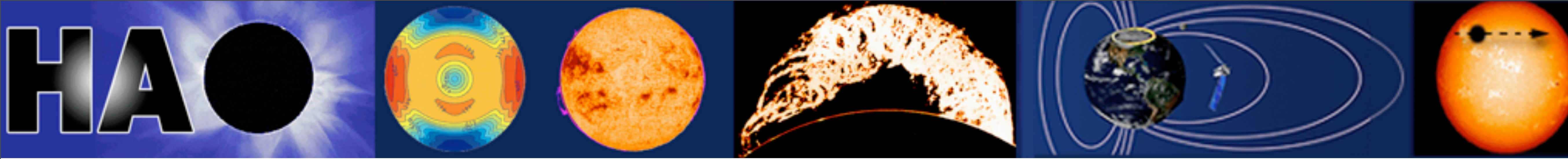
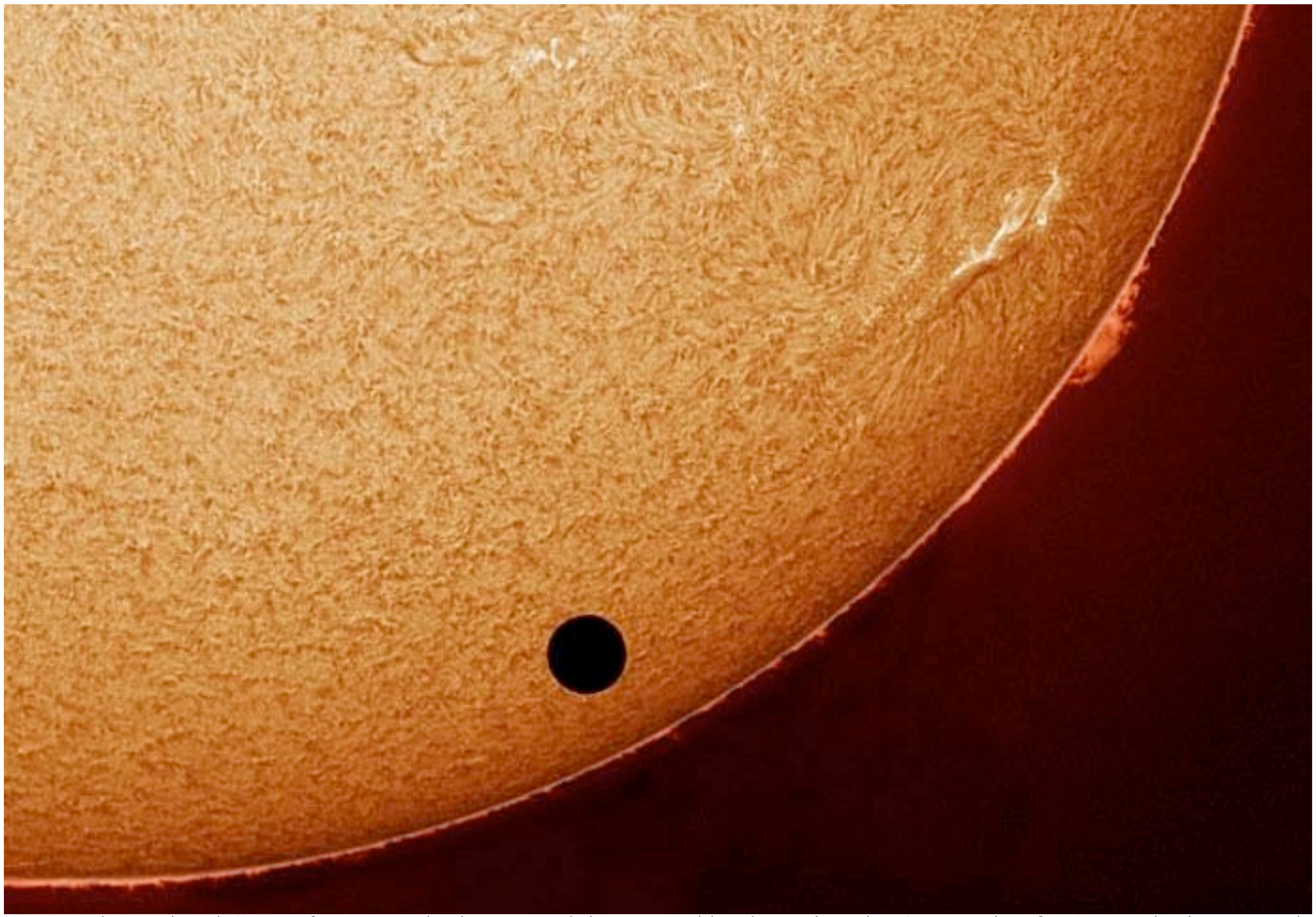


physics of the solar chromosphere

Philip Judge, *HAO, NCAR*



NCAR

June 2012

Thermosphere-Ionosphere vs chromosphere

broad commonalities

- "Earth's upper atmosphere can be categorized as a gravitationally bound partially ionized, fluid"
  - (spans ~15 scale heights; chromosphere: ~10)
  - p is a natural vertical coordinate (p=mg in chromosphere)
- "Quasi-hydrostatic balance" (subsonic vertical motions)
  - (V/C_S ~ 0.1; chromosphere* ~0.3-1)
- T increases with height (divergence of external energy flux)
- incomplete mixing (z > turbopause, 110 km)
- "magnetized" ions

*Bulk of chromosphere: not "spicules"

gross differences

Thermosphere-Ionosphere	Chromosphere
Potential **B**: δ**B** < 1% from ion. **j** (**B** from ⊕ interior, m-sphere) **E** = $\nabla\varphi$	Non-potential **B**, fields tied to sub-photosphere $\mathbf{E}_{/\!/} = \mathbf{0}$
E, σ "electrodynamics", **B** "fixed" **j** determined by **E, σ**	**v, B, σ** full MHD (coupled fluid and induction equations), "frozen field" **j** determined by **j**×**B**-∇**p**+..
heating mechanisms largely known	Electrodynamic heating: unknown
Horizontal scales ≫ vertical $\partial f/\partial x$, $\partial f/\partial y \ll \partial f/\partial z$, ~ geostrophic balance	Vertical scales ≳ horizontal Photospheric flux concentrations $\partial f/\partial x$, $\partial f/\partial y \gtrsim \partial f/\partial z$

why study the chromosphere?

Mem. S.A.It. Vol. 81, 543

Memorie della
Società Astronomica Italiana

The chromosphere: gateway to the corona?

. . . Or the purgatory of solar physics?

P.G. Judge

High Altitude Observatory, National Center for Atmospheric Research, P.O. Box 3000, Boulder CO 80307-3000, USA, e-mail: judge@ucar.edu

Abstract. I argue that one should attempt to understand the solar chromosphere not only for its own sake, but also if one is interested in the physics of: the corona; astrophysical dynamos; space weather; partially ionized plasmas; heliospheric UV radiation; the transition region. I outline curious observations which I personally find puzzling and deserving of attention.

Key words. Sun:chromosphere

energization of the mesosphere/ thermosphere/ionosphere

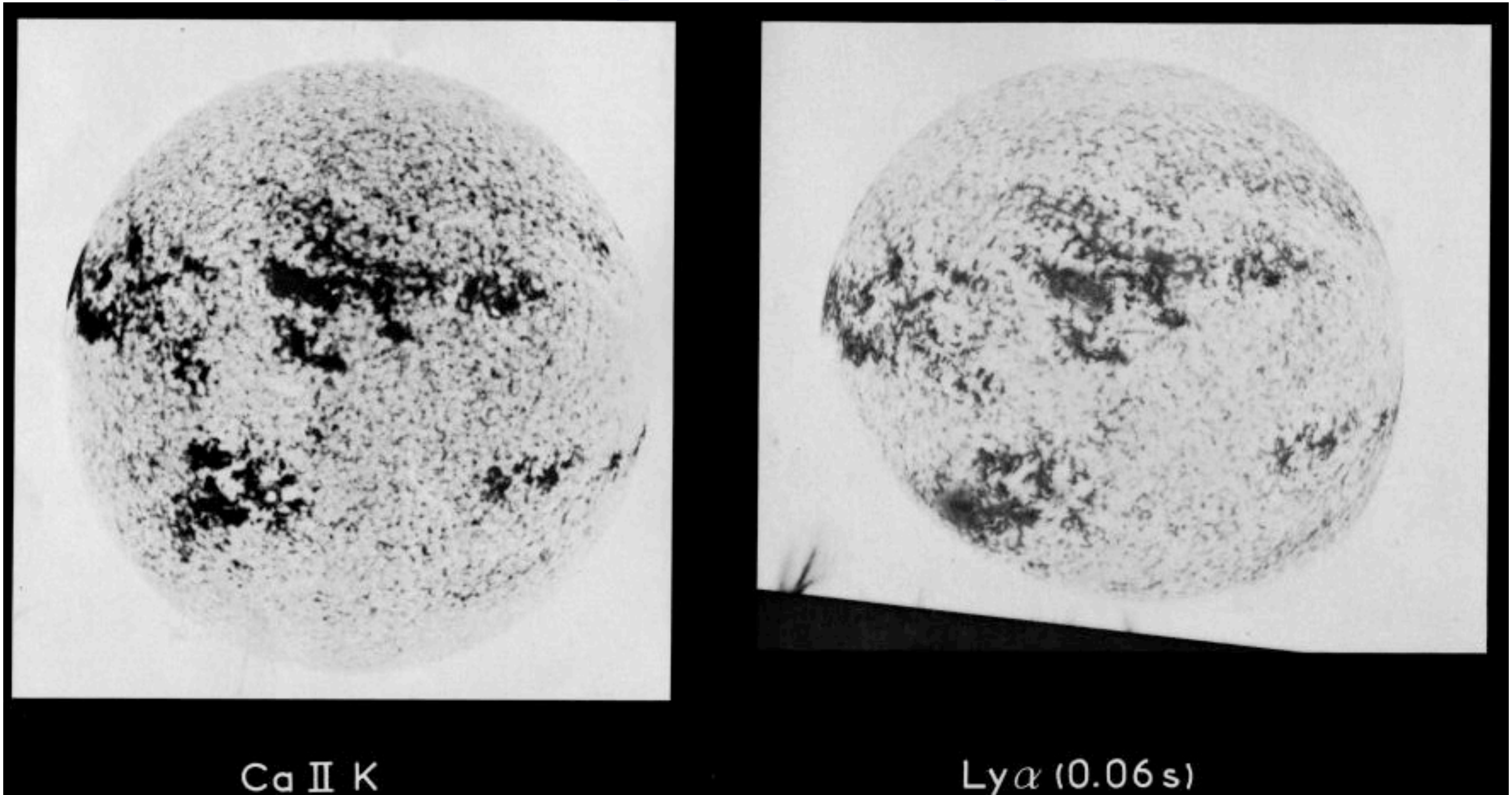


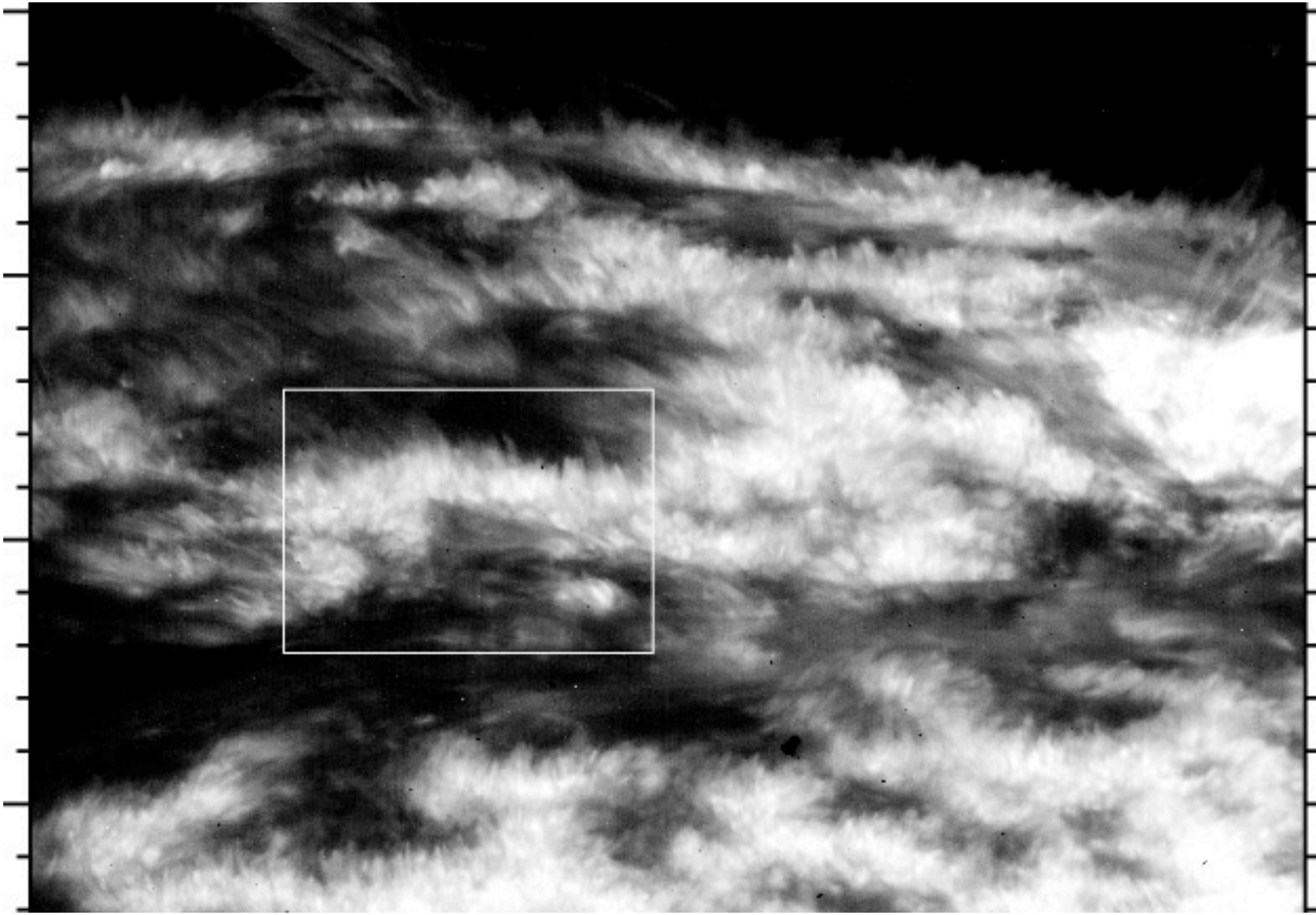
FIG. 3.—A 0.06 s exposure obtained with the TRC at Lα, showing the filamentary looplike structure of active regions. The image is truncated due to offset pointing of the XSST from disk center. The Ca II K spectroheliogram obtained at Meudon Observatory 8 hours prior to launch is shown for comparison.

BONNET et al. (see page L48)

Reversed color table

Strongest line in astrophysics
H Lyman alpha... (D layer)

VAULT
Ly-alpha
121.5 nm



10” tick
marks

Big Questions...

- what, physically, is the fine structure?
- what heats the chromosphere?
- what drives the dynamics?
- does it influence the magnetic field emerging through it?
  - boundary conditions for the corona/heliosphere

The IRIS observing programs

- Observe the region where most of the non-thermal energy is deposited and the temperature rise begins - the chromosphere and transition region - together with the region that is directly impacted - the corona.
- Collect data with spectral, spatial, and temporal resolution sufficient to reveal a range of physical processes.

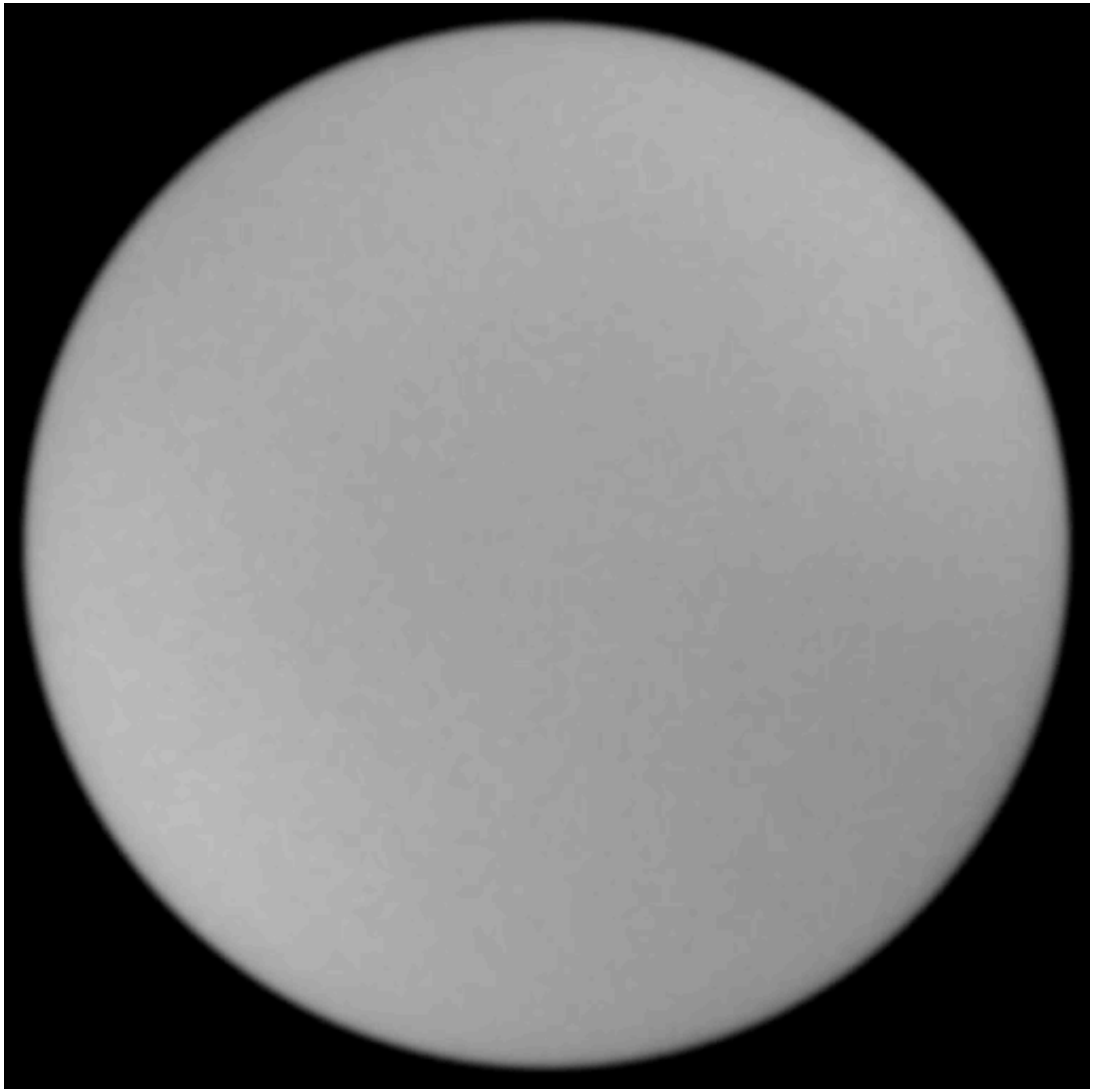
A short history

Young (1881, 1892,...)

- "...this outer envelope.. seems to be made up not of overlying strata.. but rather of flames, beams and streamers, as transient as those of our own aurora borealis.
- "the outer portion... is chiefly due to the ``corona''"
- "At its base... is what resembles a sheet of scarlet fire... This is the ``chromosphere'' , a name first proposed by Frankland and Lockyer in 1869... in allusion to the vivid redness of the stratum... It was called the ``sierra'' by Airy in 1842."
- "Stannyan 1709... the emersion of the sun was preceded by a blood-red streak of light.. for six or seven seconds" ("flash")
- Young's (1871 eclipse) visual observations of flash spectrum: "reversal" of Fraunhofer's lines
- 1893 first photograph (cf. corona 1860), "flash"

the Sun's chromosphere

- boring sun:
  - convection, turbulence, atmospheric waves
  - global (p-) modes
  - weak, stochastic chromosphere
  - no corona (almost)

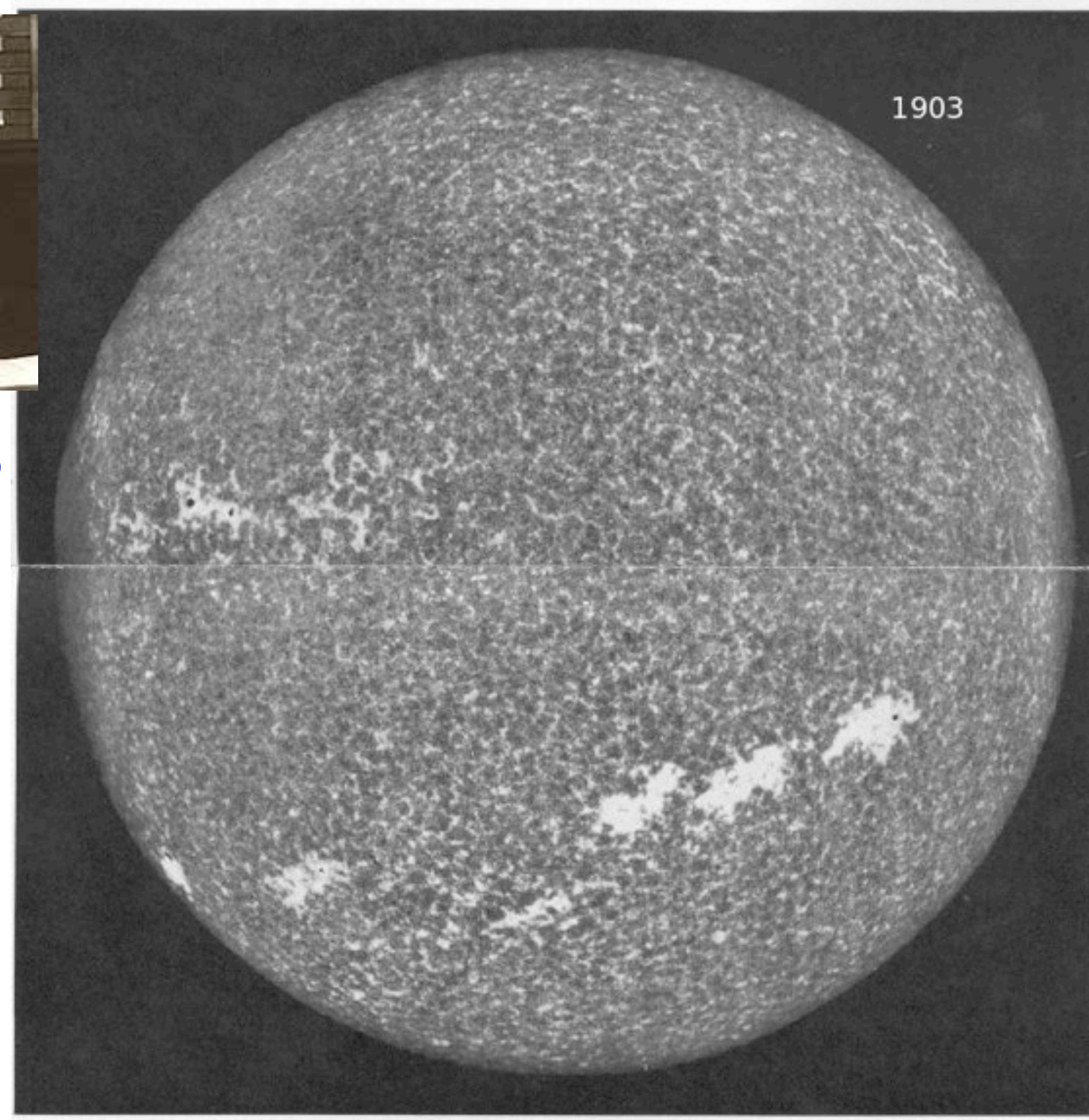


the Sun's chromosphere

Hale 1903

- boring sun:
  - convection, turbulence, atmospheric waves
  - global (p-) modes
  - weak, stochastic chromosphere
  - no corona (almost)

- interesting, magnetic Sun



THE SUN, SHOWING THE CALCIUM FLOCCULI (H, LEVEL). 1903, AUGUST 12, 8h 52m. C. S. T.
(Scale of Original Negative.)
(See p. 41.)

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

Hale 1903: Ca II H 396.8 nm

H_1 - low chromosphere

H_2 - high chromosphere

180 LINSKY AND AVRETT

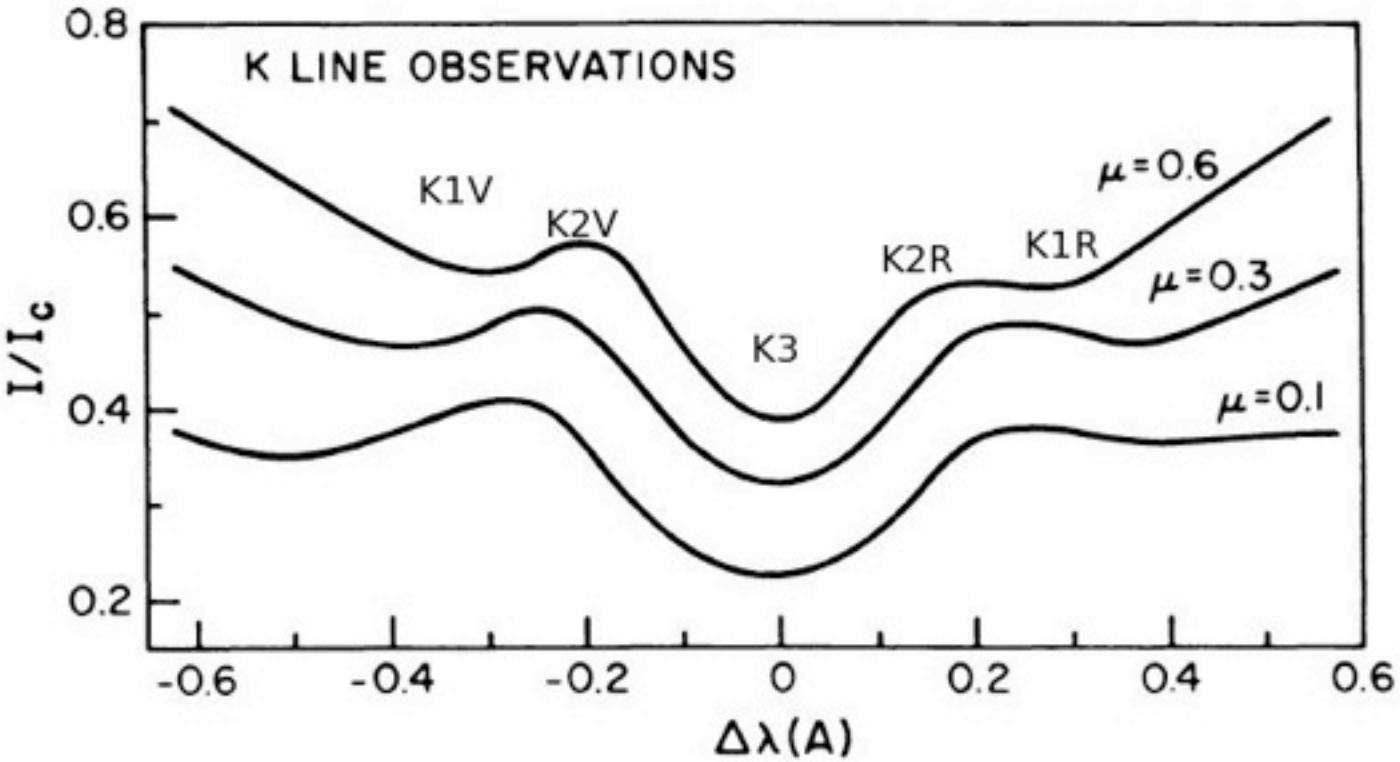


FIG. 3 — Residual intensities relative to the interpolated line center continuum at μ = 1.0 are given for the K line as observed by Zirker (1968). This figure emphasizes the appreciable limb darkening at all wavelengths and the broadening of all features in the line towards the limb.

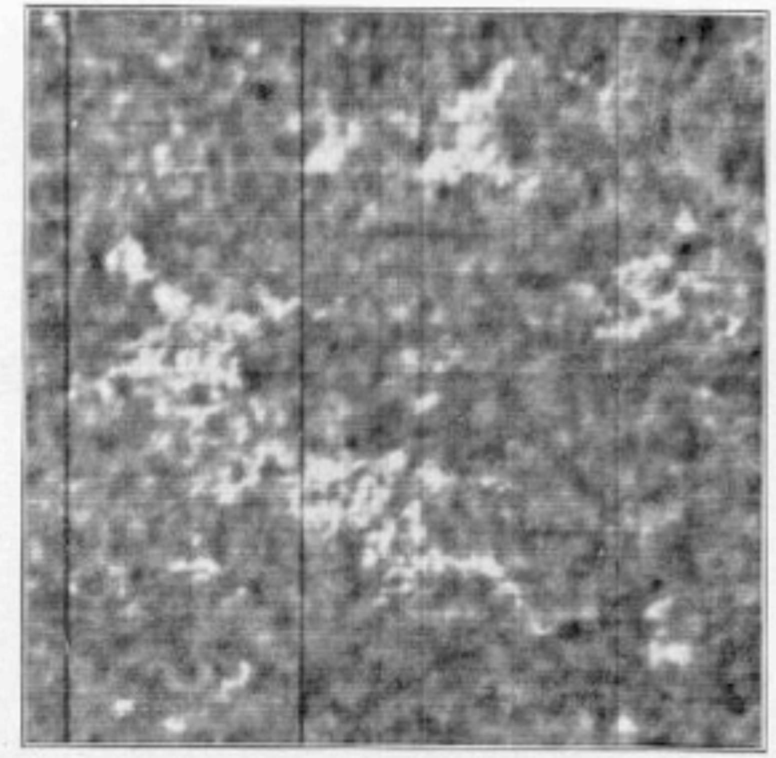


FIG. 1.—3^h 40^m. Low H_1 Level. Slit at λ3962.

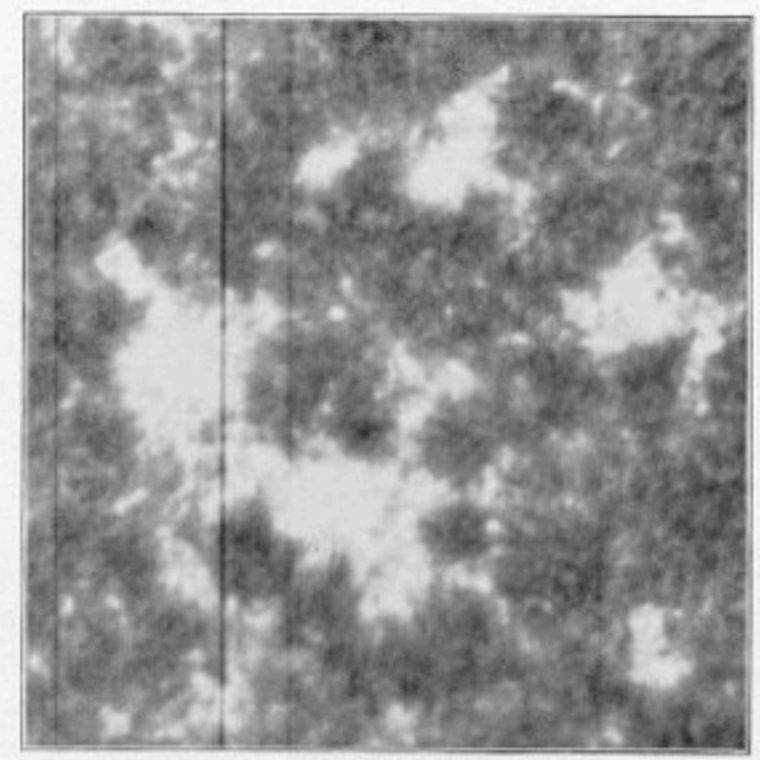


FIG. 2.—3^h 31^m. H_2 Level. Slit at λ3968.6. Same Region as Fig. 1.

MINUTE STRUCTURE OF THE CALCIUM FLOCCULI,
1903, SEPTEMBER 22.
(Scale: Sun's Diameter = 0.890 Meter.)

Leighton & colleagues ca. 1959

- Network cell, boundary ⇔ supergranular flow
- Boundary has magnetic concentrations
- Ca II emission ⇔ boundaries ⇔magnetic concentrations

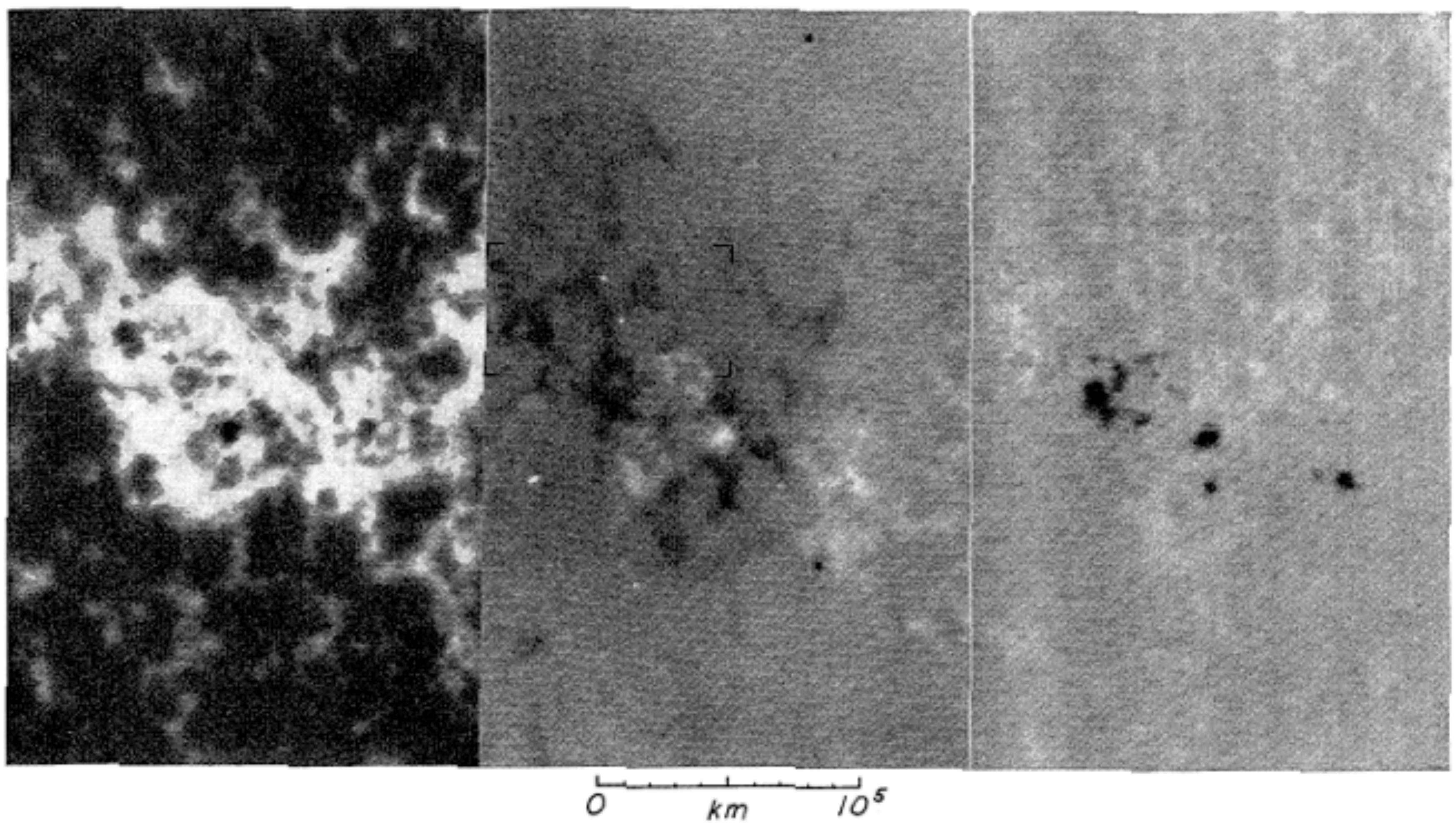


FIG. 7c.—Magnetic fields and Ca II emission around a spot group near the north meridian of the sun on September 16, 1958

A brief guide to spectrum formation

Essential radiative transfer

- Photons interact only with atoms, ions, electrons (low E)
  - absorption and emission coefficients α_ν, j_ν
- transport equation (I=distribution function for photons):

$$\mathrm{d}I_\nu(s) = I_\nu(s+\mathrm{d}s) - I_\nu(s) = j_\nu(s)\,\mathrm{d}s - \alpha_\nu(s) I_\nu(s)\,\mathrm{d}s$$

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}s} = j_\nu - \alpha_\nu I_\nu$$

$$\frac{\mathrm{d}I_\nu}{\alpha_\nu\,\mathrm{d}s} = S_\nu - I_\nu,$$

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$$\frac{\mathrm{d}I_\nu}{\alpha_\nu\,\mathrm{d}s} = S_\nu - I_\nu,$$

Standard form (1D, **μ=cosϑ**)

$$\mu\,\frac{\mathrm{d}I_\nu}{\mathrm{d}\tau_\nu} = I_\nu - S_\nu.$$

Solutions to $$\mu\,\frac{\mathrm{d}I_\nu}{\mathrm{d}\tau_\nu} = I_\nu - S_\nu.$$

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Given *S*, $I^+_\nu(\tau_\nu = 0, \mu) = \int_0^\infty S_\nu(t_\nu)\, \mathrm{e}^{-t_\nu/\mu}\, \mathrm{d}t_\nu/\mu.$

Solutions to $\mu \frac{\mathrm{d}I_\nu}{\mathrm{d}\tau_\nu} = I_\nu - S_\nu.$

Given *S*, $I_\nu^+(\tau_\nu = 0, \mu) = \int_0^\infty S_\nu(t_\nu)\, \mathrm{e}^{-t_\nu/\mu}\, \mathrm{d}t_\nu/\mu.$

Eddington-Barbier, $I_\nu^+(\tau_\nu = 0, \mu) \approx S_\nu(\tau_\nu = \mu)$

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LTE (high densities and/or optical depths): $S_\nu = \frac{2h\nu^3}{c^2}\frac{1}{\mathrm{e}^{h\nu/kT}-1} \equiv B_\nu(T).$

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non LTE (chromosphere) $S_\nu = (1 - \varepsilon_\nu) J_\nu + \varepsilon_\nu B_\nu$

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Lambda operator (integral) $$J_\nu(\tau_\nu) \;=\; \mathbf{\Lambda}_\nu[S_\nu]$$

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Lambda operator (integral) $$J_\nu(\tau_\nu) = \mathbf{\Lambda}_\nu[S_\nu]$$

non LTE: coupled integro-differential equation

One more ingredient: absorption and emission coefficients α_ν, j_ν

Continua
(b-f, f-f)

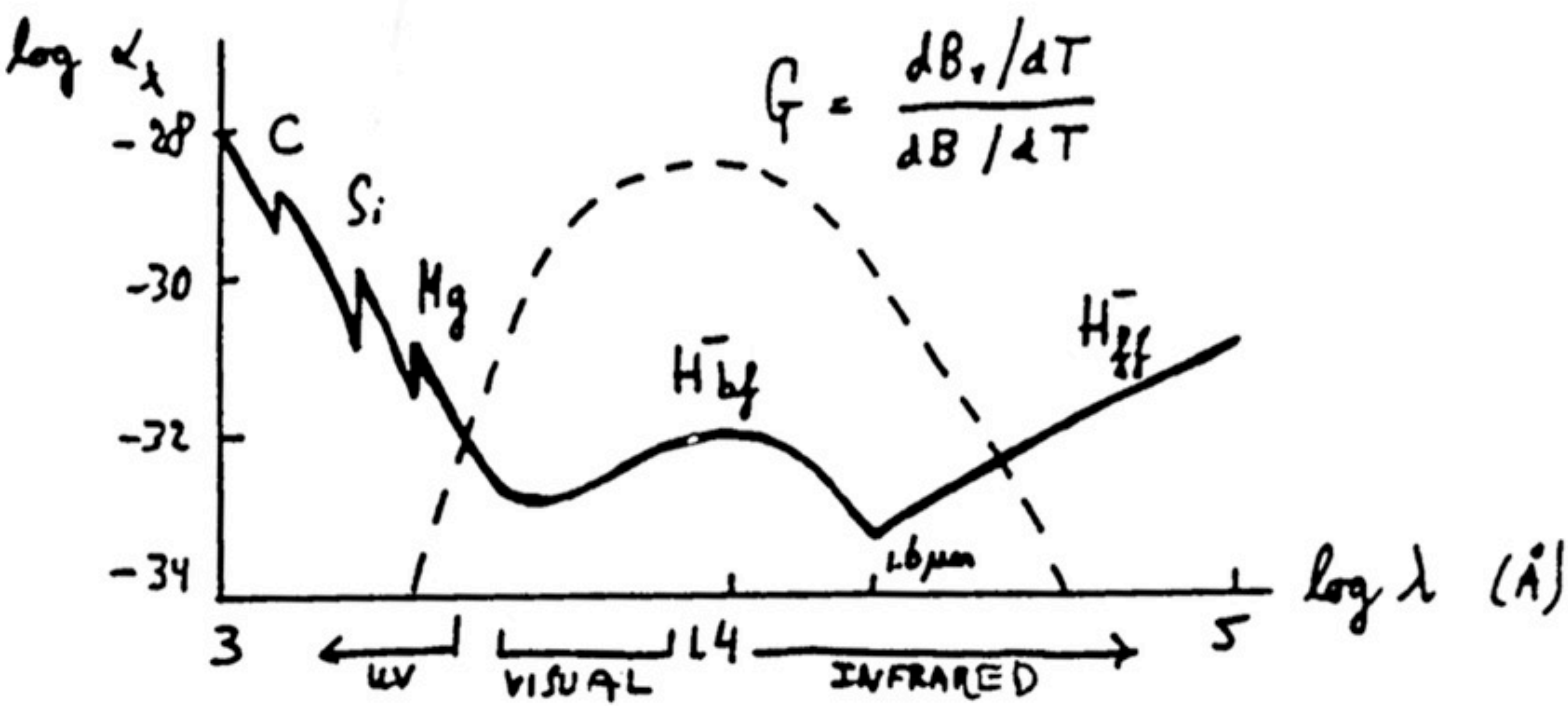
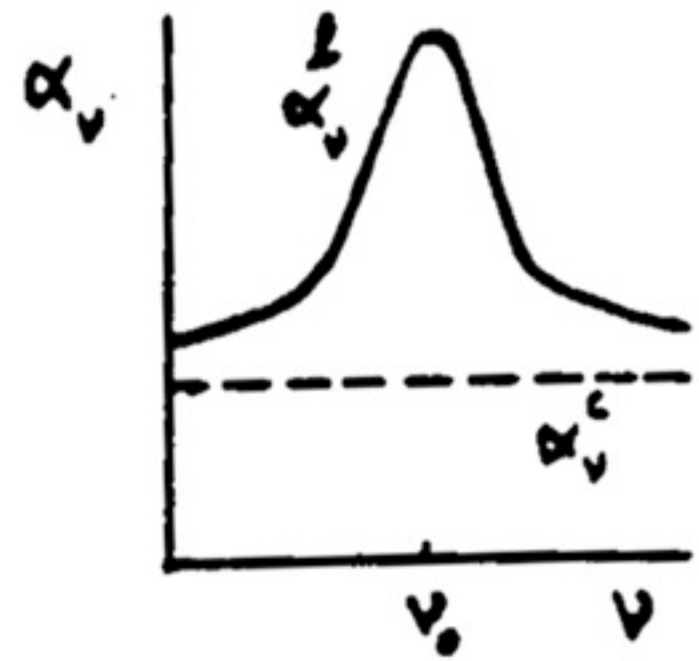
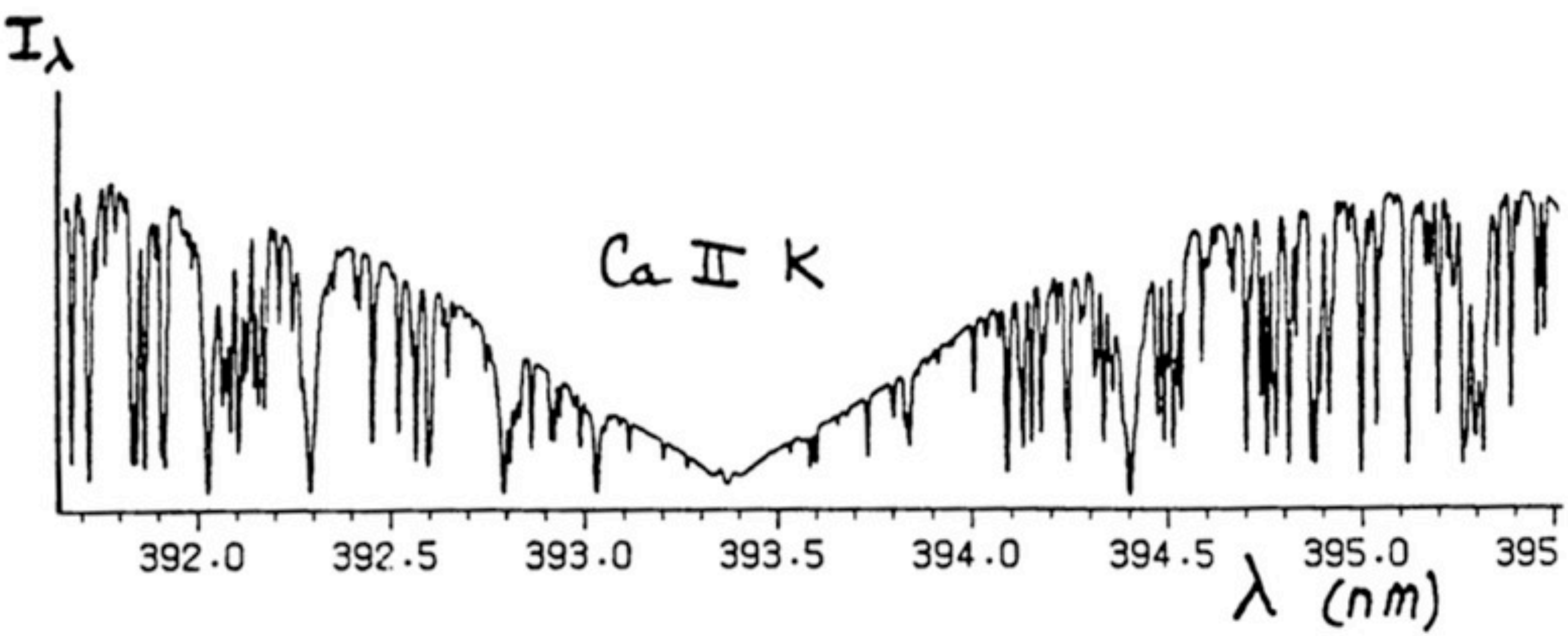


Figure 8.1: *The continuous extinction coefficient in the photosphere of the Sun.*

One more ingredient:
absorption and emission coefficients α_ν, j_ν

Lines and
elastic scattering
(Rayleigh)





The optically thin case

Transition region and corona

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}s} = j_\nu - \alpha_\nu I_\nu$$

"Thin" means α_ν ds << 1, then with $I(s=\infty) = I_0$,

The optically thin case

Transition region and corona $$\frac{\mathrm{d}I_\nu}{\mathrm{d}s} = j_\nu - \alpha_\nu I_\nu$$

"Thin" means α_ν d*s* << 1, then with $I(s=\infty) = I_0$,

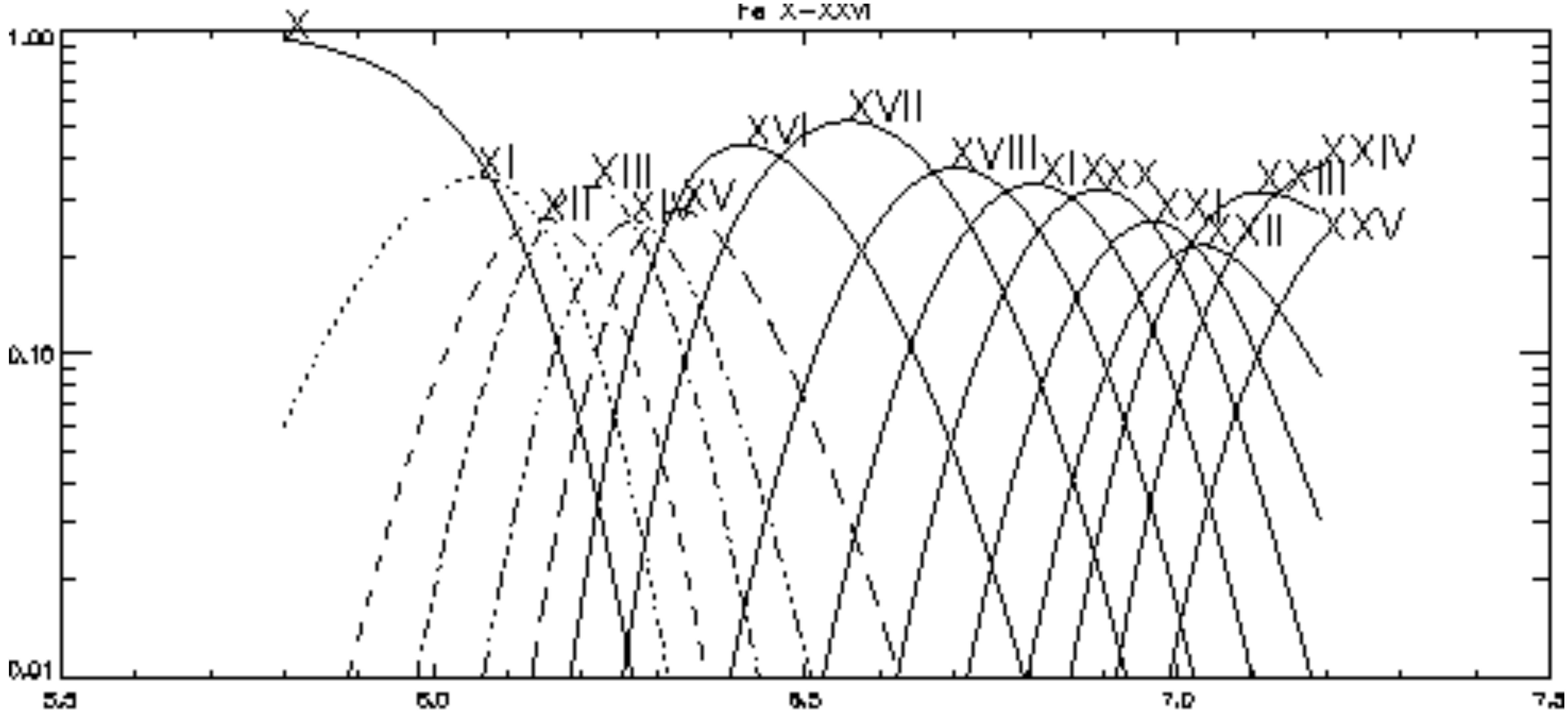
$$I_\nu(0) - I_0 = \int_\infty^0 j_\nu ds$$

$$j_\nu ds \propto N_e^2 G(T) \frac{ds}{dT} dT$$

$$I_\nu(0) - I_0 = \int_0^\infty \left[N_e^2 \frac{ds}{dT} \right] G(T) dT = \int_0^\infty \xi(T) G(T) dT$$

$\xi(T)$: "emission measure"

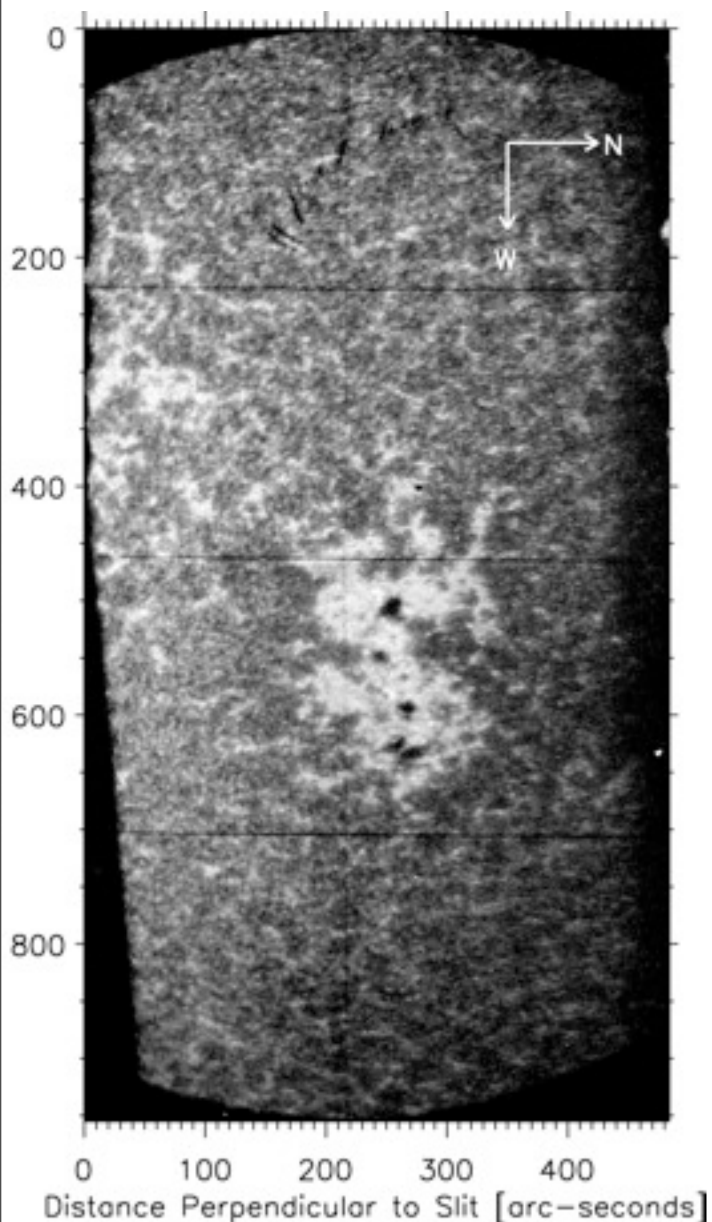
Low density, optically thin case



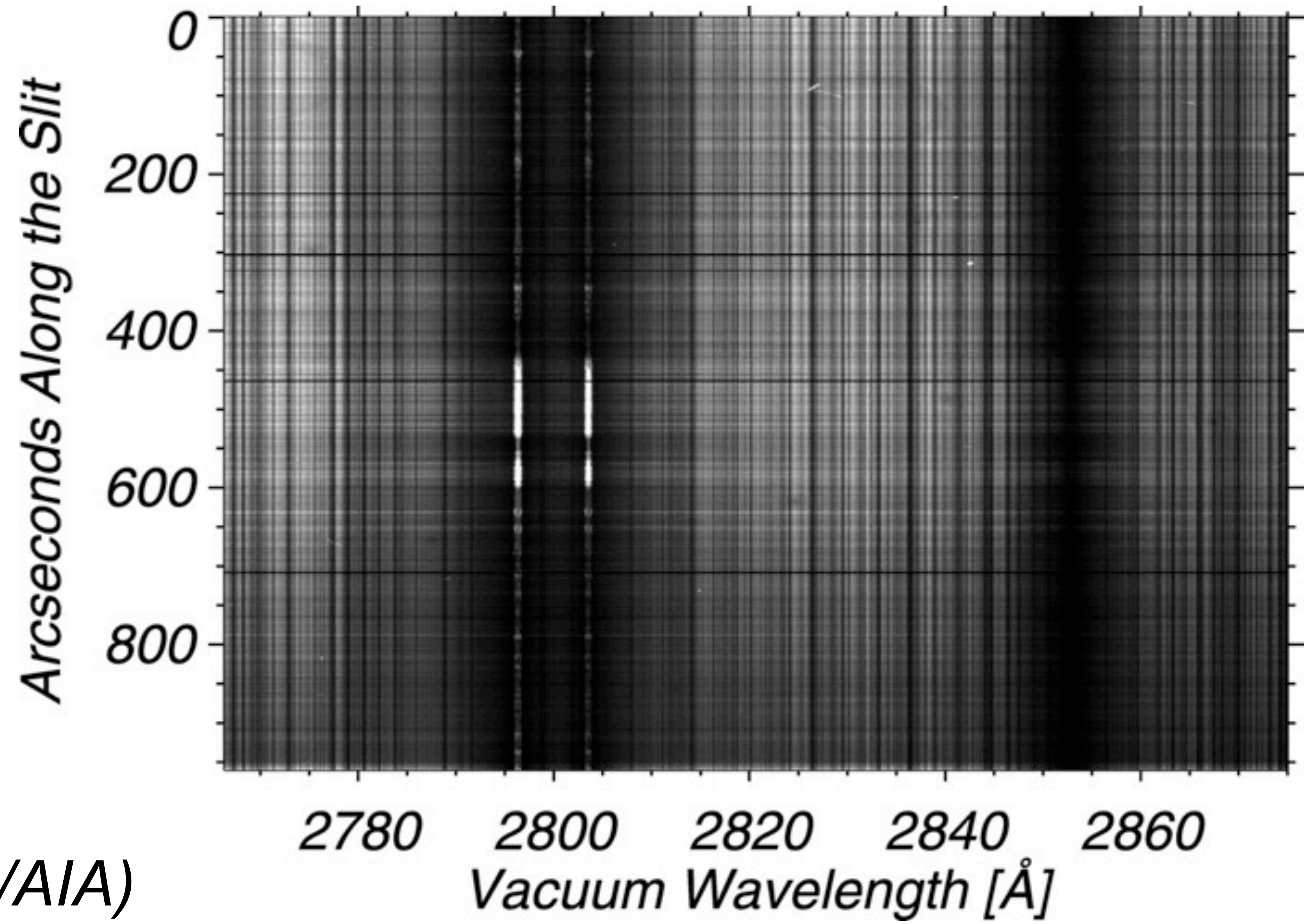
SDO/IRIS: ions with 2 or more electrons removed
are best considered as a function of electron temperature

2-body collisions: no detailed balance, no Saha equlibrium

Examples relevant to the IRIS mission

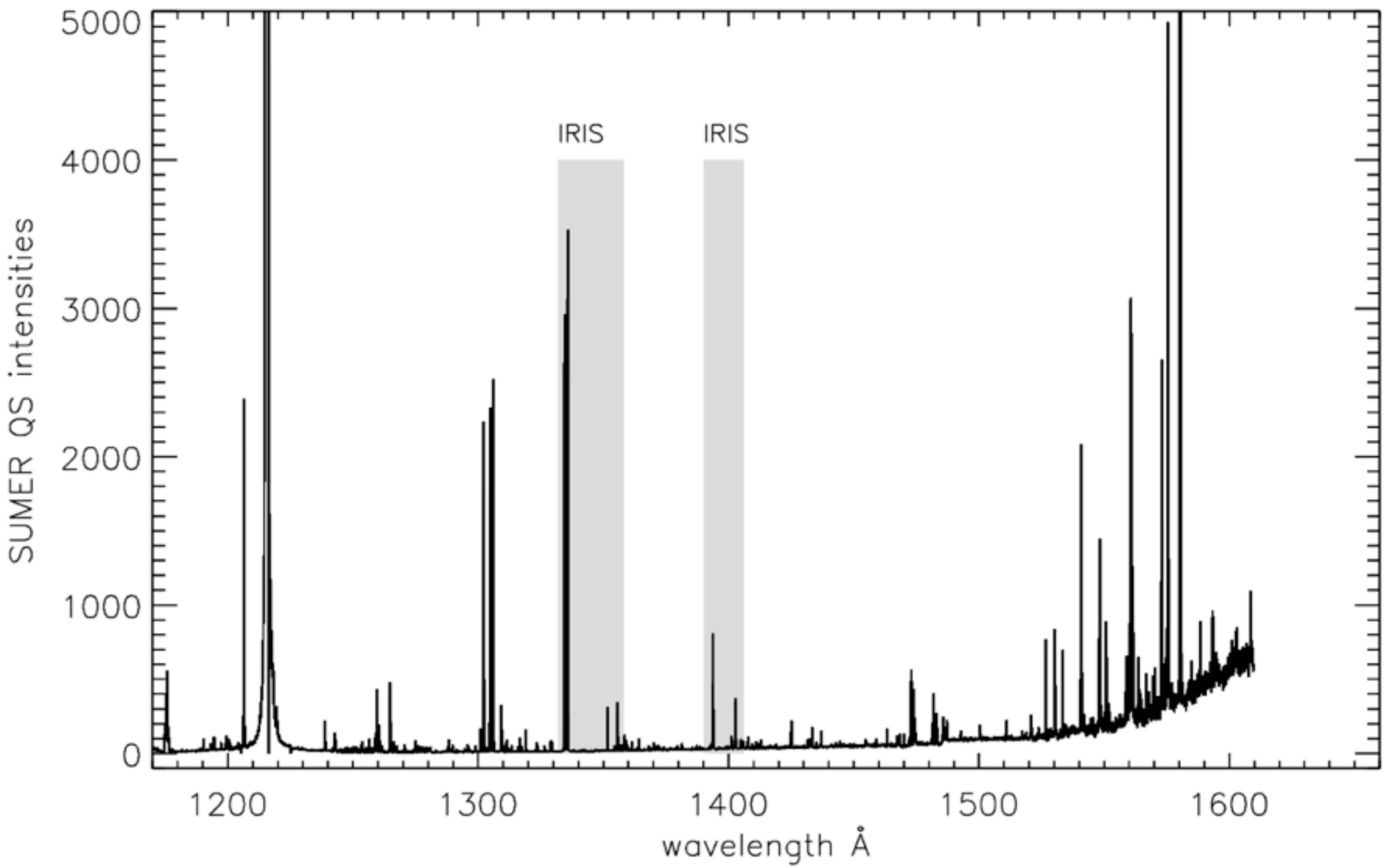


160 nm (like SDO/AIA)



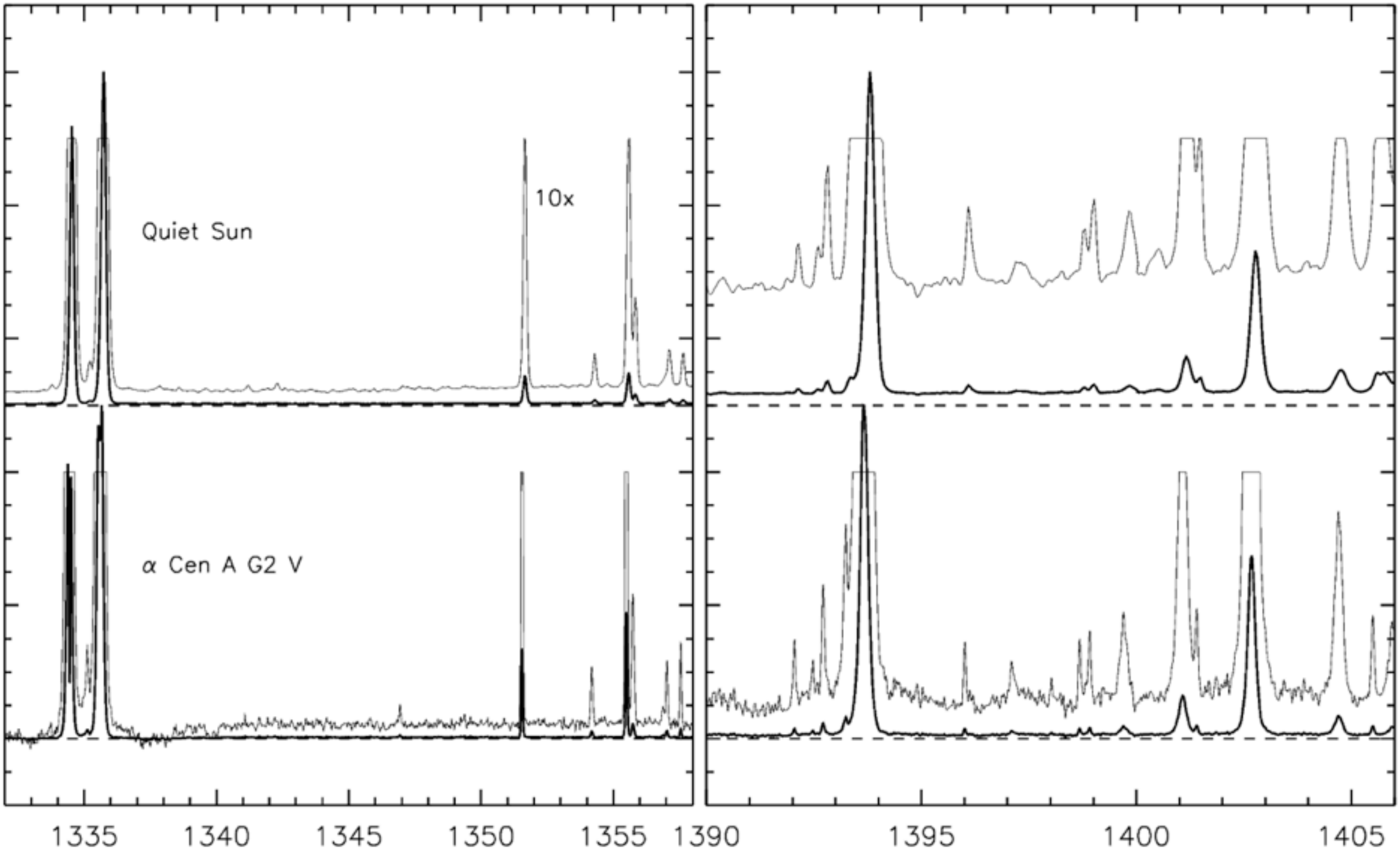
HRTS-9 1995 April 18. *High-Resolution Center-to-Limb Variation of the Quiet Solar Spectrum near Mg II*, J. S. Morrill and C. M. Korendyke, ApJ **687** (2008) 646

Examples relevant to the IRIS mission



Wavelength Å

Examples relevant to the IRIS mission



Thermal structure

Why must chromospheres exist?

- For *any reasonable** heating mechanism, the Sun must produce a *partially ionized stratified upper atmosphere* (subject to $\mathbf{j}\times\mathbf{B}$ forces) because of
  - $\nabla p + \rho \mathbf{g} \sim 0$,
  - (~ subsonic)
  - energy balance

*$\nabla . F_{EM}$ ~F/2000 km

F~ observed 10^7 erg/cm^2/s

HAO

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- For *any reasonable** heating mechanism, the Sun must produce a *partially ionized stratified upper atmosphere* (subject to **j**×**B** forces) because of
  - $\nabla p + \rho \mathbf{g} \sim 0$,
  - (~ subsonic)
  - energy balance

$$\epsilon = 3p/2 + \chi_H n_e$$

$$p = (n_H + n_e + ...)kT, \quad \chi_H = 13.6 \text{ V} \gg kT/e$$

$$\frac{\partial \epsilon}{\partial t} + \nabla \cdot \mathbf{v}(\epsilon + p) = \nabla \cdot F_{EM} - Q_R.$$

$$\frac{dQ_R}{dT} \sim exp(-T/T_0)$$

while $n_e/n_H < 1$ (partially ionized)

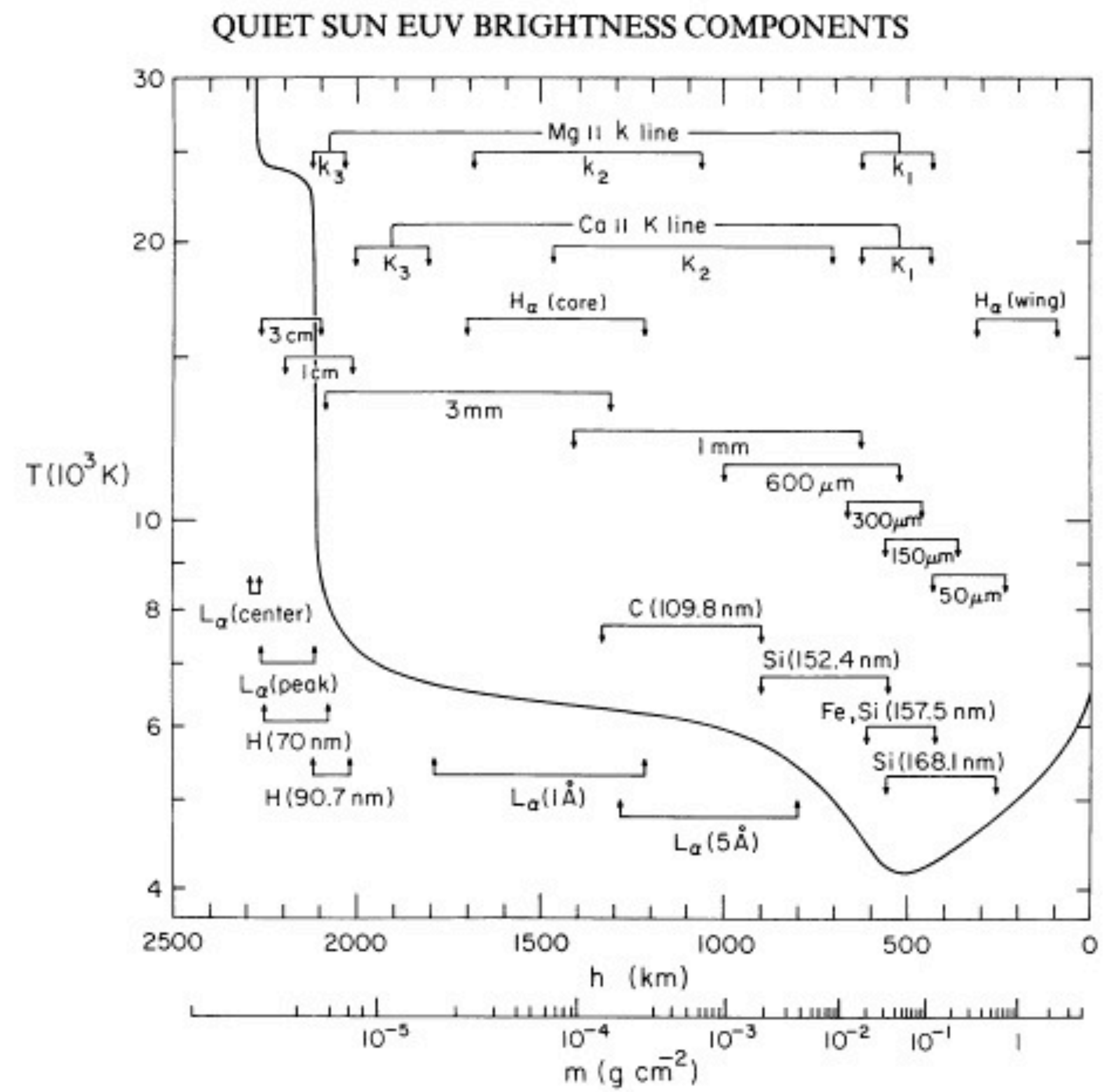
$$\frac{dn_e}{dT} \sim n_H exp(-T/T1)$$

*$\nabla . F_{EM}$ ~F/2000 km

F~ observed 10^7 erg/cm^2/s

“disk chromosphere”

- UV/EUV: HSRA, VAL, FAL,...
- hydrostatic
  - much called into question
- consider-
  - eclipse data (flash)
  - subsonic motions
  - oscillation data
  - ...
- gross stratification is sound
  - P(corona)=10^{-5} P(photosphere)
  - type I spicule models

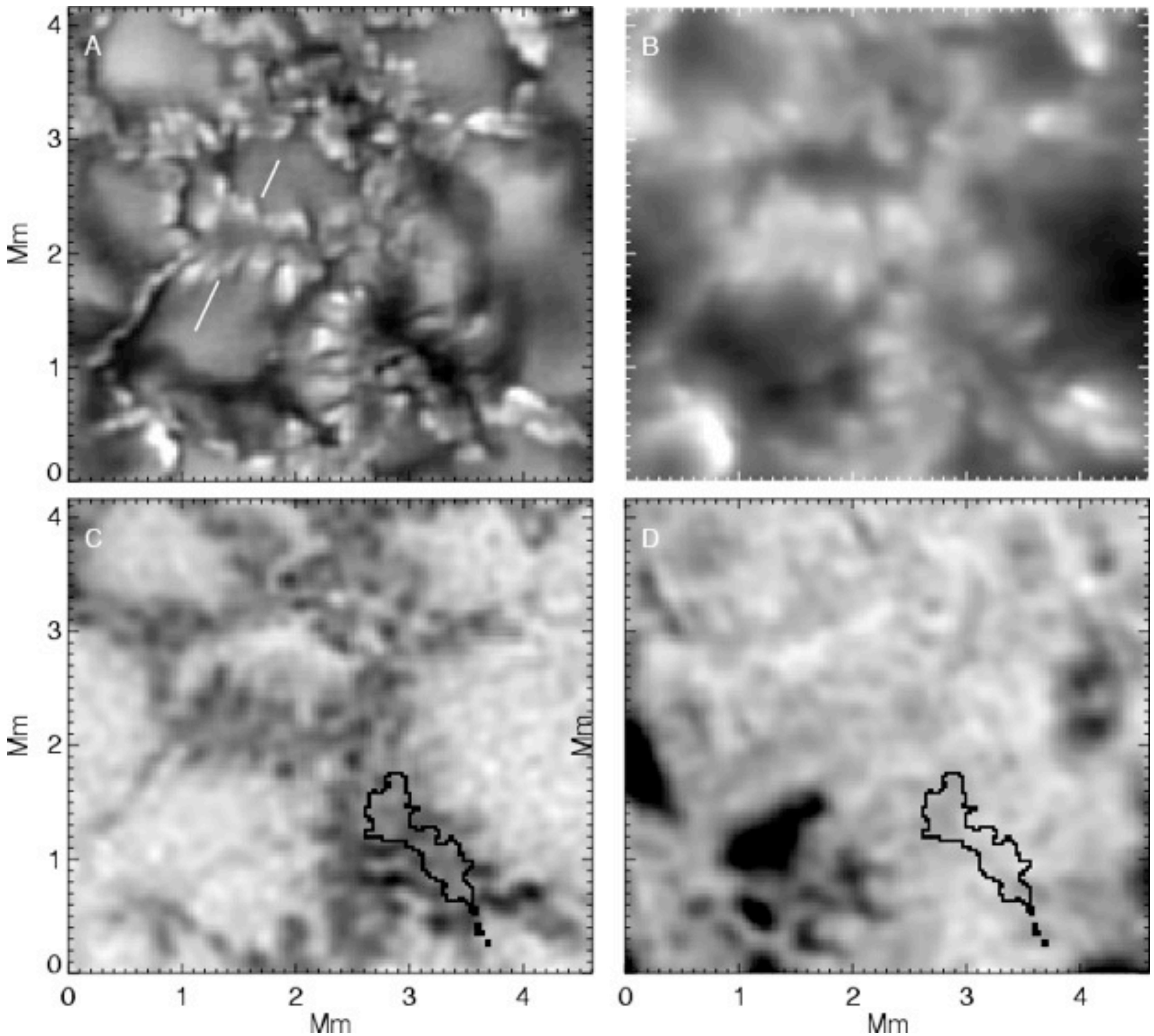


chromosphere spans 1.5-2 Mm

Magnetic structure, associated dynamics

magnetic fields at the chromospheric base
Berger et al 2004 A&A: network/plage

- SST data:
  - A. G-band
  - B. Ca II H 3Å
  - C. magnetogram
  - D. Ni I doppler



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

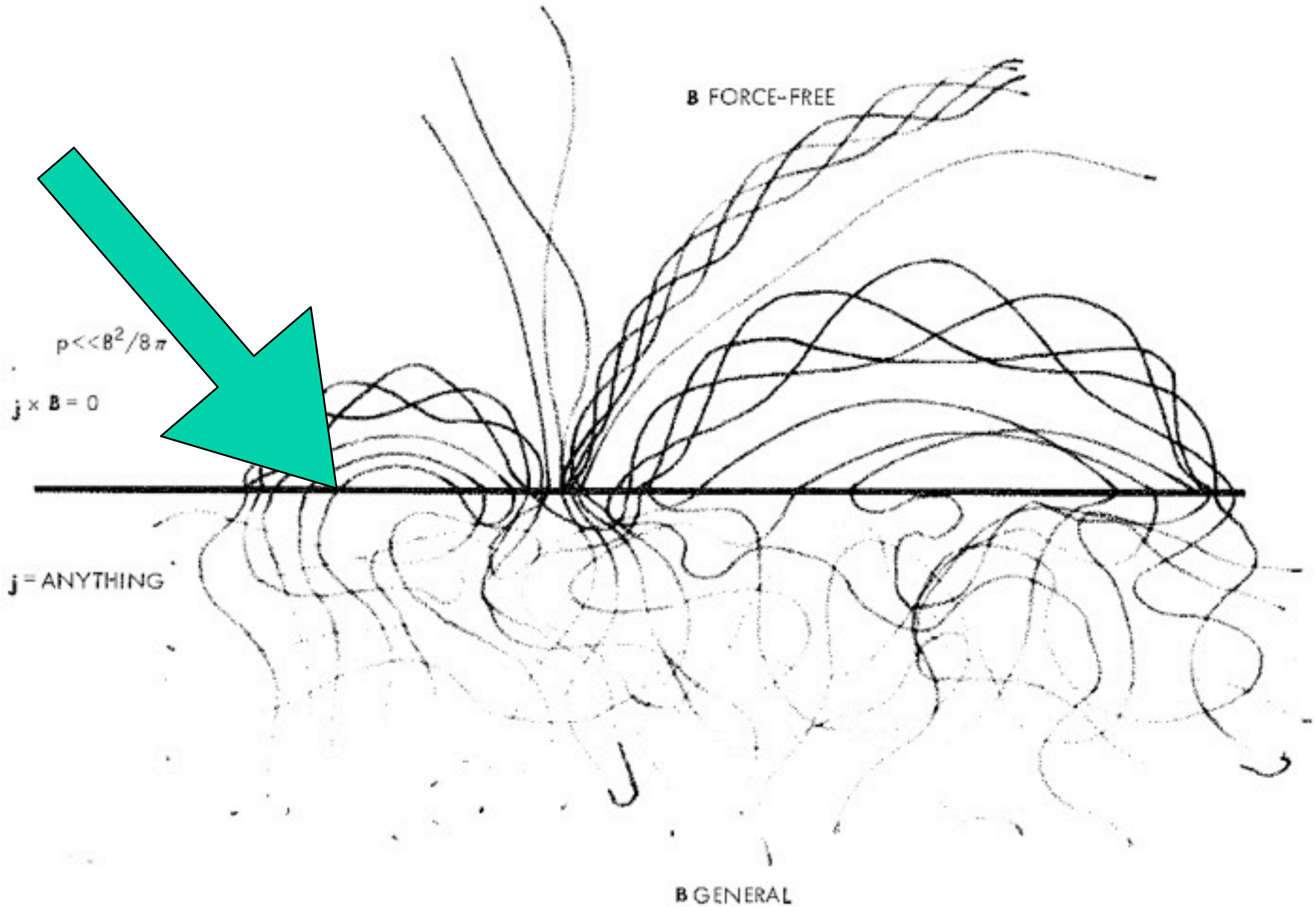
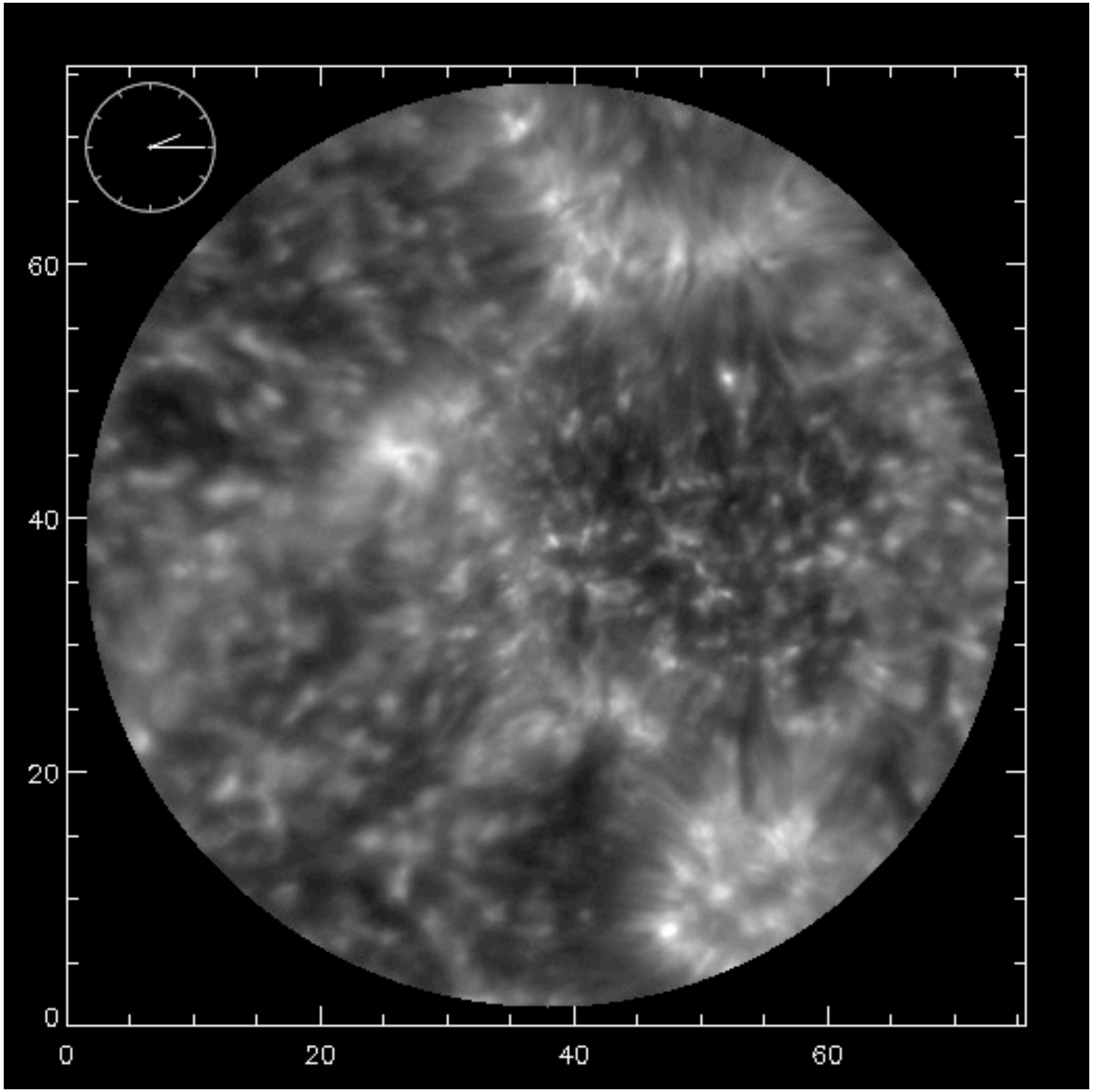


FIGURE 44–2. Magnetic field in a turbulent conducting medium. The fluid pressure is assumed large compared with magnetic forces below the dividing plane and small above it.

390

magnetism and dynamics: IBIS Ca II IR triplet QS chromosphere

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



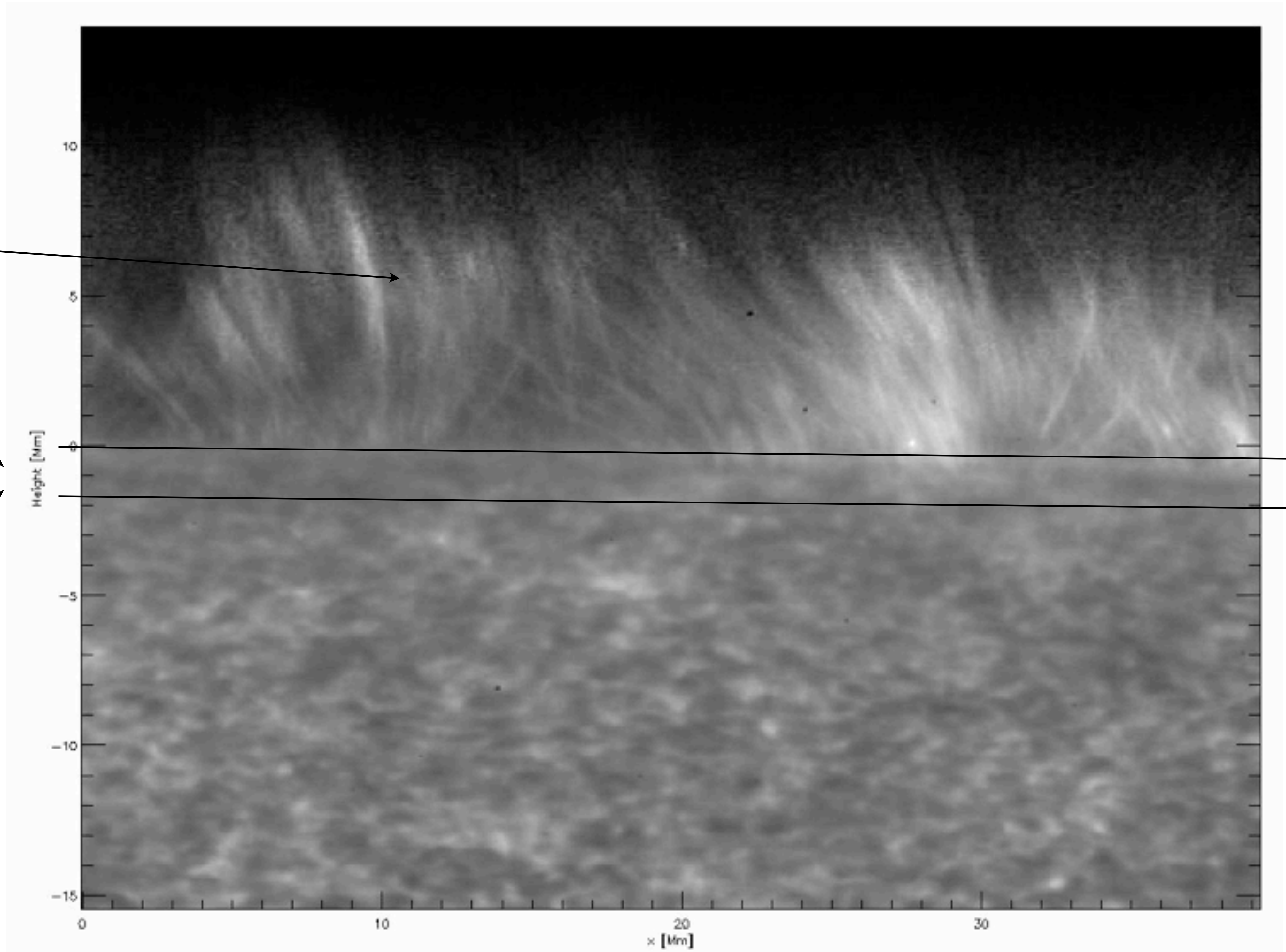
magnetism and dynamics: Spicules

- Hinode data (radial filter to enhance spicules, M. Carlsson)
- Fast dynamics (de Pontieu et al. 2007), connects to corona?

spicules *arise from within* the chromo-sphere

Lifetimes 1 min

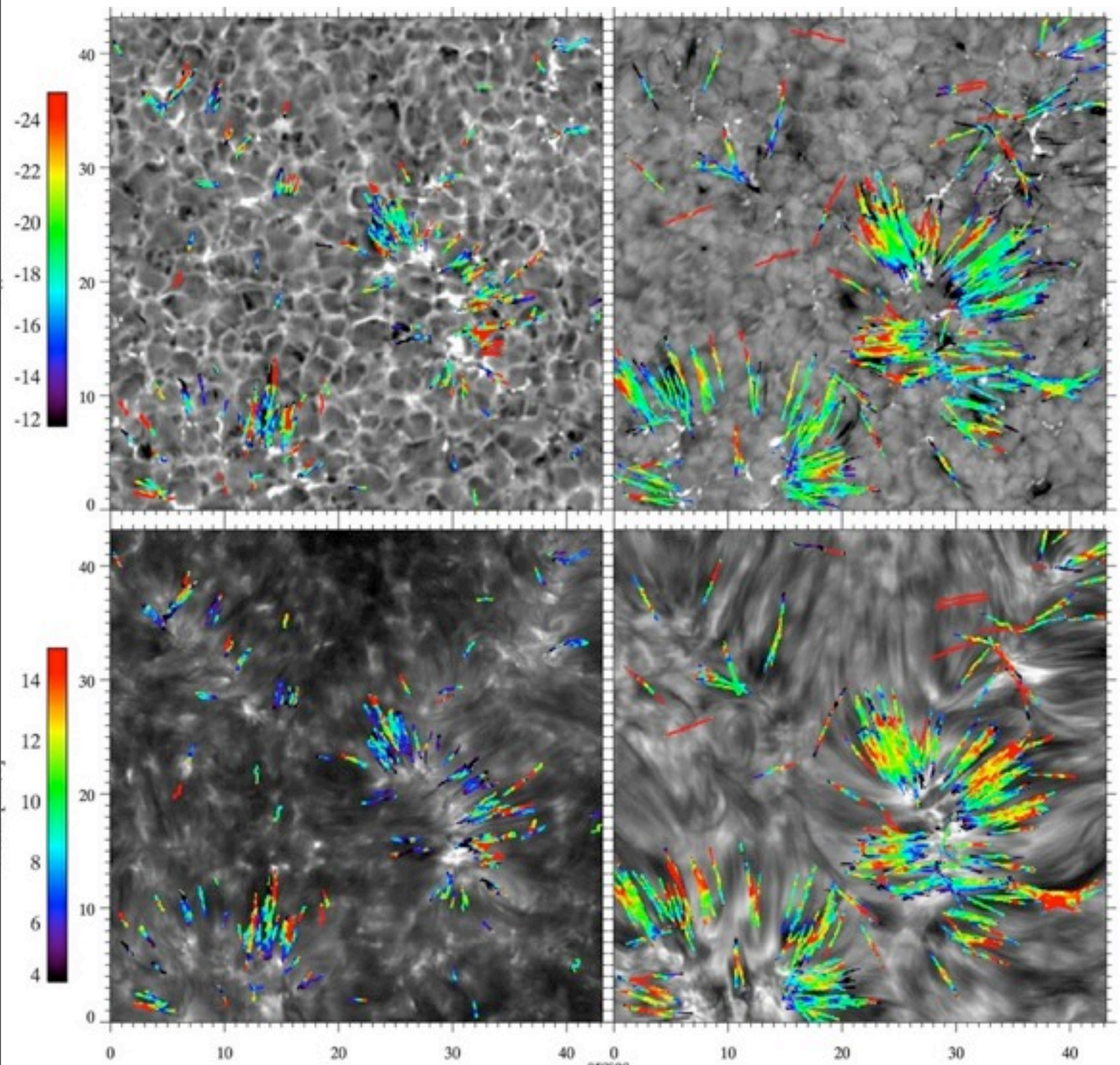
stratified VAL chromosphere 1.5Mm only

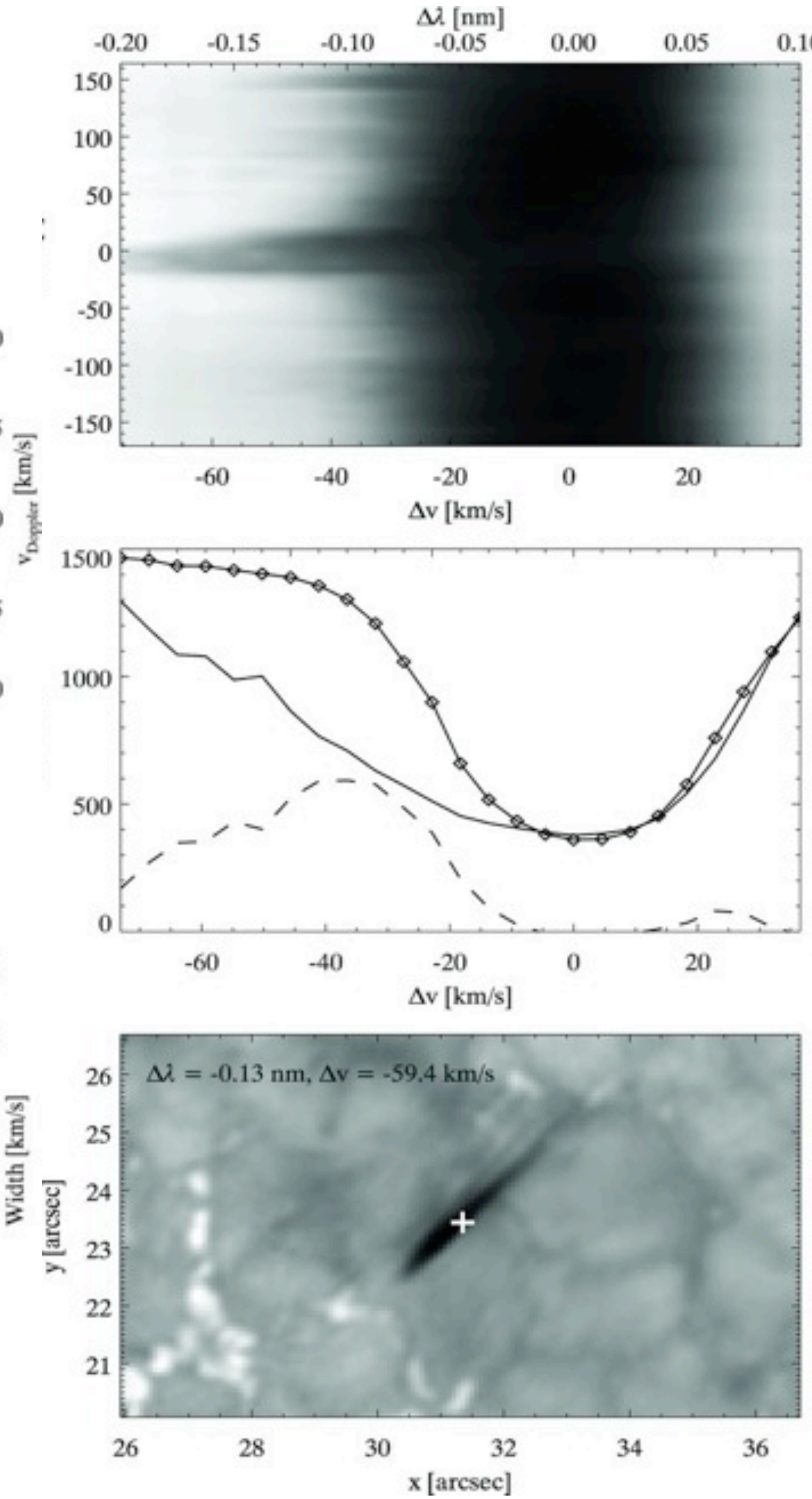


HAO

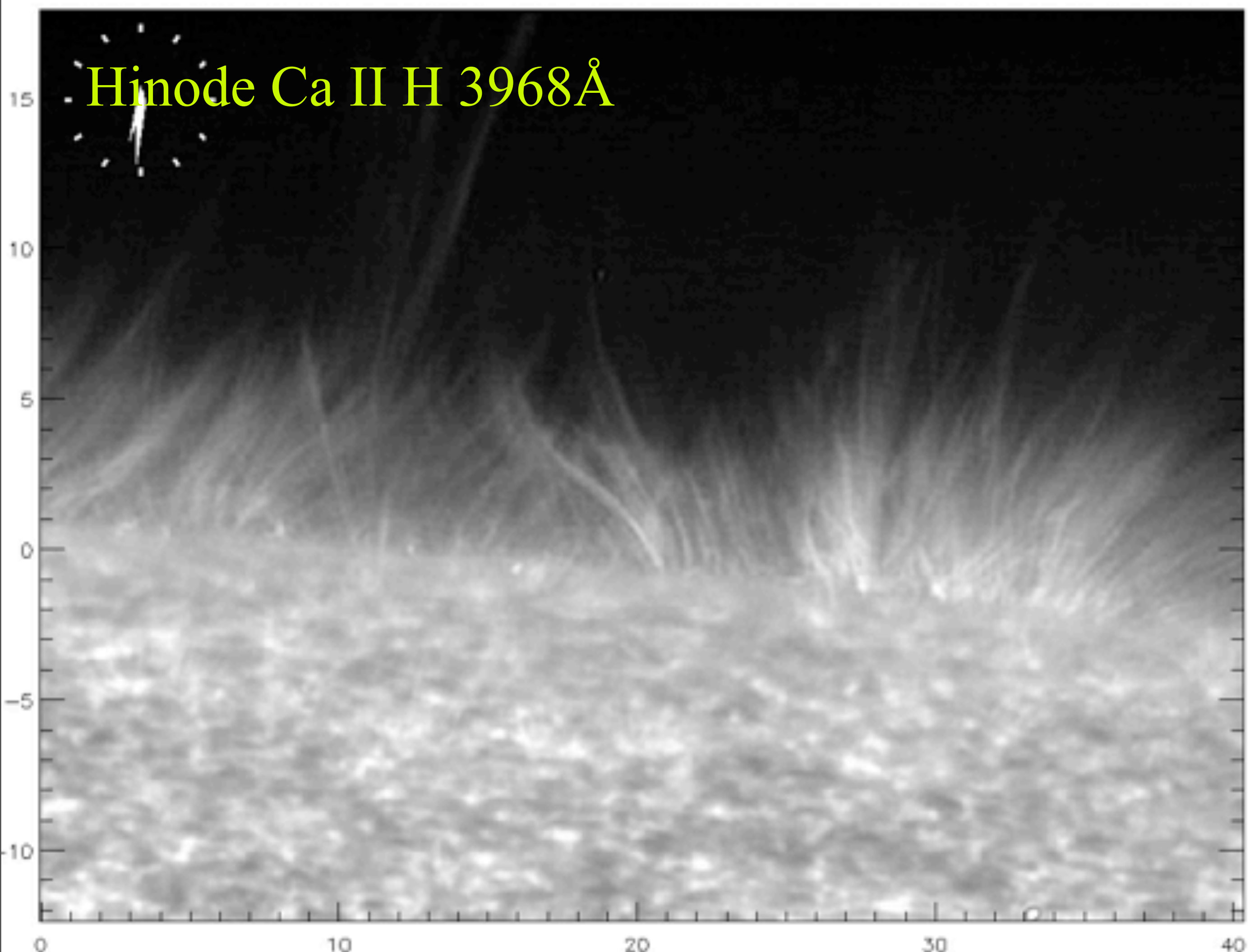
magnetism and dynamics: On disk "spicules"

- SST data Rouppe v.d Voort et al 2009

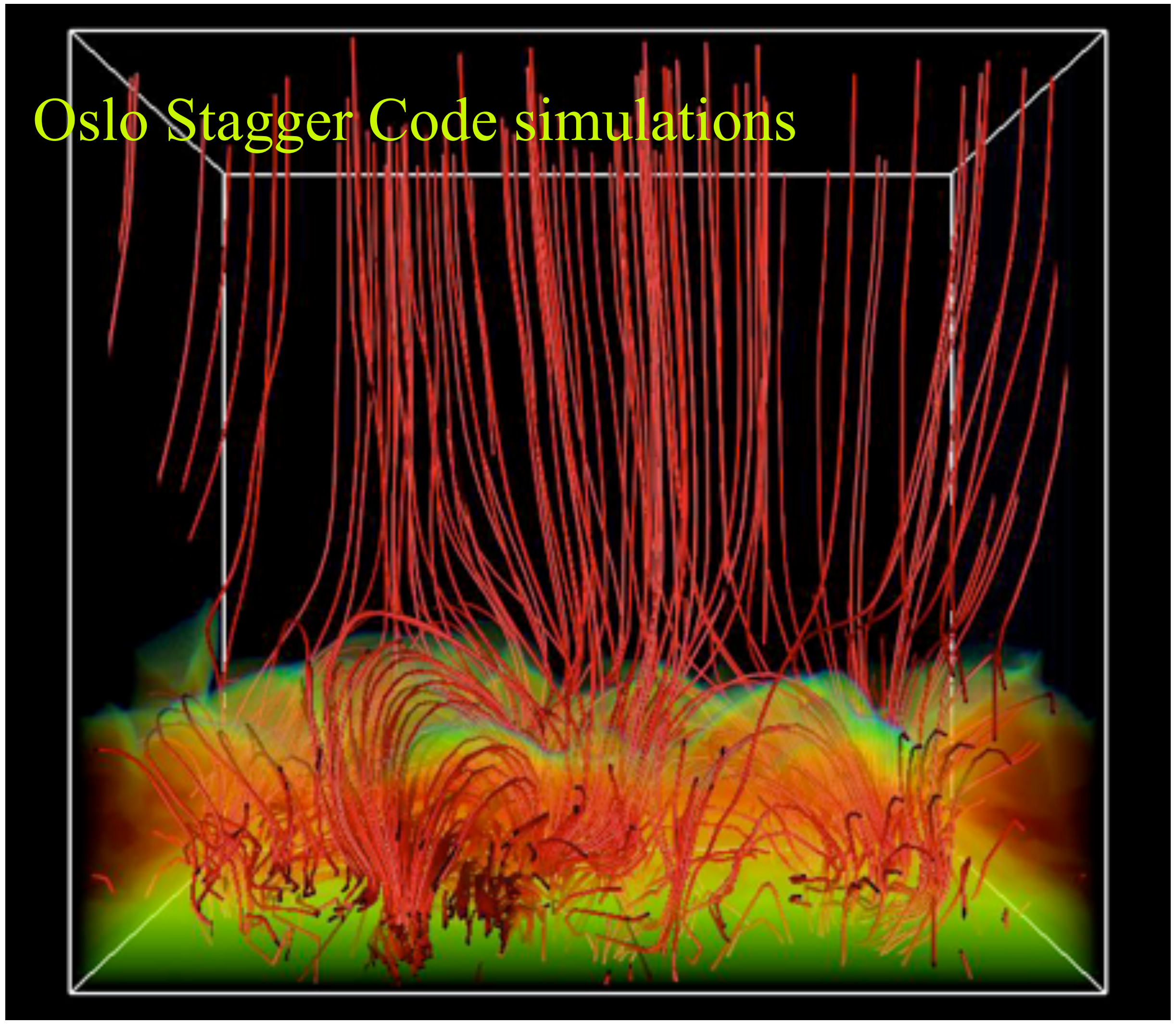




What role do Alfvenic waves play in energizing the solar atmosphere?

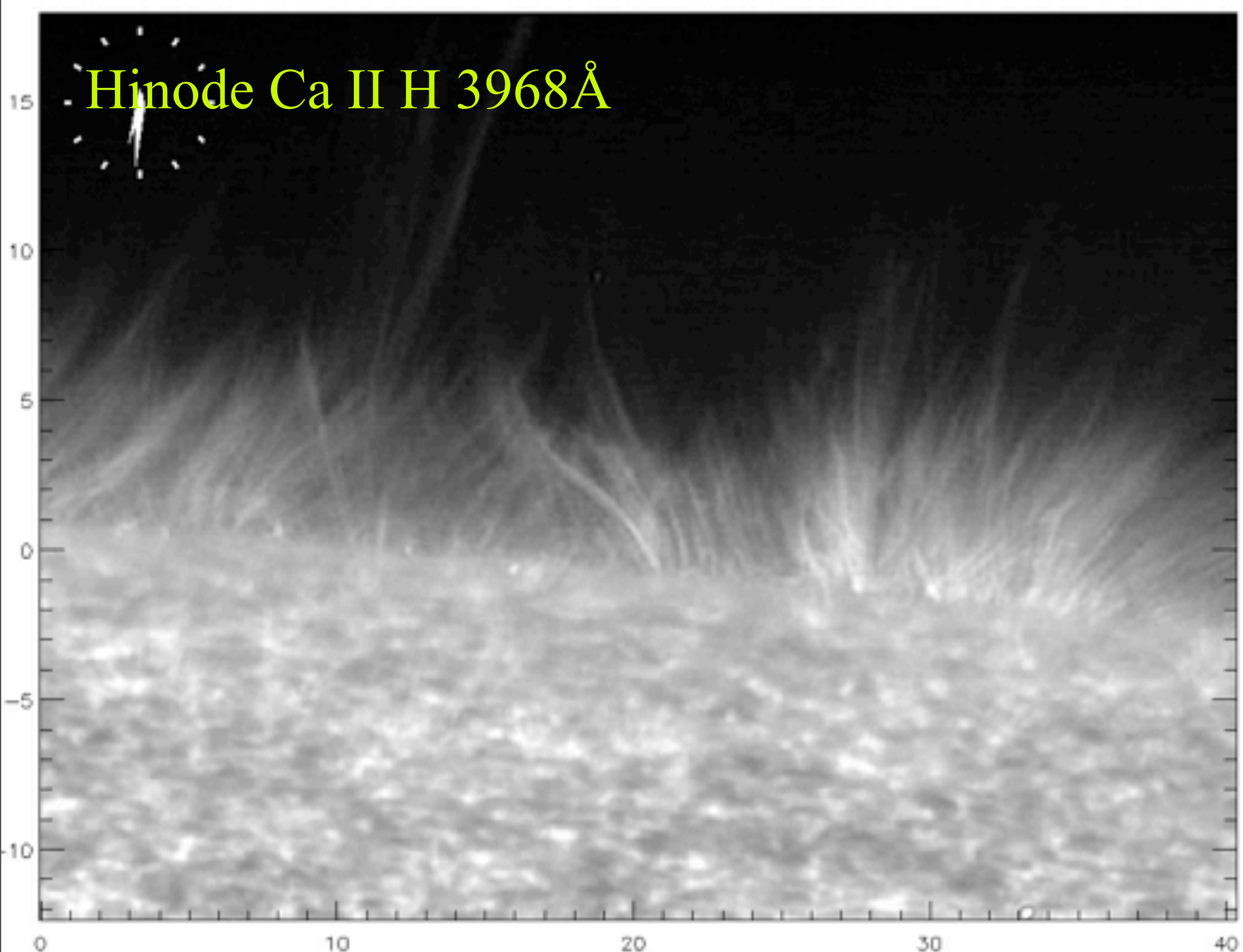


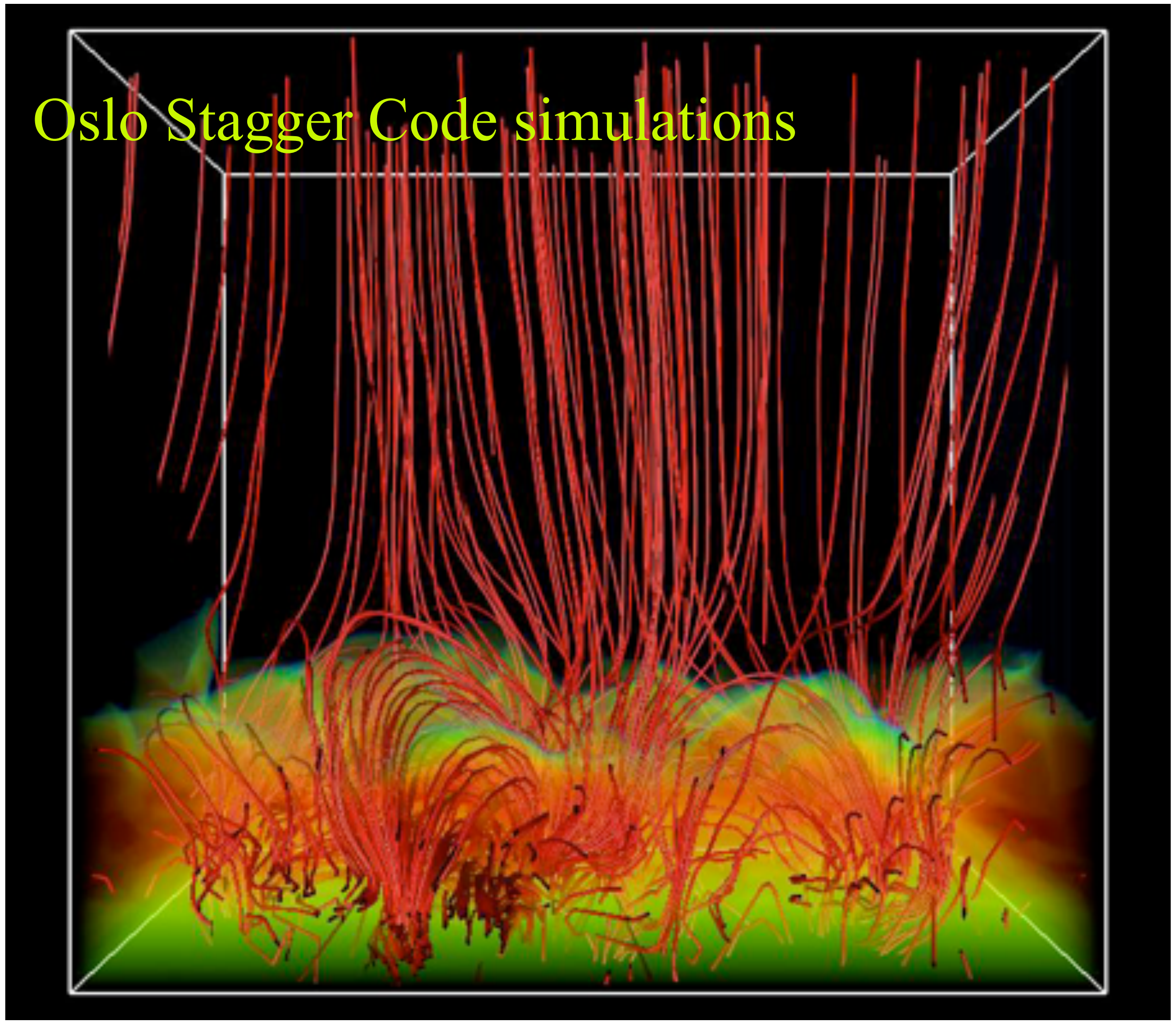
Alfvenic waves ubiquitous and strong in chromosphere/TR/corona (Hinode/SDO-AIA), but *generation, power spectrum, propagation, damping and dissipation* poorly known



3D MHD simulations show Alfvenic waves with similar properties

What role do Alfvenic waves play in energizing the solar atmosphere?





Alfvenic waves ubiquitous and strong in chromosphere/TR/corona (Hinode/SDO-AIA), but *generation, power spectrum, propagation, damping and dissipation* poorly known

3D MHD simulations show Alfvenic waves with similar properties

Thermal coverage and resolution of IRIS will provide insight in how much power is reflected/dissipated/mode-coupled throughout the interface region, and what remains for the corona- B. de Pontieu

What IRIS might see..
HRTS (Dere et al 2003)

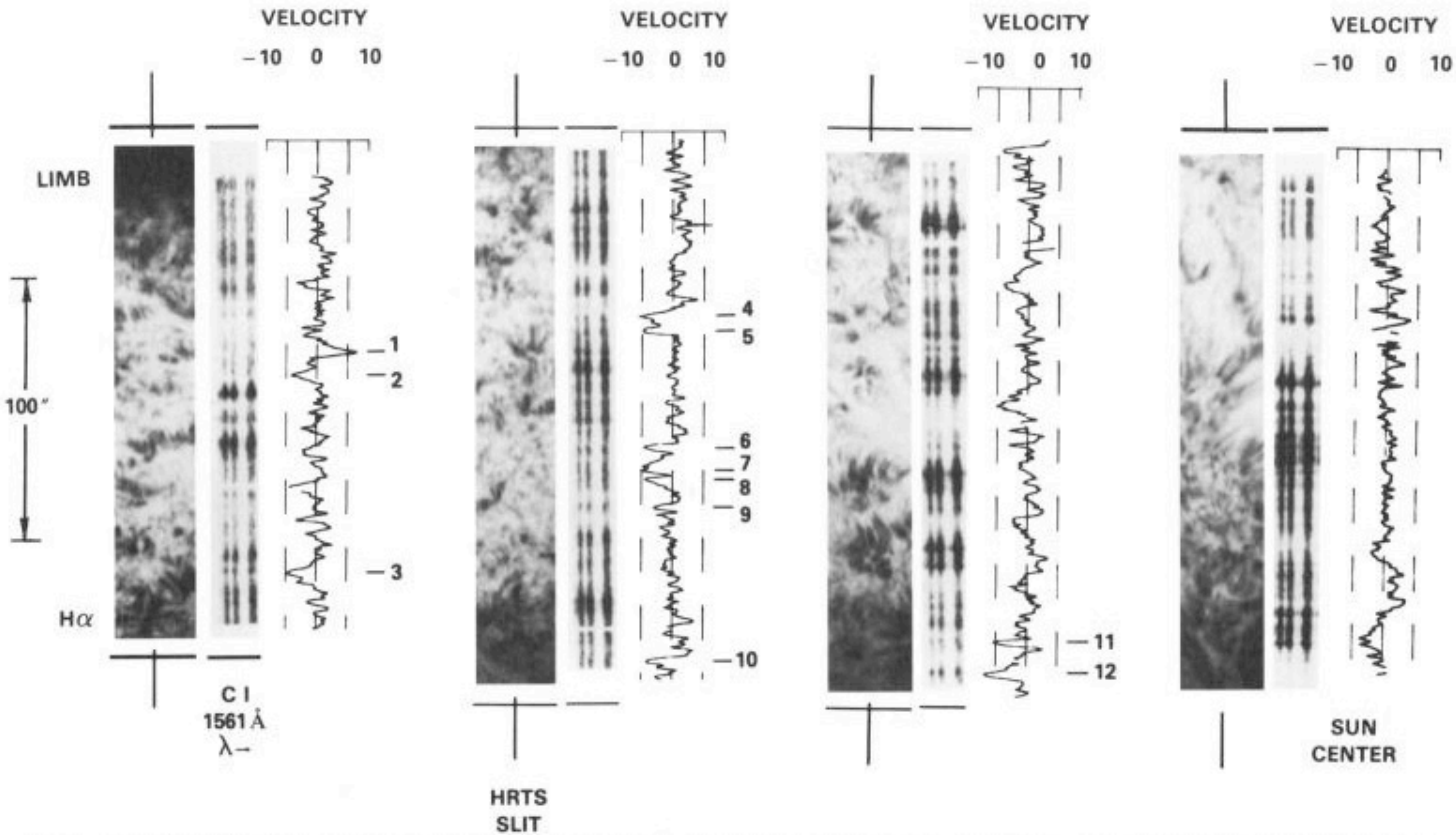


FIG. 2.—HRTS 3 profiles of C I and the near simultaneous Hα − 0.6 Å spectroheliograms obtained by the Sacramento Peak Observatory. Also shown are the net line-of-sight Doppler velocities derived from the C I λ1560.7 and λ1561.4 lines according to eq. (1). The dashed lines denoted the zero and 3 σ velocity values. The positions of chromospheric jets are marked and numbered, with tick marks to the left indicating blueshifts and tick marks to the right, redshifts.

DERE *et al.* (*see* page L65)

What IRIS might see..
HRTS (Dere et al 2003)

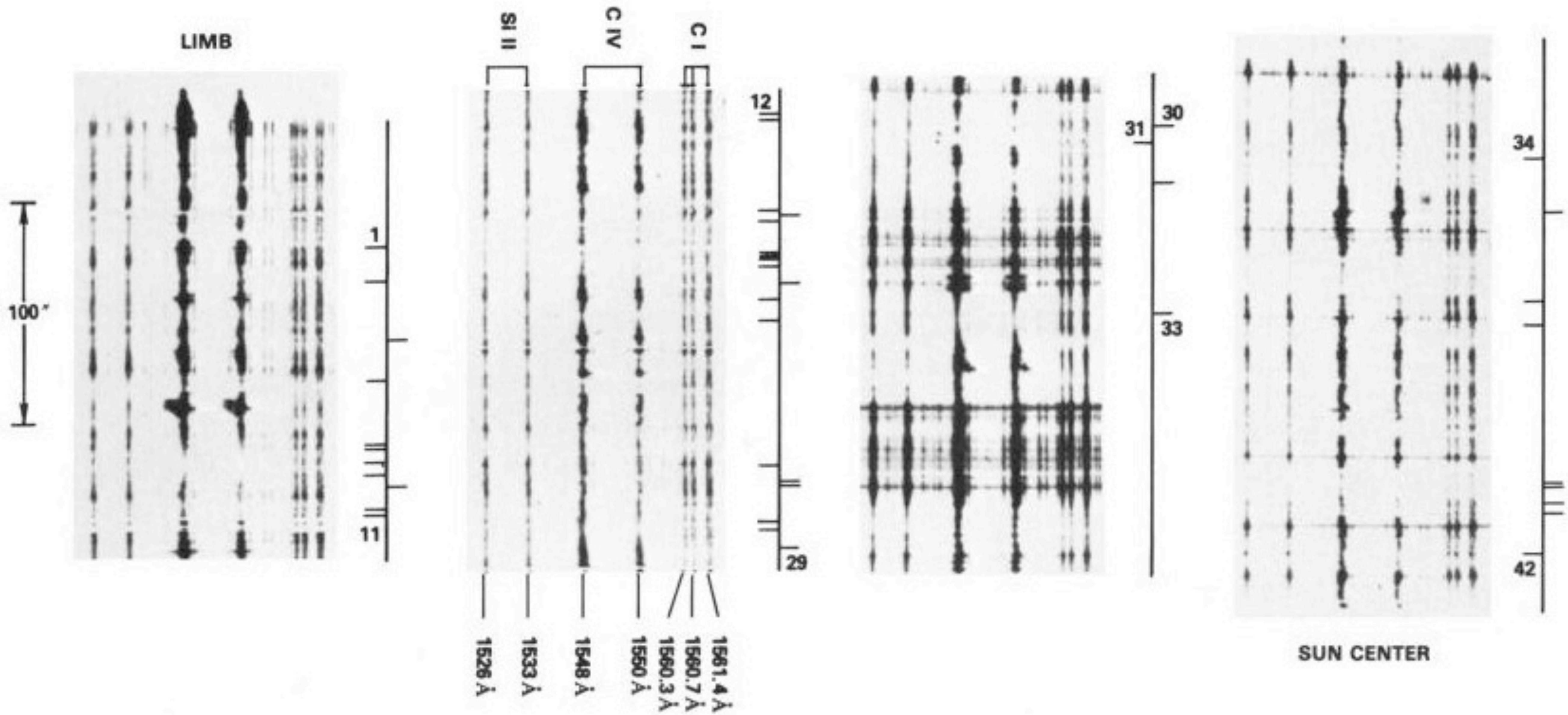


FIG. 1.—HRTS I profiles of Si II, C IV, and C I with the positions of the chromospheric jets marked and numbered, with tick marks to the left indicating blueshifts and tick marks to the right, redshifts.

DERE *et al.* (*see* page L65)

What IRIS might see..
HRTS (Dere et al 2003)

TABLE 2

A Comparison of Chromospheric Jet and Spicule Properties

Parameter	Chromospheric Jets	Visible Spicules
Velocity (km s^{-1})	$\leqslant 20$	25
Dimensions (arcsec)	1–4 (along slit)	diameter = 1, length = 10
Birthrate (cm^{-2} s^{-1}) ...	3×10^{-20}	5.5×10^{-20}
Lifetime.................	40 s	5 min.
Temperature (K)	1.6×10^4	1.7×10^4 at 4000 km
Density (cm^{-3})	1×10^{11}	1.5×10^{11} at 4000 km

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Alfvén Waves are Easy: Mode Conversion in Magnetic Regions

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Received 7th June 2011

Abstract. Alfvén waves are shown to be readily generated by mode conversion from fast MHD waves reflecting off the steep atmospheric Alfvén speed gradient in active region atmospheres. A simple analytic description of this process in terms of an 'interaction integral' indicates that it is spread over many vertical scale heights, and indeed fills the whole active region chromosphere for waves of moderate helioseismic degree ℓ, even up to $\ell = 1000$ or more. This suggests that active region chromospheres are Alfvén wave factories.

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Although the fast wave reflects (roughly at the height where $\omega = a\,k$, with a the Alfvén speed and k the horizontal wavenumber), it couples to the third MHD wave type, the Alfvén wave, provided that gravity **g**, the magnetic field **B**, and the wavevector **k** are not coplanar (Cally & Goossens 2008).

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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)
  - $Q_{fr} = \mathbf{j}.\mathbf{E} = j^2/\sigma + (\xi_n\, \mathbf{j}\times\mathbf{B} - \mathbf{G})^2/\alpha_n,$
  - "ambipolar diffusion"/star formation (1950s Schlüter, Cowling)
- $\mathbf{G} = \mathbf{0} \Rightarrow$ "Cowling conductivity" $\sigma_\perp^*$
  - $Q_{fr} = j_\parallel^2/\sigma + j_\perp^2/\sigma_\perp^*$ $\quad \sigma/\sigma_\perp^* = 1 + 2\,\xi_n\, \omega_e\tau_e\, \omega_i\tau_i, \quad >>1$
  - $\Rightarrow$ *rapid dissipation of* $\mathbf{j}_\perp$
  - Goodman & colleagues: wave heating
  - Arber & colleagues: flux emergence

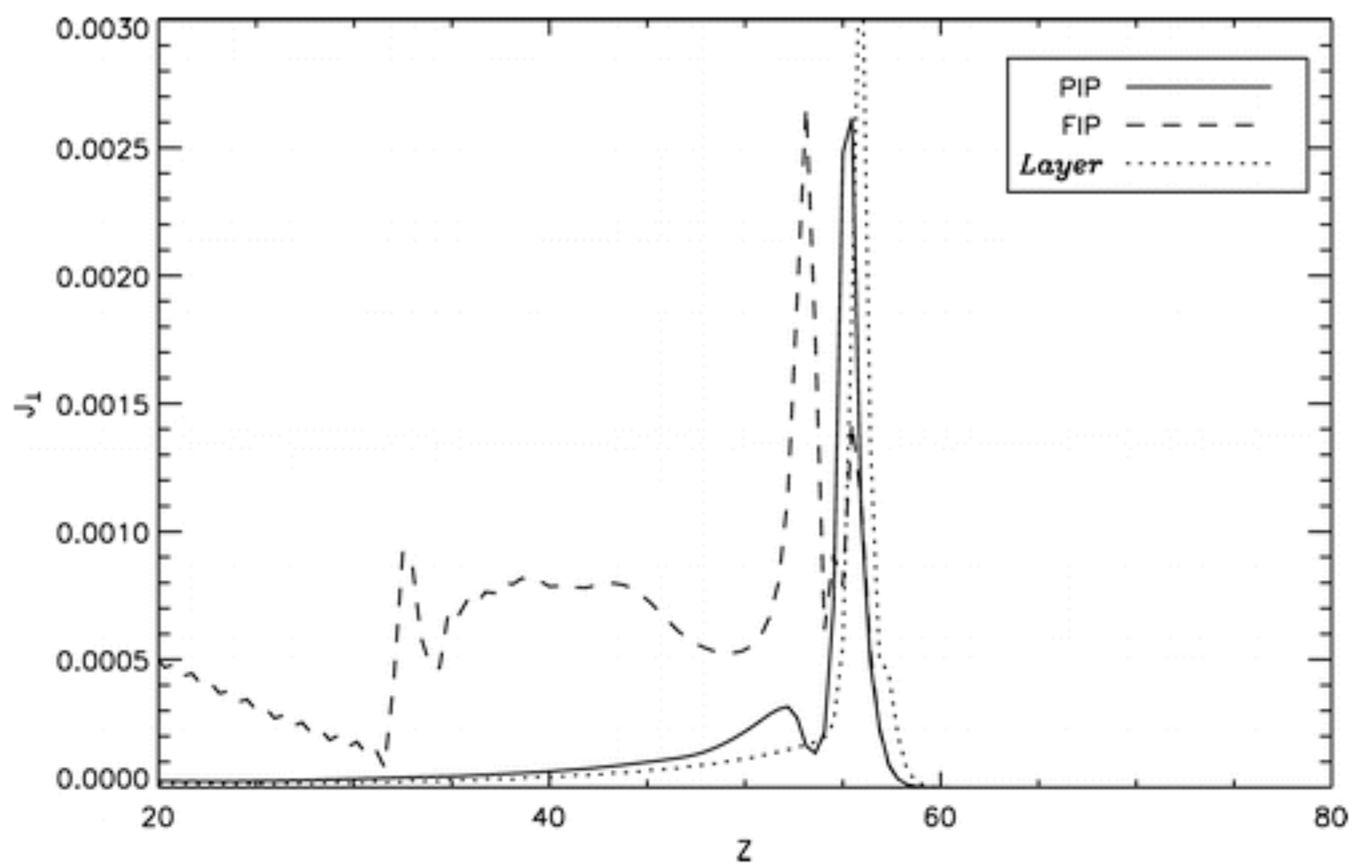
$\mathbf{G} = \xi_n \nabla p - \nabla p_n$

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 $t = 160$.



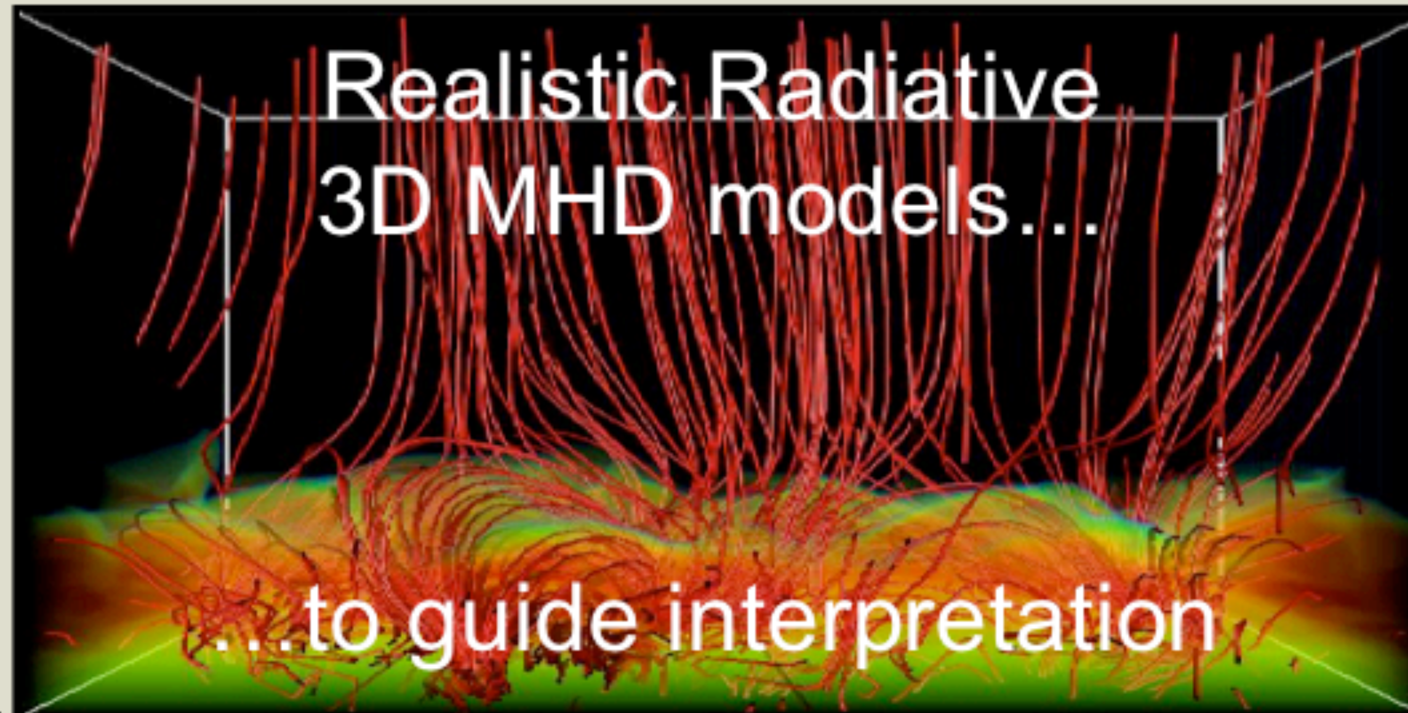
*...radical effect on **j** and flux emergence process*

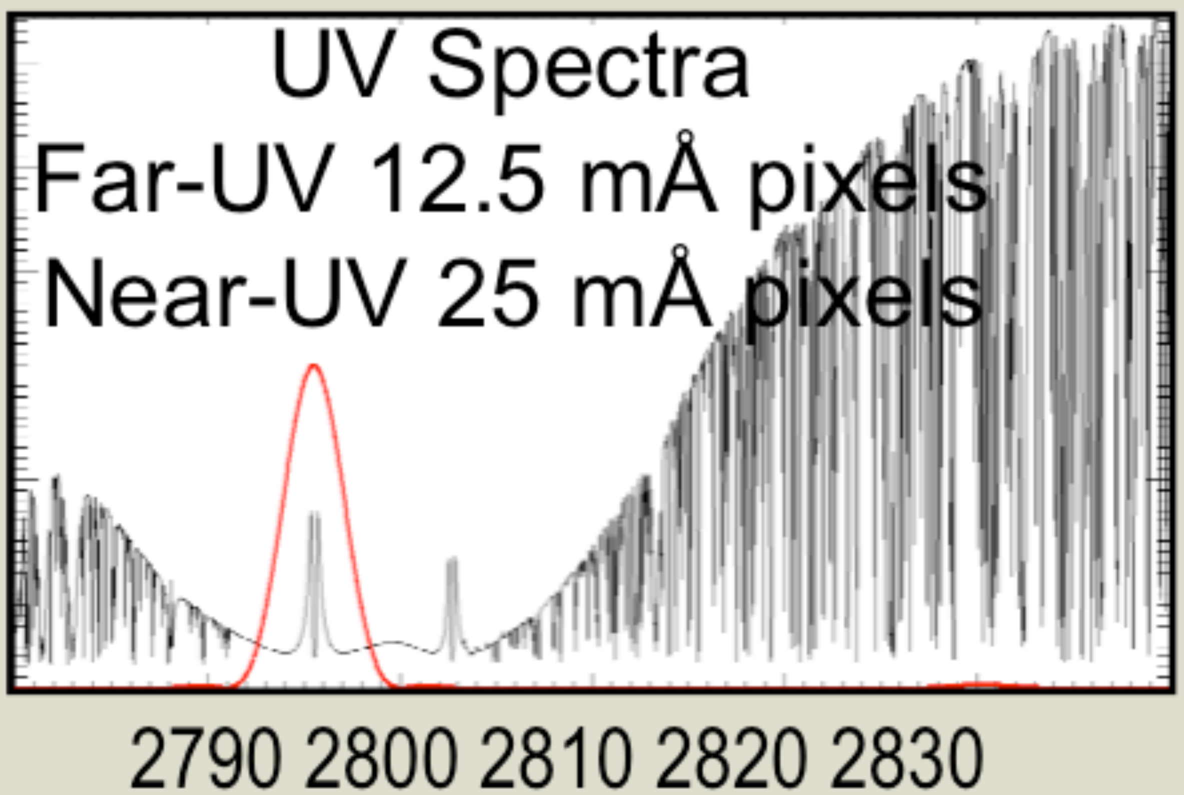
partially ionized plasma II

- $\sigma_\perp^*$ is some steps removed from σ (kinetic theory)
  - case **G** $\neq$ **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

The future

IRIS mission



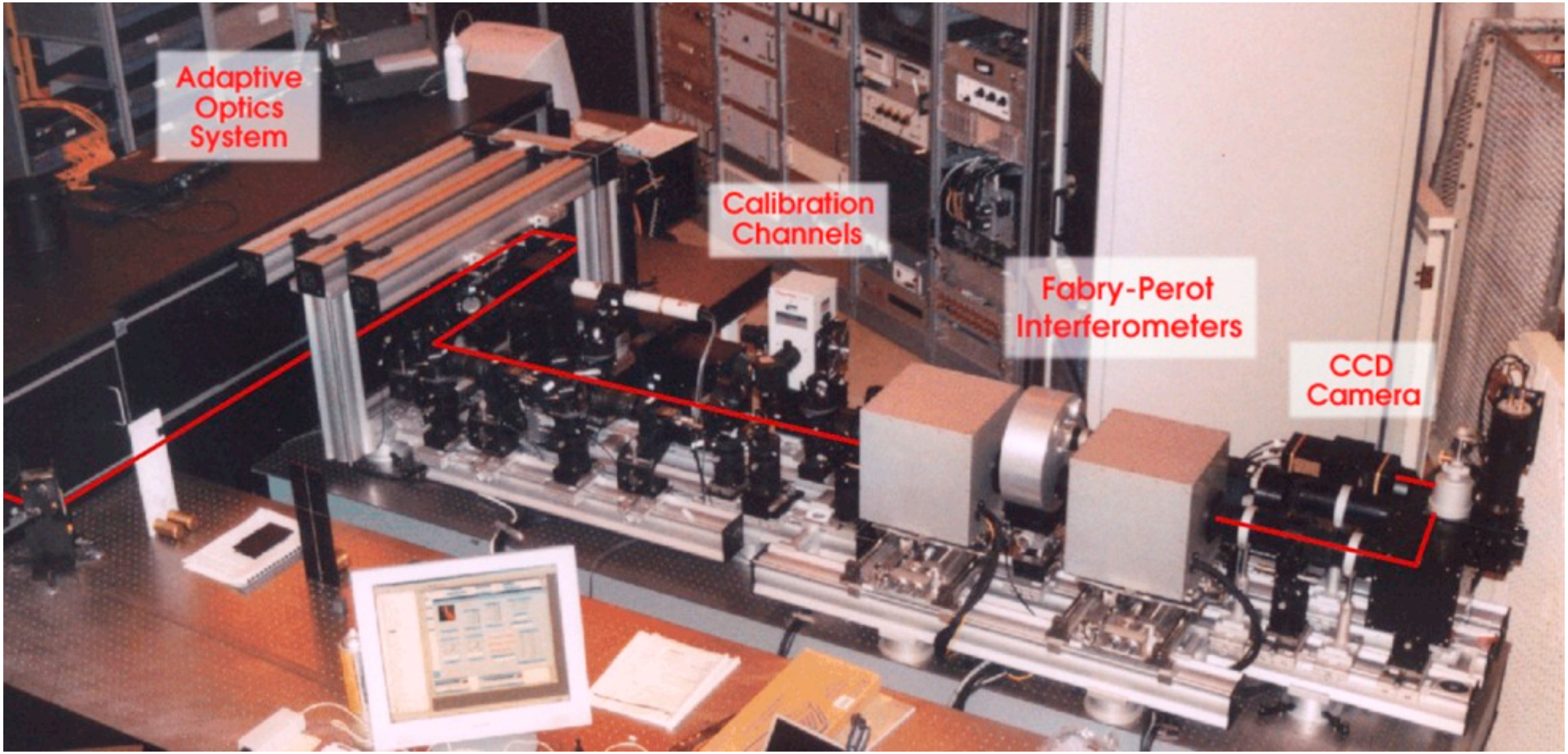


20 cm UV telescope:
1/6 arcsec pixels

multi-channel spectrograph
far-UV: 1332-1358 Å, 1390-1406 Å,
40 mÅ resolution, effective area 2.8 cm^2
near-UV:2785 - 2834 Å,
80 mÅ resolution, effective area 0.3 cm^2

slit-jaw imaging
1335 Å & 1400 Å with 40 Å bandpass each;
2796 Å & 2831Å with 4Å bandpass each.

IBIS- Cavallini & colleagues



Also TESOS, CRISP, GFPI,...

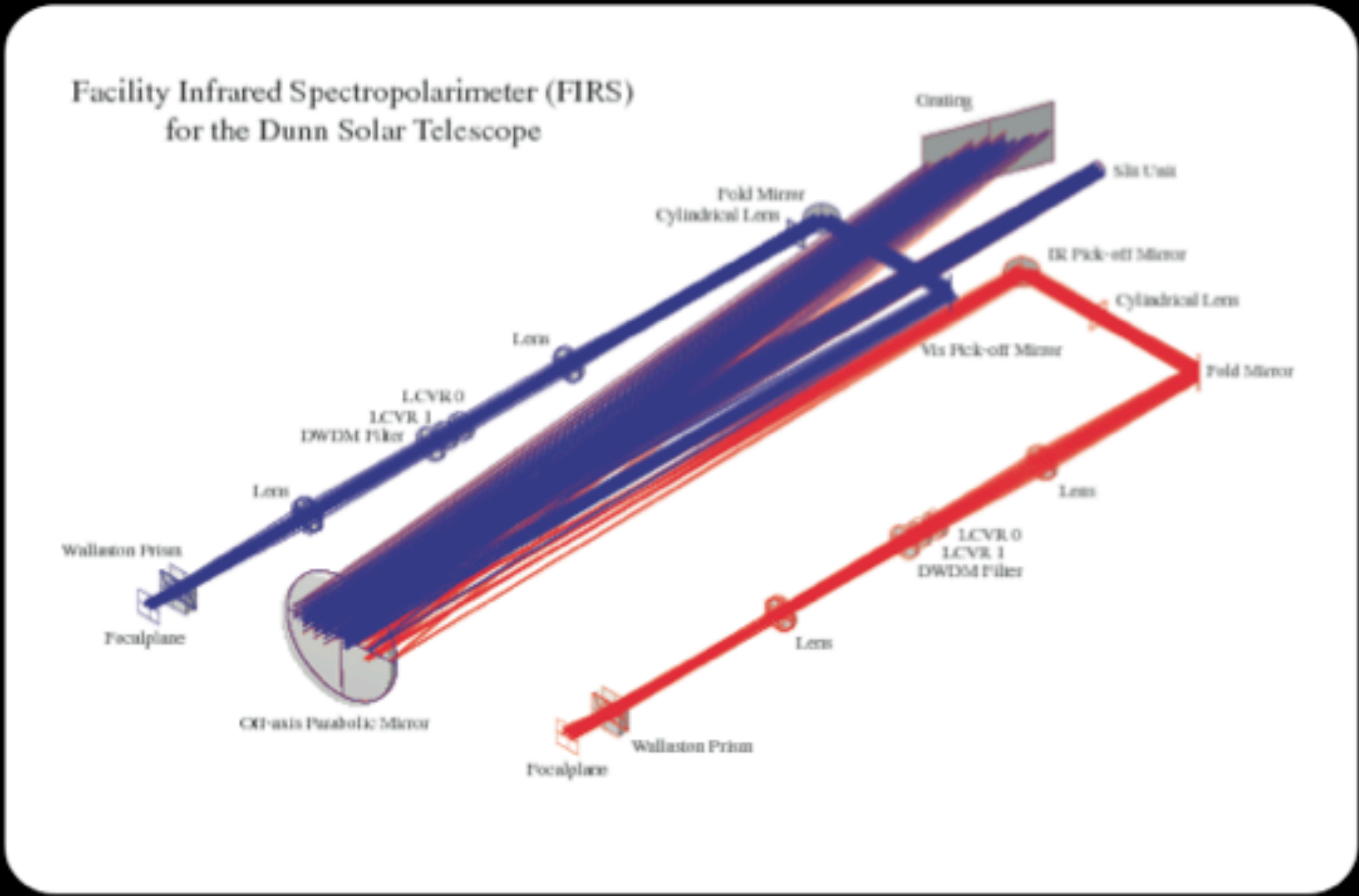
Facility InfraRed Spectropolarimeter

Telescope: DST

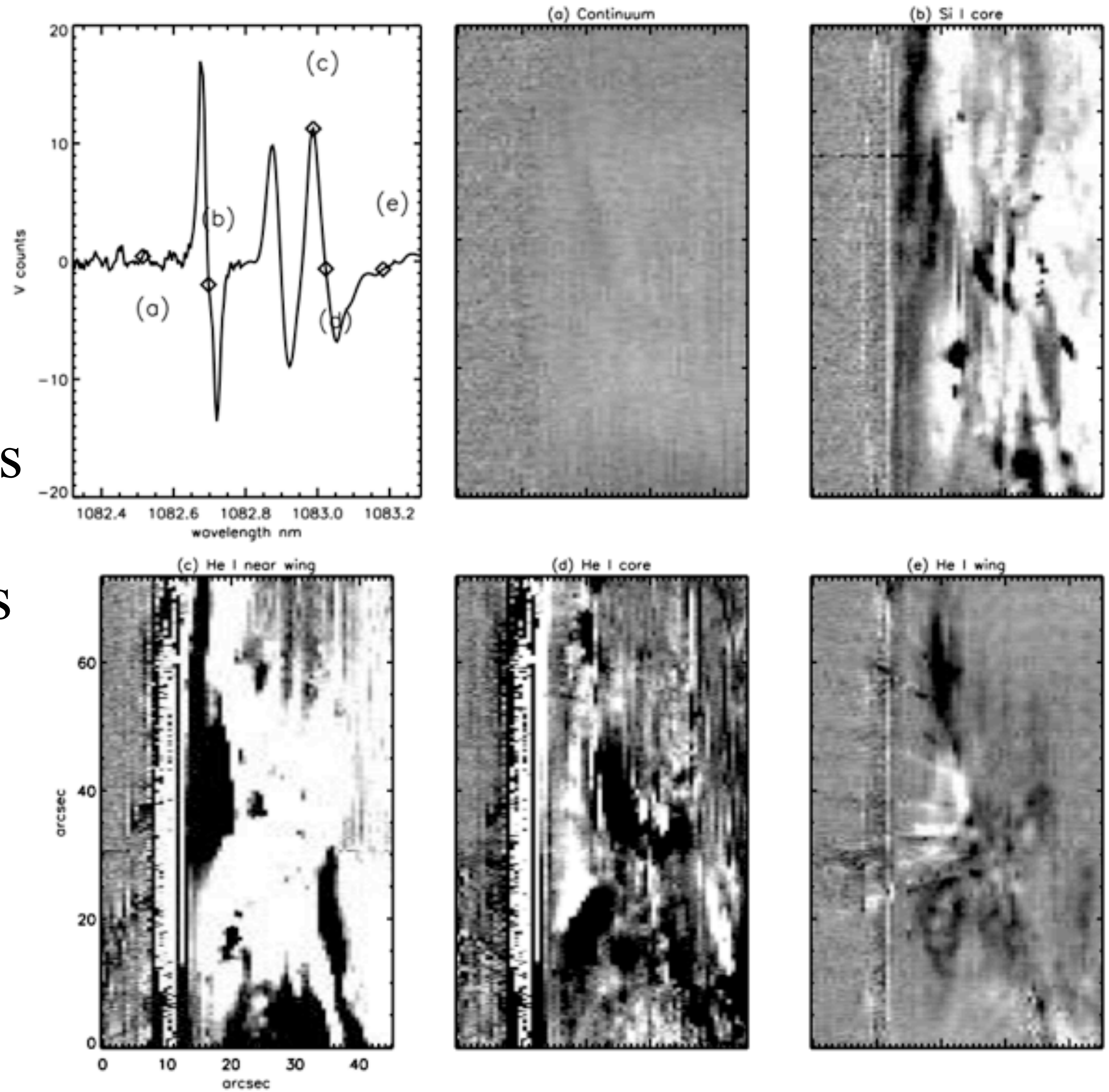
Features: diffraction limited, dual beam, 4-slits for high cadence (20 min.) rasters

Wavelengths: simultaneous 6302, 15650 or 6302, 10830 and runs concurrently with IBIS 8542, G-band camera

Now available for general use!



FIRS and IBIS Support for IRIS mission



Polarimetric measurements with sensitivity sufficient to measure magnetic fields in the chromosphere and in coronal plasma

FIRS data Judge et al. (in prep).