem to be rapidly heated to (at least) transition region temperatures, sending material through the chromosphere at speeds of order 50–150 $\mathrm{km\,s^{-1}}$. The properties of Type II spicules suggest a formation process that is a consequence of magnetic reconnection, typically in the vicinity of magnetic flux concentrations in plage and network. Both types of spicules are observed to carry Alfvén waves with significant amplitudes of order 20 $\mathrm{km\,s^{-1}}$.

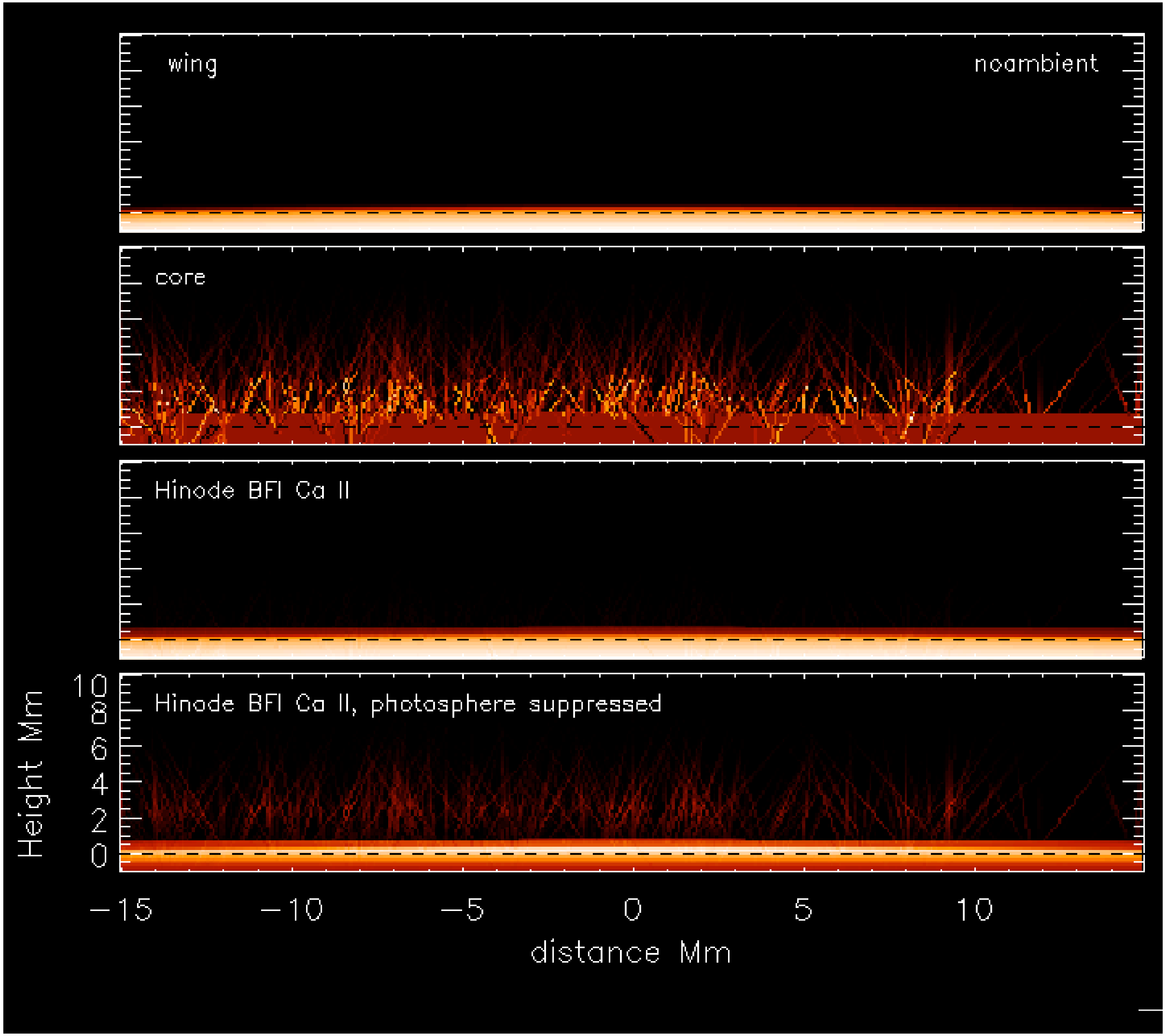
HAO

Formal solutions





Formal solutions

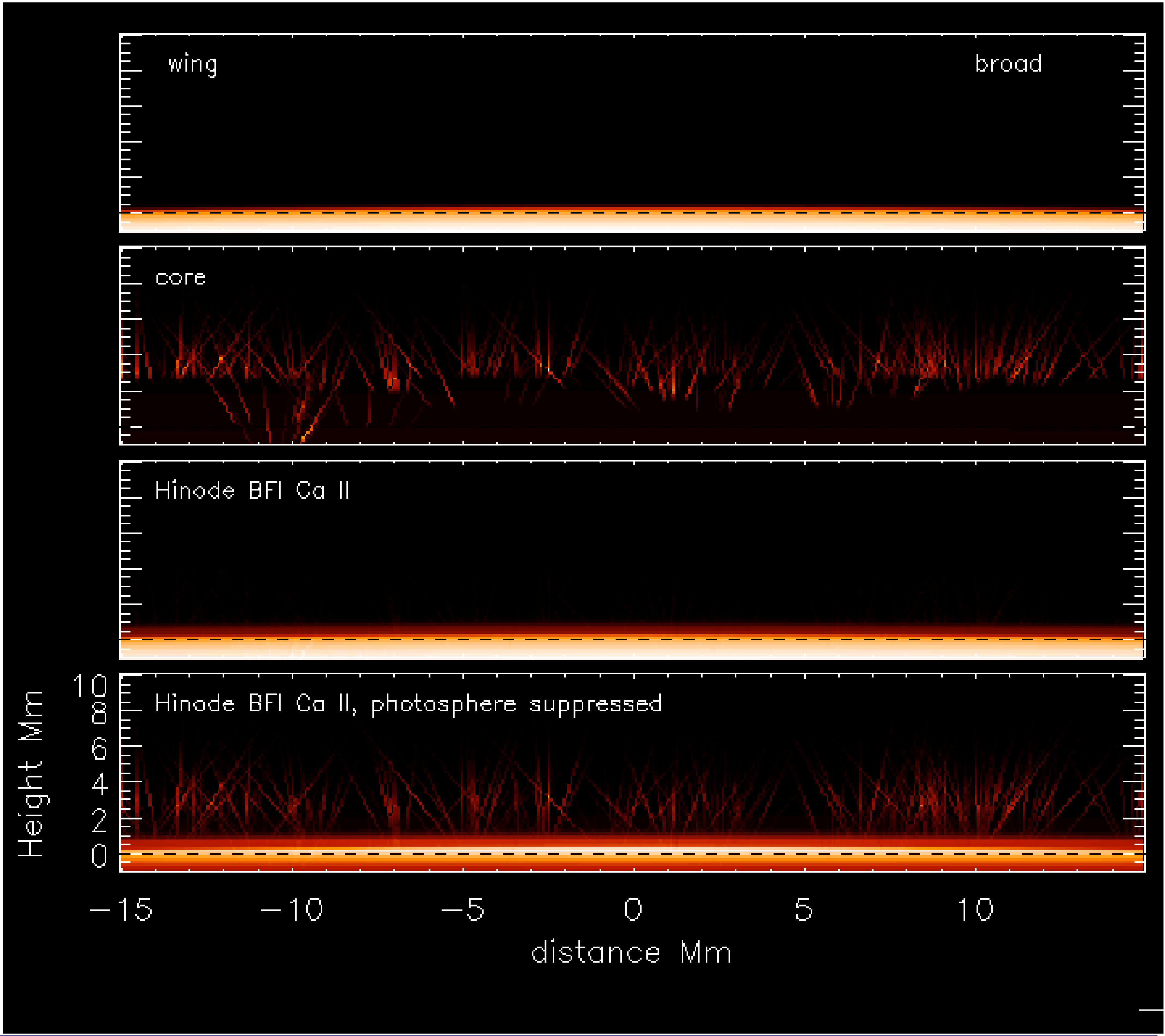


Formal solutions

Broad emission Doppler shifted out of opacity in ambient medium

Hinode BFI does not see most of the chromosphere at the limb. It sees some "type I" spicules

Ambient medium is there and dominates mass,...



chromosphere ≠ spicules

....visibility of spicules at limb implies this

total spicule II mass ~ $4\times10^{-17}\,M_\odot$

total chromosphere mass ~ $10^{-12}\,M_\odot$

Within the network

enthalpy flux density ~ 5×10^5 erg cm^{-2} s^{-1} (Athay, 20 km/s)

~ 2×10^6 (de Pontieu 80 km/s)

Alfvénic flux density > 5×10^5

radiative flux density ≥ 2×10^7 i.e. "lossy"

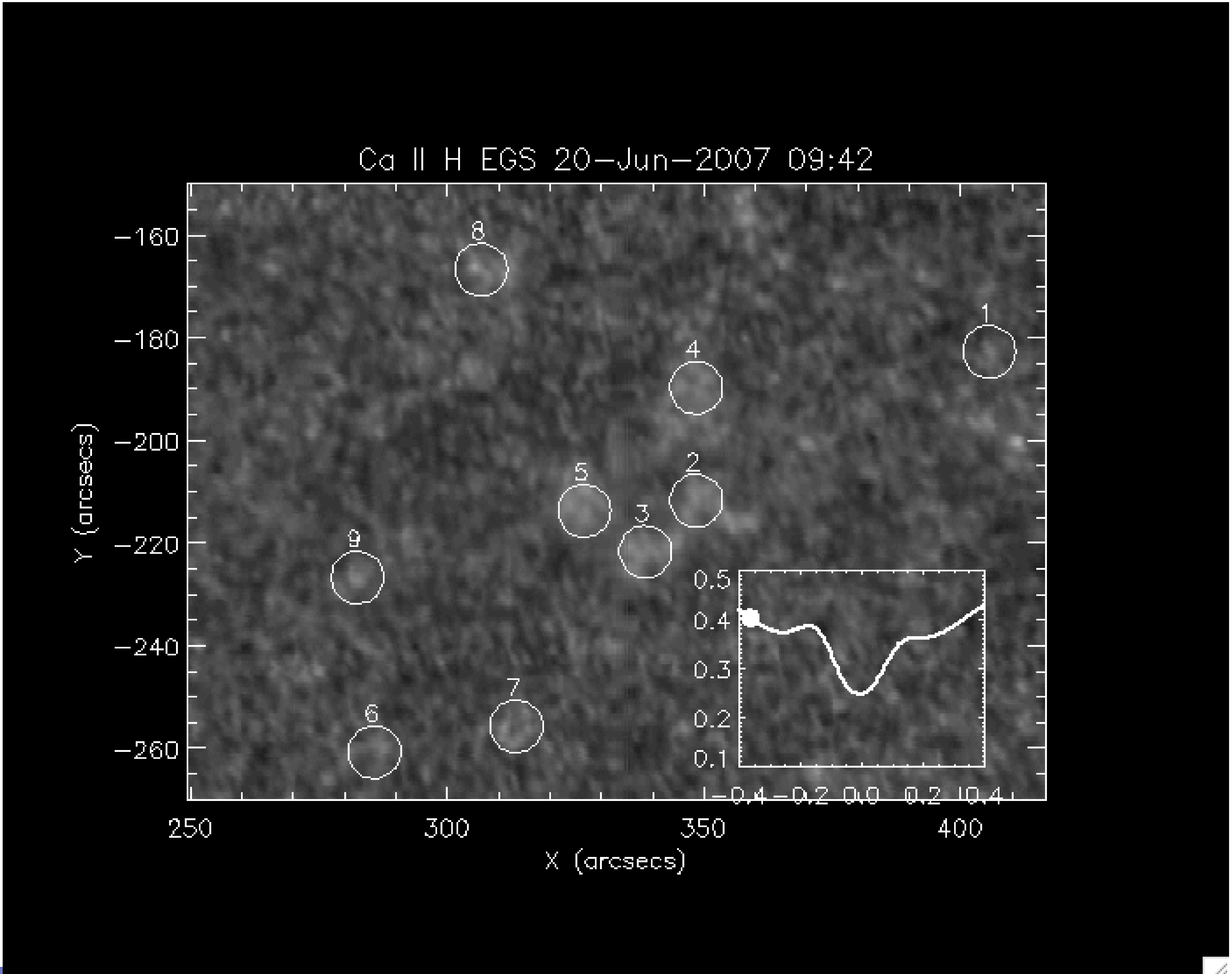
(" corona ~ 8×10^5)

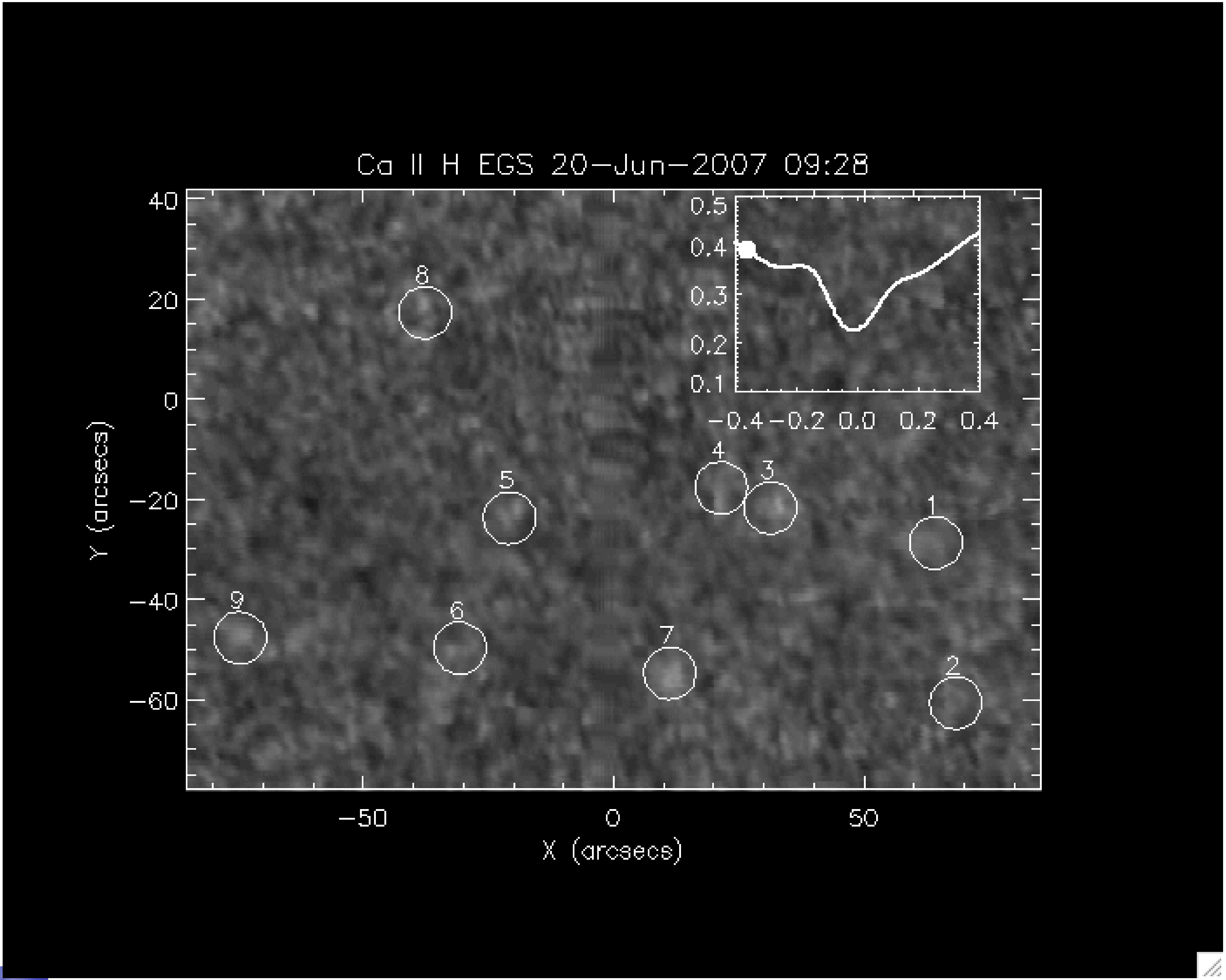
➜ spicules *arise from* the chromosphere, and are important for the corona, by increasing mass/energy exchange

HAO

an odd property of the network chromosphere

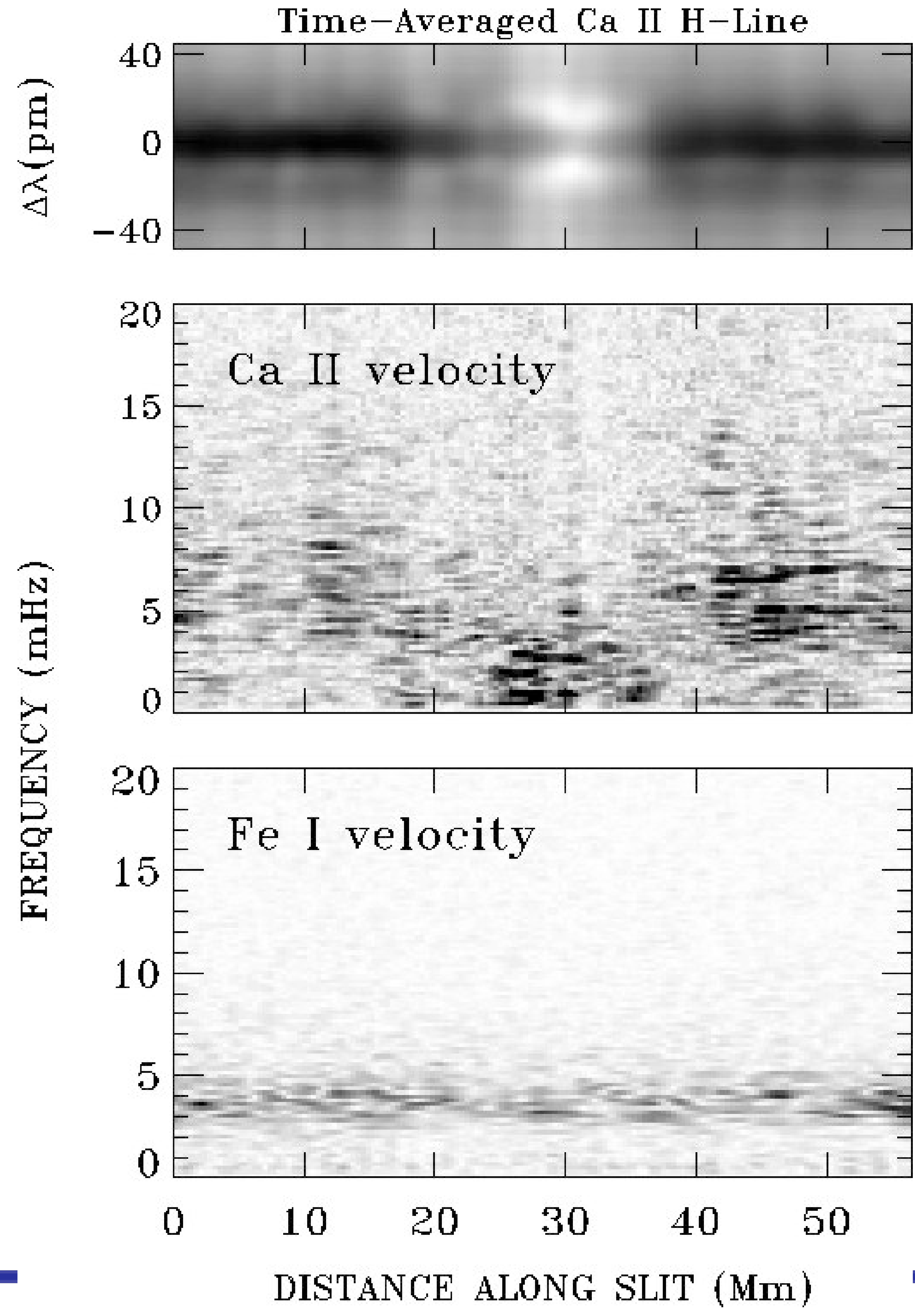
Schmidt


Ca II H EGS 20-Jun-2007 09:42
−160
−180
−200
−220
−240
−260
Y (arcsecs)
250
300
350
400
X (arcsecs)
1
2
3
4
5
6
7
8
9
0.5
0.4
0.3
0.2
0.1
−0.4
−0.2
0.0
0.2
0.4


Ca II H EGS 20-Jun-2007 09:28
Y (arcsecs)
X (arcsecs)
40
20
0
−20
−40
−60
−50
0
50
1
2
3
4
5
6
7
8
9
0.5
0.4
0.3
0.2
0.1
−0.4
−0.2
0.0
0.2
0.4

dynamics: ground-based Ca II

- Lites, Rutten, Kalkofen 1993
  - Ca II H λ/Δ λ ≈ 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*

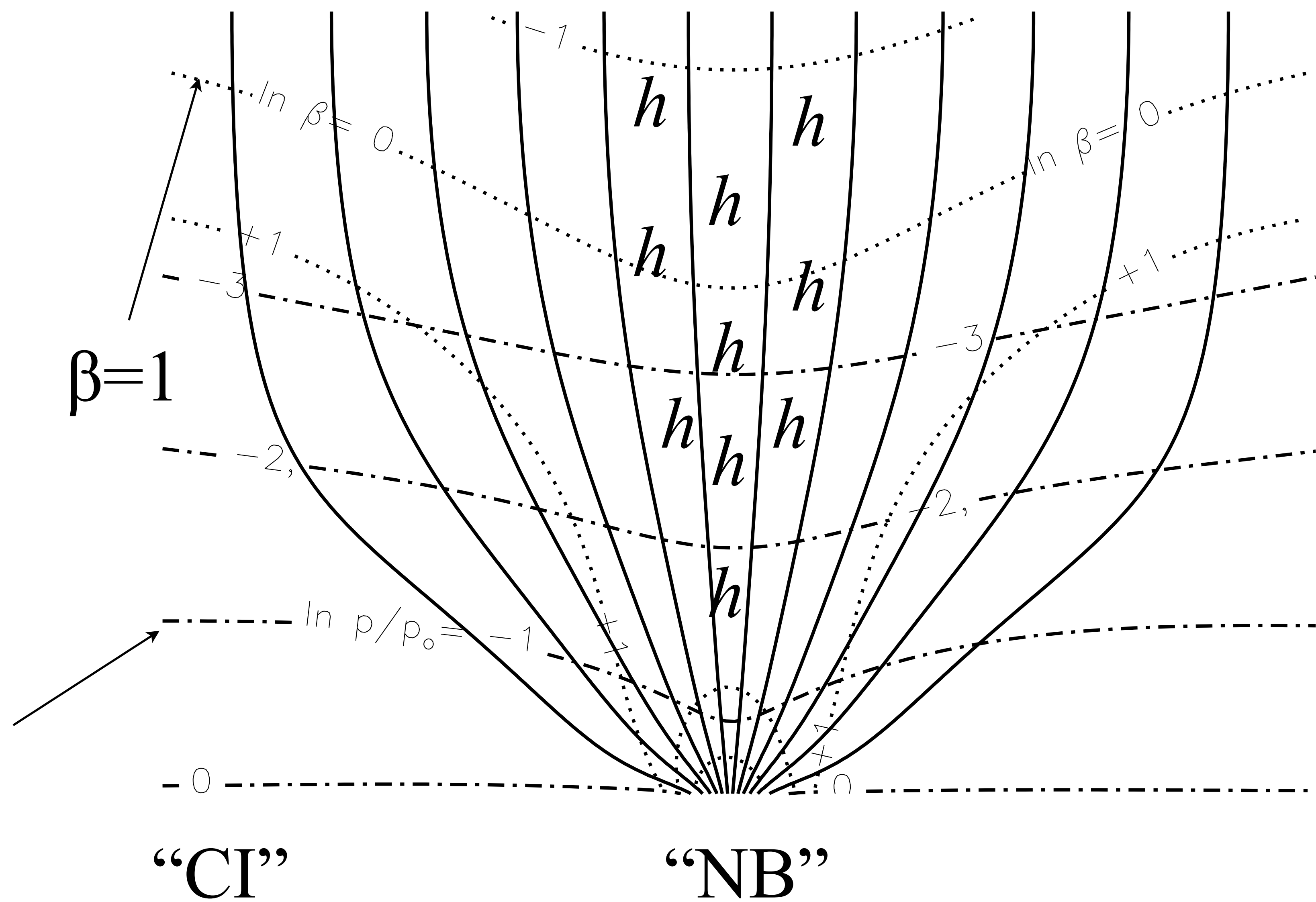


Conundrum

force and energy imbalance?

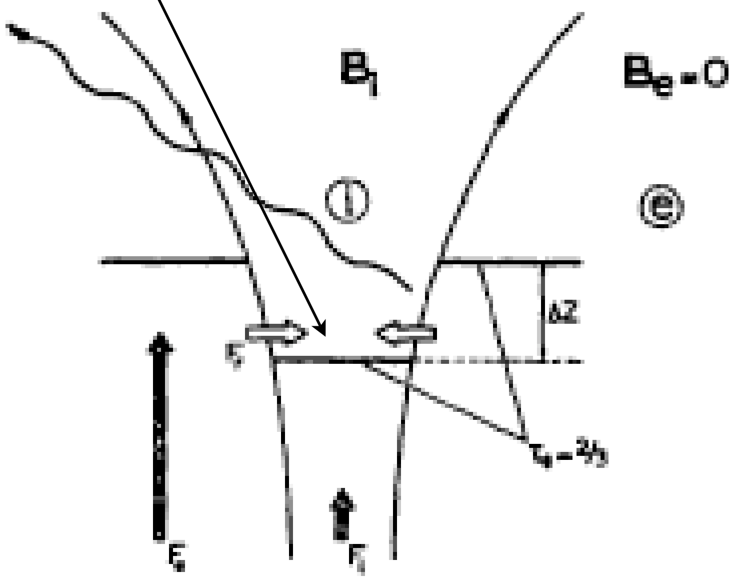
- To produce bright chromospheric emission, VAL models require high P where B is high (marked "*h*")

BUT- magnetostatic equilibrium requires low P where B is high



suggestion 1:
Solanki, Steiner & Uitenbroek (1991)

- $dP/dz = -\rho g$ invariant with $z \rightarrow z + constant$
- slide entire NB atmosphere ↓(*Wilson anxiety"*)
  - satisfy horizontal pressure equilibrium
  - get same *vertical* emergent intensity



However

- VAL F/A pressures require >2 scale heights *anxiety, 250km*
- models are built from 5"x5" observations
- implies NB is "deeper" than CI..
- is this consistent with 3D MHD models?

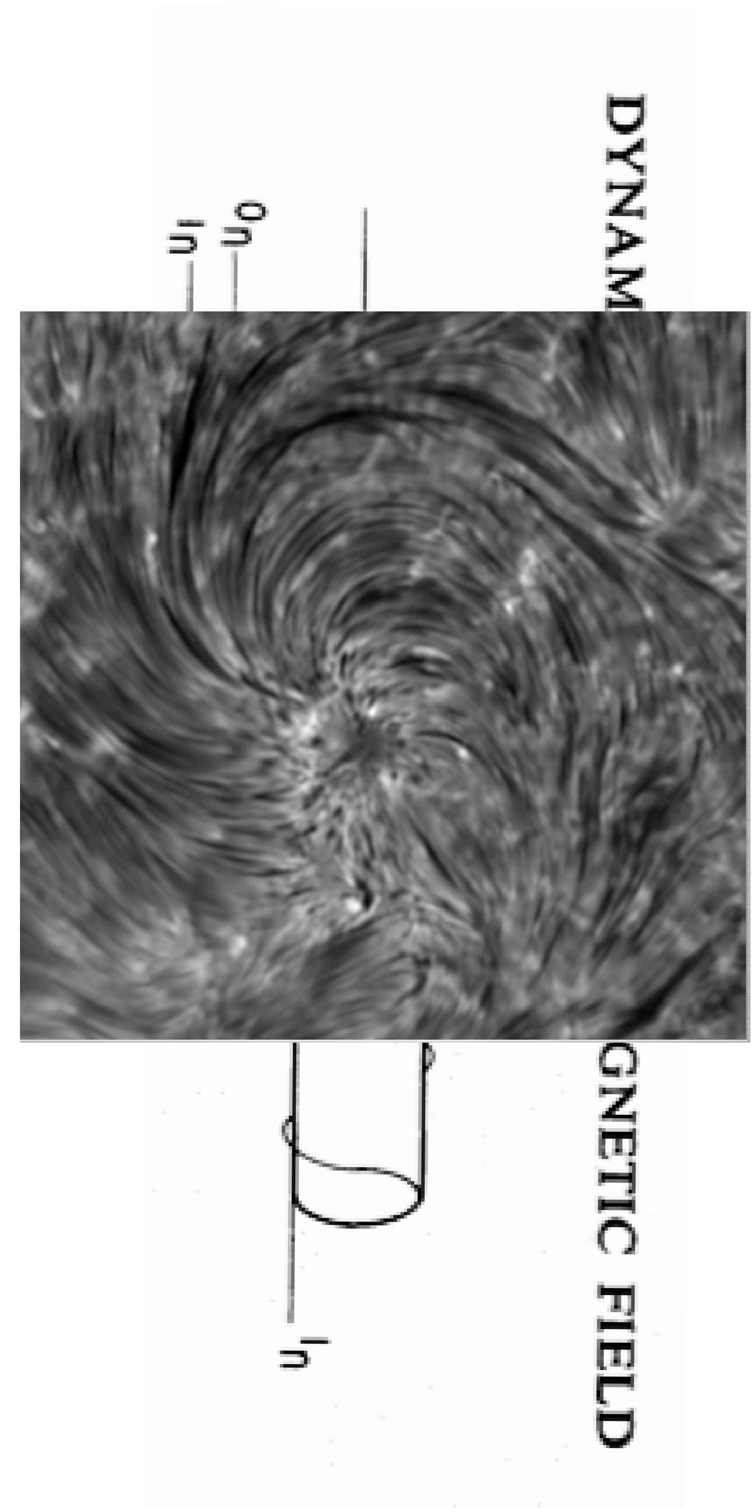
suggestion 2: Increase NB brightness without increasing plasma pressure

- Radiative cooling time 90 sec (Anderson & Athay 1989)
- perturbations of *P* travel ~10 km/s (high β fast+slow modes)
  - NB→CI wave 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*

suggestion 3: 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

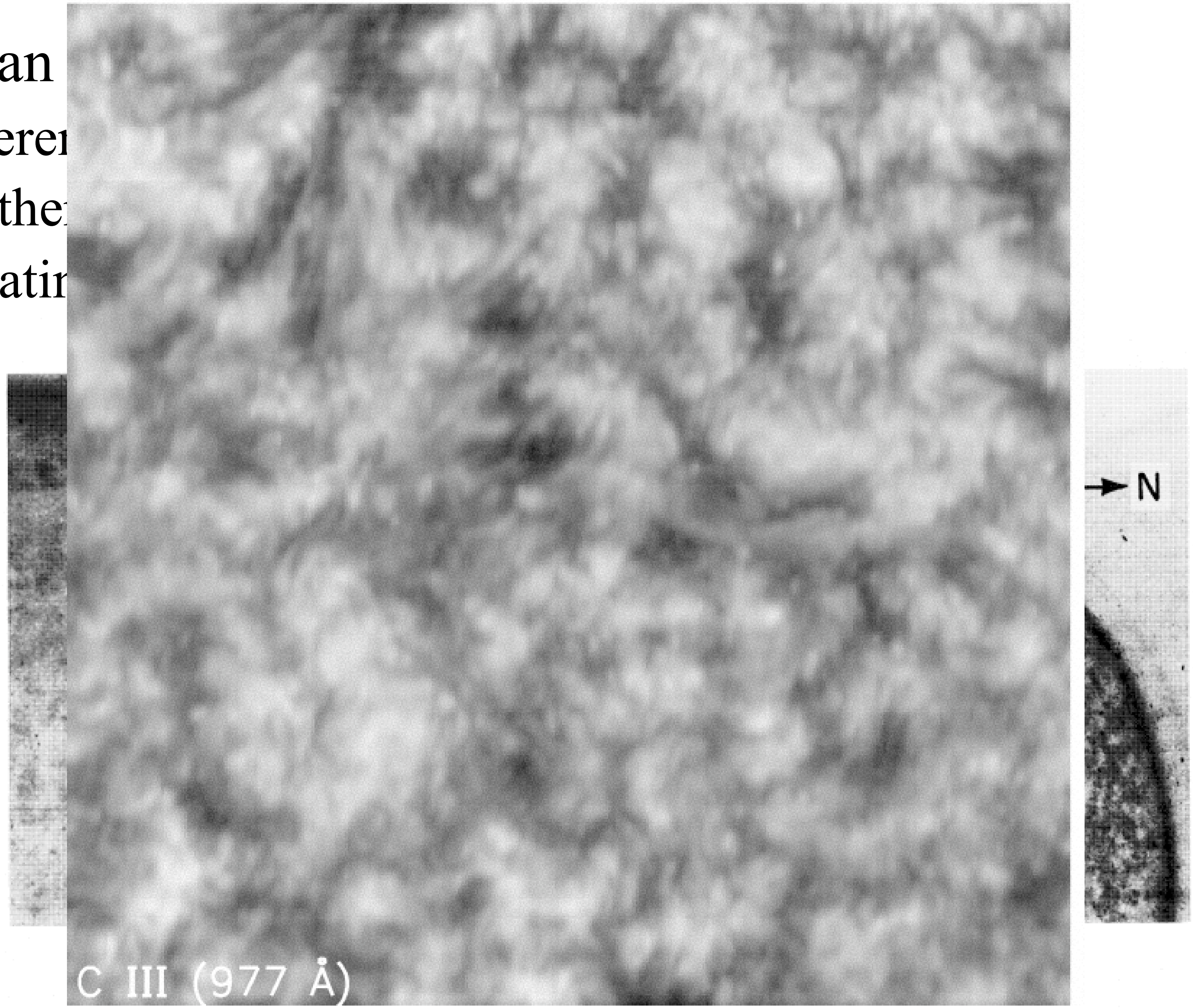
- *possibly a magnetic source for type spicules II*



chromosphere - corona
thermal interface

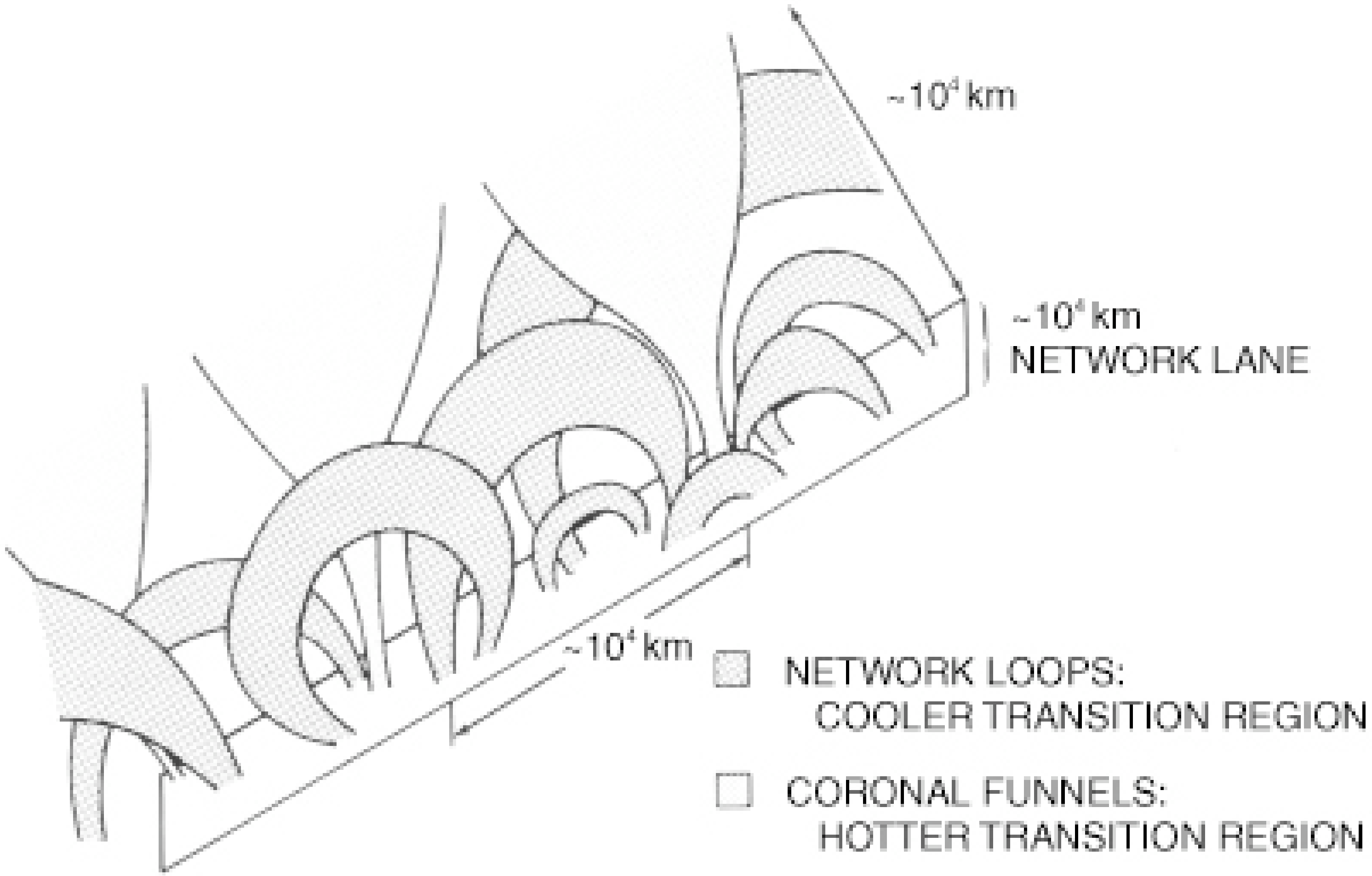
The problem- observations

- Feldman
  - differen
  - TR the
  - radiatin



Dowdy et al. (1986)

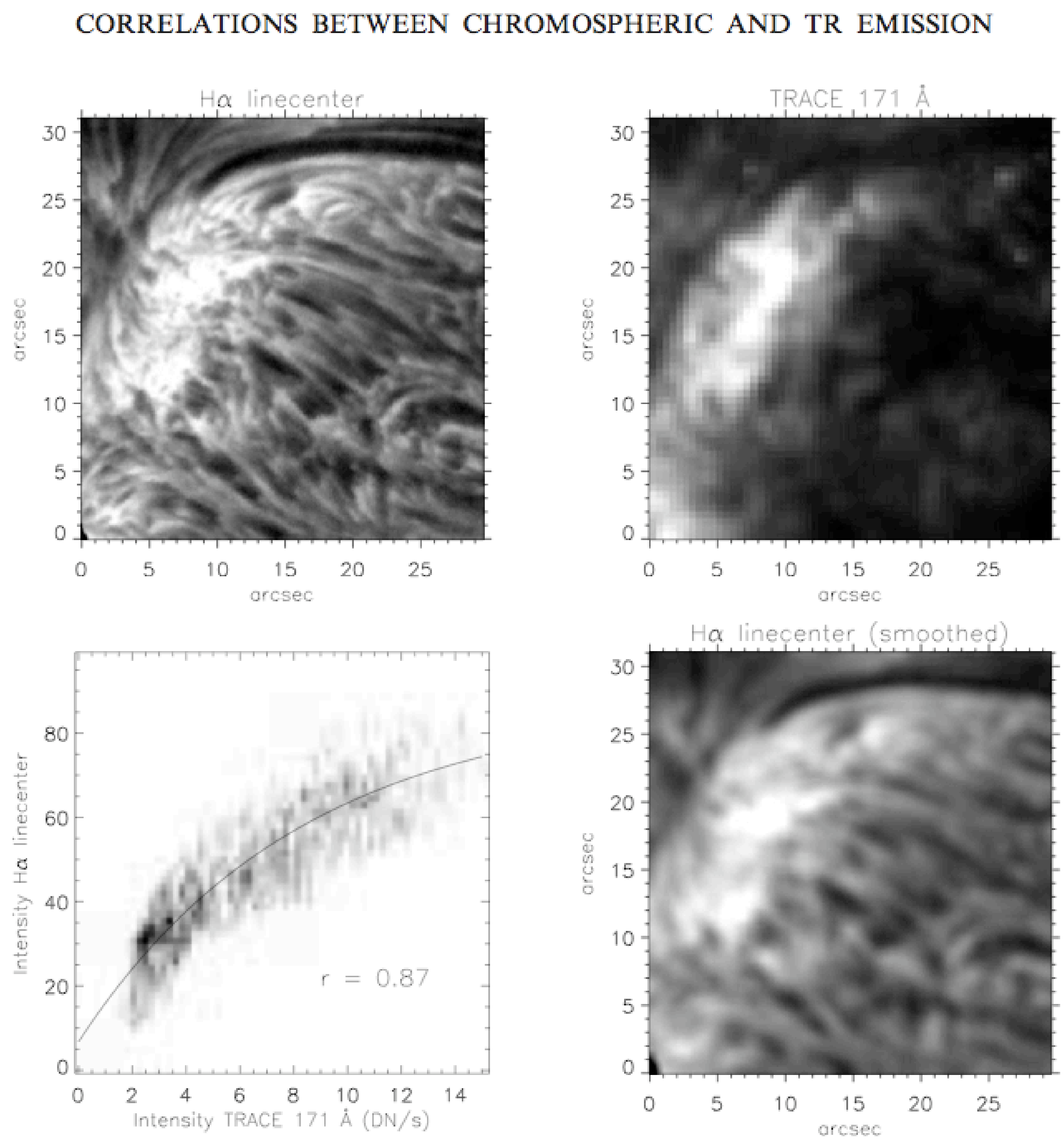
- Mixed polarity within network boundaries
- tries to explain "UFS"
- indeed these are thermally and magnetically separate entities



Depontieu et al 2003: TRACE/SST data

Yet...

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



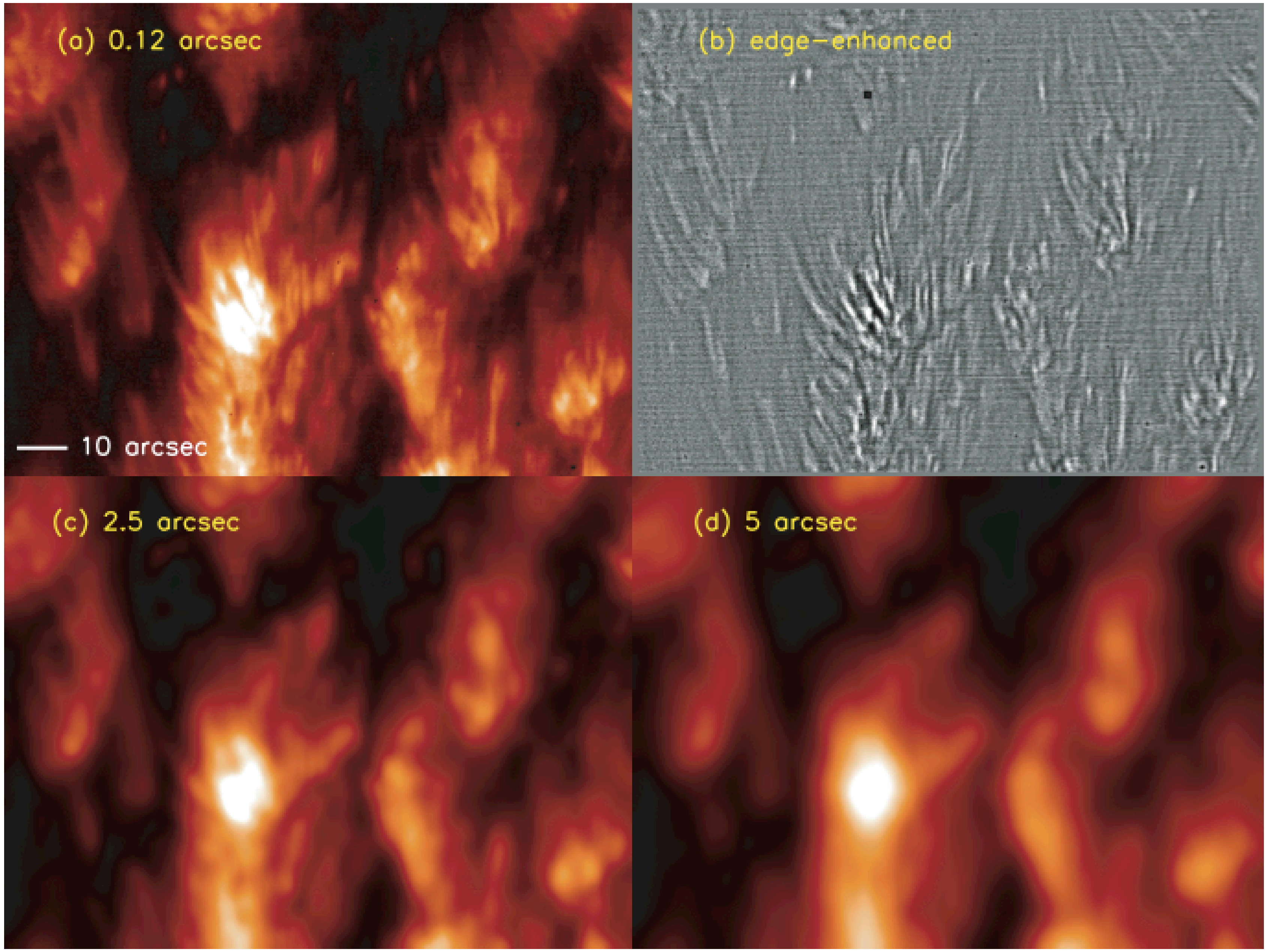
Questions concerning cool loops

- 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 ApJ)

- VAULT $L\alpha$ 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 $L\alpha$ threads

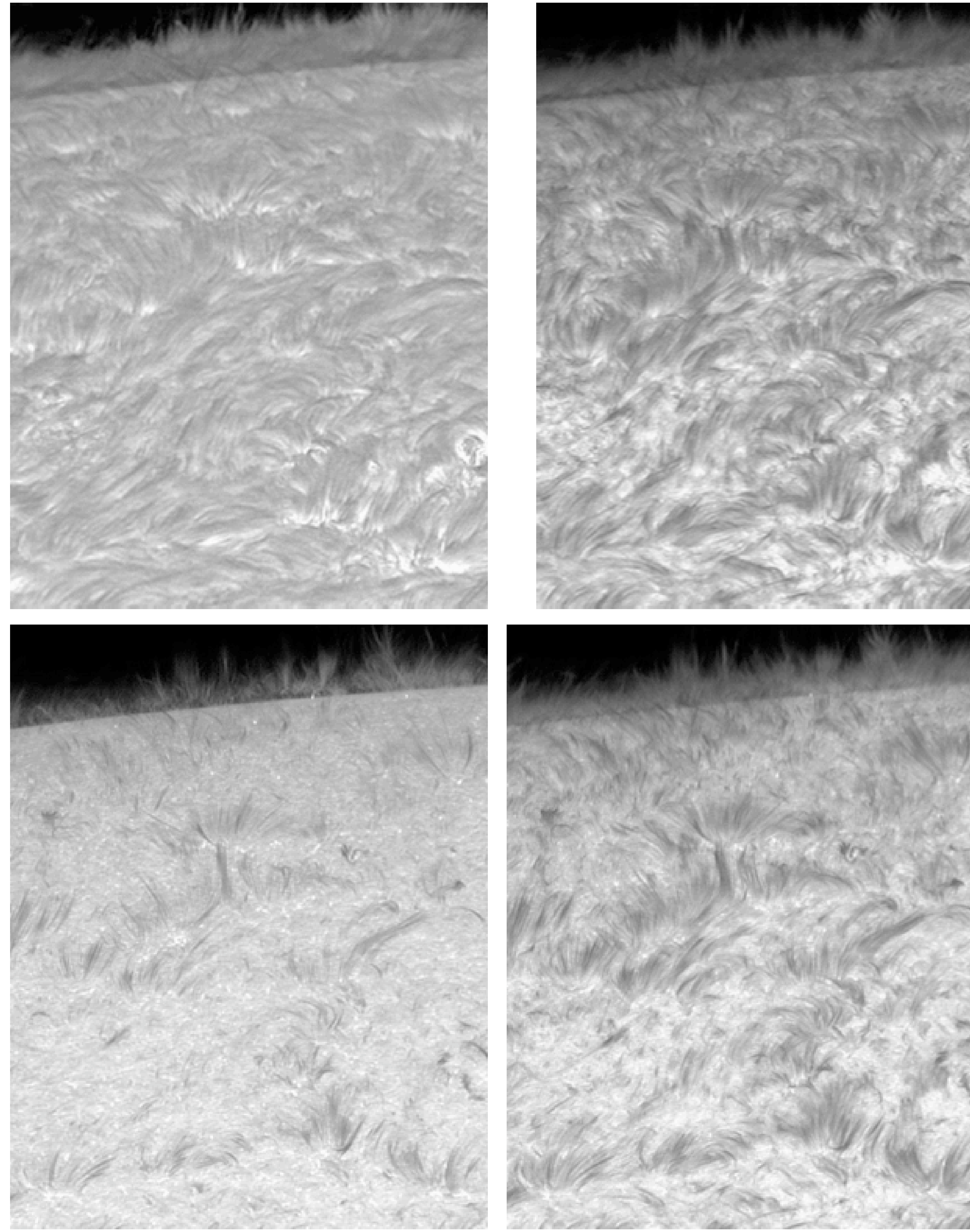
Patsourakos et al:



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

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:



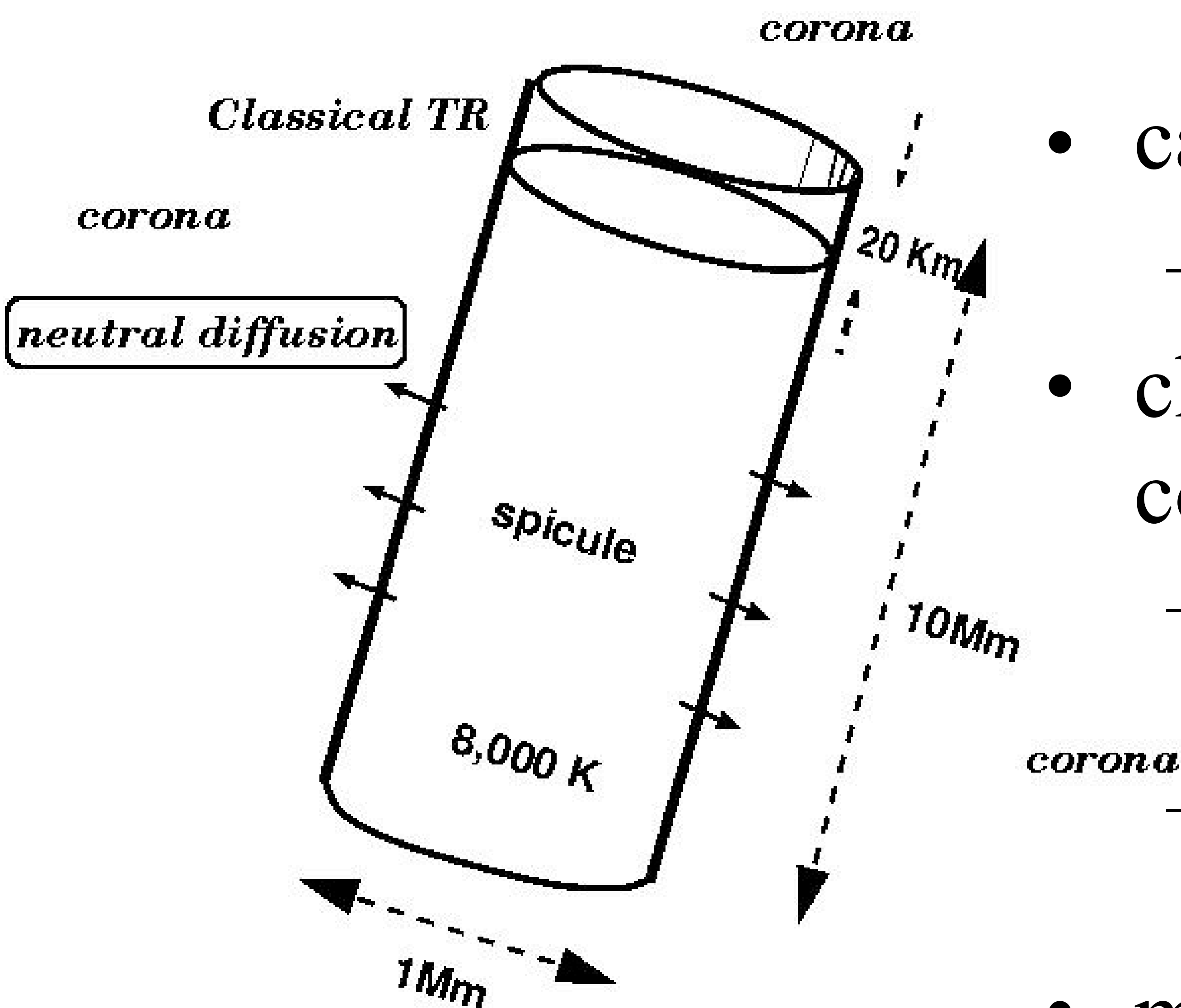
consider α in

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

and coronal base

Judge (2008) ApJL 683, 87-90

"spicule" → cross field diffusion→ TR radiation



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

the chromosphere as a partially ionized magnetic boundary layer

partially ionized plasma

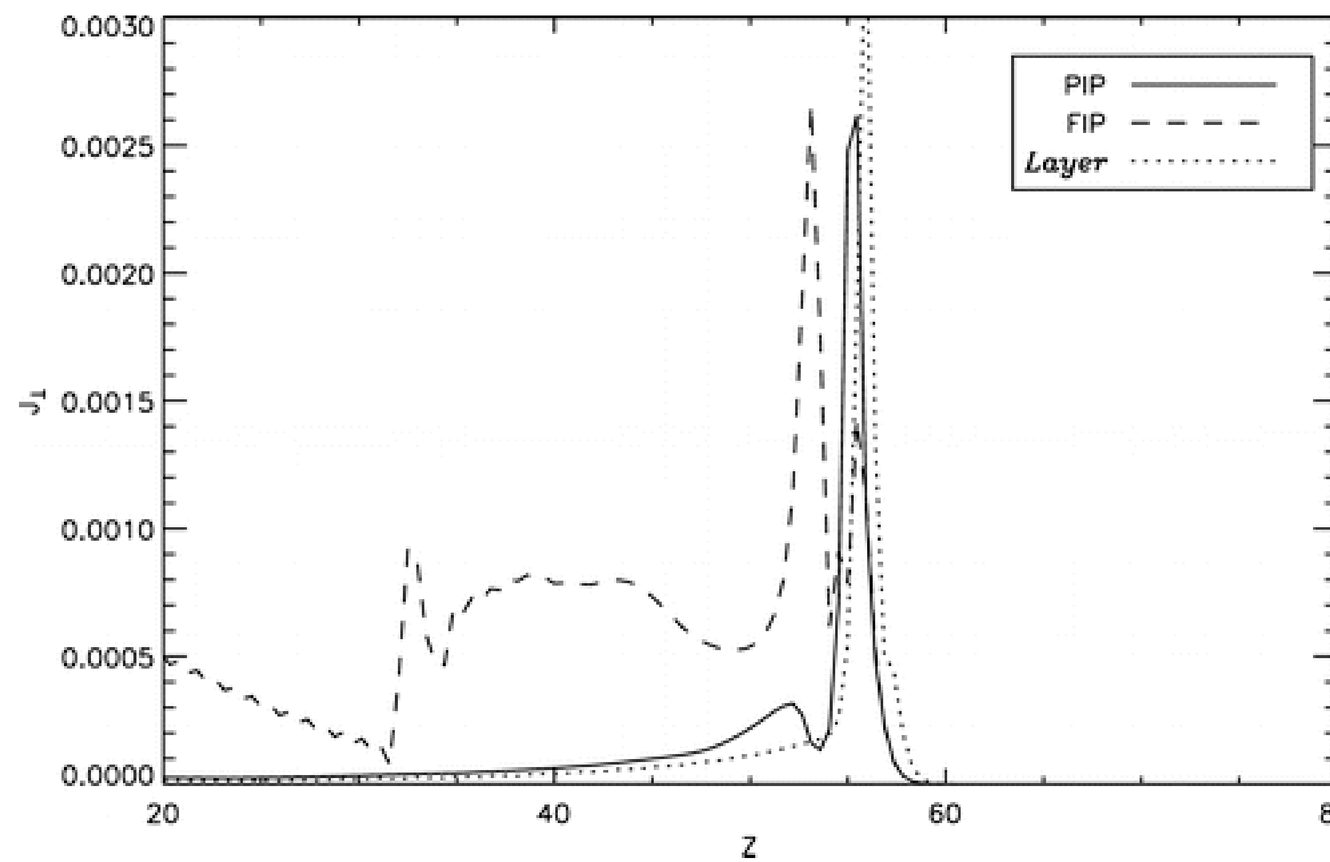
- partial ioniz$^n \Rightarrow$ 3-fluid *frictional dissipation, heating*
- efficient damping by ion-neutral collisions
- Kinetic theory (Braginskii 1965)
  - $Q_{fr} = \mathbf{j}.\mathbf{E} = j^2/\sigma + (\xi_n\, \mathbf{j} \times \mathbf{B} - \mathbf{G})^2/\alpha_n$, $\quad \mathbf{G} = \xi_n \nabla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

Chromospheric dissipation of j⊥

- Braginskii (1965): certain motions (G...) dissipate j⊥
  - 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⊥~0; j×B~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 $t = 160$.



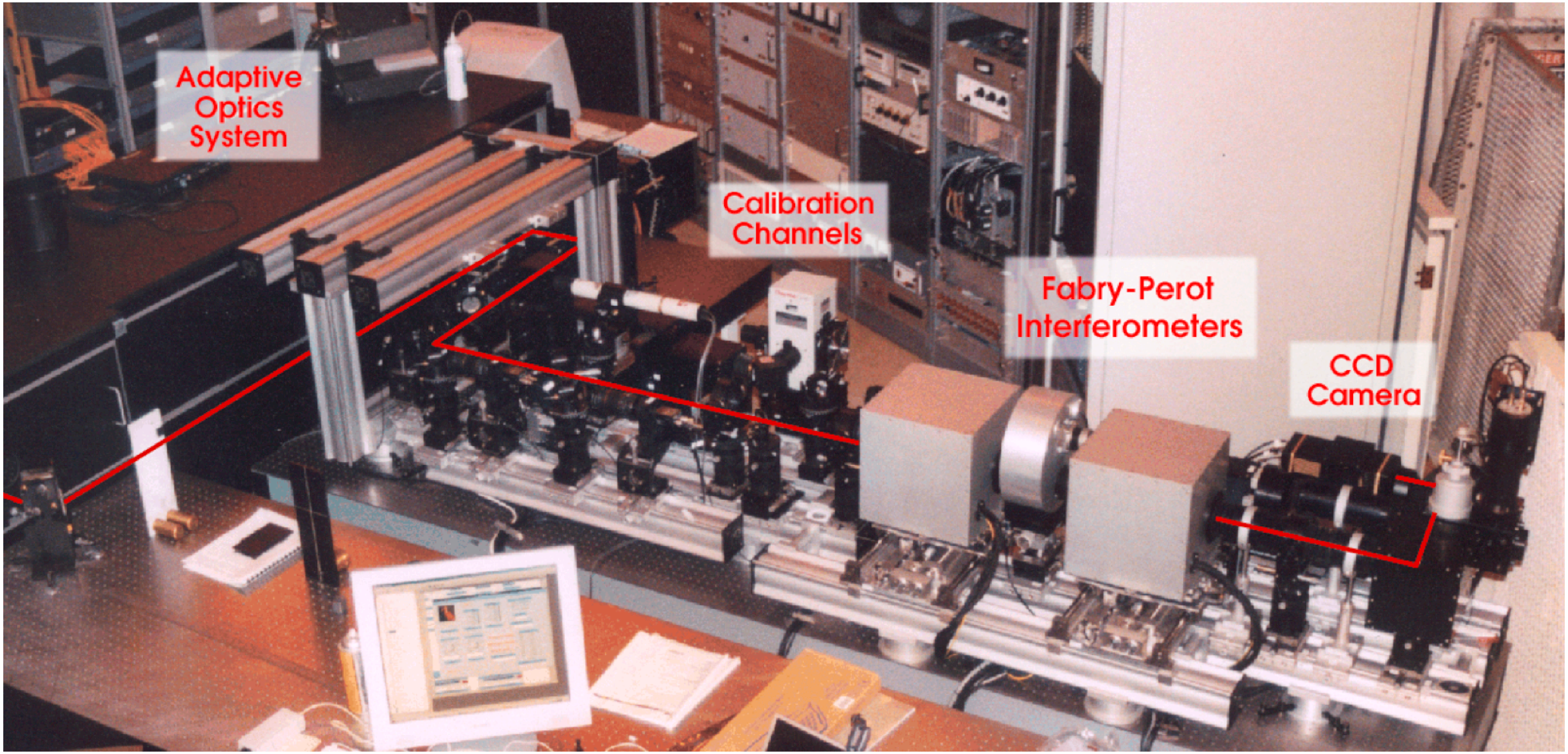
*...radical effect on **j** and flux emergence process*

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

imaging spectroscopy/ spectropolarimetry

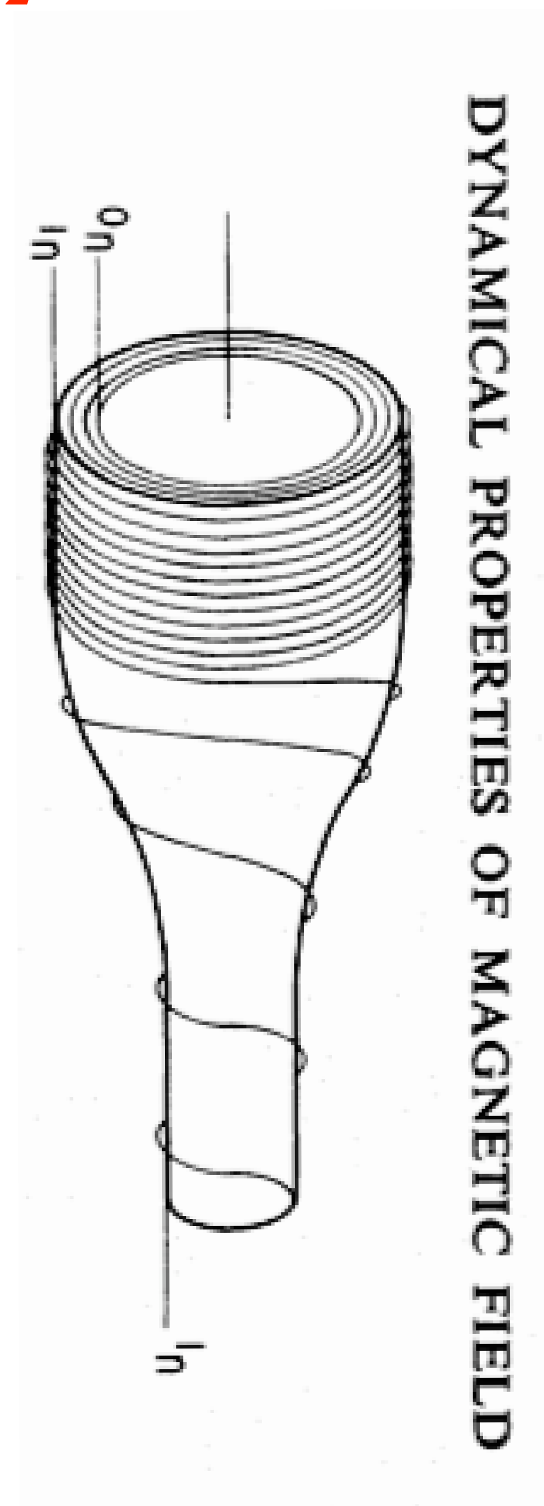
IBIS- Cavallini & colleagues

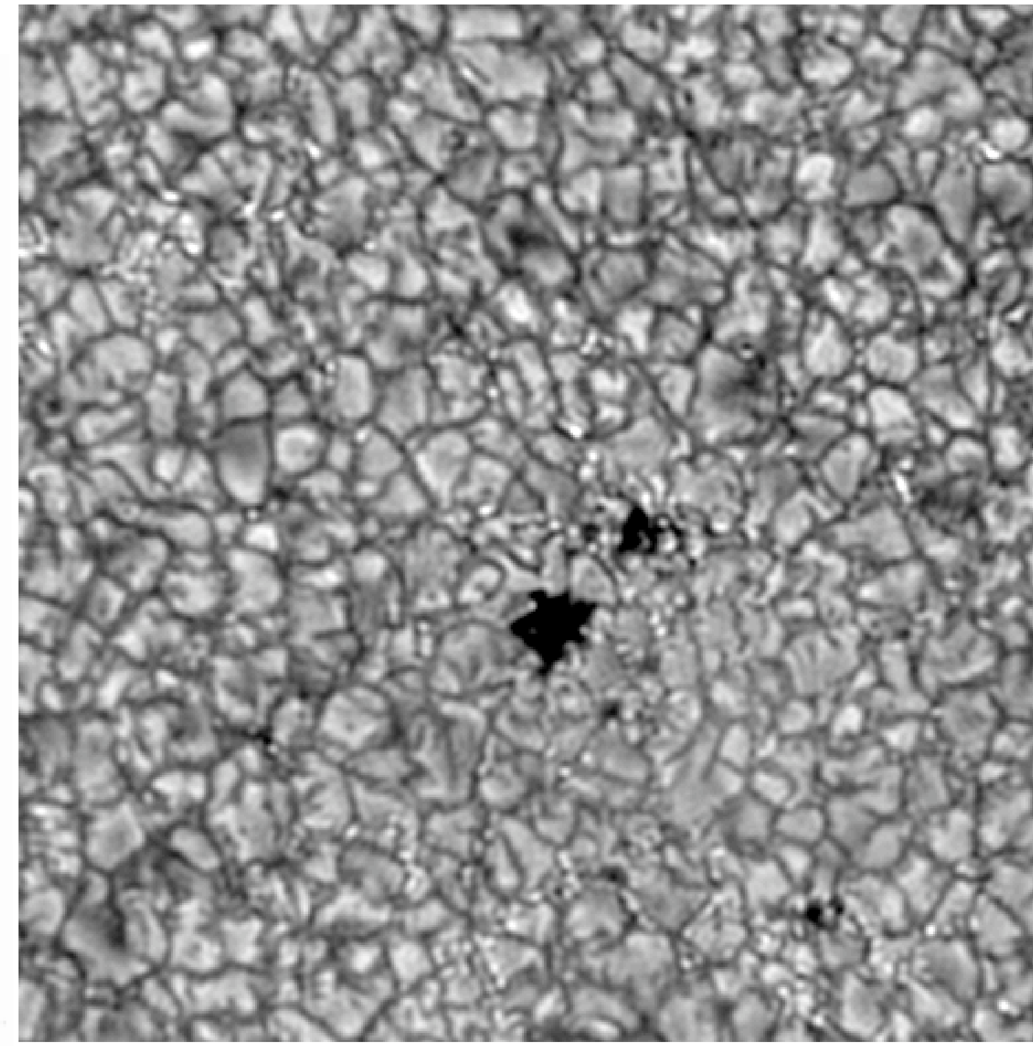


Also TESOS, CRISP, GFPI,...

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*





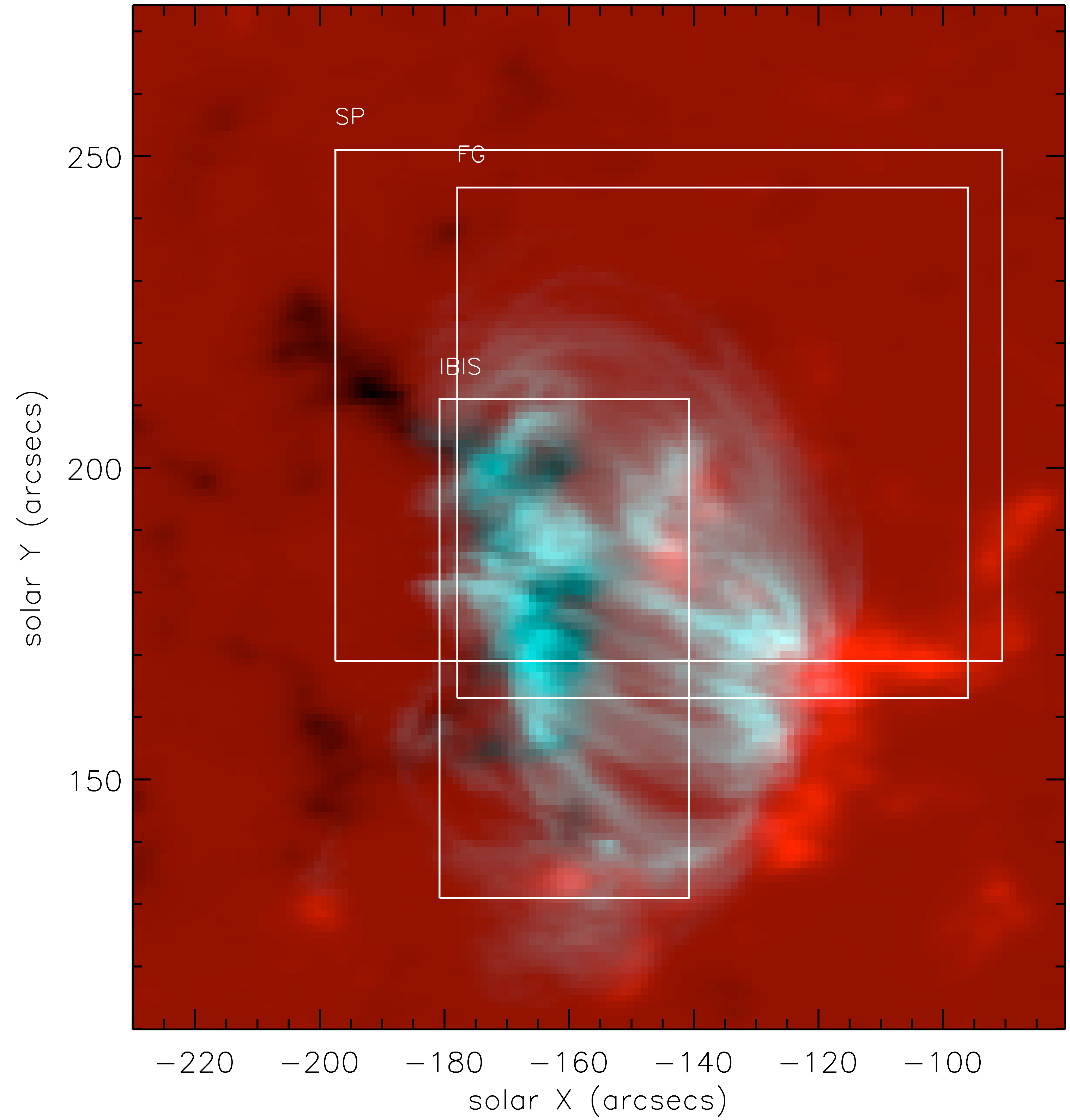
photospheric and chromospheric imaging spectropolarimetry

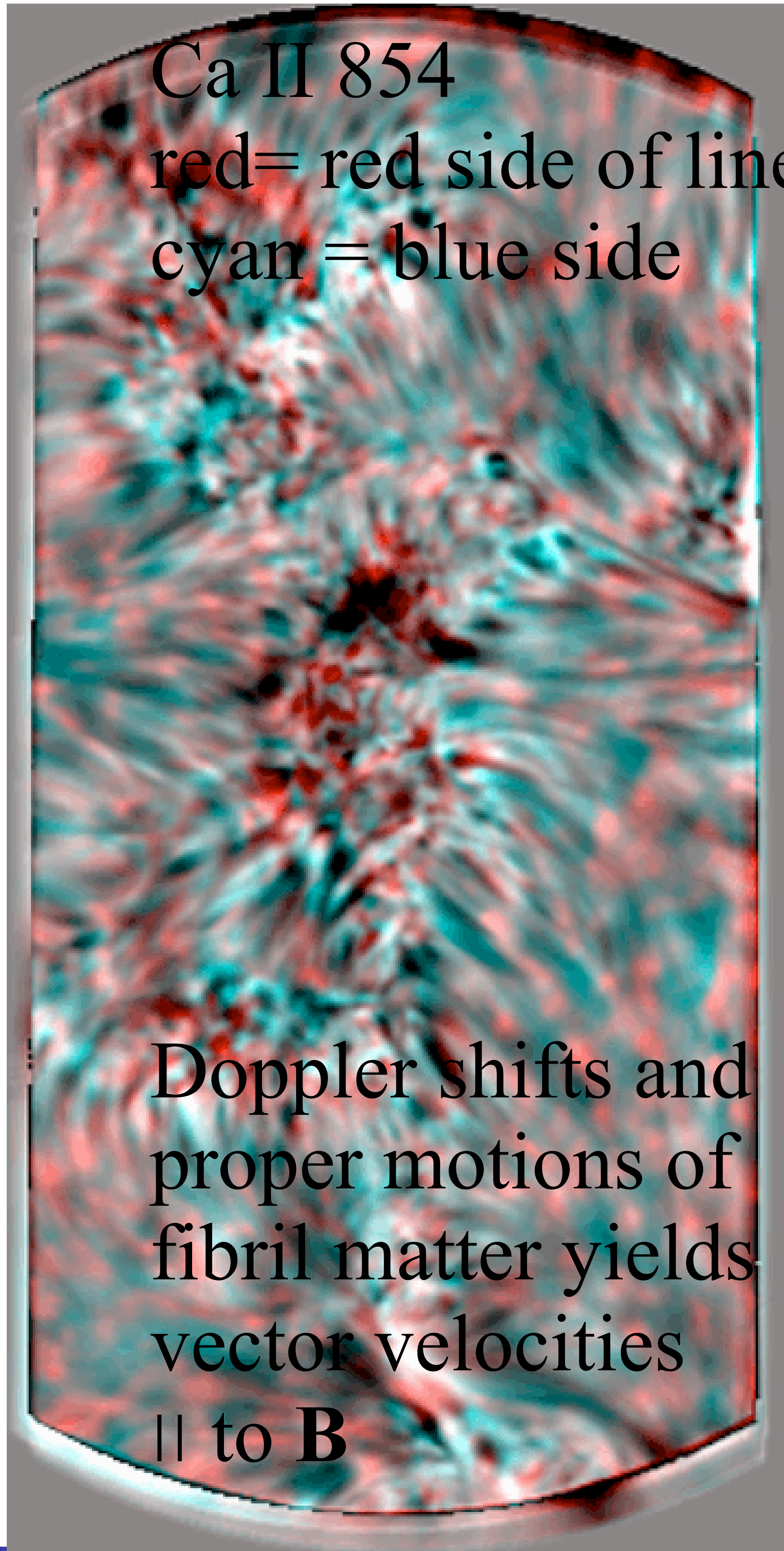
NOAA 10996
20 May 2008

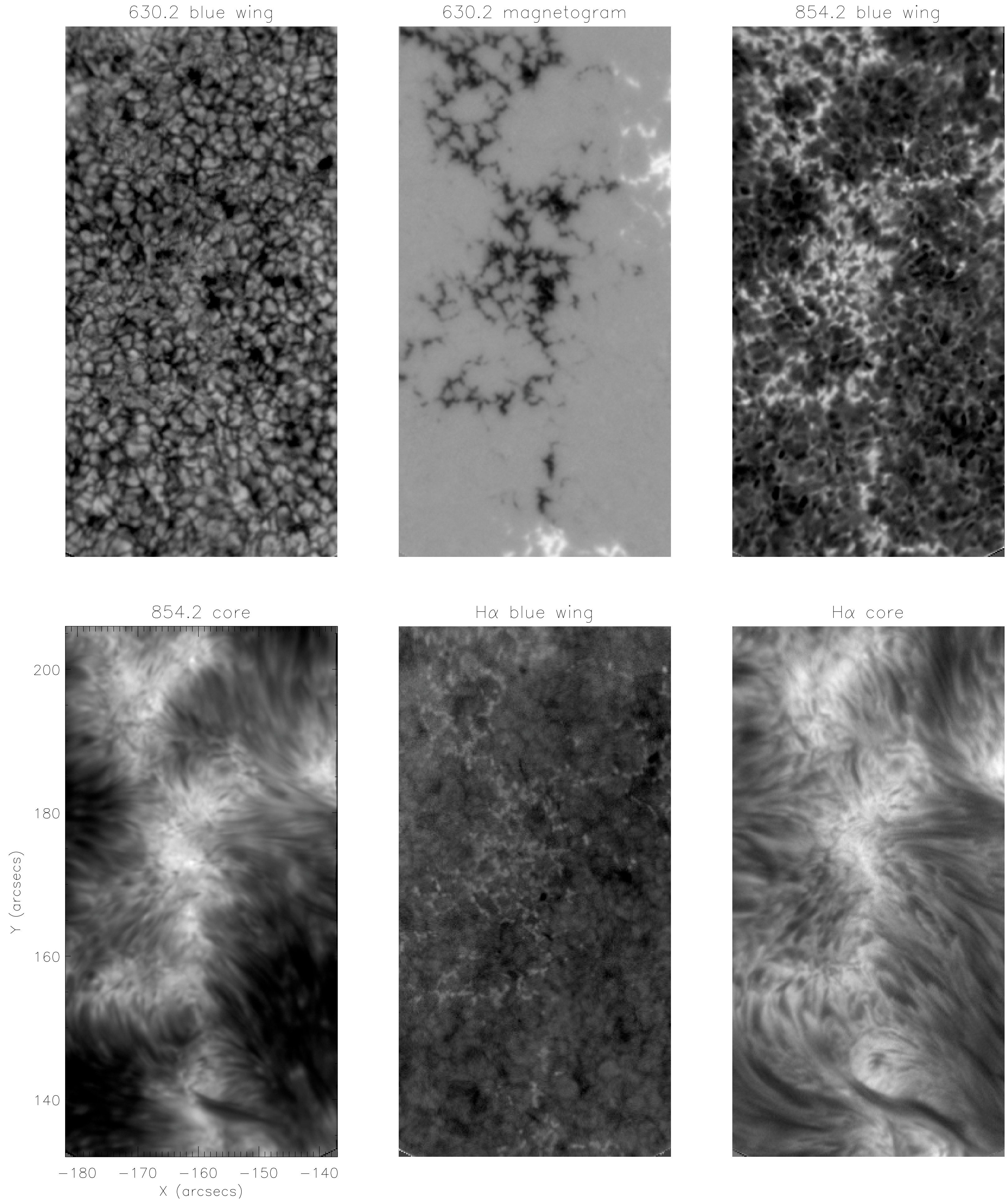
SOLIS plus TRACE

IBIS
HINODE sot xrt

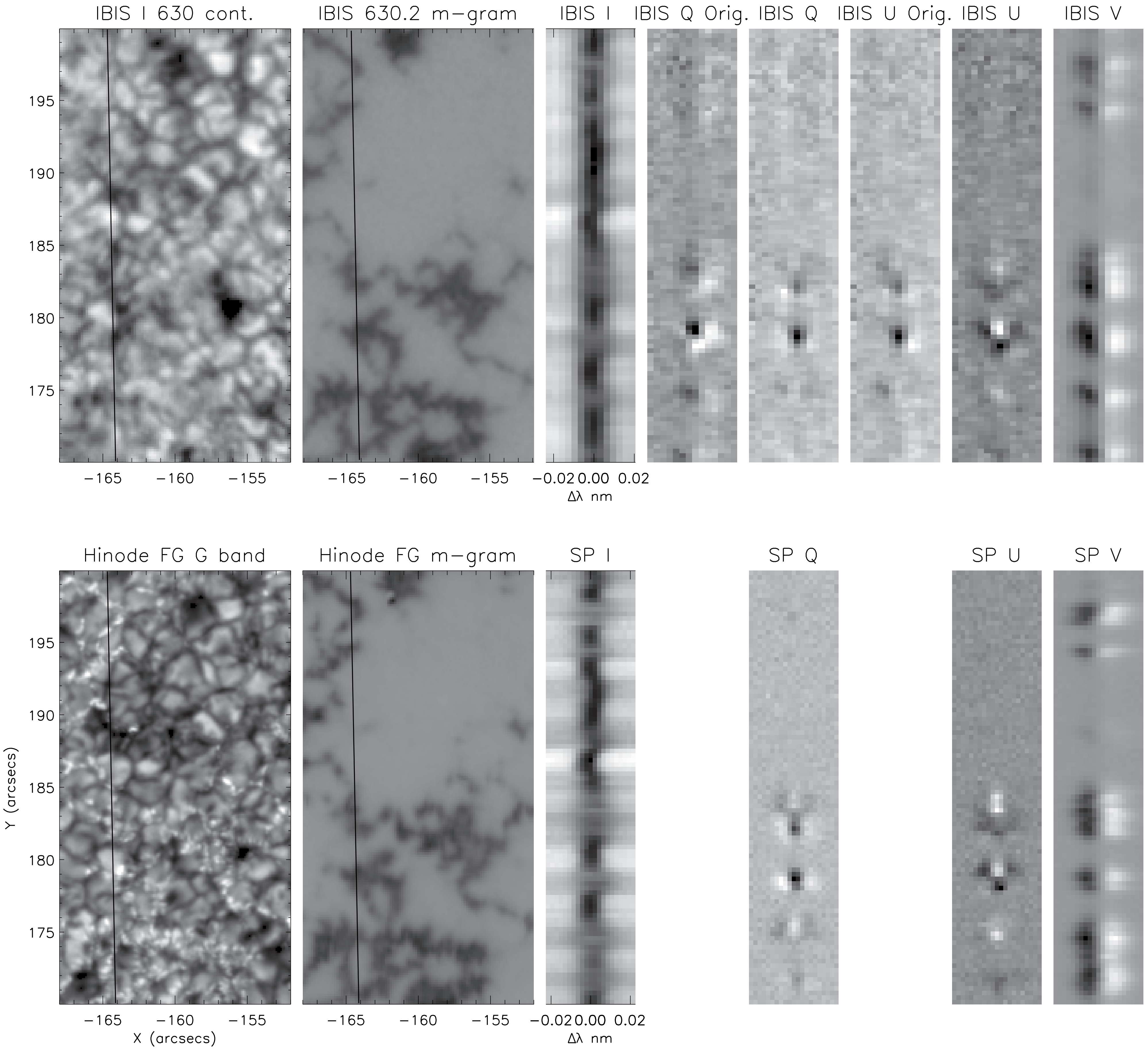
Judge et al 2009
(ApJ submitted)

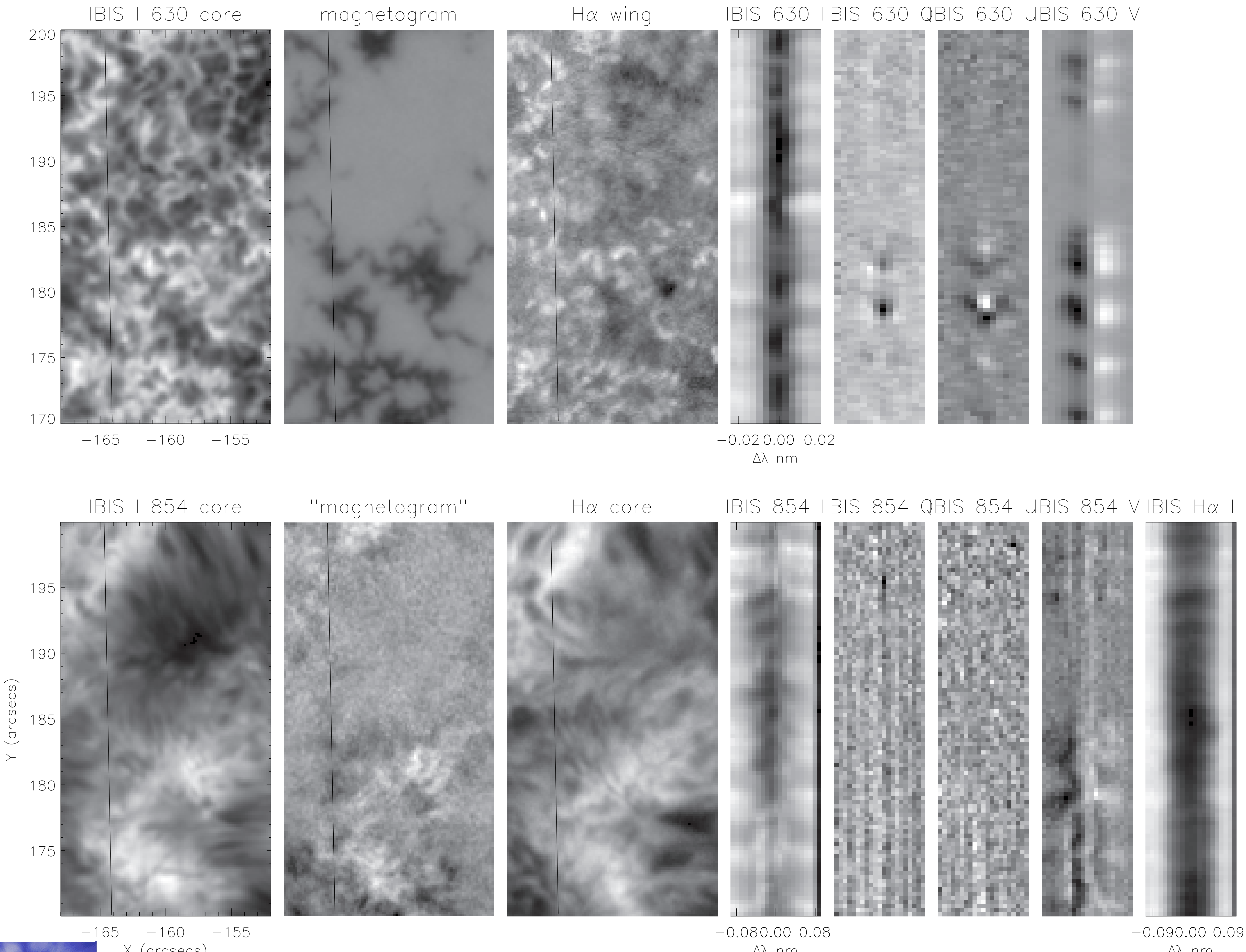



Ca II 854
red= red side of line
cyan = blue side
Doppler shifts and
proper motions of
fibril matter yields
vector velocities
|| to **B**

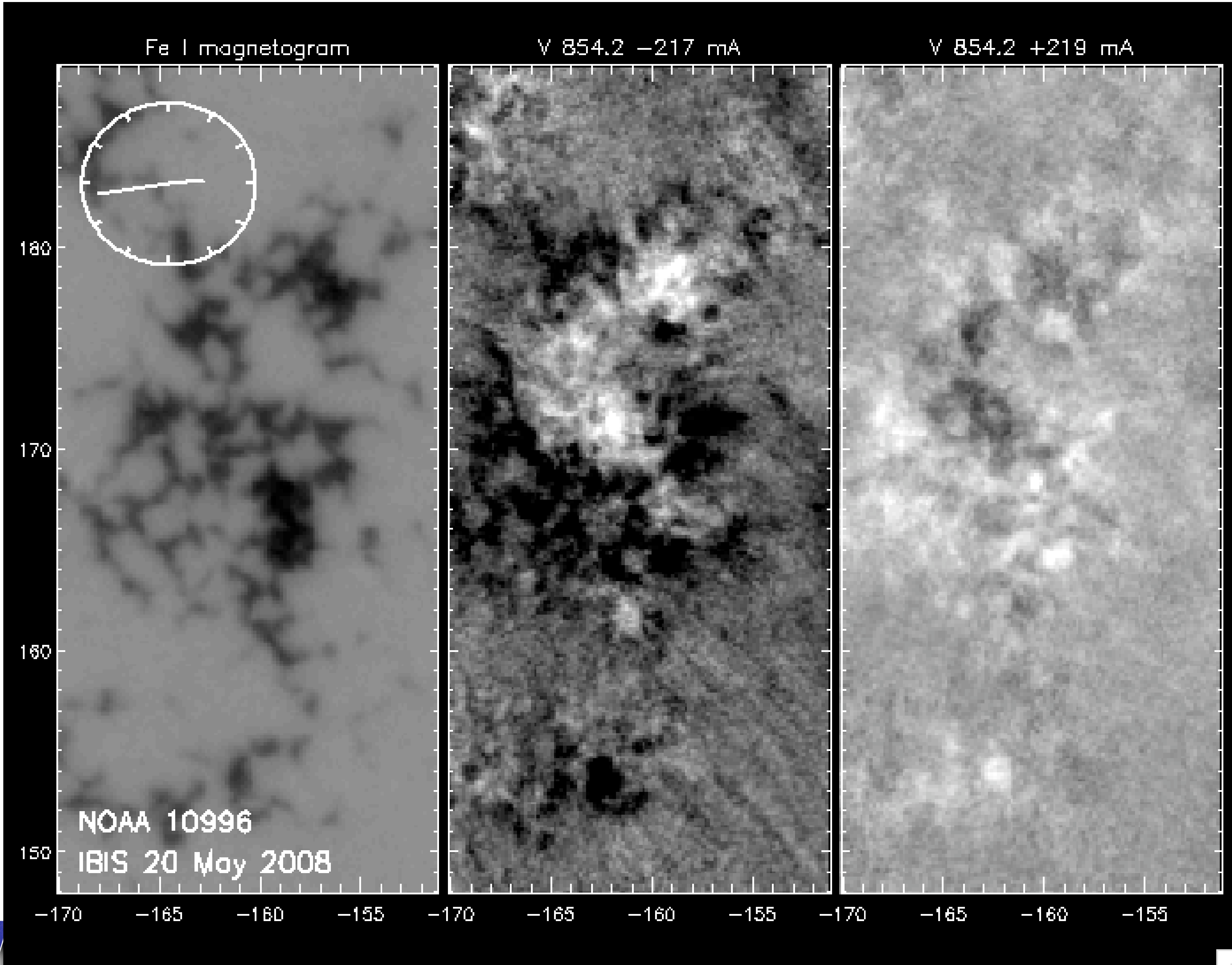

630.2 blue wing
630.2 magnetogram
854.2 blue wing
854.2 core
Hα blue wing
Hα core
200
180
160
140
Y (arcsecs)
−180
−170
−160
−150
−140
X (arcsecs)

Hinode data confirm IBIS as a vector spectro-polarimeter

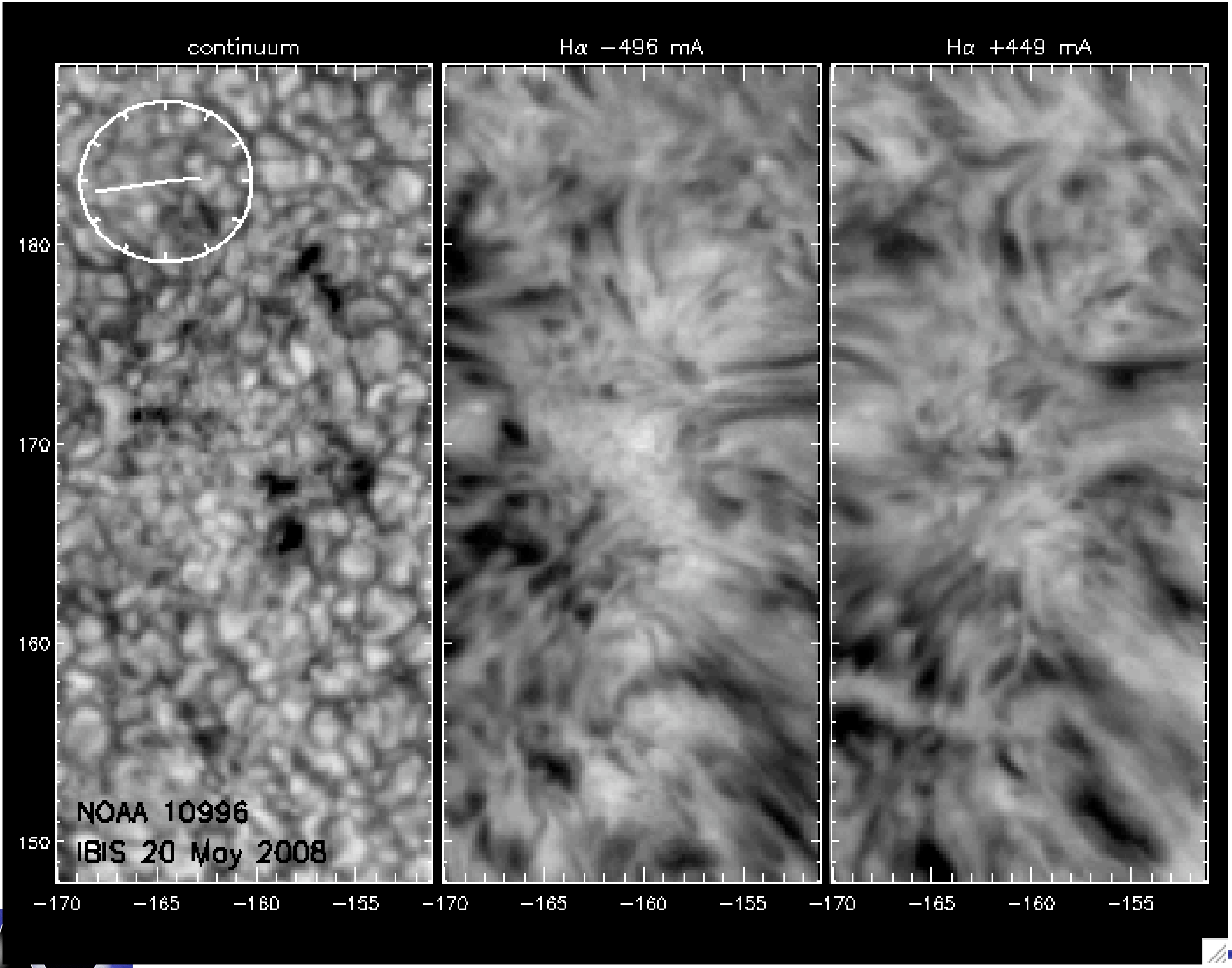




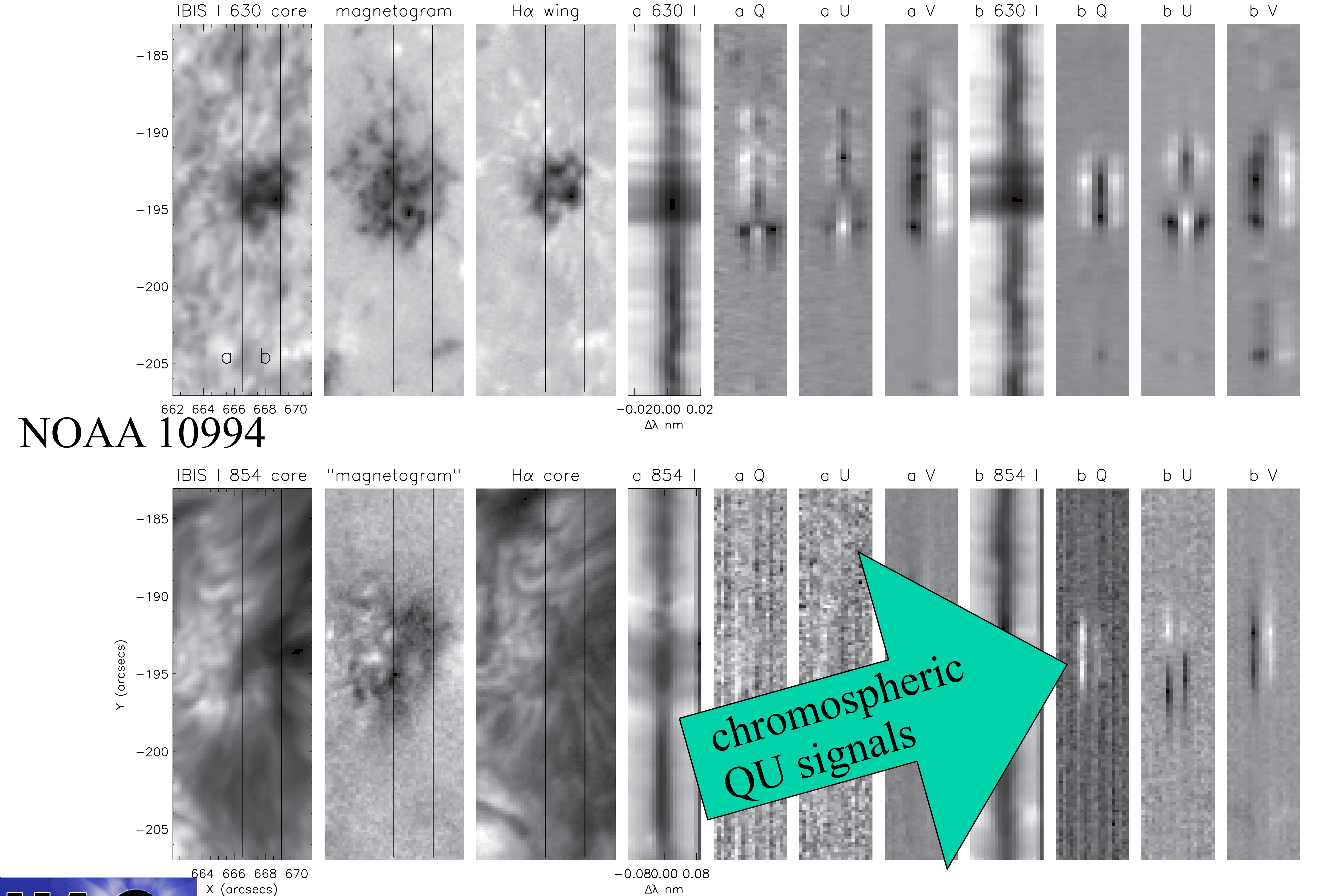
IBIS I 630 core
magnetogram
Hα wing
IBIS 630 I
IBIS 630 Q
IBIS 630 U
IBIS 630 V
200
195
190
185
180
175
170
−165 −160 −155
−0.02 0.00 0.02
Δλ nm
IBIS I 854 core
"magnetogram"
Hα core
IBIS 854 I
IBIS 854 Q
IBIS 854 U
IBIS 854 V
IBIS Hα I
Y (arcsecs)
195
190
185
180
175
−165 −160 −155
X (arcsecs)
−0.08 0.00 0.08
Δλ nm
−0.09 0.00 0.09
Δλ nm



Fe I magnetogram
V 854.2 −217 mA
V 854.2 +219 mA
180
170
160
150
NOAA 10996
IBIS 20 May 2008
−170
−165
−160
−155



continuum
Hα −496 mA
Hα +449 mA
180
170
160
150
NOAA 10996
IBIS 20 May 2008
−170
−165
−160
−155



IBIS I 630 core
magnetogram
Hα wing
a 630 I
a Q
a U
a V
b 630 I
b Q
b U
b V
NOAA 10994
IBIS I 854 core
"magnetogram"
Hα core
a 854 I
chromospheric QU signals
Y (arcsecs)
X (arcsecs)
Δλ nm

for the future:
Infrared imaging spectroscopy/ spectropolarimetry

Unique capabilities:

- Extended periods of excellent seeing over bigger FOV
- Zeeman effect enhancement (Fe I 1560nm, ...)
- He I 1083nm as a diagnostic of the magnetic and velocity fields at the coronal base

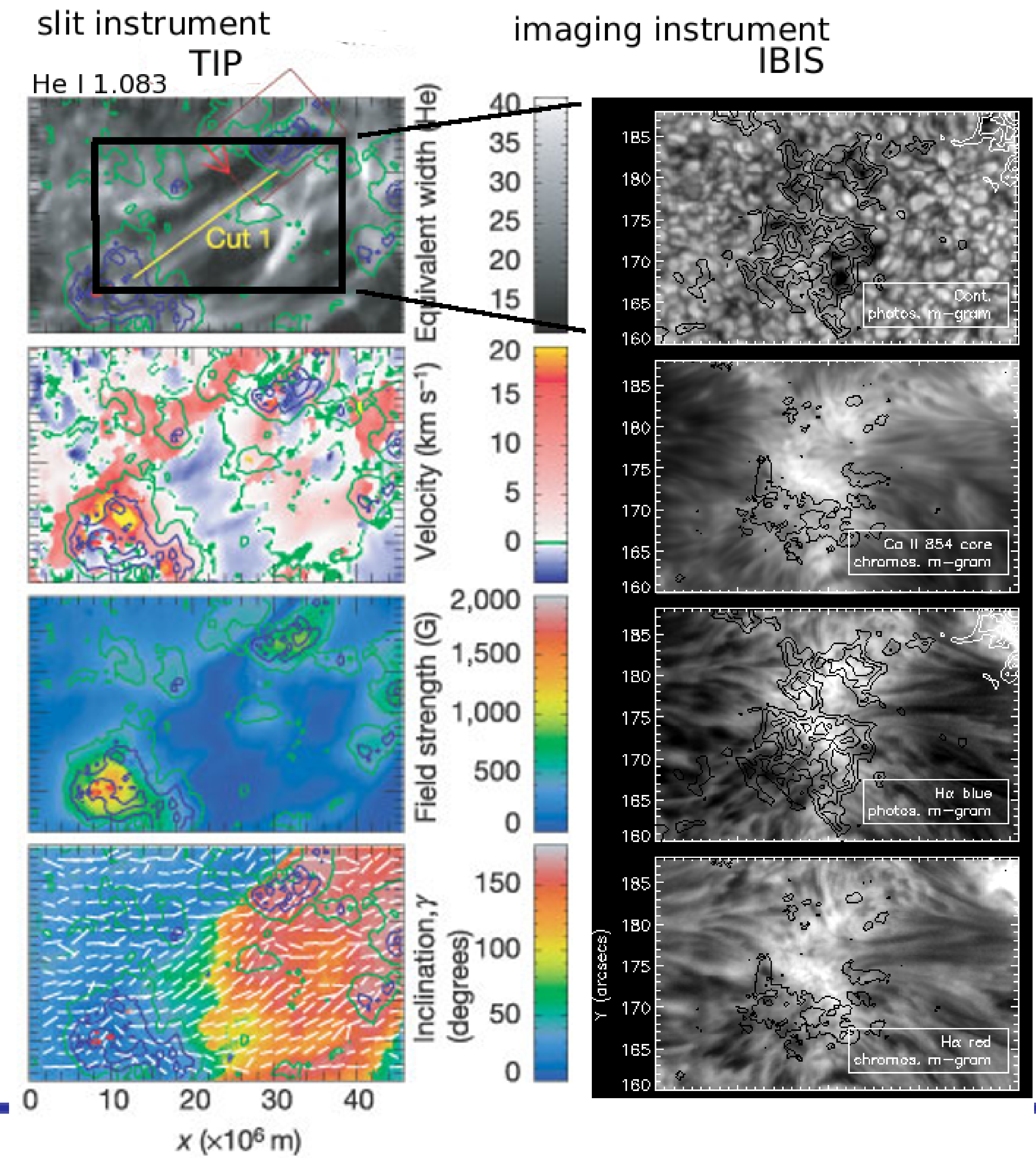
NIRBIS:

- joint NSO/INAF/HAO proposal to NSF MRI R^2 program
- 1000-1600 nm community instrument with IBIS
- enhance SDO, IRIS,...

NIRBIS combines TIP or SPINOR and IBIS

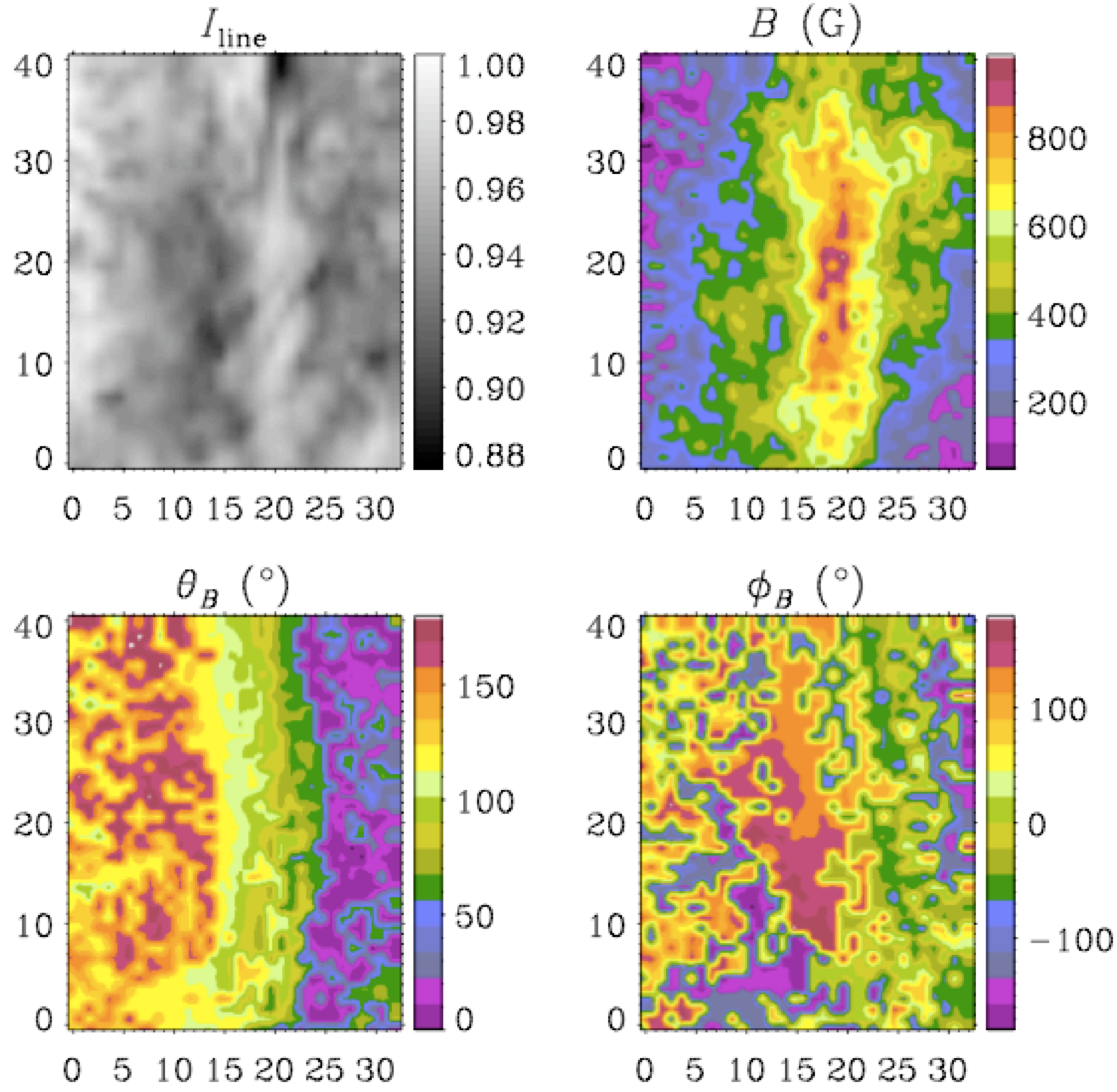
TIP - Solanki et al 2003
magnetic field at coronal base

IBIS - Judge et al 2009
advantages of images



Inversions of He I 10830

Casini & Centeno, unpublished



so, why should anyone care?

You should, if you care about...

- the corona
- space weather
- partially ionized plasmas
- dynamos
- heliospheric UV radiation
- the transition region
- challenging MHD problems

(Oh, and the chromosphere too)