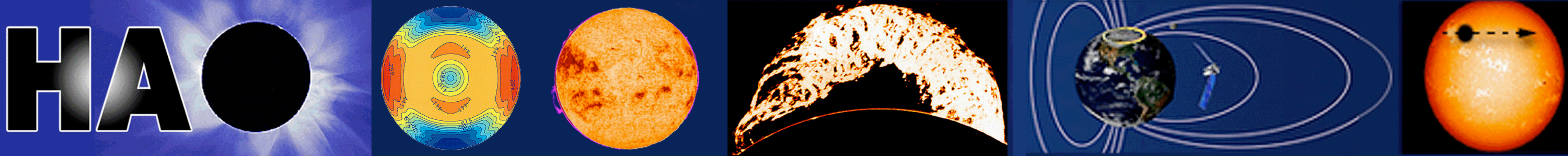
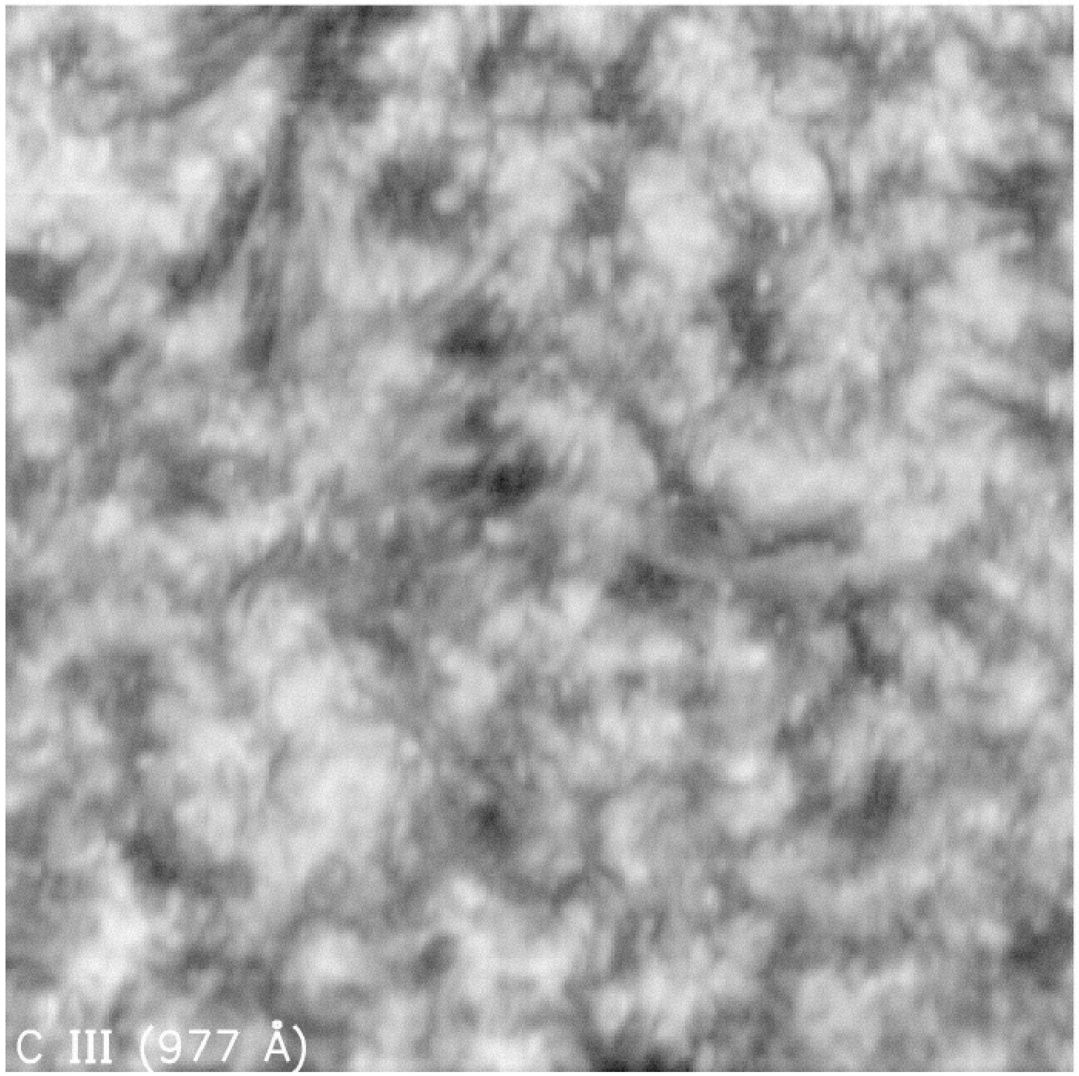


On the solar transition region

Philip Judge, HAO

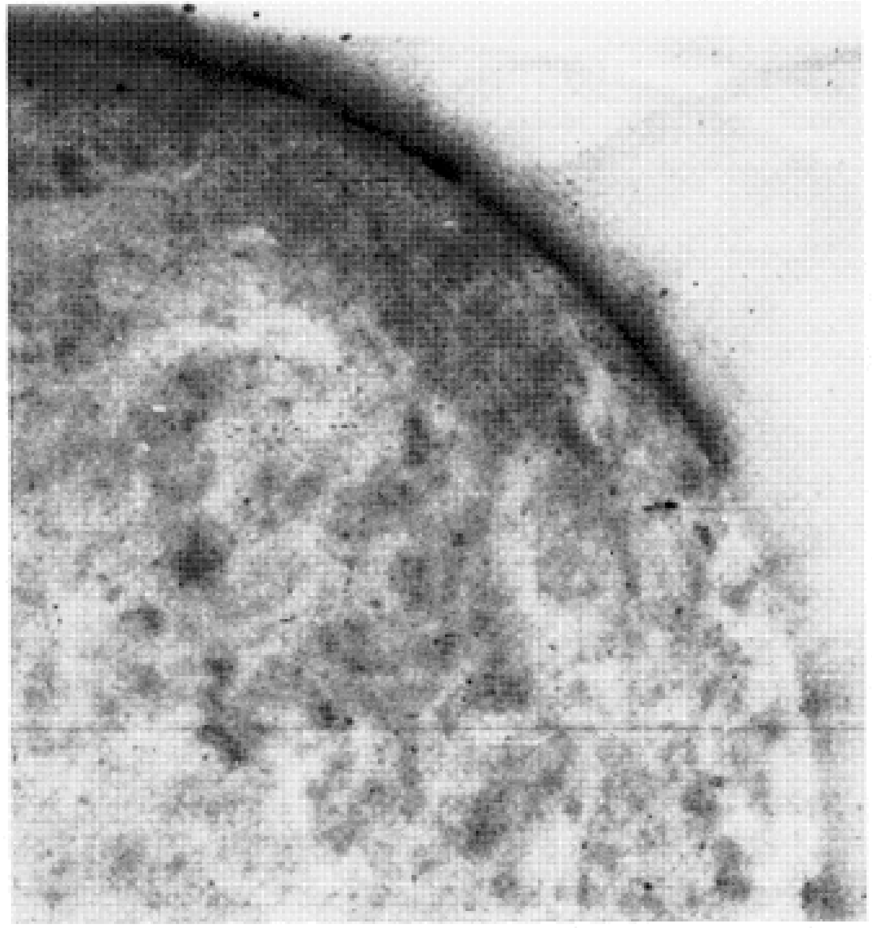
- The problem: history, status
- VAULT Lα, magnetic fields
    - Judge & Centeno 2008
- A simple explanation
    - Judge 2008
- Conclusions



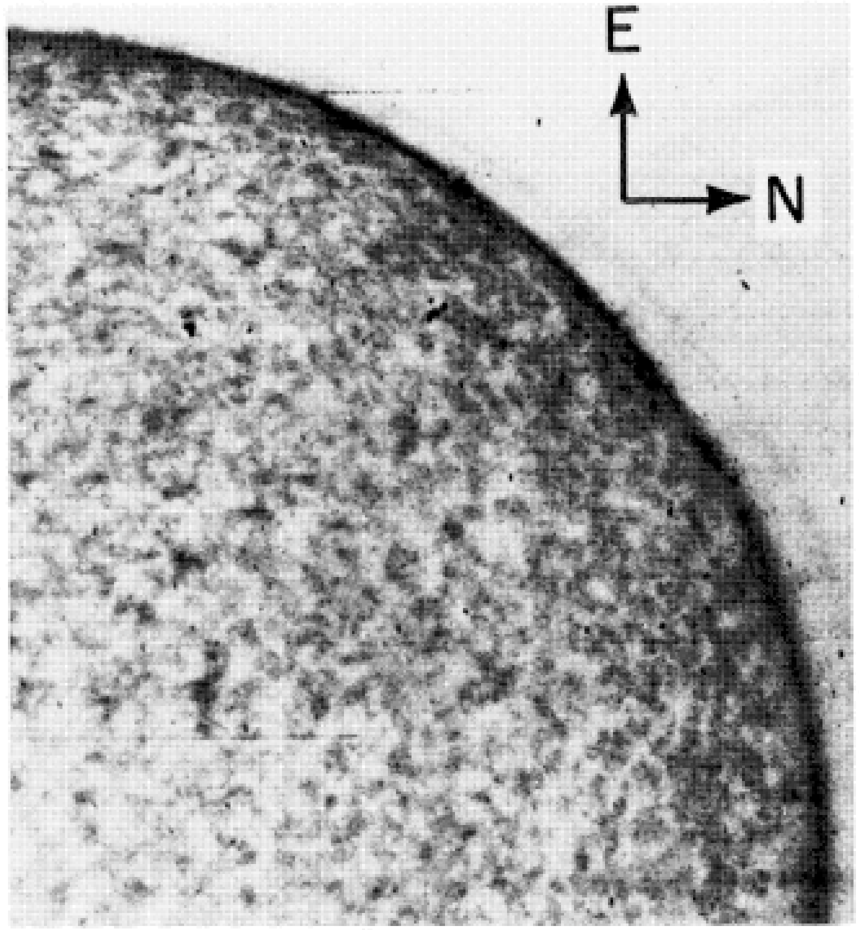
May 8 2008

The problem- observations

- Feldman and colleagues (1983-)
  - different morphology 10^4 -10^6 K, other properties
  - TR thermally, magnetically isolated from the corona
  - radiating entity = “unresolved fine structures”



Mg IX 368Å



Ne VII 465Å

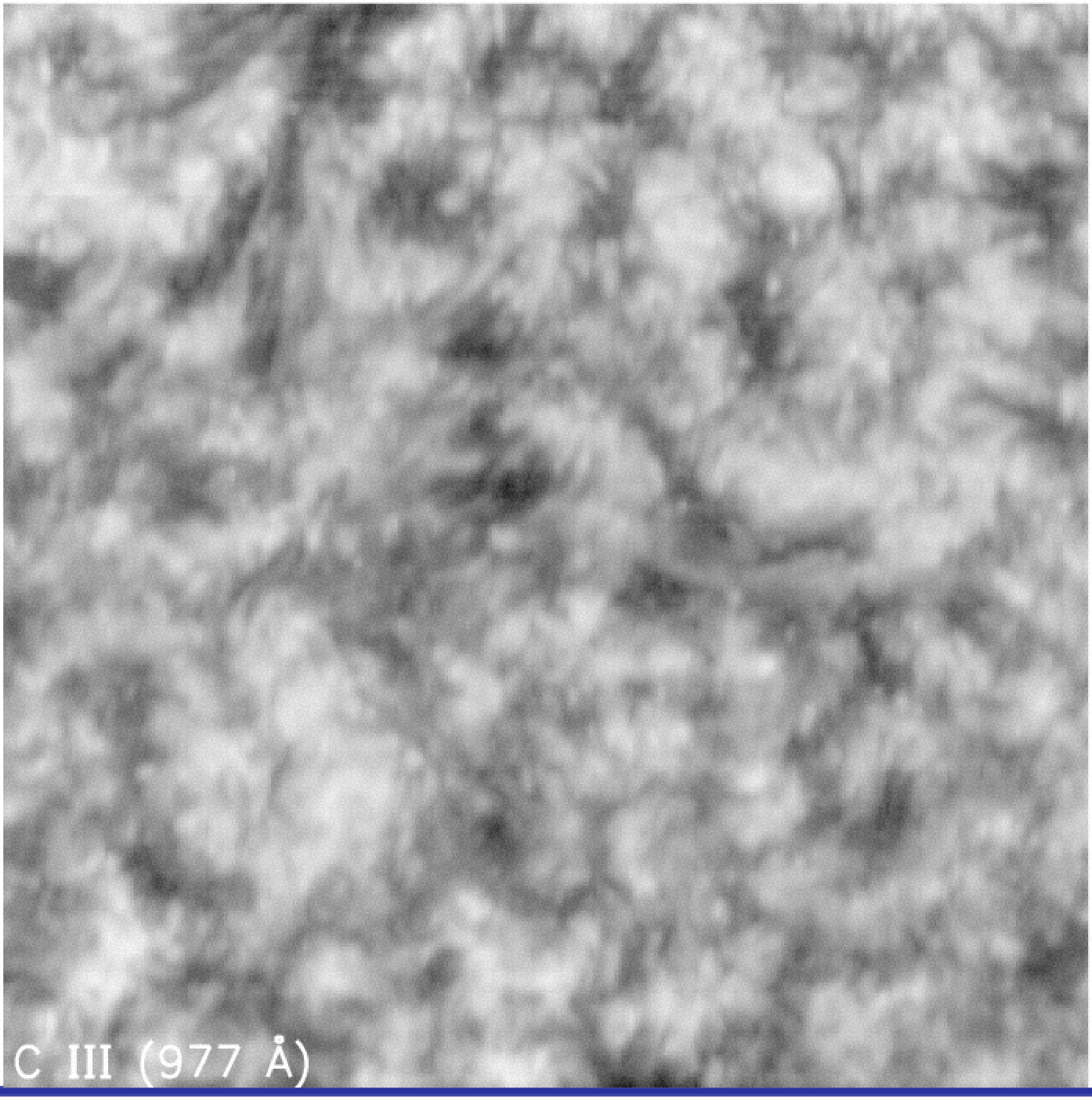
Intensity image of a typical TR line, QS

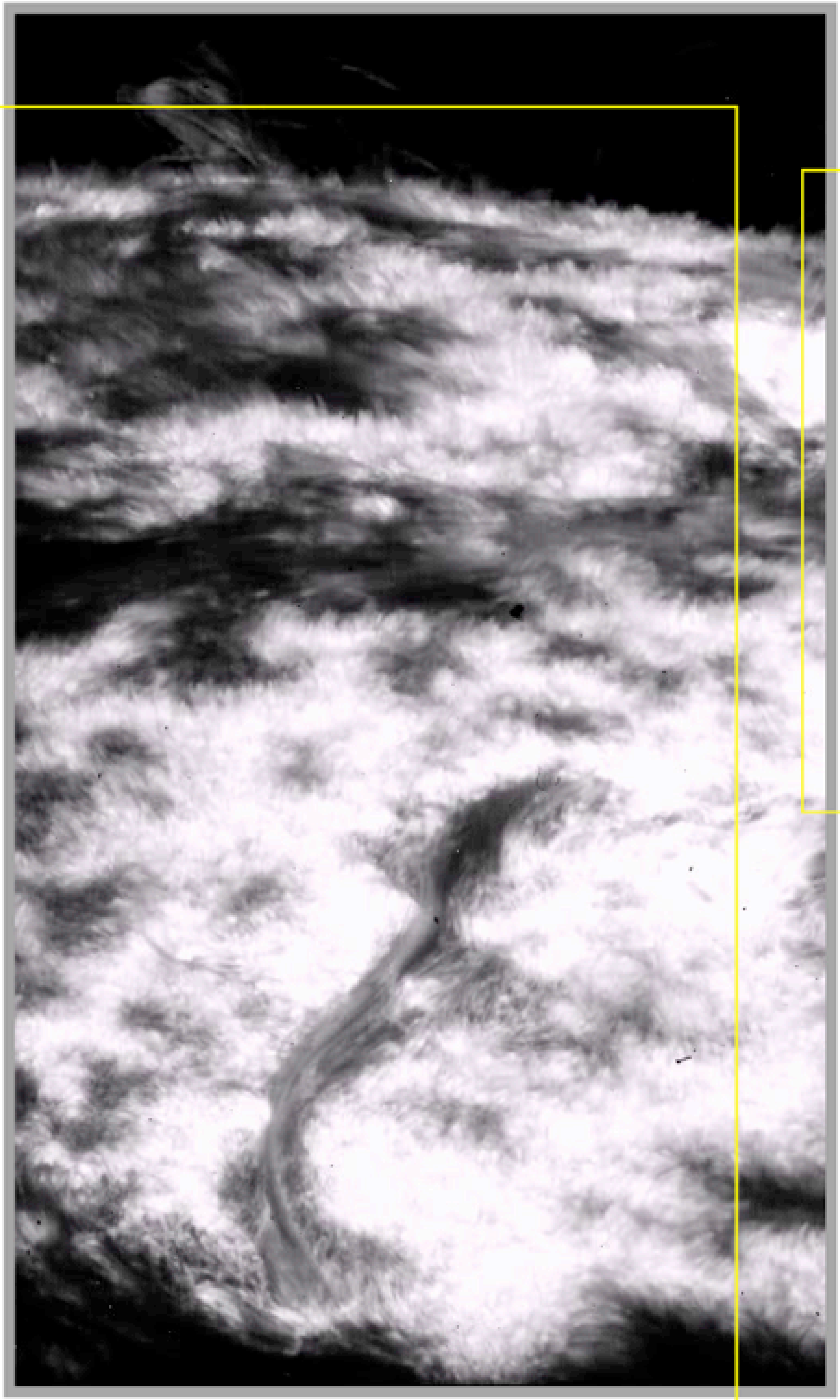
Feldman et al 2001

SUMER 300x300”

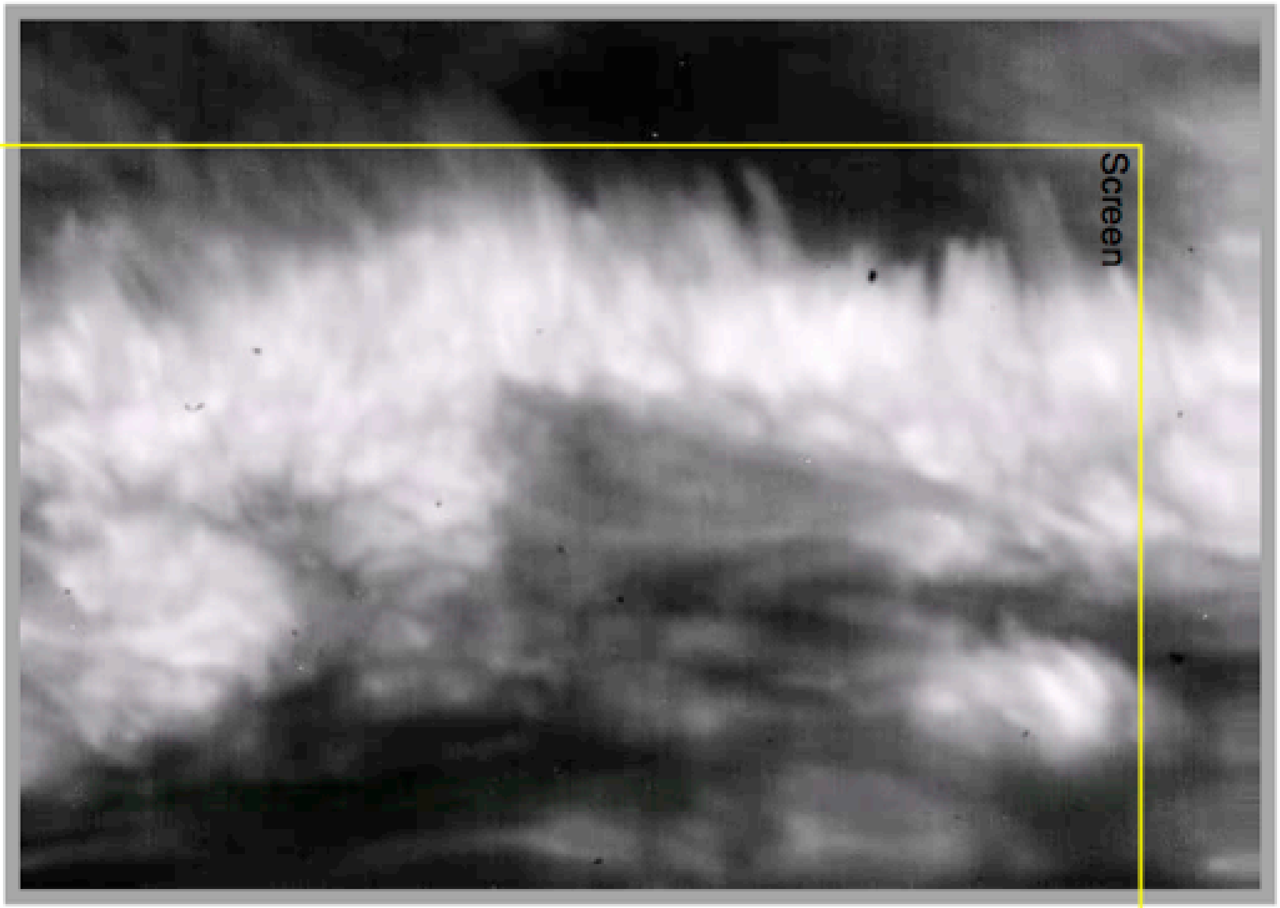
no obvious relationship to the corona...

Feldman concludes that the TR is thermally and magnetically isolated...





duration: 51 s, Δt = 17 s, 4 frames



- temporal variations apparent even in brief limb sequence
- Lyα jets appear much like Hα DFs
- difference: the former bright against dark cell interior whereas the later dark against a bright plage
- we choose to call these jets Lyα dynamic fibrils (DFs)

The theoretical problem

- Field-aligned conduction models fail < 10^5 K
  - Insufficient radiation: Athay 1966, Gabriel 1976, Jordan 1980
  - TR plasma cannot radiate 10^6 erg cm^{-2} s^{-1} downward conductive flux
  - Solution? Fontenla et al: move cool atoms along field lines by diffusion where they radiate. Cally- turbulent heat transport
  - does not account for UFS
- "Cool loops"
  - Rabin & Moore (1984), Antiochos & Noci (1986)...
  - basically extended chromospheres near 10^5 K => low-lying (usually short) loops, <10Mm say
  - Dowdy et al (1986) mixed small-scale polarities within NW boundaries
  - Cally & Robb (1991)- stability?

Gabriel 1976, Athay 1981,1982

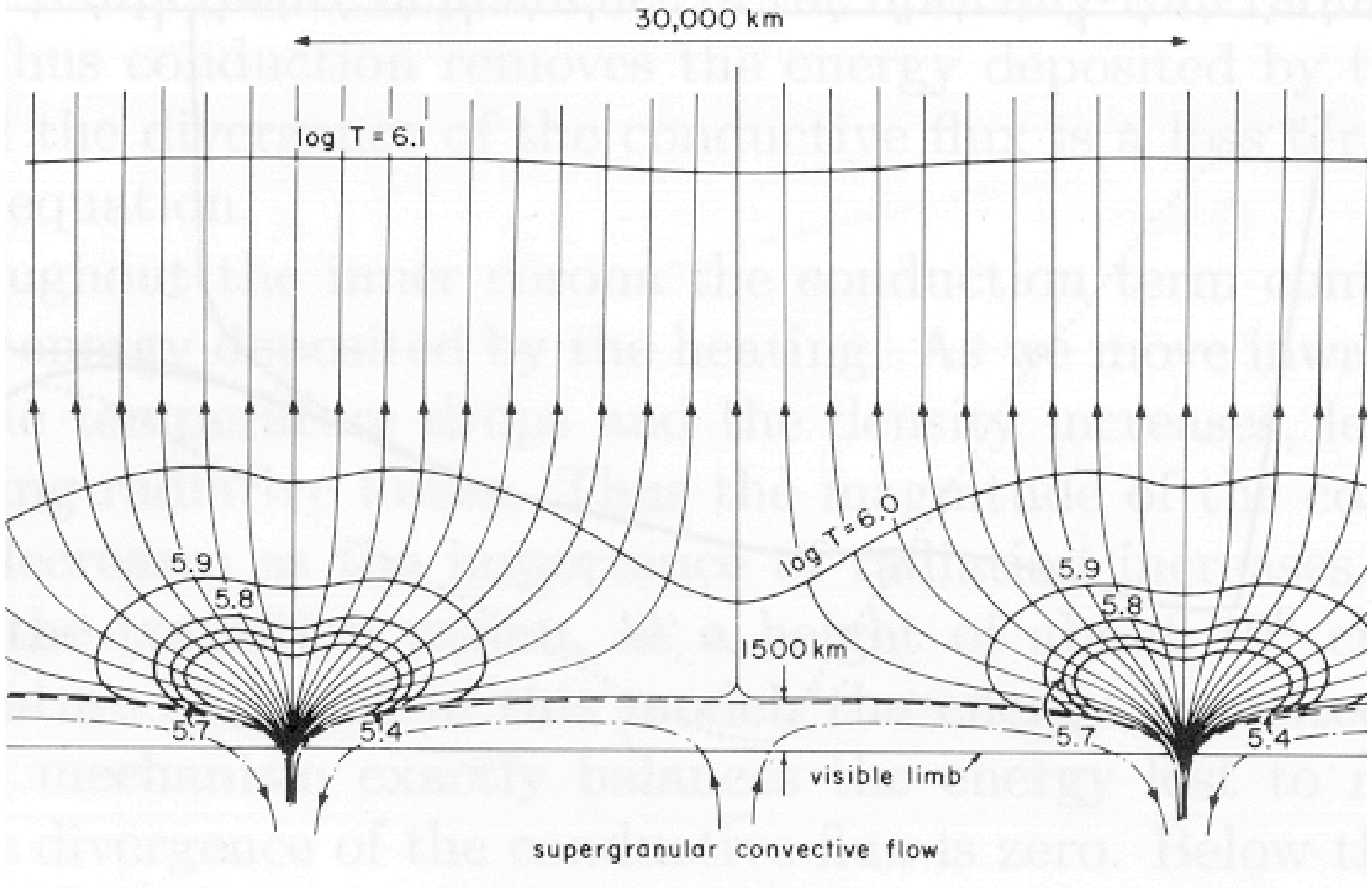


Fig. 7.4. Magnetic field geometry suggested by Gabriel (1976

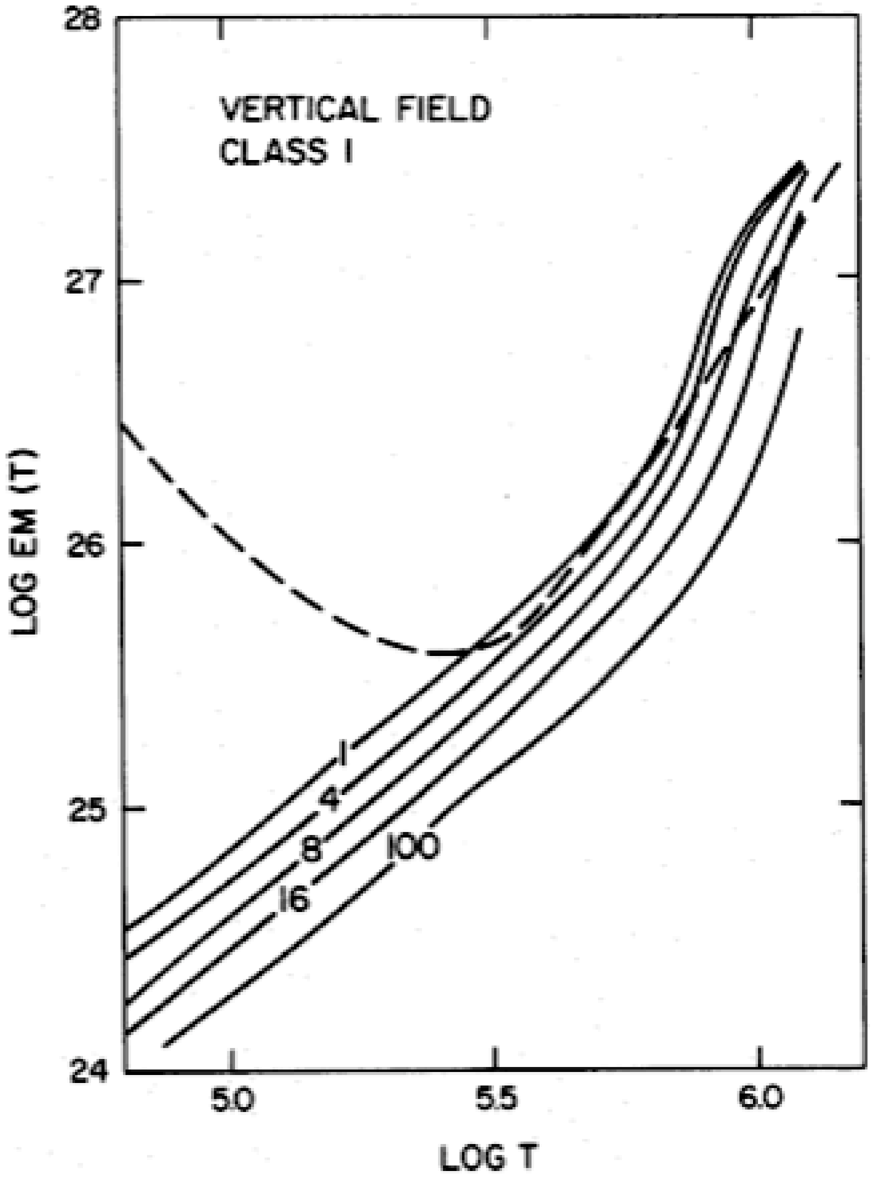
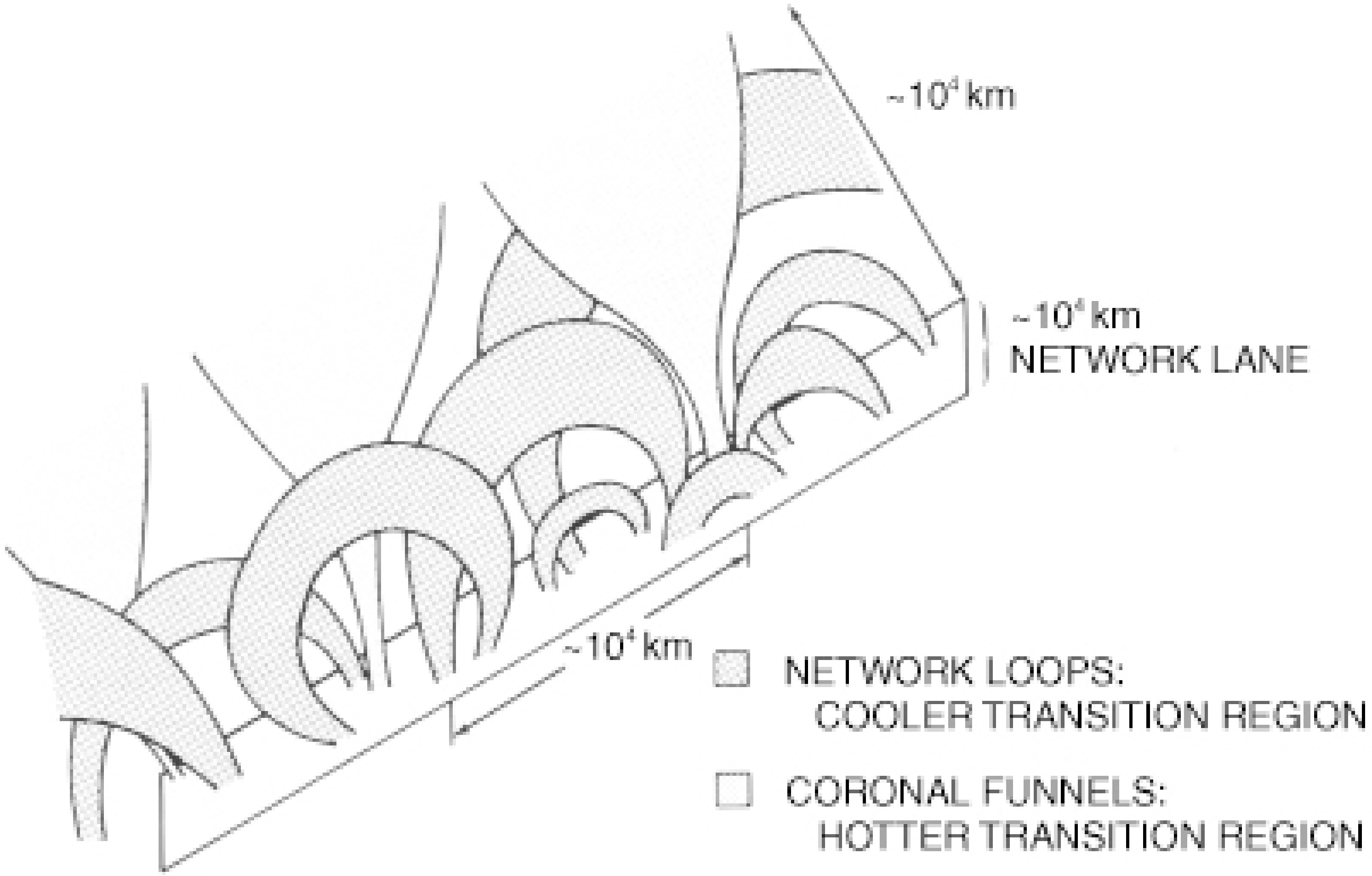


FIG. 5.—Comparison of empirical emission measures (*dashed lines*) to computed emission measures for different values of T_s (*solid lines*, labeled in units of 10^5 K) for class 1 models.

Dowdy et al. (1986)

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



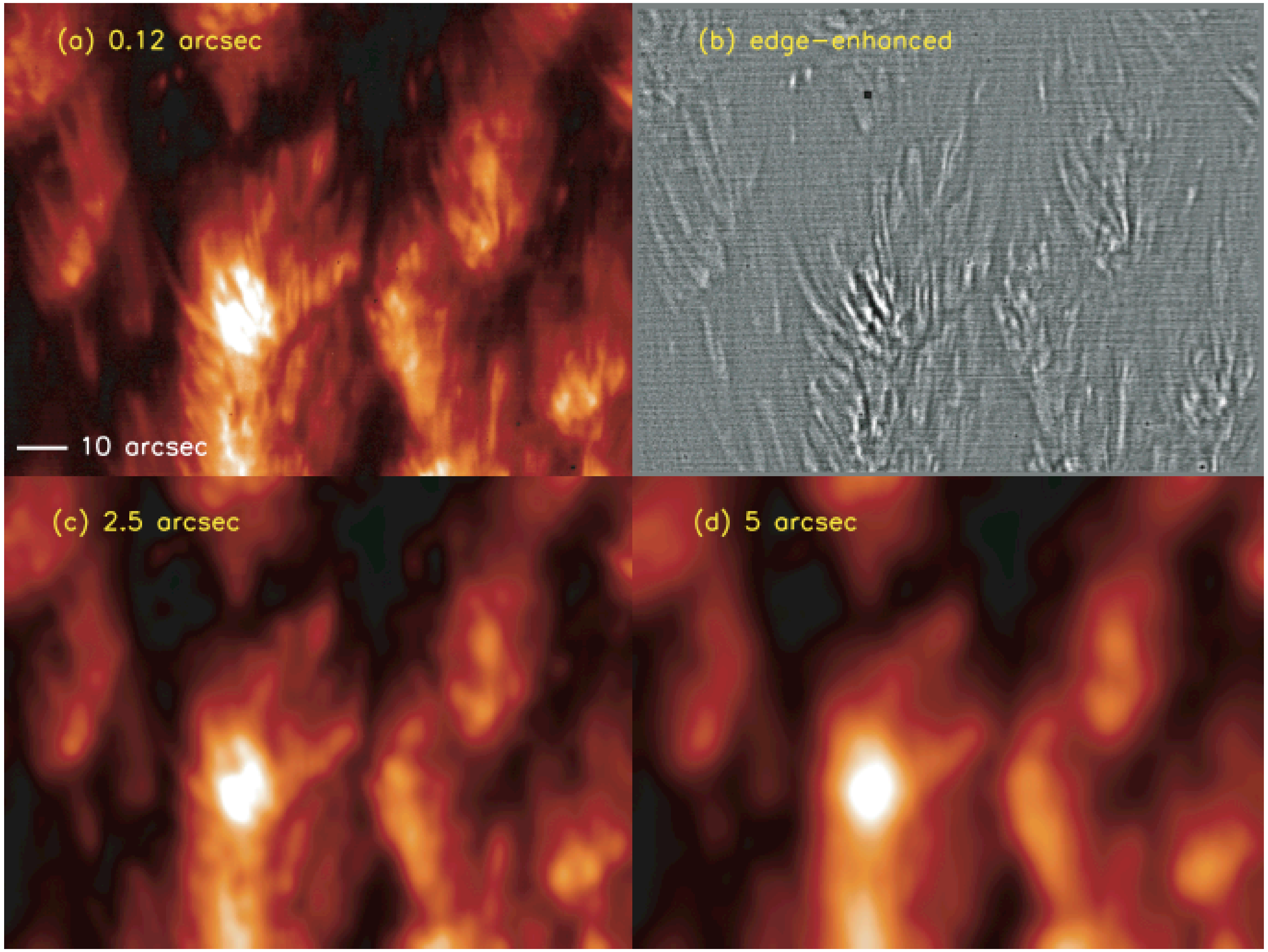
Current status

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

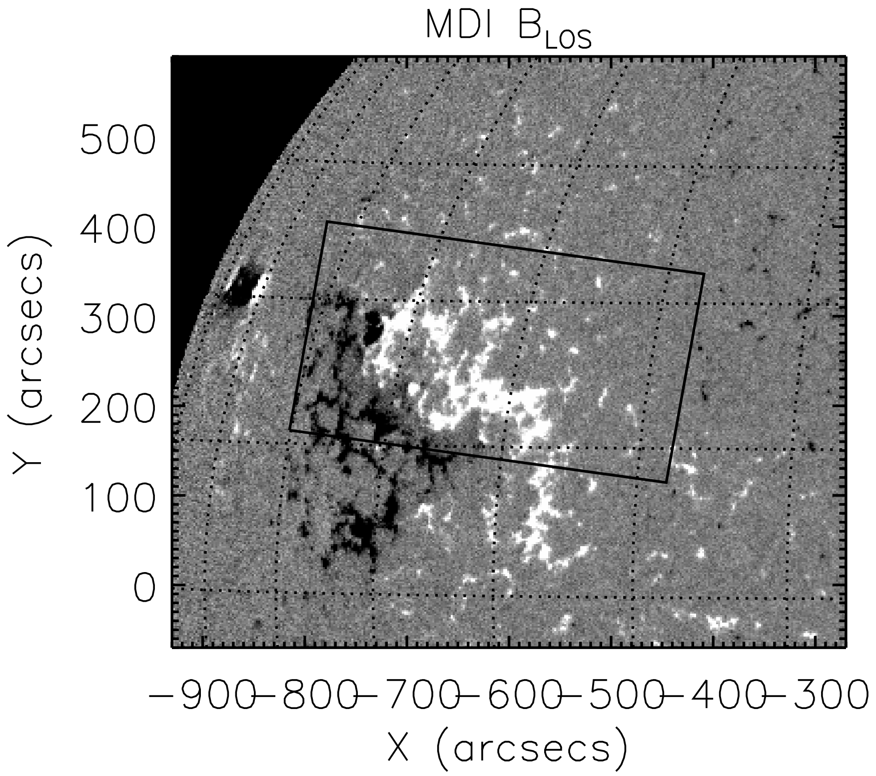
Judge & Centeno (2008)

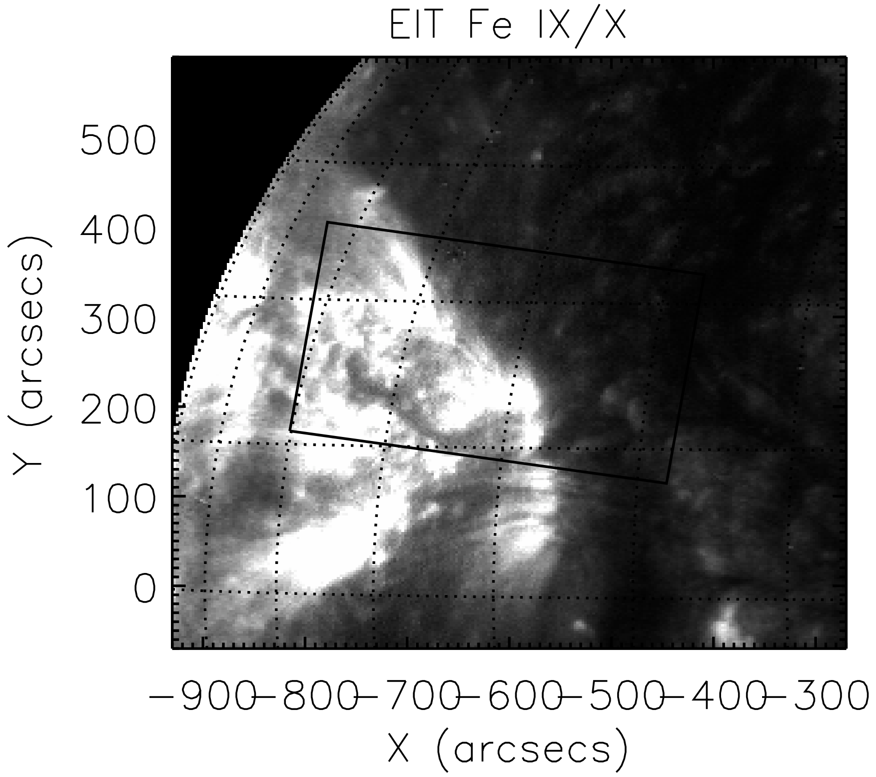
- VAULT data vs. KPNO magnetic data
  - supplemented by Hinode SP vector polarimetry
- Prompted by Patsourakos et al (2007)
  - We noted something “odd” about proposed cool loops
  - large-scale alignment of Lα threads

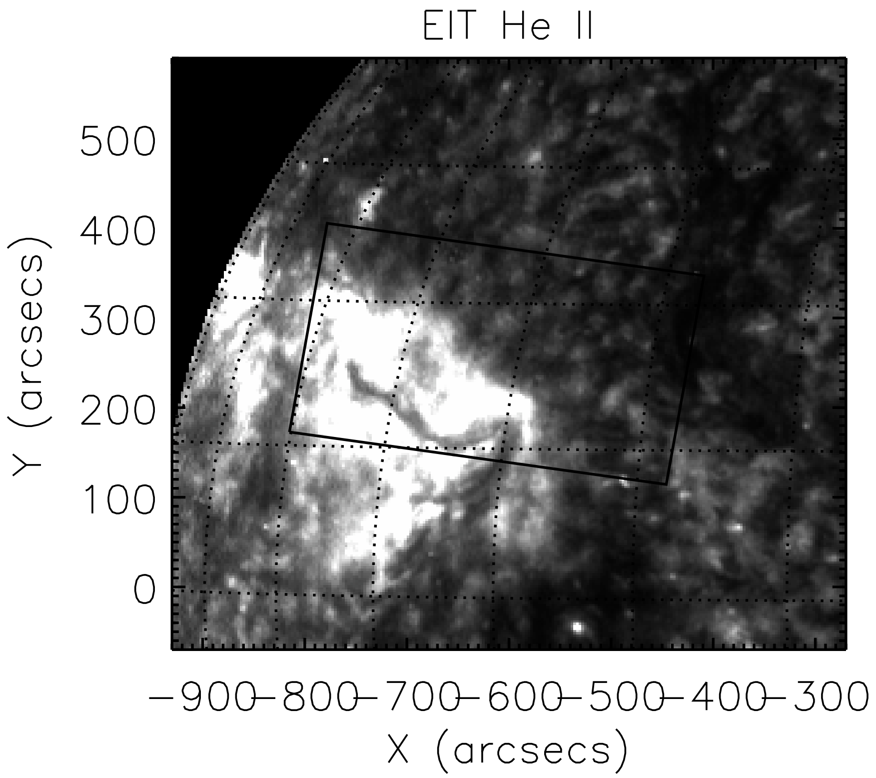
Patsourakos et al:

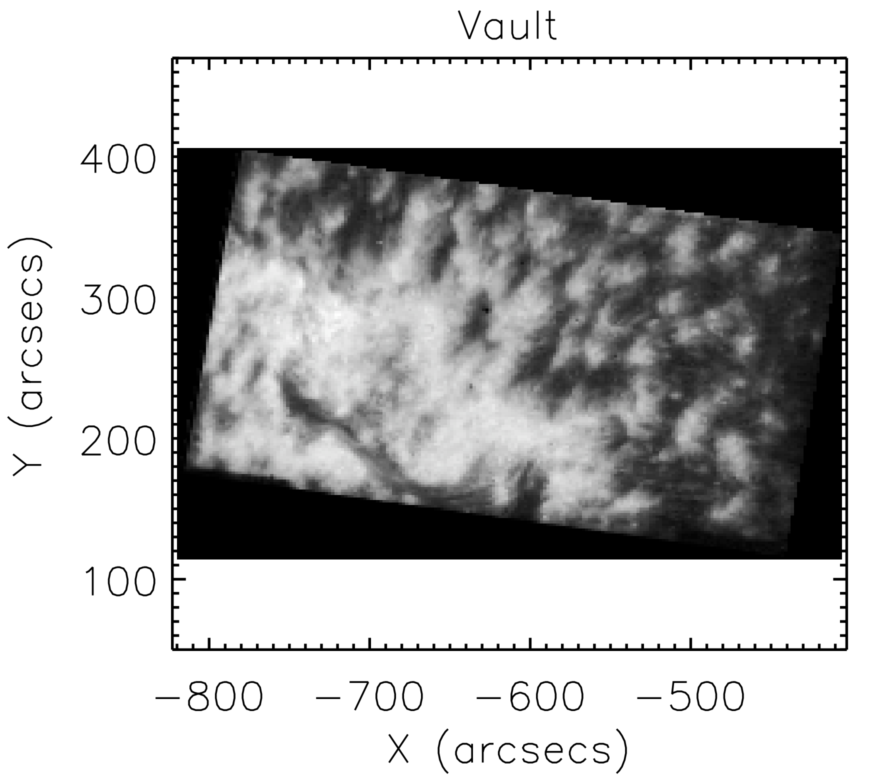


Magnetic fields and Lα


MDI B_{LOS}


EIT Fe IX/X


EIT He II


Vault

Active and “quiet” Sun.

“quiet”=NW region

not really so quiet?

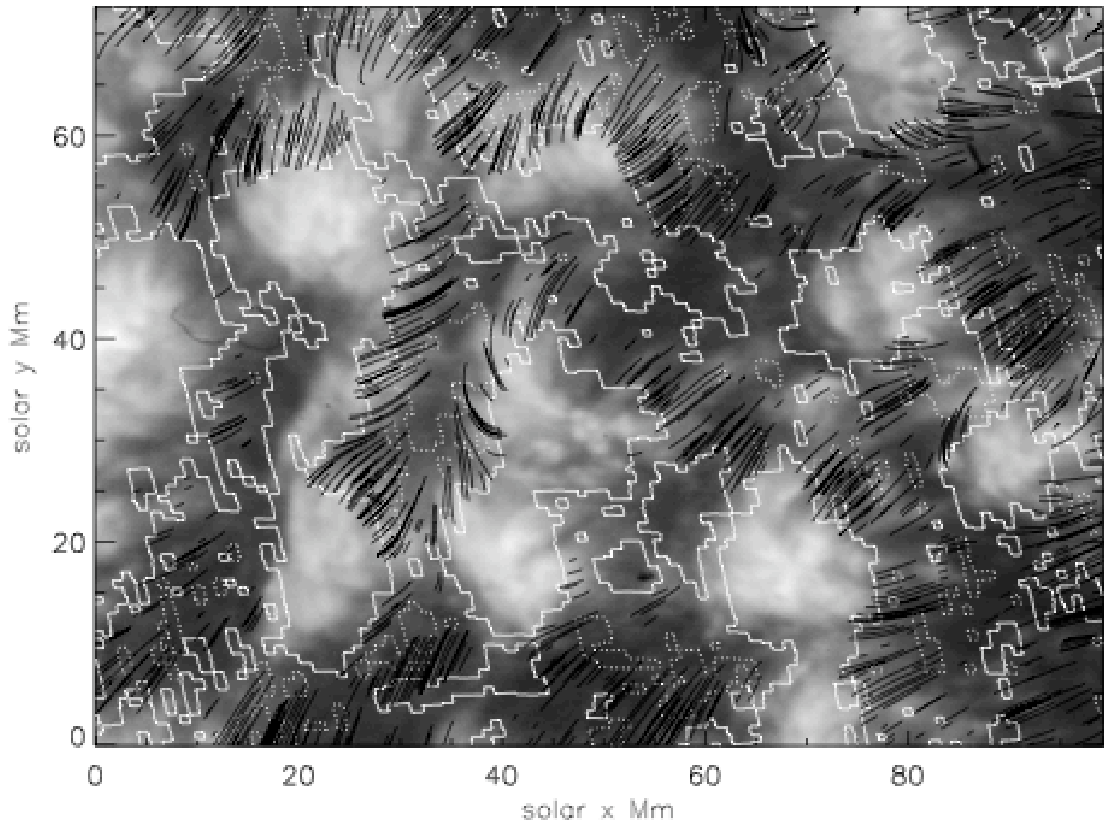
KPVT+POTL FIELDS+VAULT

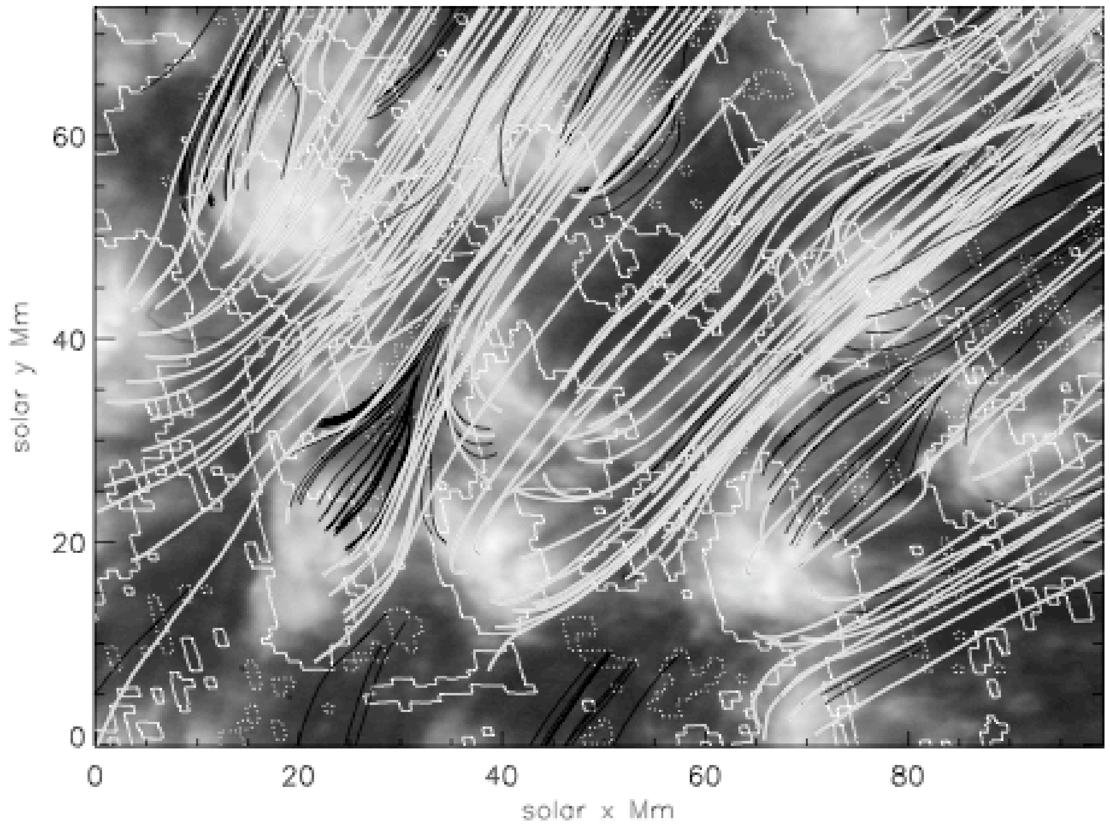
Black=low-lying loops (h<5Mm)
Gray= long

Stability requires that
low-lying are possibly cool
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.





MDI vs KPVT vs HINODE

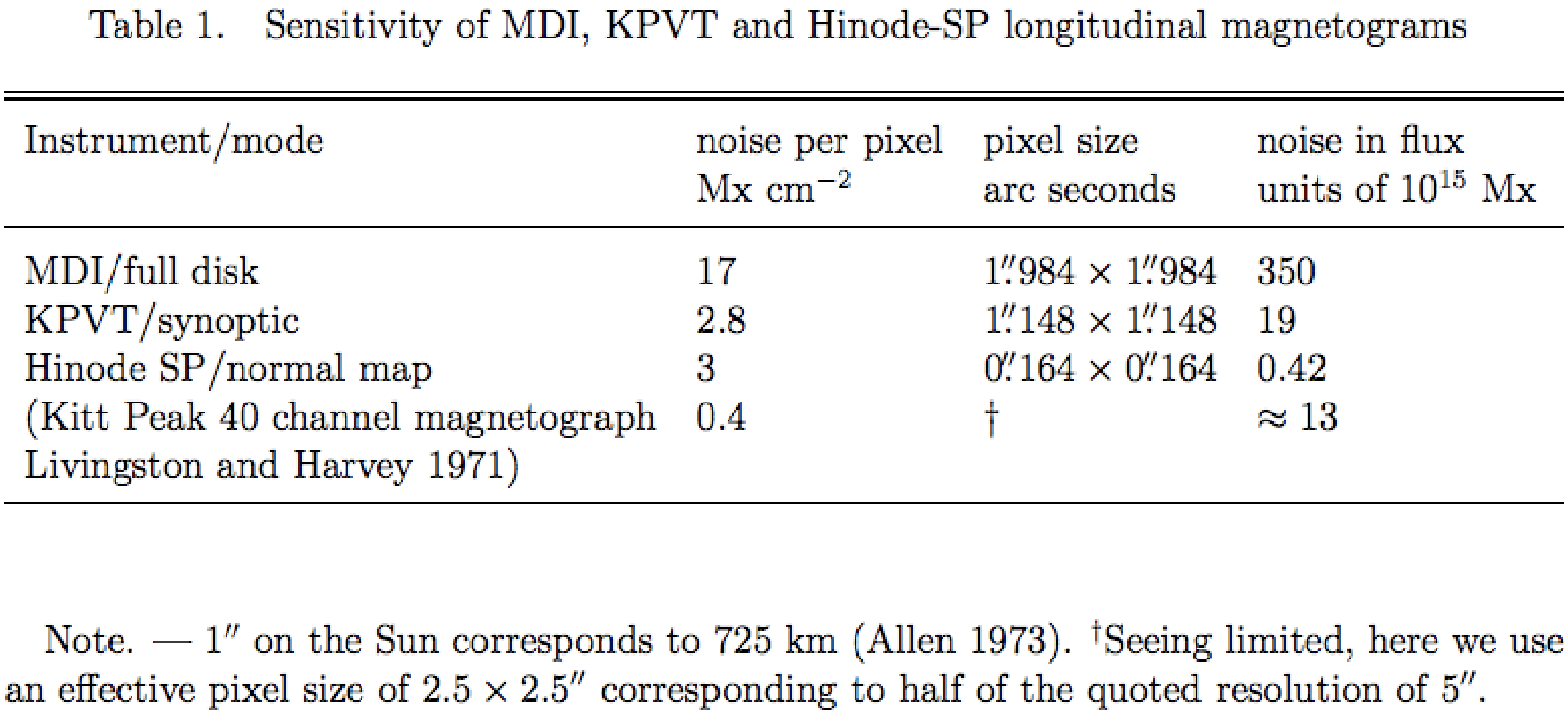


Table 1. Sensitivity of MDI, KPVT and Hinode-SP longitudinal magnetograms

Instrument/mode	noise per pixel Mx cm^{-2}	pixel size arc seconds	noise in flux units of 10^{15} Mx
MDI/full disk	17	1.″984 × 1.″984	350
KPVT/synoptic	2.8	1.″148 × 1.″148	19
Hinode SP/normal map	3	0.″164 × 0.″164	0.42
(Kitt Peak 40 channel magnetograph Livingston and Harvey 1971)	0.4	†	≈ 13

Note. — 1″ on the Sun corresponds to 725 km (Allen 1973). †Seeing limited, here we use an effective pixel size of 2.5 × 2.5″ corresponding to half of the quoted resolution of 5″.

Hinode & flux missing from KPVT

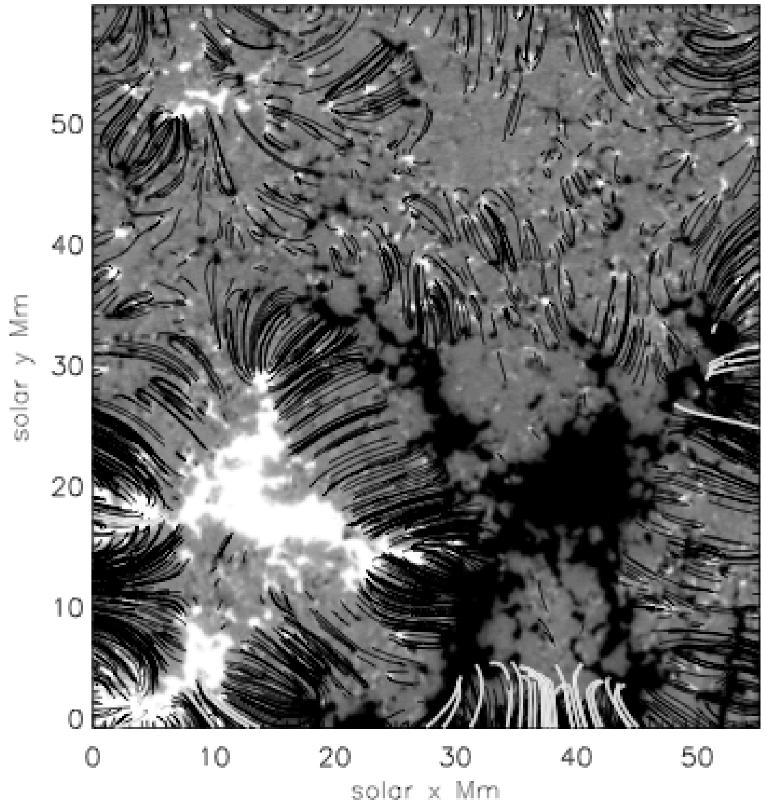
small ARs observed by Hinode SP

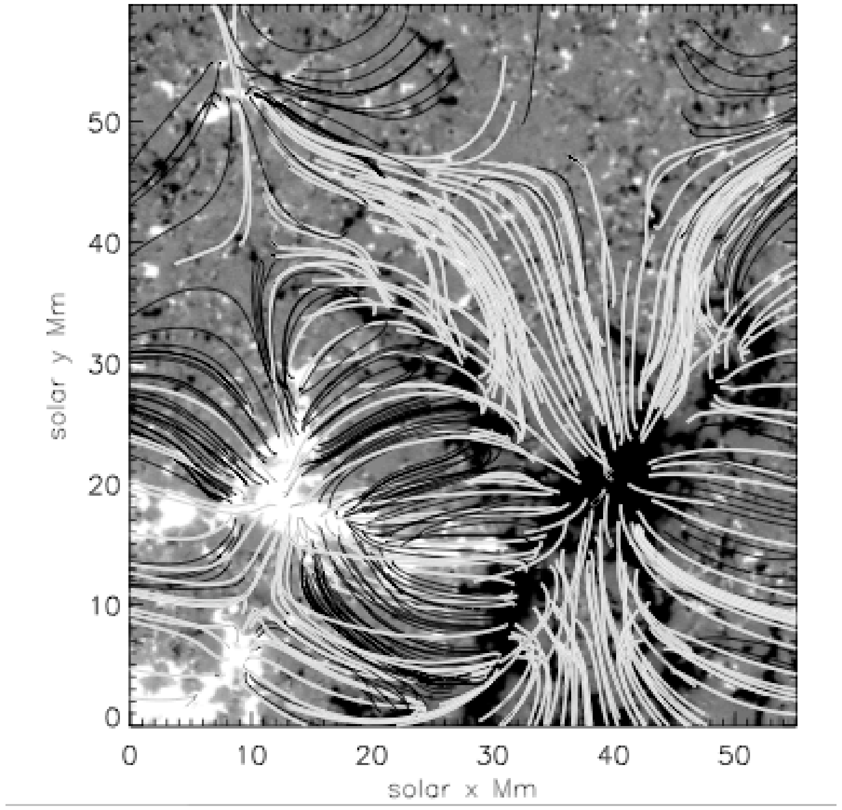
0.164” pixels, 0.33” resolution

KPVT only misses 25% of pixels containing magnetic flux seen by Hinode SP, even though it is 45x less sensitive

Strong flux concentrations - long loops again - low-lying (possibly cool) loops cannot penetrate into bright core concentrations

weak concentrations (quiet Sun), cool loops indeed possible.





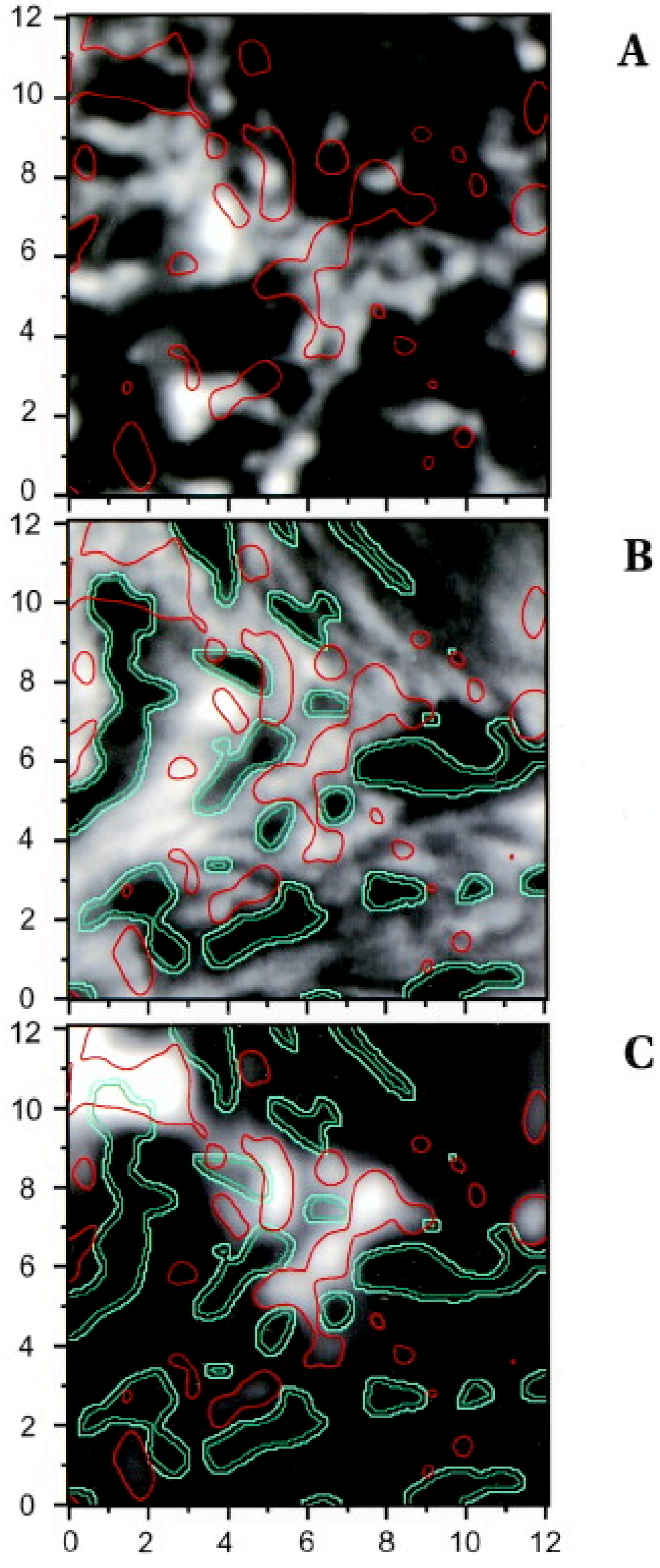
Irrelevance of fields on scales below 0.8Mm for Lα

- Sources on scales L can reach heights typically L
- Lα must form above $\tau_{\mathrm{cont}}=1$, i.e. 0.8Mm
  - because of simple stratification
  - (VAL/FAL places Lα at about 2Mm)
- Hinode has resolved down to ~0.24Mm
- KPVT and Hinode have sufficient resolution and sensitivity to discount smaller cool loops
  - all important sources of potential cool loops are already in the data
- In strong flux concentrations (e.g., seen by VAULT) cool loops are no longer a credible option

If not cool loops then what? Judge (2008)

- Prompted by
  - VAULT analysis
  - Corona/chromosphere interface at high resolution (Berger et al 1999) ->
  - spicules (“type II”)
  - He I EUV problem (Pietarila & Judge 2004
- Simple, cross-field diffusion
  - cool tubes projecting into the corona
  - no **j**x**B** force on neutrals

Berger et al.



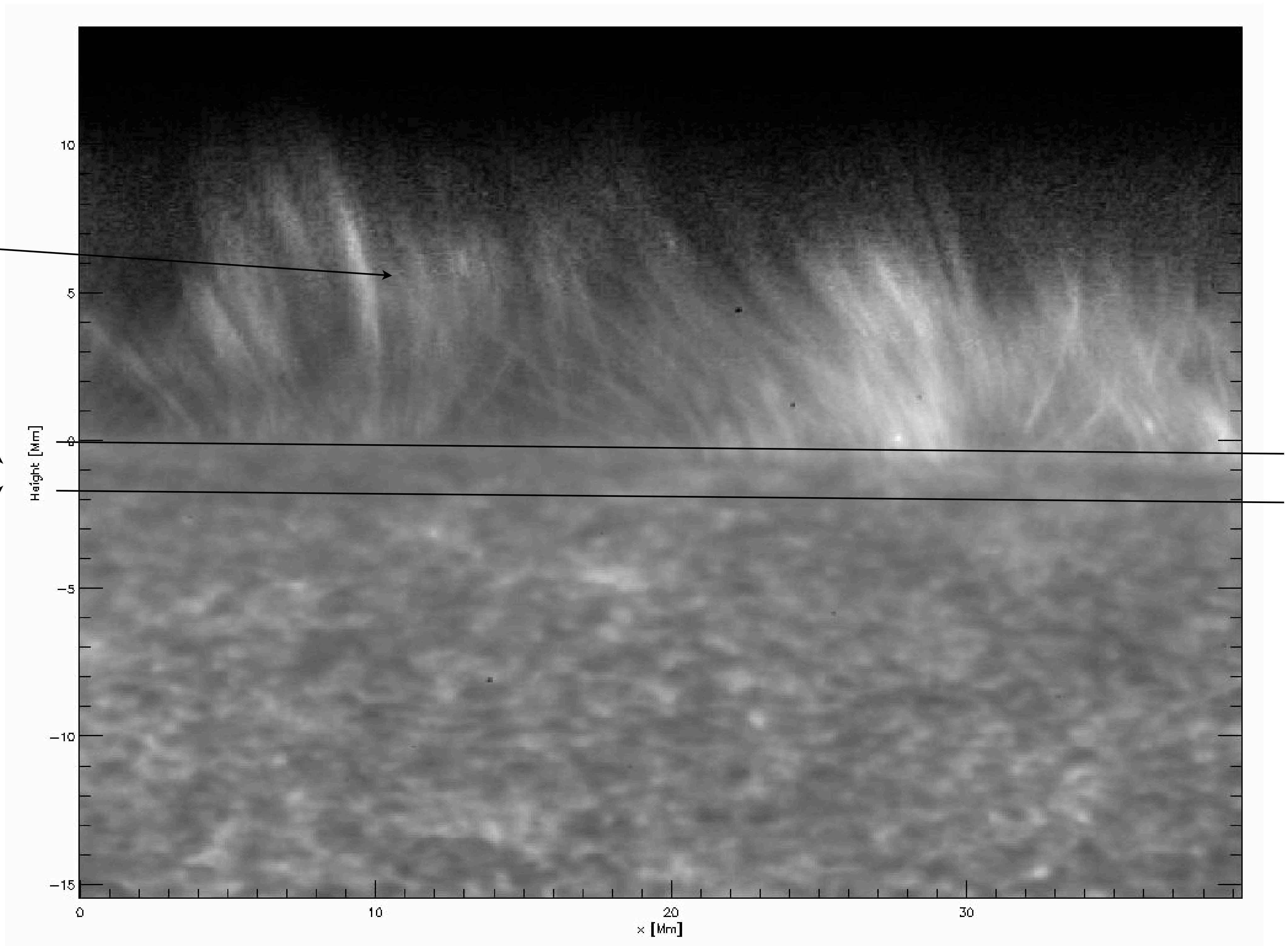
Ca II + 171

Hα +171

171

Spicules, fibrils..

- Hinode data (radial filter to enhance spicules, M. Carlsson)
- base of the corona (coronal hole)- vertical thermal boundaries

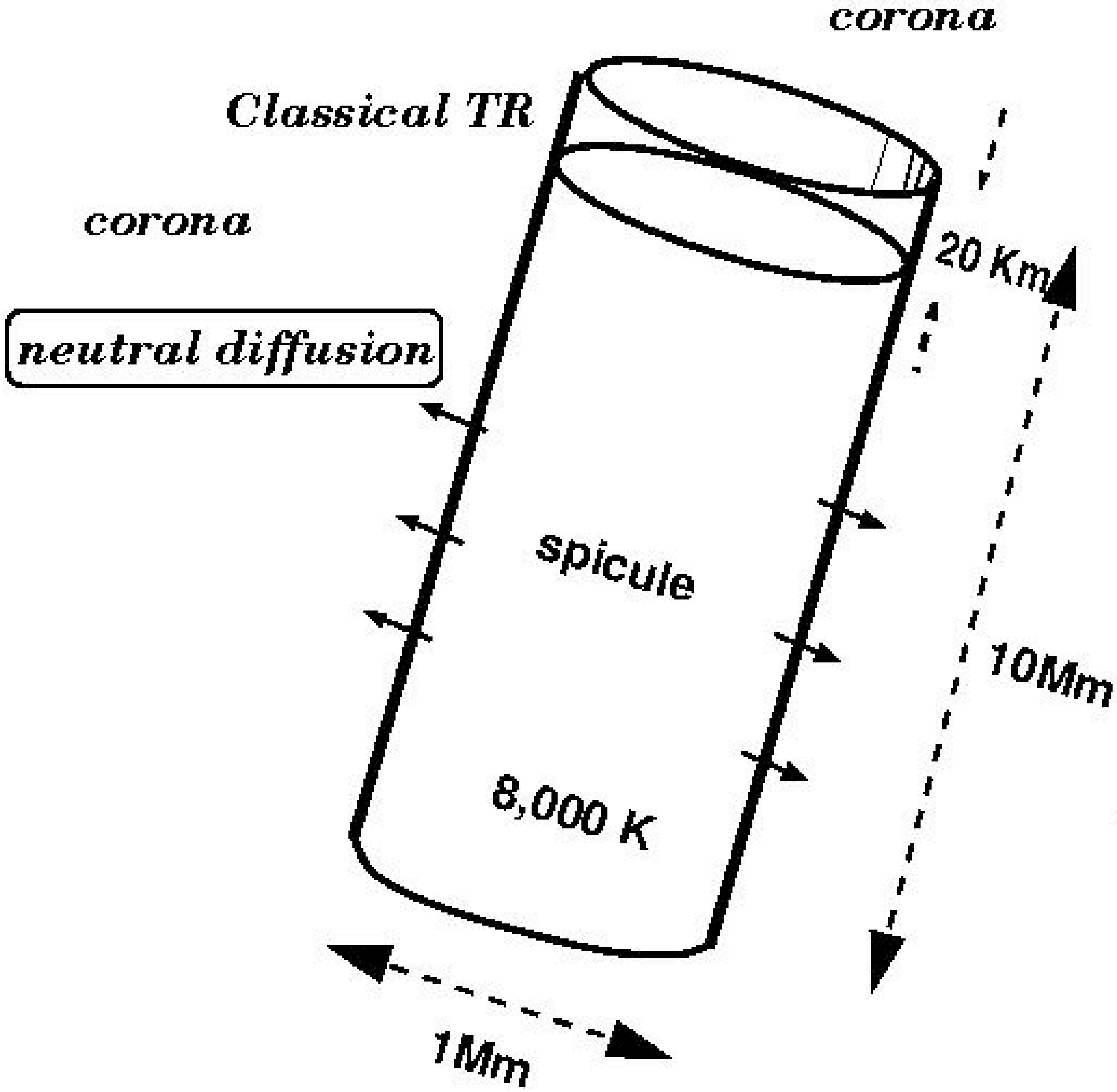


spicules *arise from within* the chromosphere

stratified VAL chromosphere ↕
1.5Mm only

Initial conditions

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	
$\overline{v}$	km s^{-1}	13	$T^{1/2}$
n_c	cm^{-3}	10^{11}	
τ_{nn}	s	1.4×10^{-2}	$n_n^{-1}T^{-1/2}$



Kinetic processes

hot protons impacting hydrogen atoms				
$\tau_{pn}(CT)$	s	1.0×10^{-2}	$n_p^{-1}T^{-1/2}$	"CT" = charge transfer
H atom mfp	km	6.5×10^{-2}	n_p^{-1}	
cool hydrogen atoms impacting protons				
$\tau_{np}(CT)$	s	8.0×10^{-5}	$n_n^{-1}T^{-1/2}$	
proton mfp	km	5.8×10^{-3}	n_n^{-1}	
$\omega_p \tau_{np}$		7.7		
hot electrons impacting H atoms				
τ_{12}	s	9.5×10^{-2}	$n_e^{-1}T_e^{-1/2}e^{10.2e/kT_e}$	excitation of $n = 2$ level
τ_{1k}	s	8.2×10^{-2}	$n_e^{-1}T_e^{-1/2}e^{13.6e/kT_e}$	ionization
τ_{k1}	s	4.0×10^{5}	$n_e^{-1}T_e^{+1/2}$	radiative recombination

Kinetic results (t< 0.1s,say)

initial mass flux $\frac{1}{4} n_c \overline{v}_c \sim 2 \times 10^{16} \;\; \text{particles s}^{-1} \text{ cm}^{-2},$

electrons lose energy $\varepsilon = 5 n_h (I + E) e$ per unit volume at the rate

$$\frac{\varepsilon}{t} \gtrsim \frac{5 n_h (I + E) e}{7 \tau_{1\kappa}} \approx 0.13 \;\; \text{erg cm}^{-3} \text{ s}^{-1},$$

Lα flux $f \approx \frac{3}{7} \varepsilon 3 v_c^{diff} \approx 5.6 \times 10^3 \;\; \text{erg cm}^{-2} \text{ s}^{-1}$

-factor 100-300 lower than VAULT thread values, 30 smaller than average network.

This uses only *local* thermal energy, and does not include non-linear dynamics.

5 moment equations of motion including diffusive fluxes

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

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

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

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

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

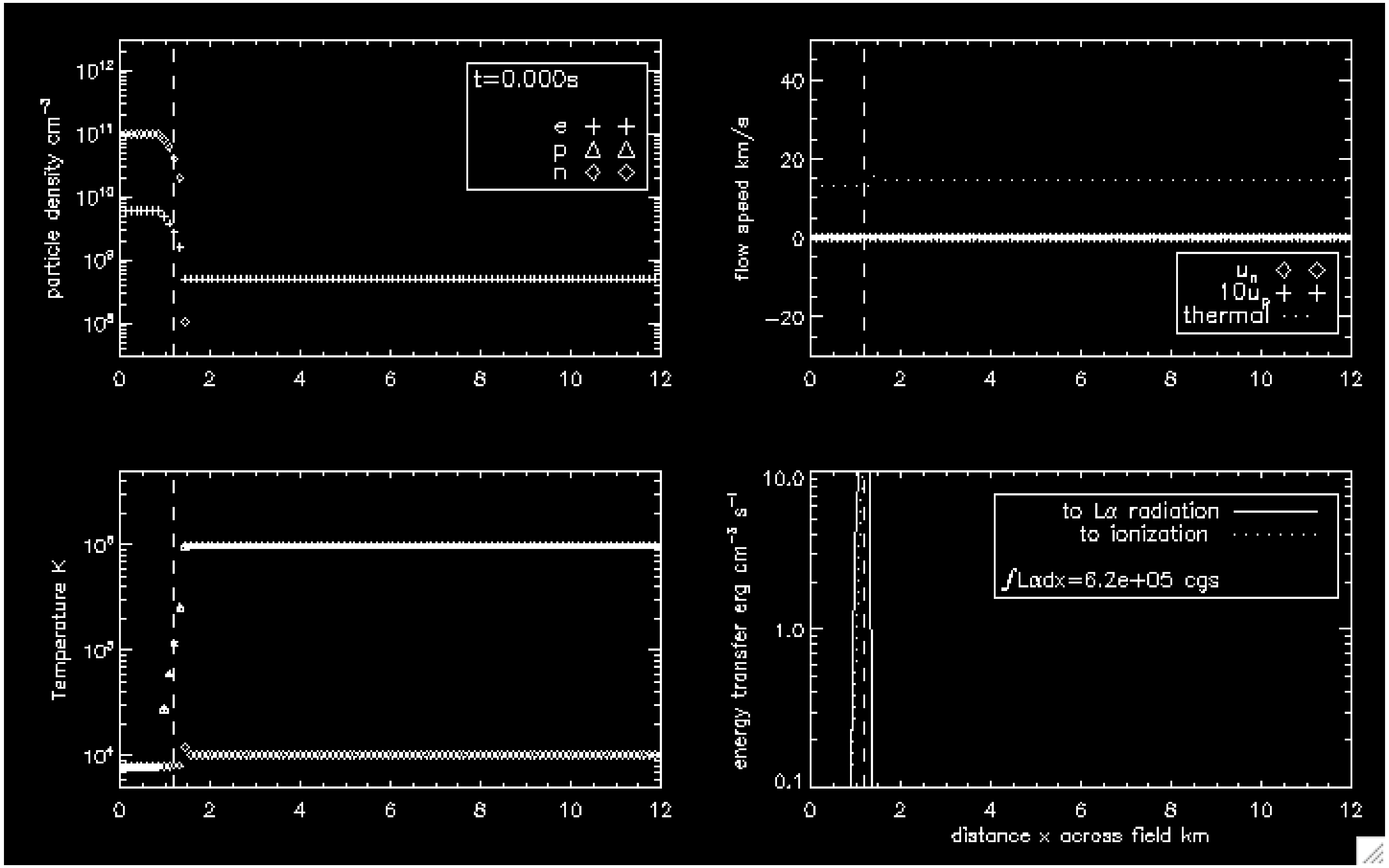
- when d_s^i, $\frac{\delta}{\delta t}$, Q L are 0, => Euler for s
- λ = mean free path, $\overline{v}_s(x) = \sqrt{\frac{8kT_s}{\pi m_s}}$, $E_s = \frac{3}{2}n_s kT_s + \frac{1}{2}m_s n_s u_s^2$, $p_s = n_s kT_s$
- $\frac{\delta X_s}{\delta t}$, non-linear collisions for species s (Schunk 1977).
- Solve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

Results

non-linear

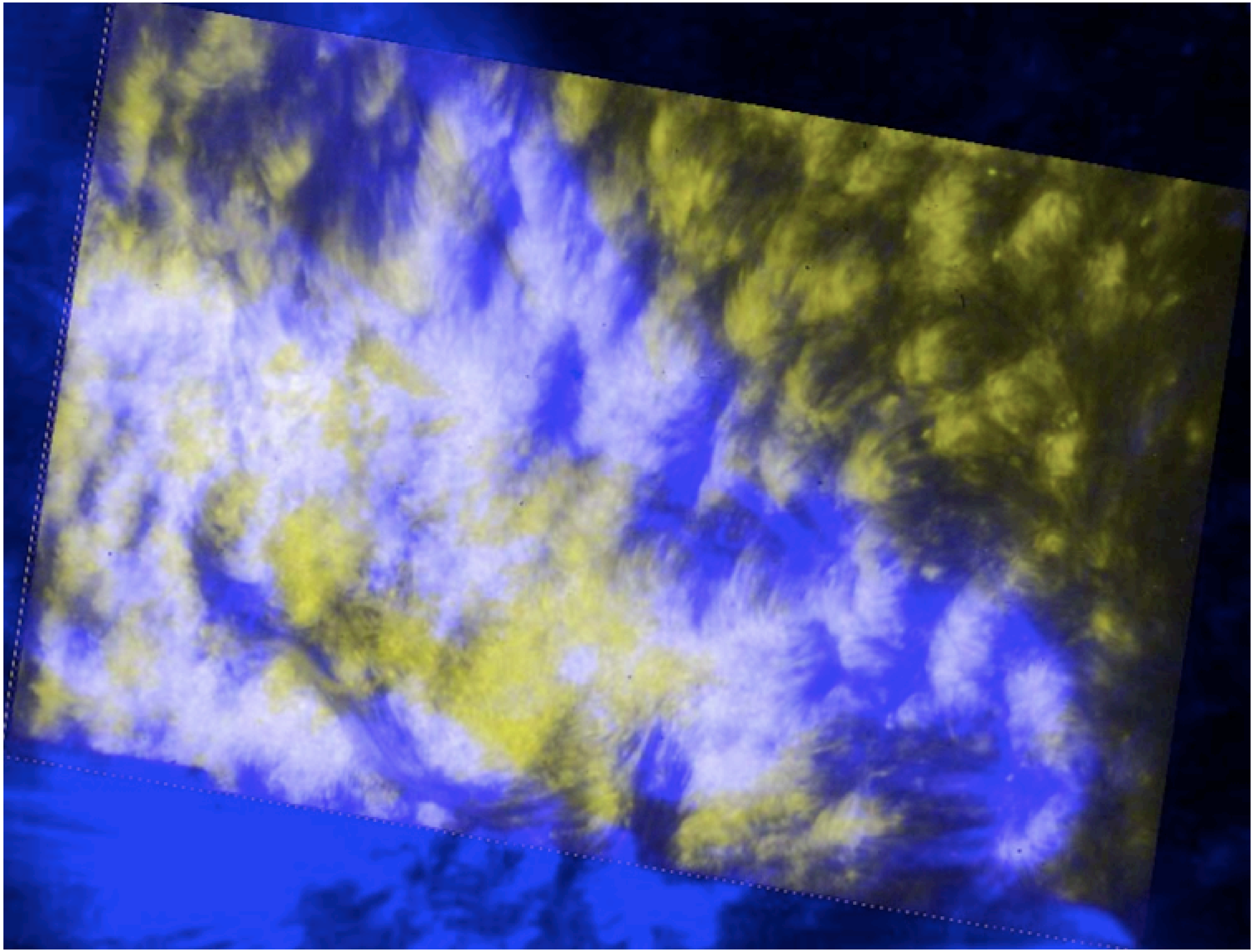
10x Lα from (linear) kinetic estimate

local energy only- no field aligned conduction



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

VAULT+TRACE



Speculation: field-aligned conduction, subsequent dynamics

- Spicules launched from chromosphere
- speed ~10 km/s?
- diffusion speed 0.8km/s
- Diffusion front makes angle 0.8/10 radians wrt field lines
- entire length of the spicule is exposed to the field-aligned heat flux
- spicule sheath is cooler, denser than initial corona
    - radiates in trace species (C III,...)?
    - pressure gradients insufficient to support additional mass
    - downflows?

Conclusions

- A simple model might explain a long-standing problem of energy balance in extended structures in the lower TR
- missing ingredient is cross-field diffusion of neutrals
- chromosphere supplies the mass, corona the energy.
  - no need for cool loops and they don't explain active network anyway (Judge & Centeno 2008)
  - Feldman's "UFS" in this model is thermally connected
- Calculations for Lα are promising, (also Lβ, He I 584)
  - this is the hardest line to explain, others may follow?
- Future
  - 2D calculations including field-aligned conduction and dynamics are needed
  - more observations of the chromosphere/corona interface