The Solar Atmosphere

(as seen from the)

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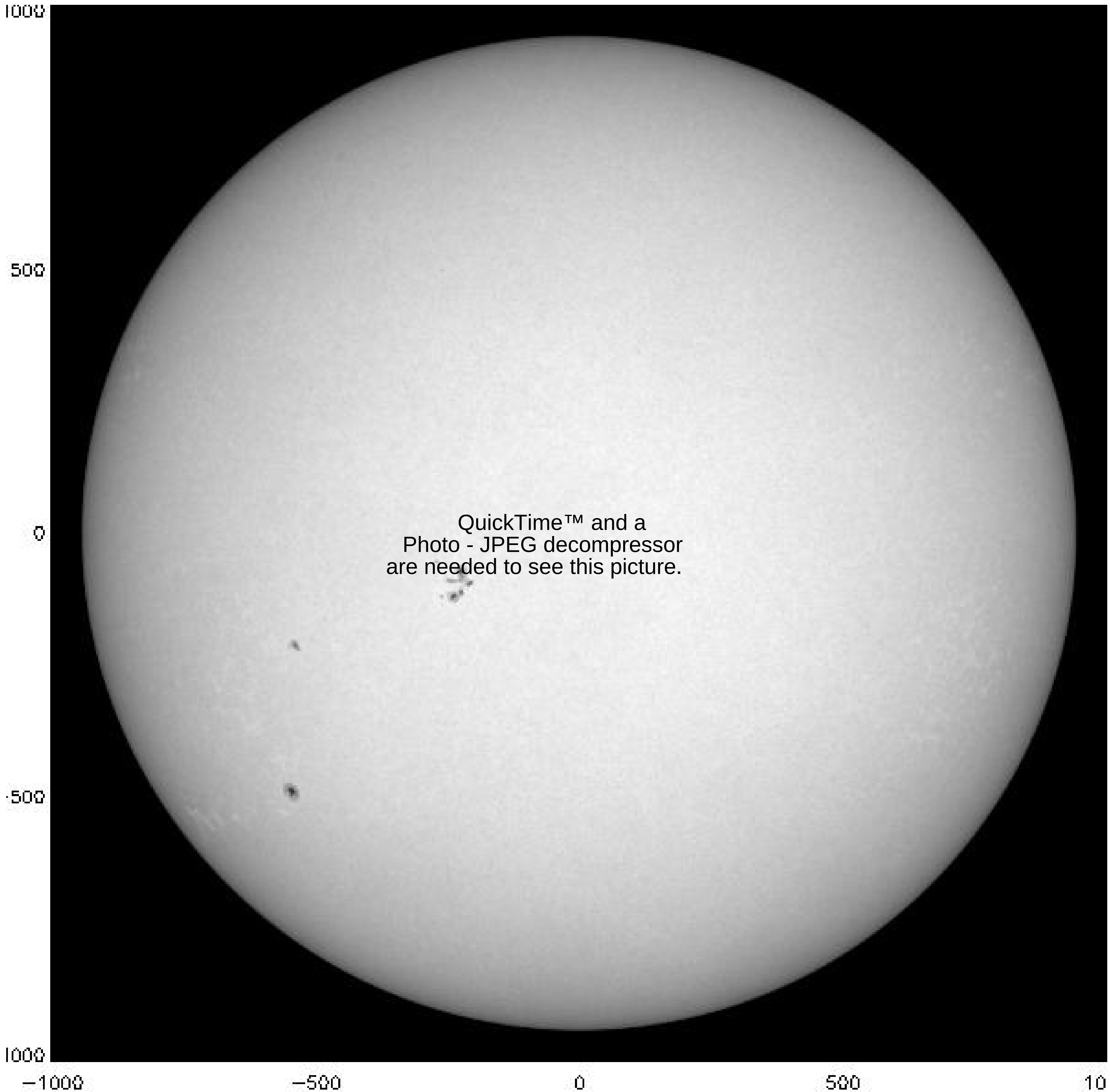
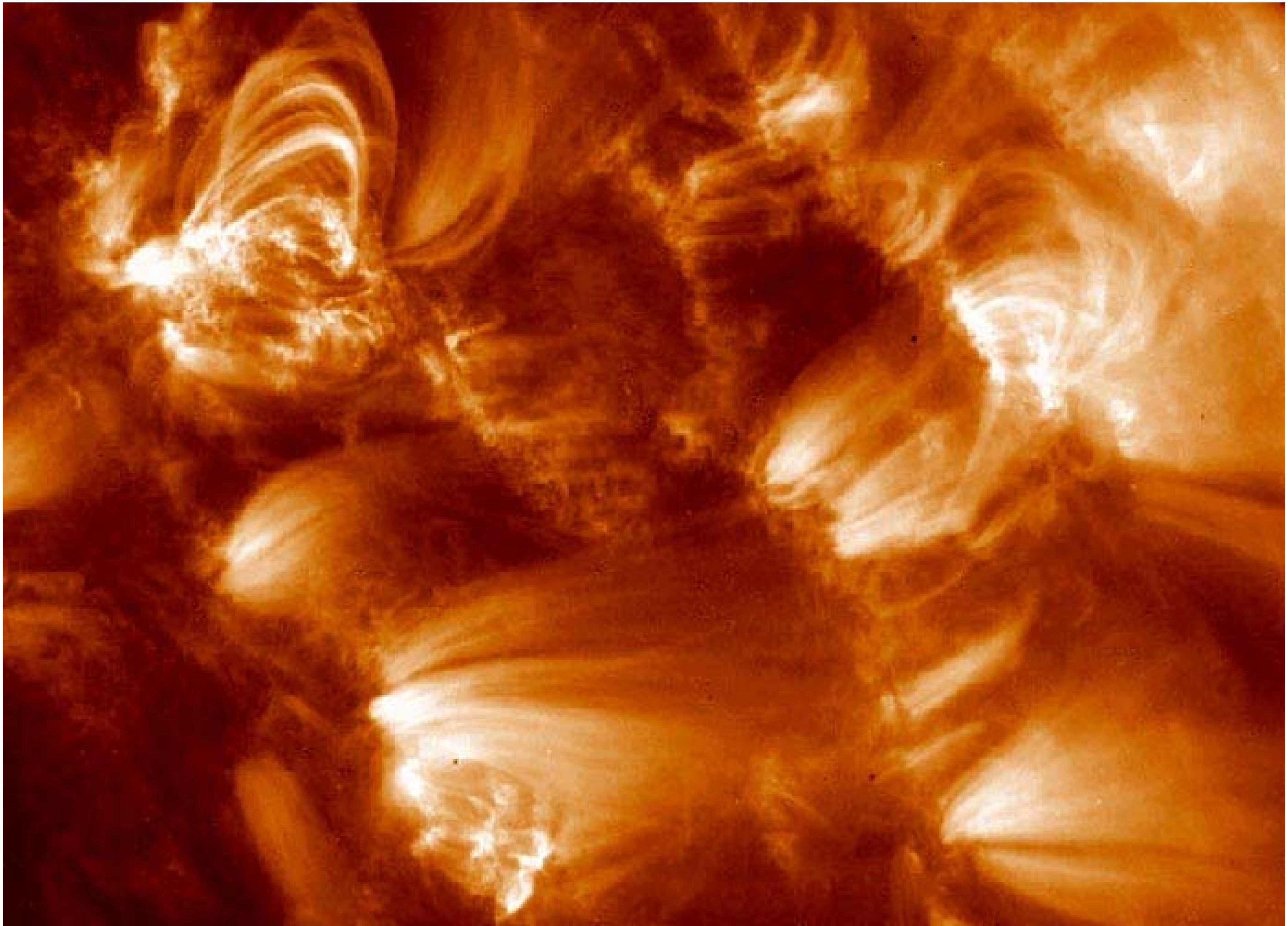
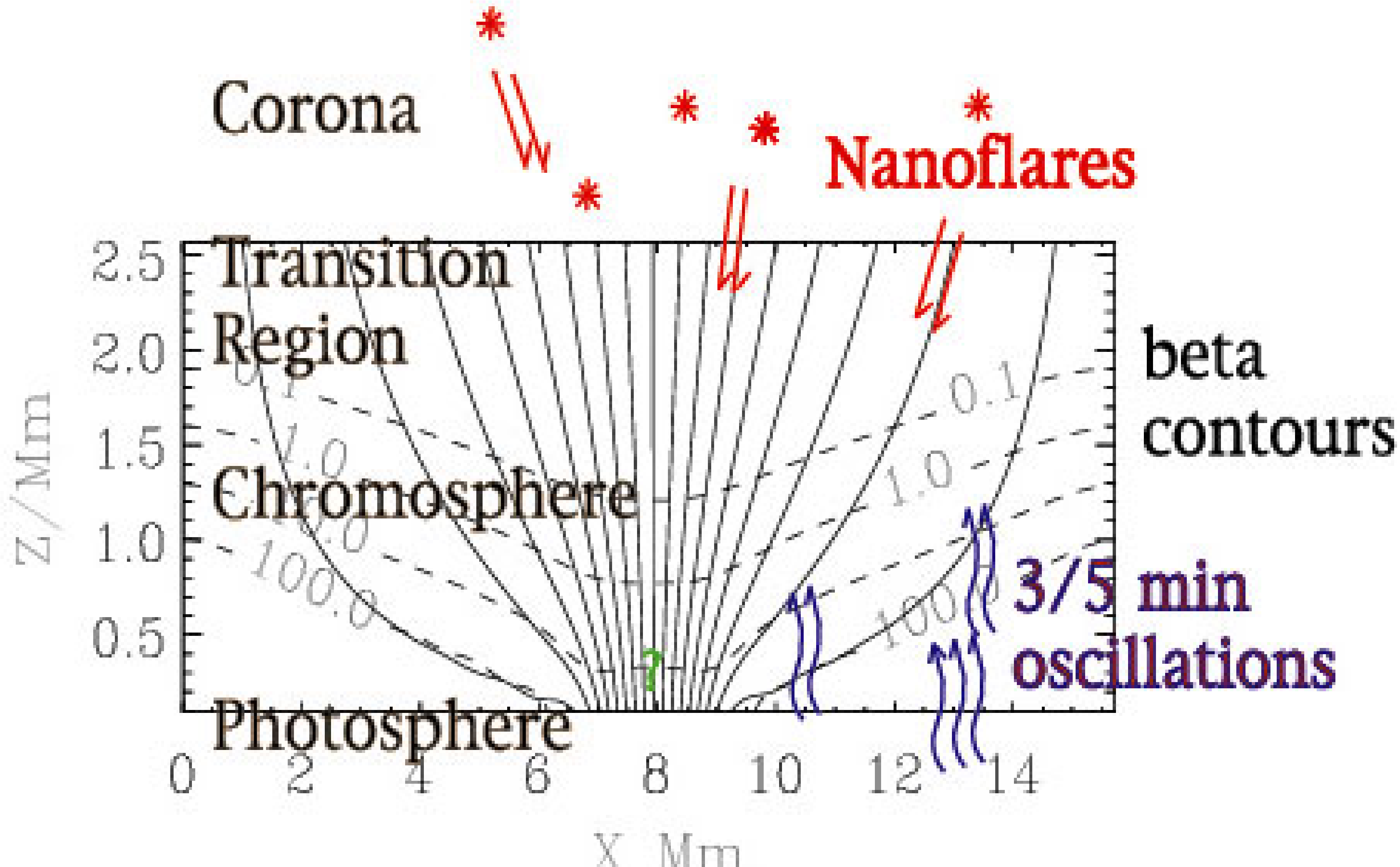
Viggo H. Hansteen


QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.
1000
500
0
-500
1000
−1000
−500
0
500
10

Sun: July 29, 1998 with TRACE 171Å

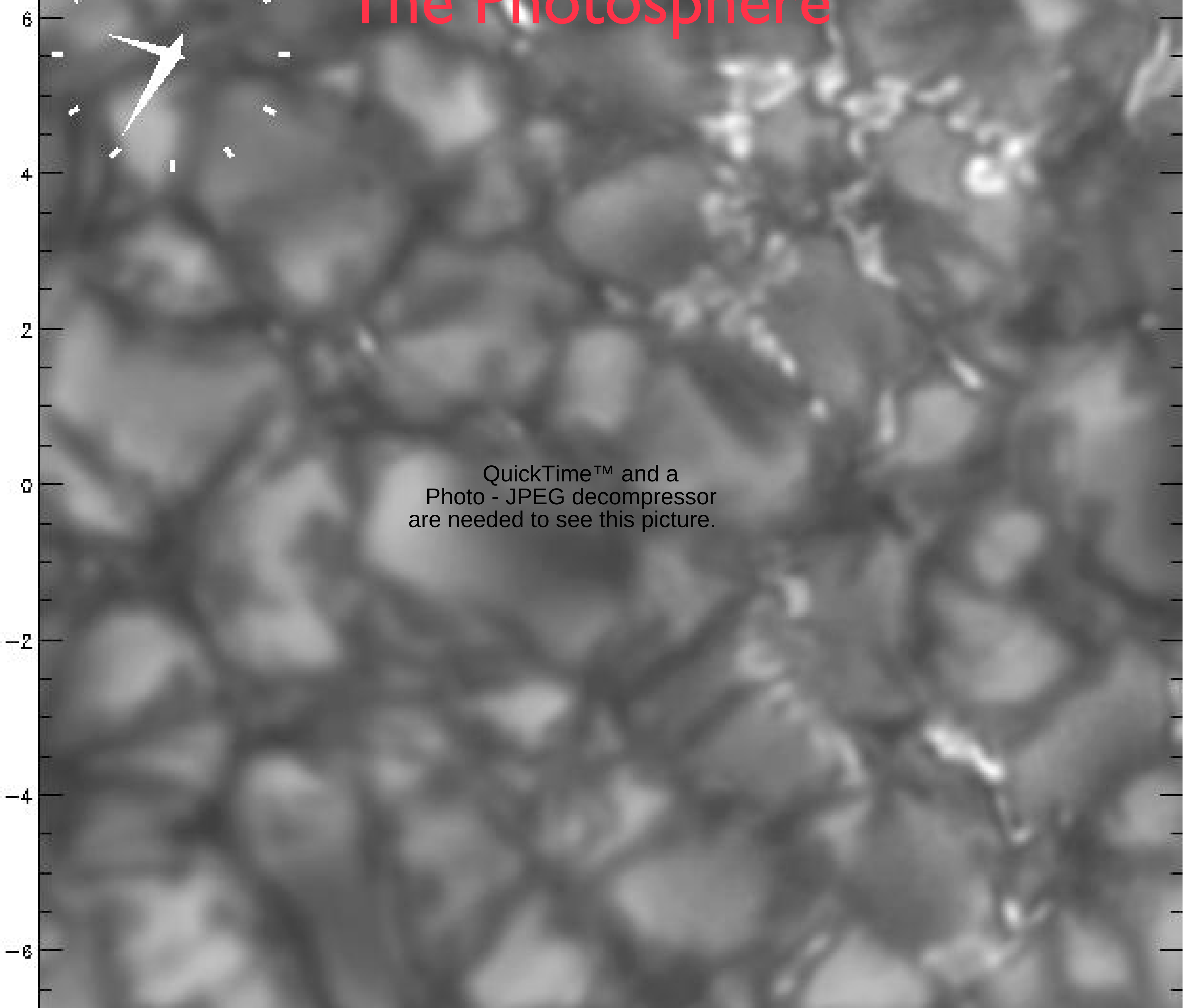


Solar Atmospheric structure: Expected dynamics and energetics



- The photosphere
  - braiding of the magnetic field; injection of Poynting flux
  - injection of acoustic flux
- The chromosphere
  - conduit of waves and other motions
  - region where $\beta \approx 1$
- The Transition Region and Corona
  - deposition of energy flux
  - diagnostic signatures of waves and heating

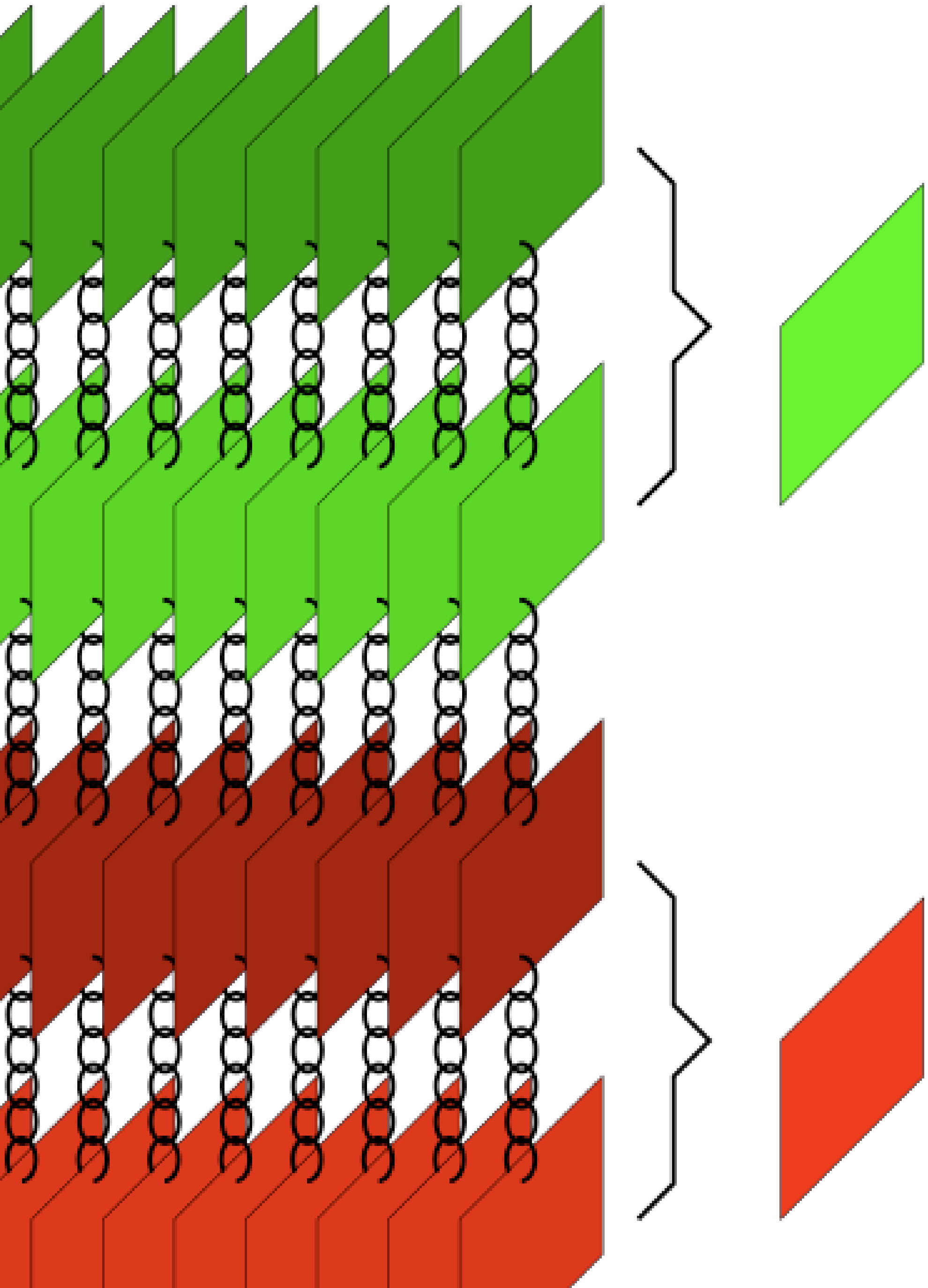
The Photosphere

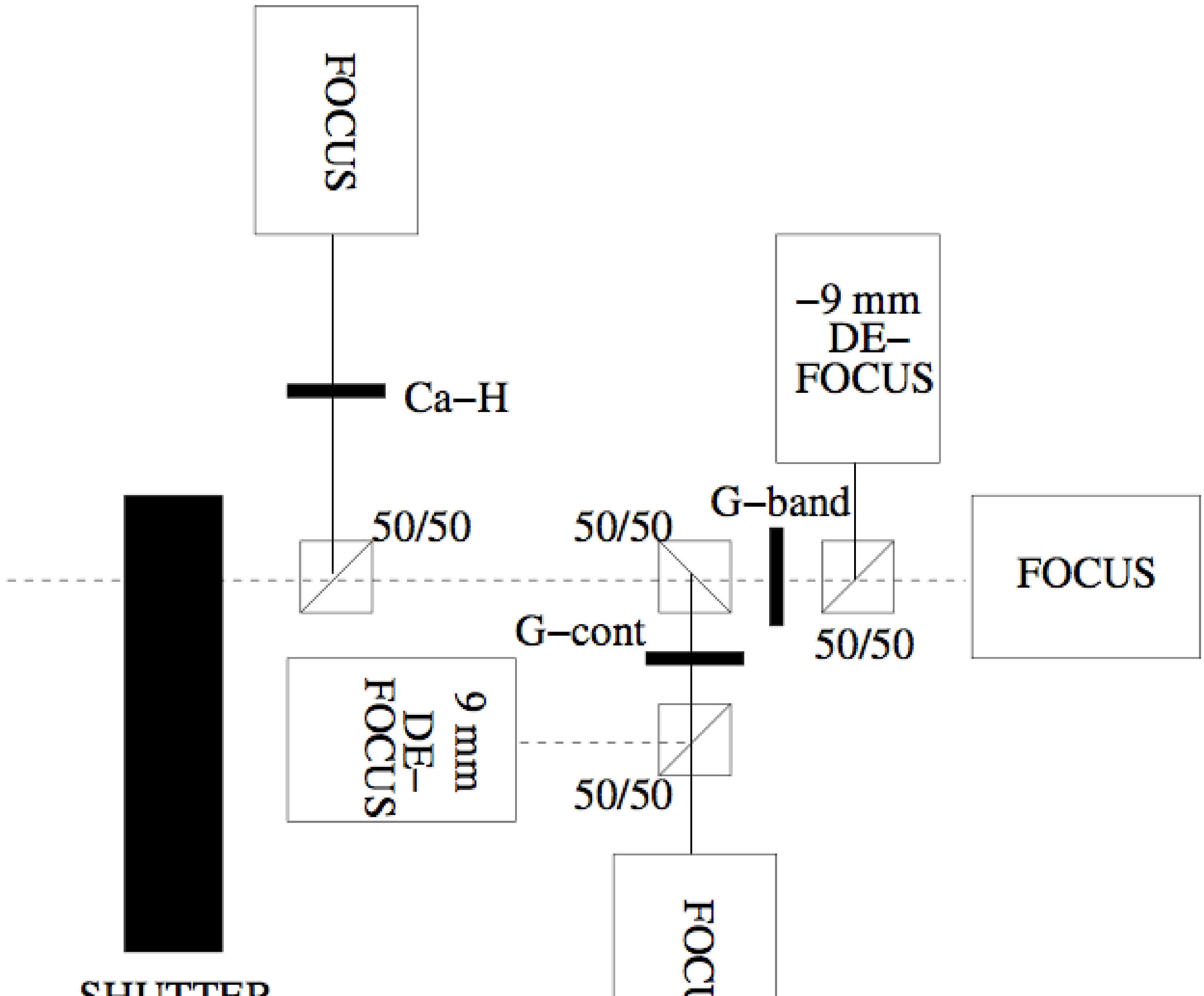


Muchachos on La Palma, Canary Islands

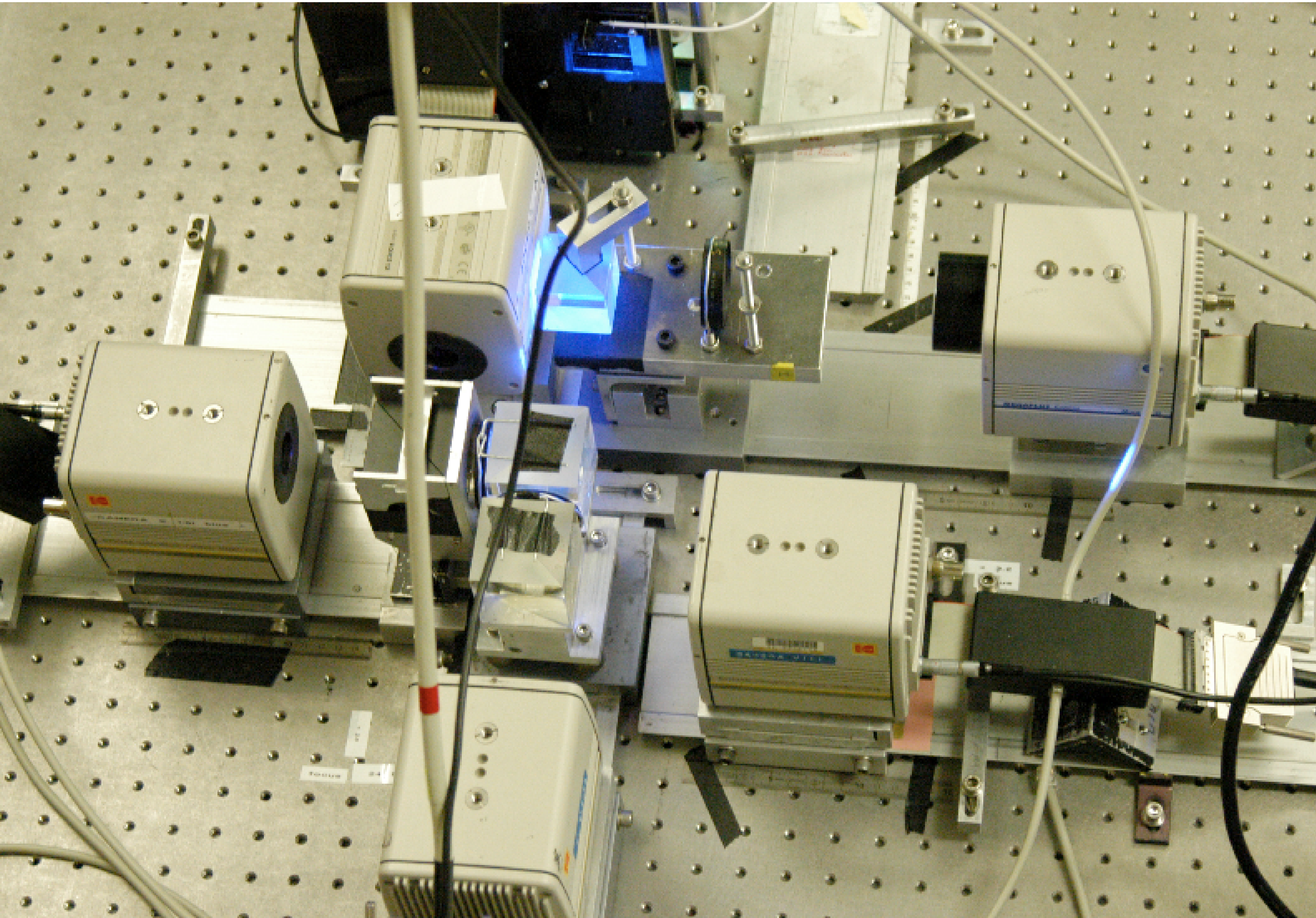
- Solar image restoration by MOMFBD - upcoming article in Solar Physics by Michiel van Noort et al.
- Images and movies cadence 0.3-20s, spatial resolution 0.1”
- G-continuum, Ca II H-line, Fe 6302, ...

2 Object Multi-Frame Phase Diversity

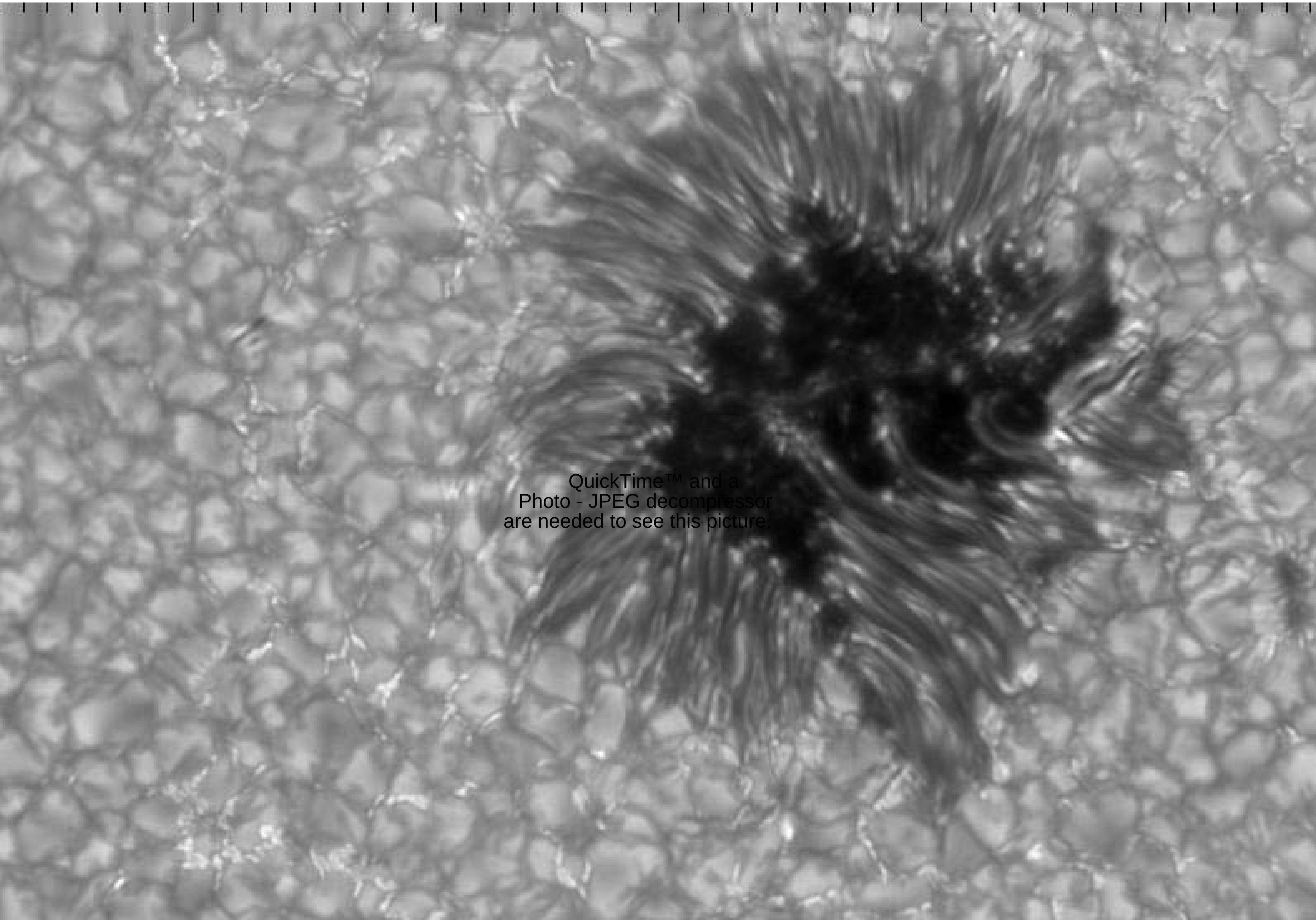



FOCUS
Ca–H
50/50
50/50
G–band
–9 mm
DE–
FOCUS
FOCUS
50/50
G–cont
9 mm
DE–
FOCUS
50/50

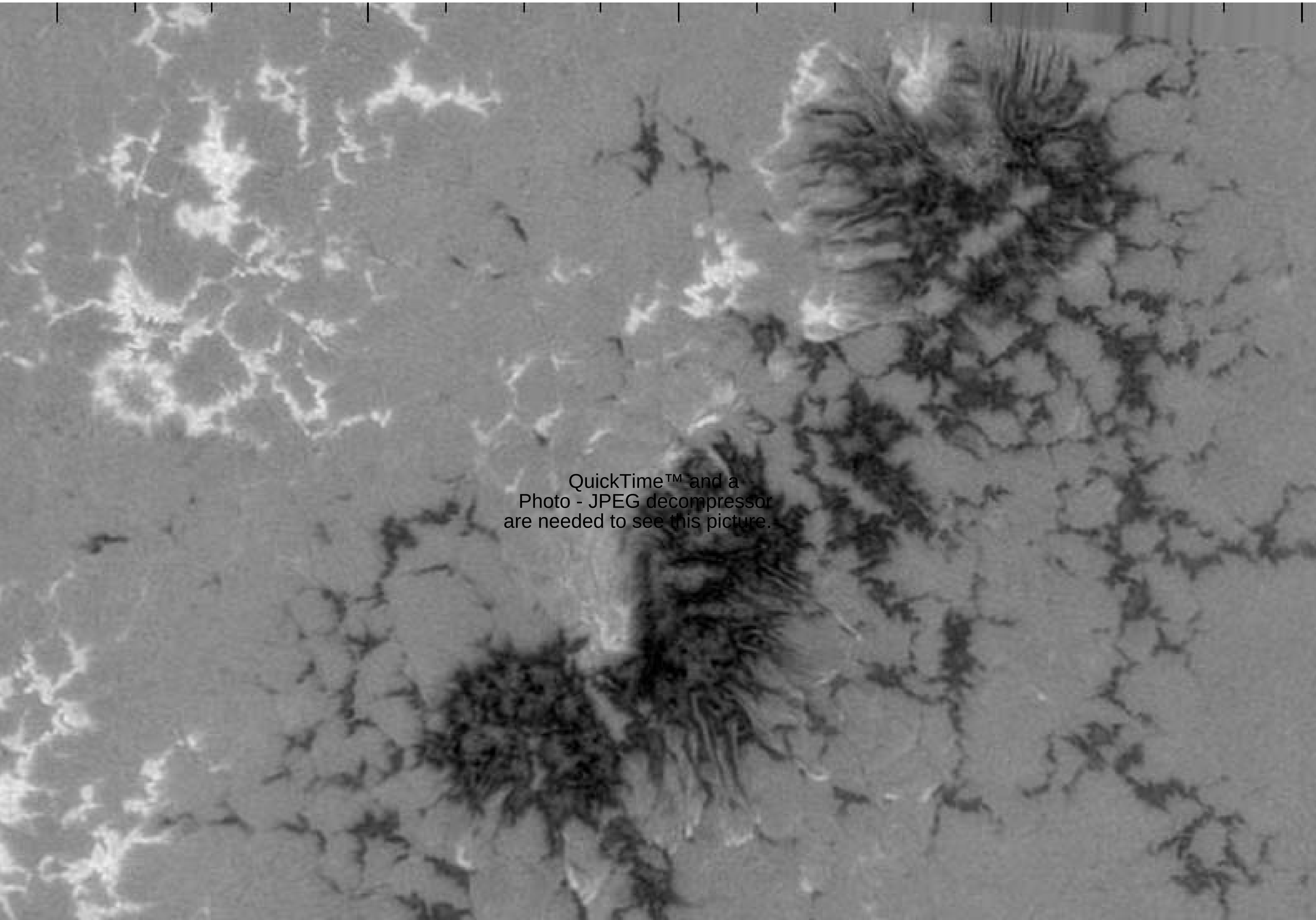
CCT Blue Beam Optical Setup



20 Aug 2004, G-band



21 Aug 2004, Magnetogram



□□□□Hinode)

Launch
eptember 23, 2006
apan/US/UK mission
(Norway, ESA)

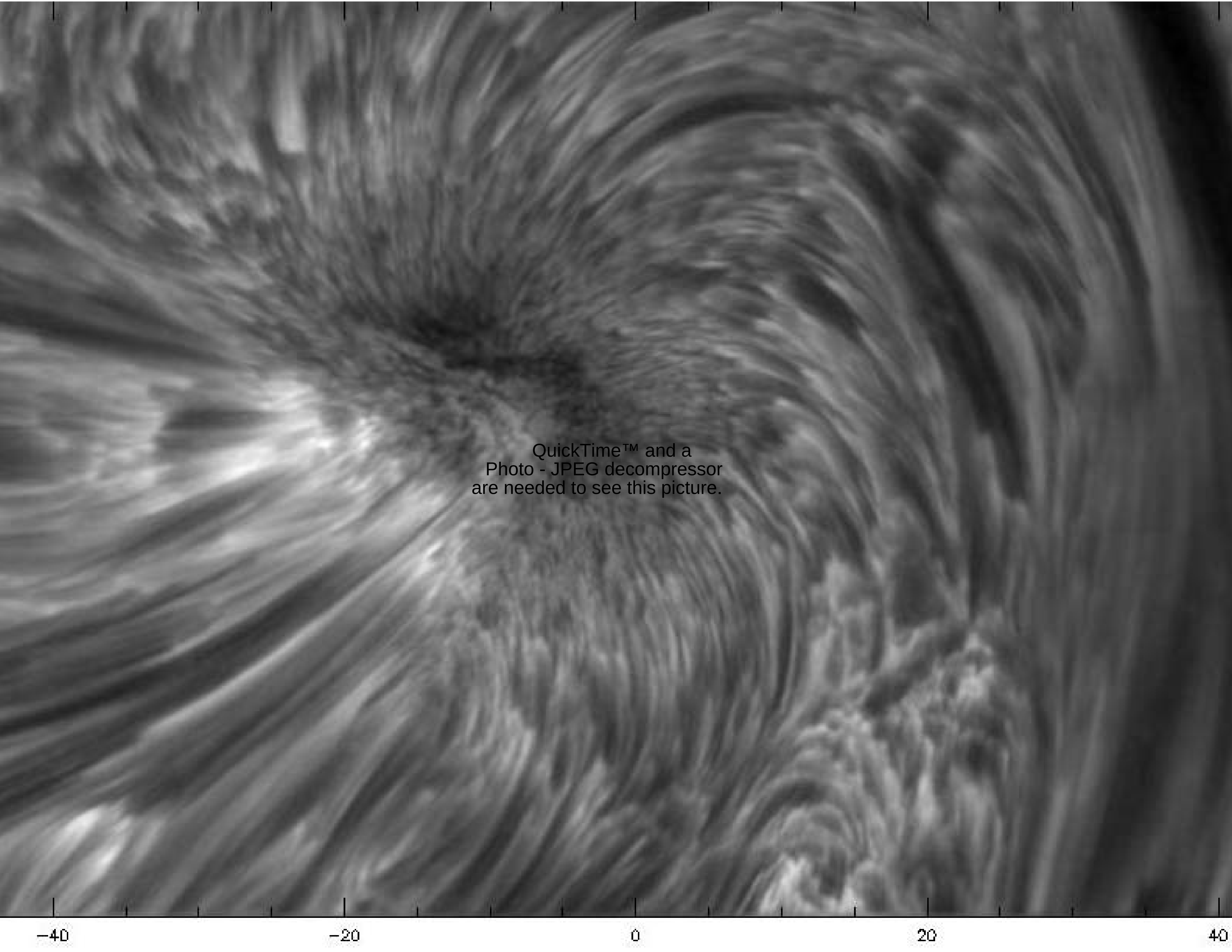
Solar Optical Telescope

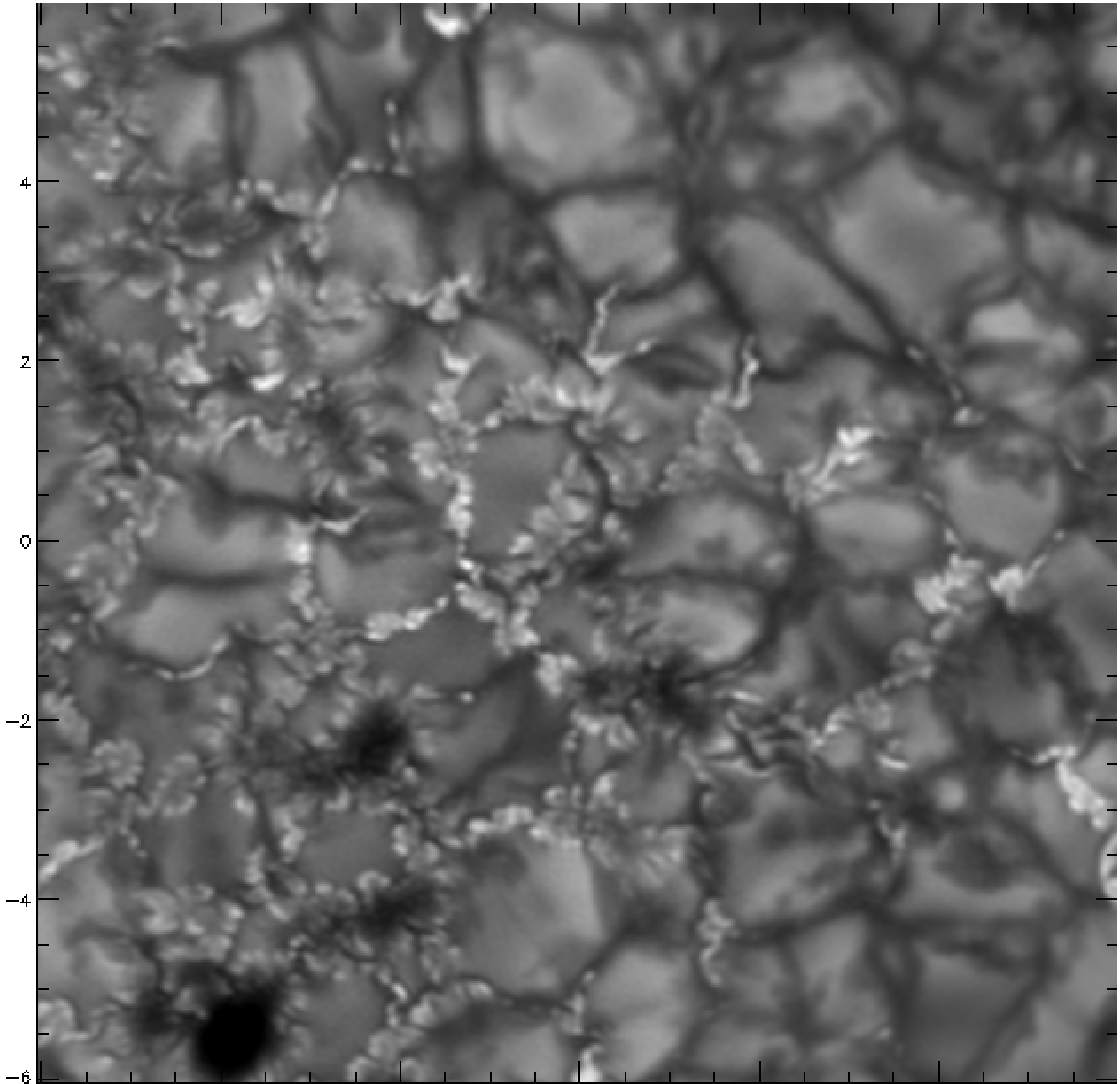
X-Ray Telescope

Extreme UV Imaging Spectrograph

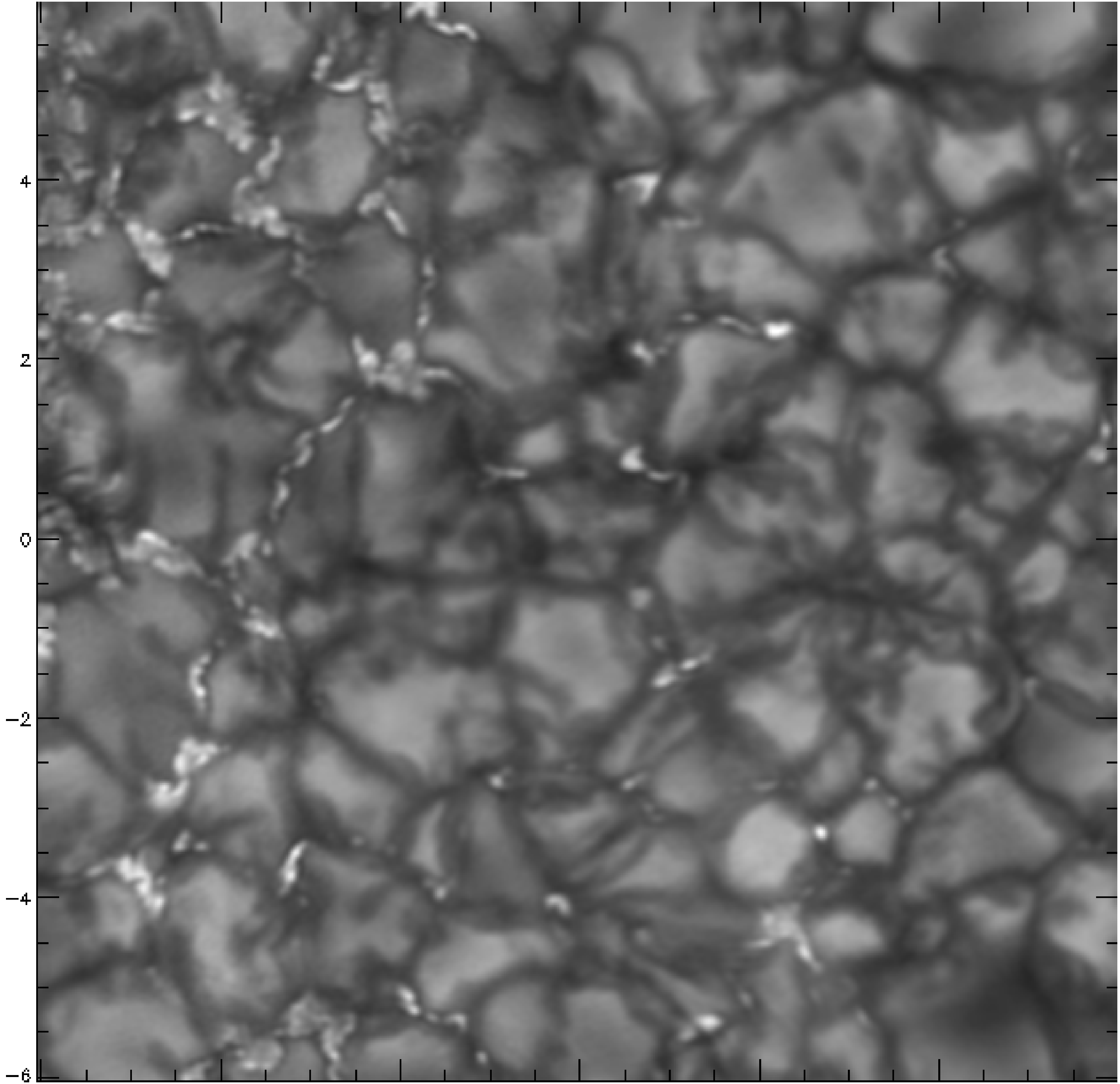
Dec 13 2006, Hinode/SOT Flare

QuickTime™ and a
Sorenson Video 3 decompressor
are needed to see this picture.


QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.
−40
−20
0
20
40



4
2
0
−2
−4
−6



4
2
0
−2
−4
−6

The MHD equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$+ \nabla \cdot (e\mathbf{u}) + p\nabla \cdot \mathbf{u} = \nabla \cdot \mathbf{F}_r + \nabla \cdot \mathbf{F}_c + \eta j^2 +$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u} + \tau) = -\nabla p + \mathbf{j} \times \mathbf{B} - g\rho$$

some equation of state $\quad 1 \quad p$

Solution of the energy equation with radiation

$$\nabla \mathbf{F}_r = 4\pi \int_\lambda \epsilon_\lambda \chi_\lambda (B_\lambda - J_\lambda) d\lambda$$

- Assume opacities in LTE and coherent scattering
- Calculate group mean opacities and group mean source functions
- The resulting 3d scattering problem is solved by iteration

oup number defined by $i = \mathrm{Int}\left(\frac{\log[\tau_0(\tau_\lambda = 1)]}{\Delta \log(\tau)}\right) + \mathrm{const}$

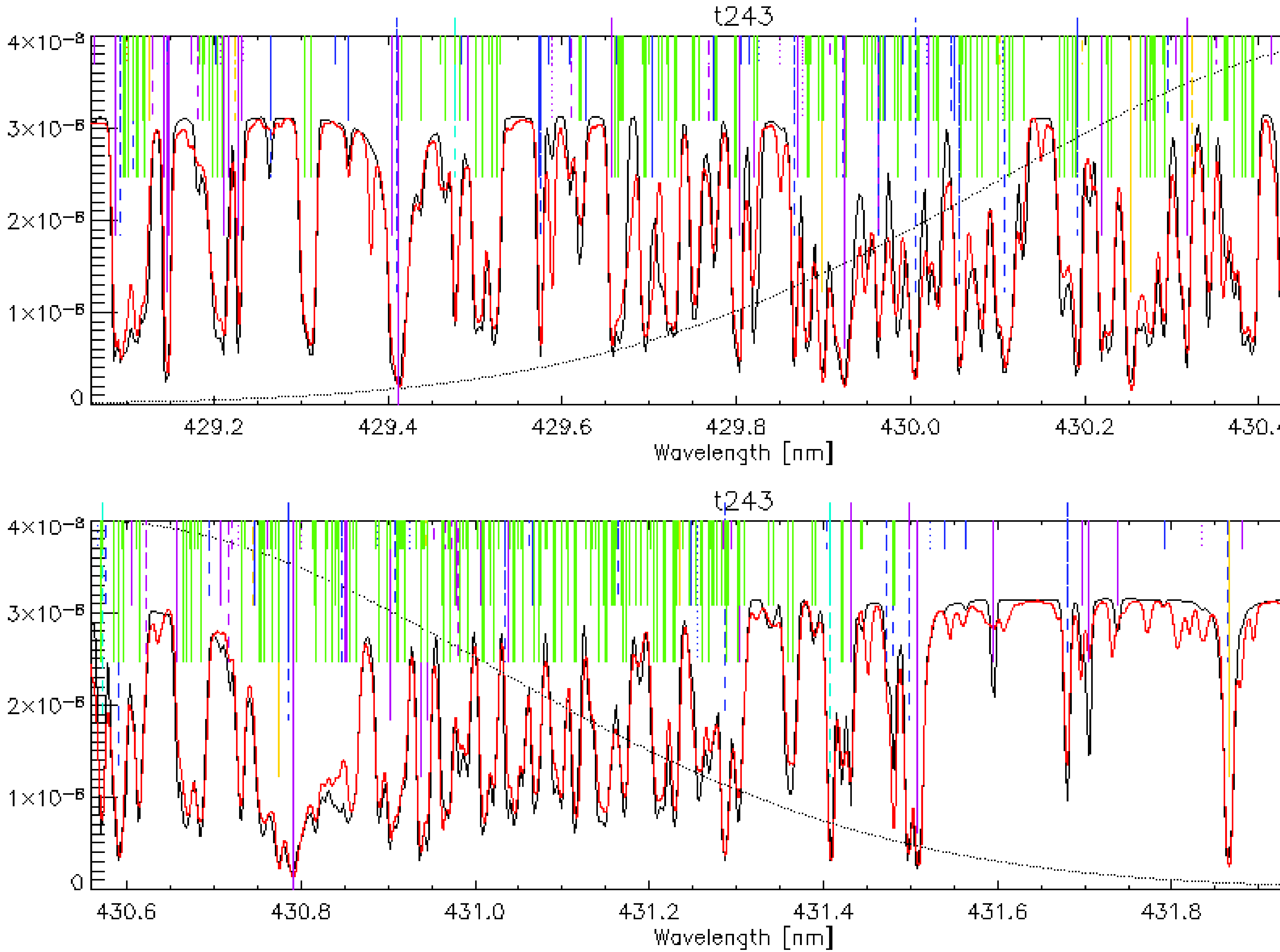
$$\int_{\Delta\lambda i} \frac{\partial I_\lambda}{\partial r} d\lambda = \int_{\Delta\lambda i} (\sigma_\lambda J_\lambda + \kappa_\lambda B_\lambda - \chi_\lambda I \lambda) d\lambda$$

$$\frac{\partial I_i}{\partial r} = \sigma_i^J J_i + \kappa_i^B B_i - \chi_i^I I_i$$

vith $I_i \equiv \int_{\Delta\lambda i} I_\lambda d\lambda$ then $\chi_i^I = \frac{\int_{\Delta\lambda i} \chi_\lambda I_\lambda d\lambda}{I_i}$ etc

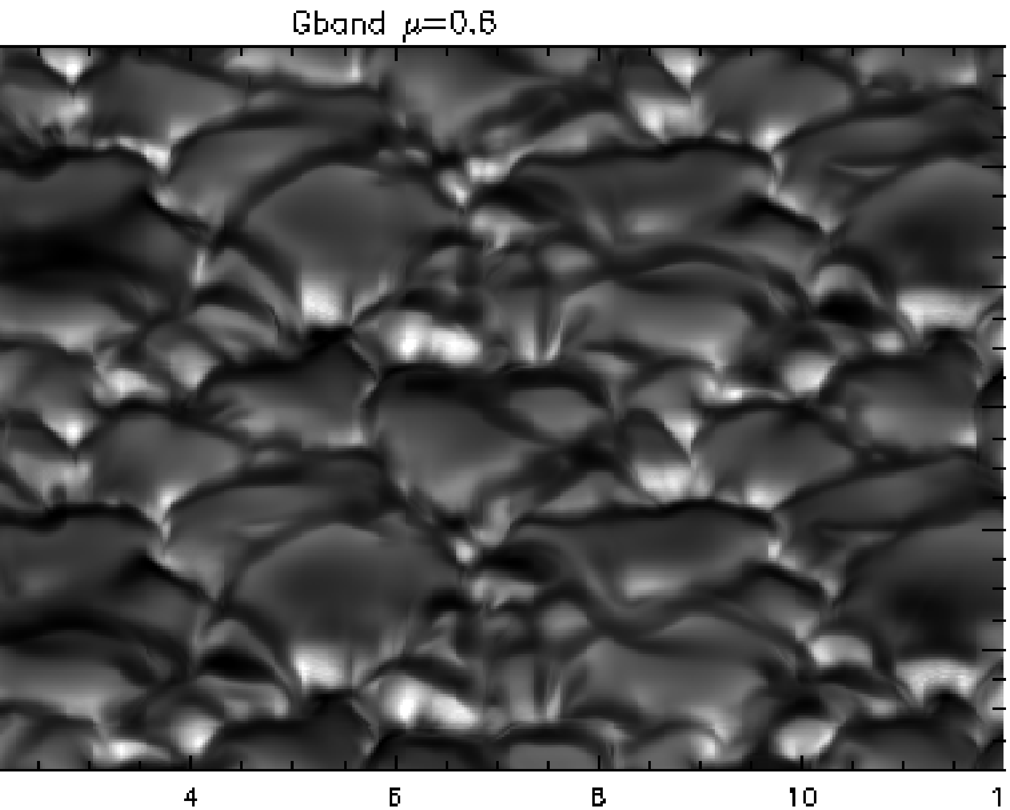
$$S_i = \frac{\sigma_i^J J_i + \kappa^B B_i}{\chi_i^I} \qquad J_i = \Lambda(\chi_i^I)\,[S_i]$$

- Nordlund/Stein code
- multi-group opacities, 4 bins
- Initial field 250G, vertical, single polarity
- 253x253x163 simulation
- RT each snapshot, 2728 frequency points
- Line blanketing: 845 lines

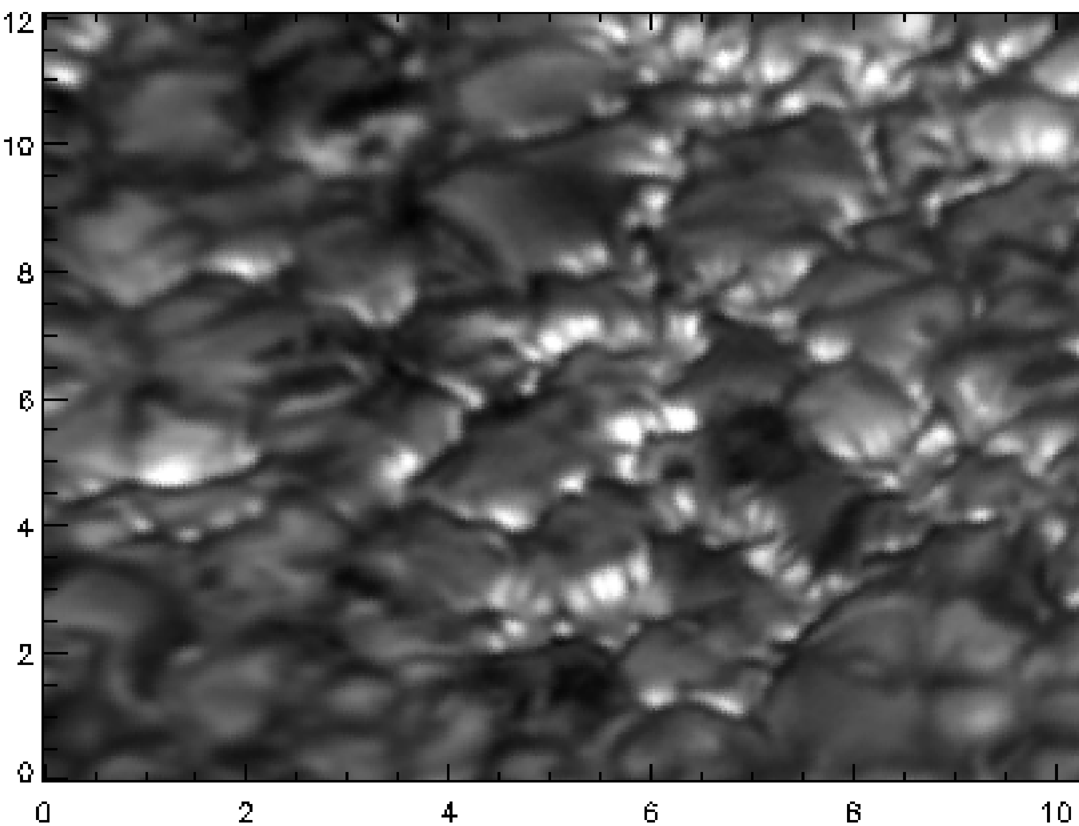


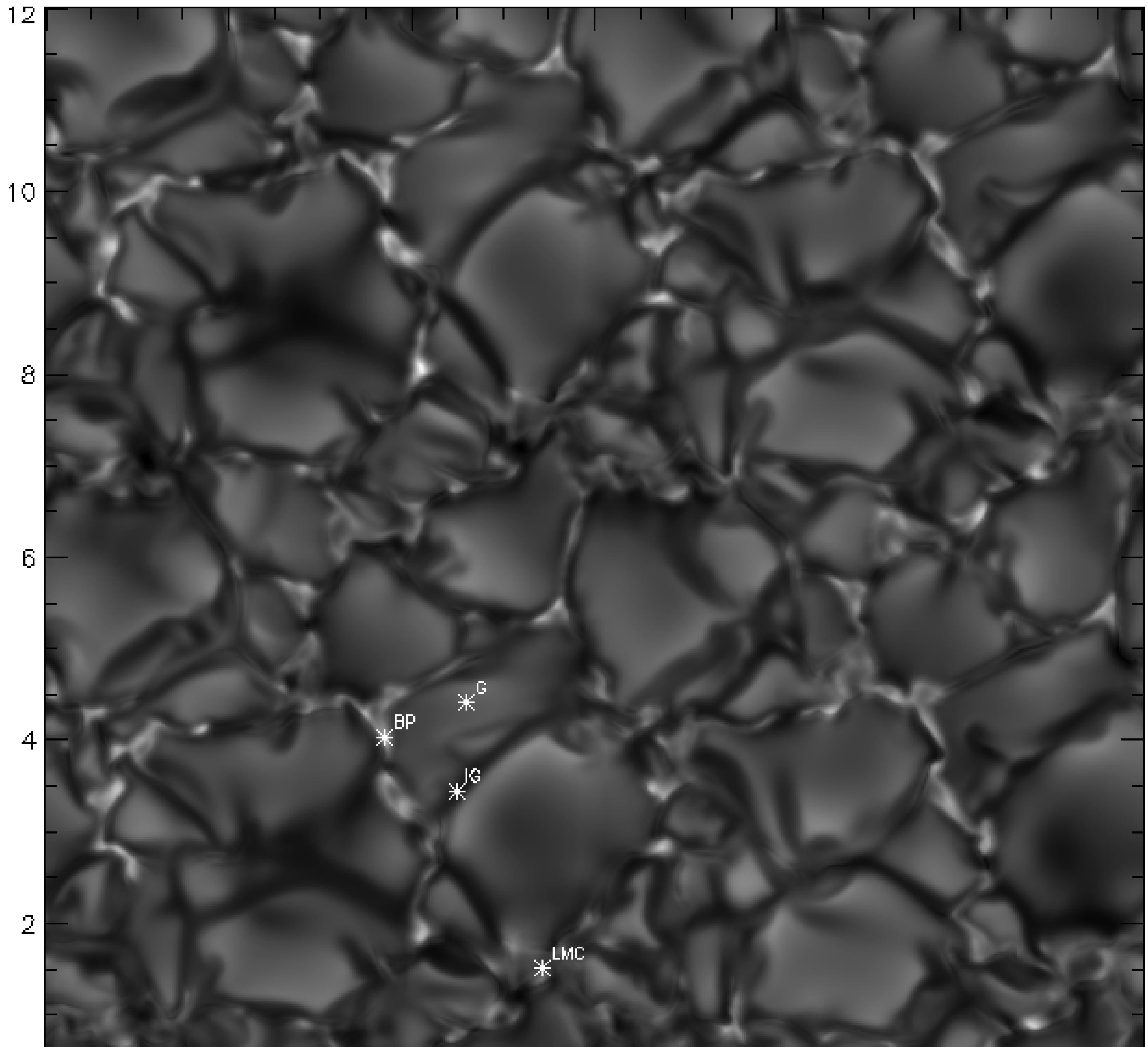
t243
4×10⁻⁸
3×10⁻⁸
2×10⁻⁸
1×10⁻⁸
0
429.2
429.4
429.6
429.8
430.0
430.2
Wavelength [nm]
t243
430.6
430.8
431.0
431.2
431.4
431.6
431.8
Wavelength [nm]

imulation, mu=0.6



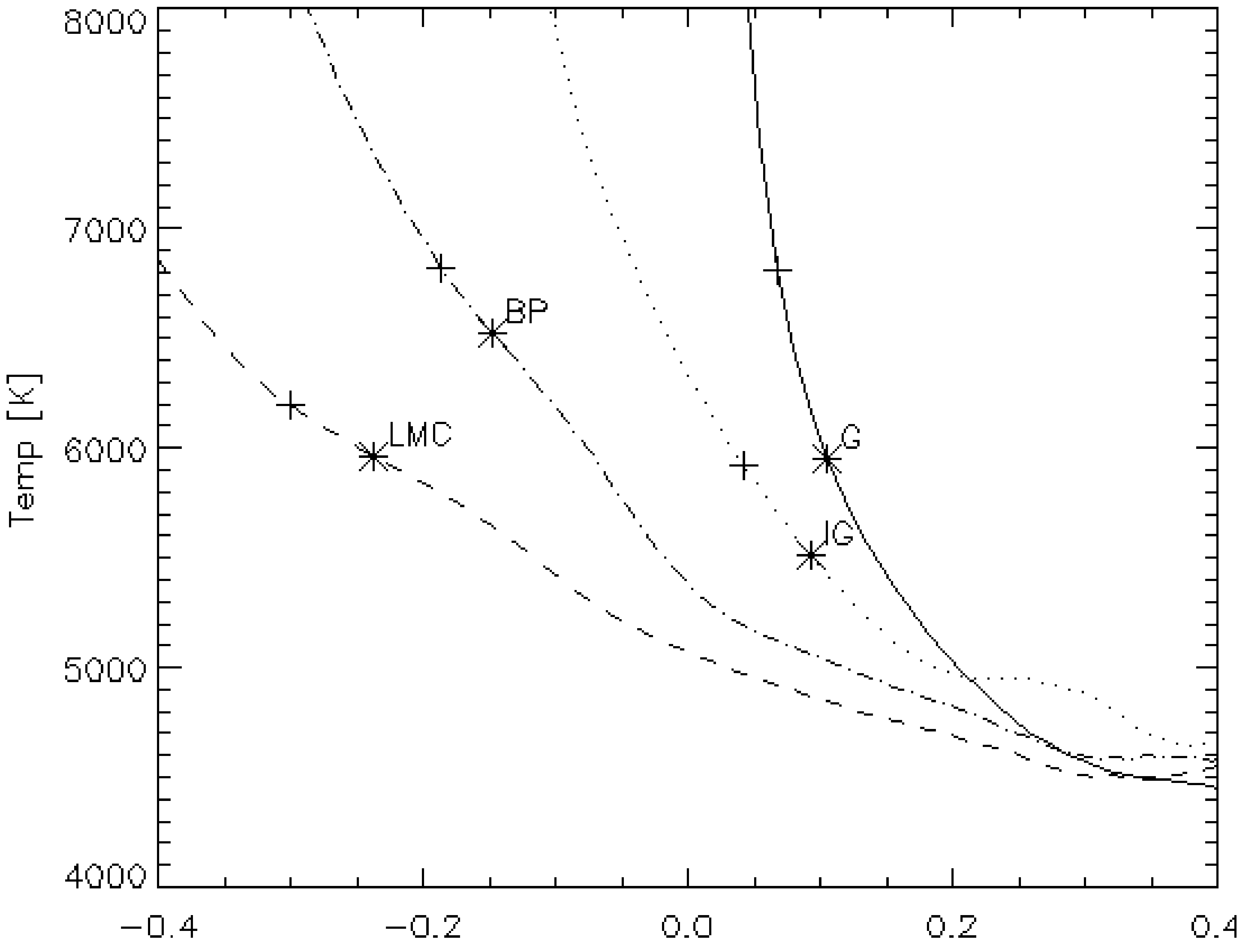
Observation, mu=0.6





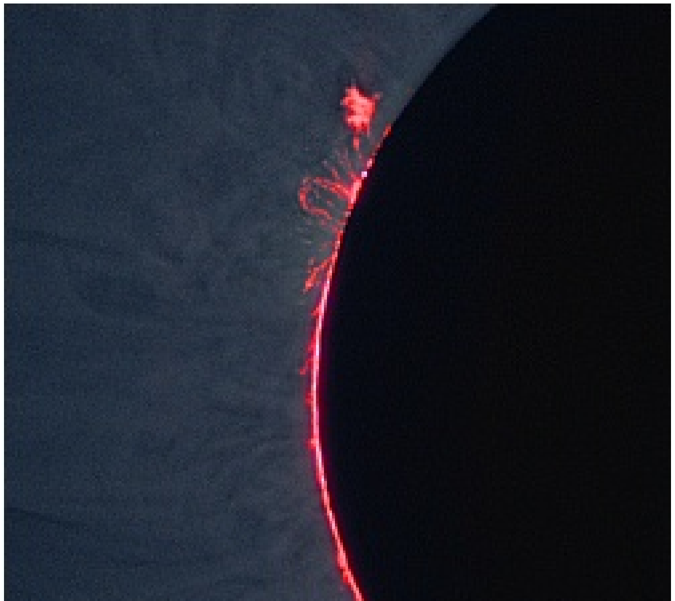
12
10
8
6
4
2
G
BP
IG
LMC

Temperature structure

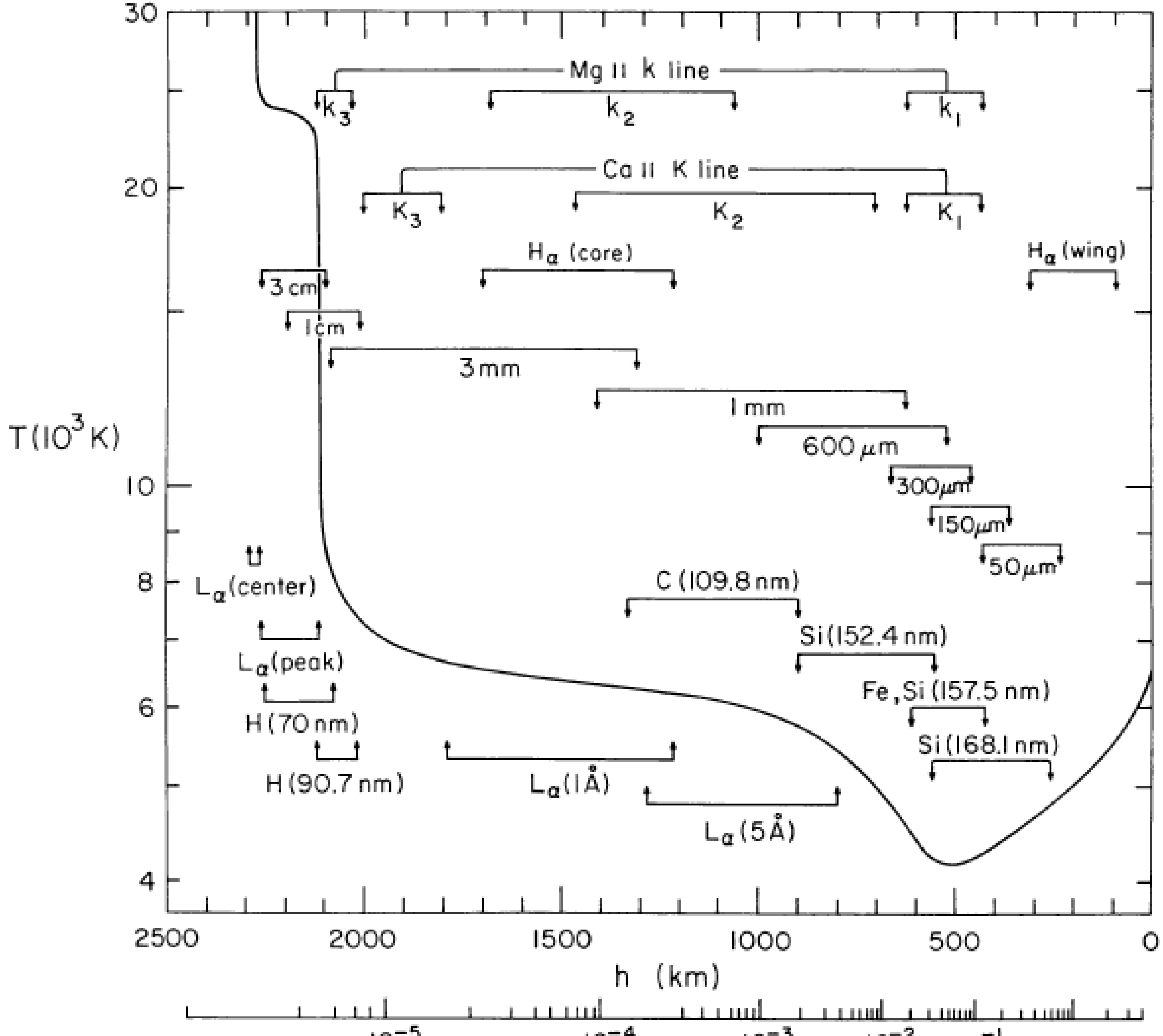


The chromosphere

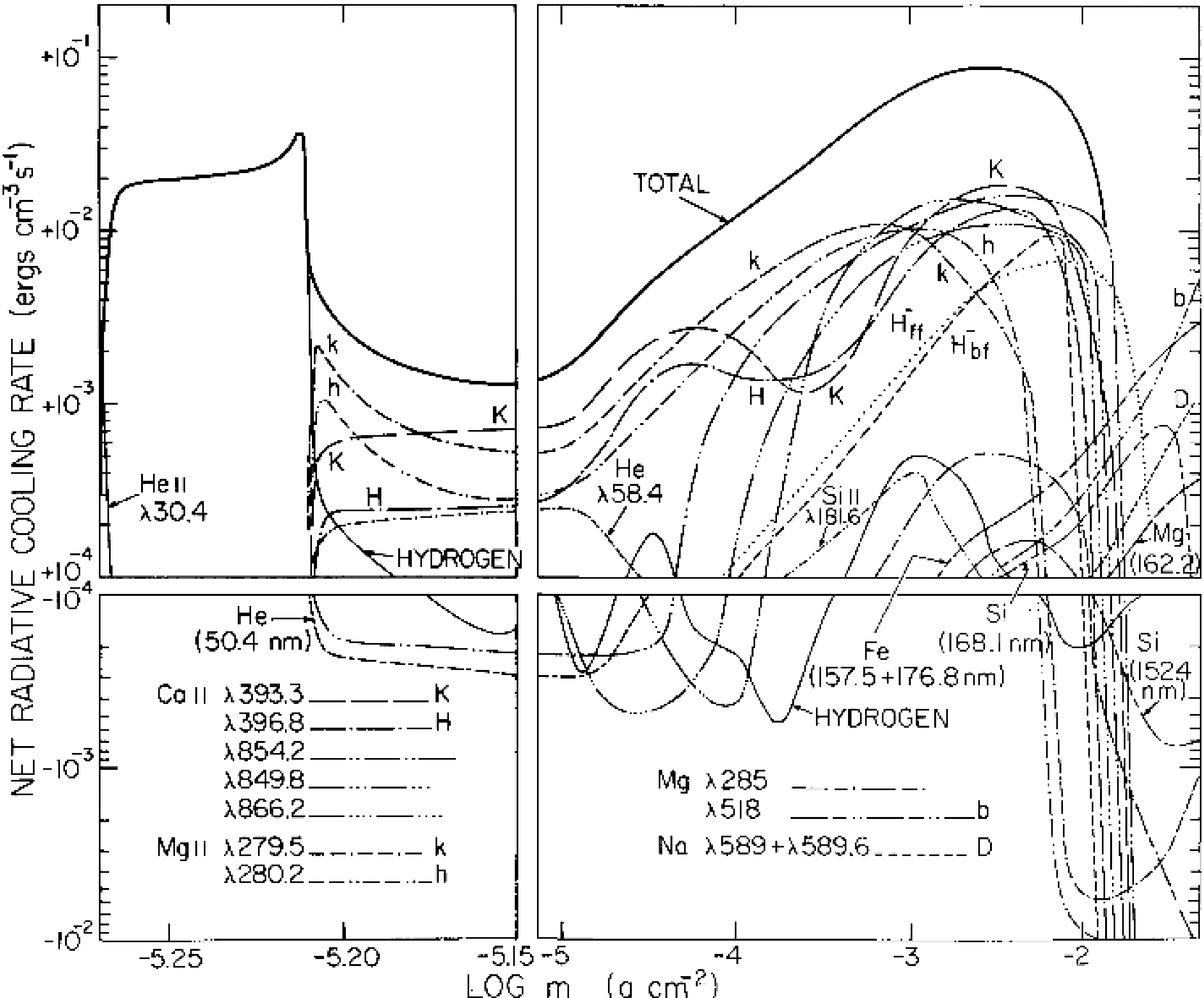
nosphere chrooma = [Greek] color; sphairos = [Greek] ball. The
osphere is a layer in the Sun that is roughly between about 400 kr
m above the solar surface. The temperature in the chromosphere
between about 4000 K at the bottom (the so-called temperature
um) and 8000 K at the top. The chromosphere shows up in image
n the center of the H-alpha spectral line and also (briefly) near the
ng and end of a total solar eclipse.(Sac Peak web-page)



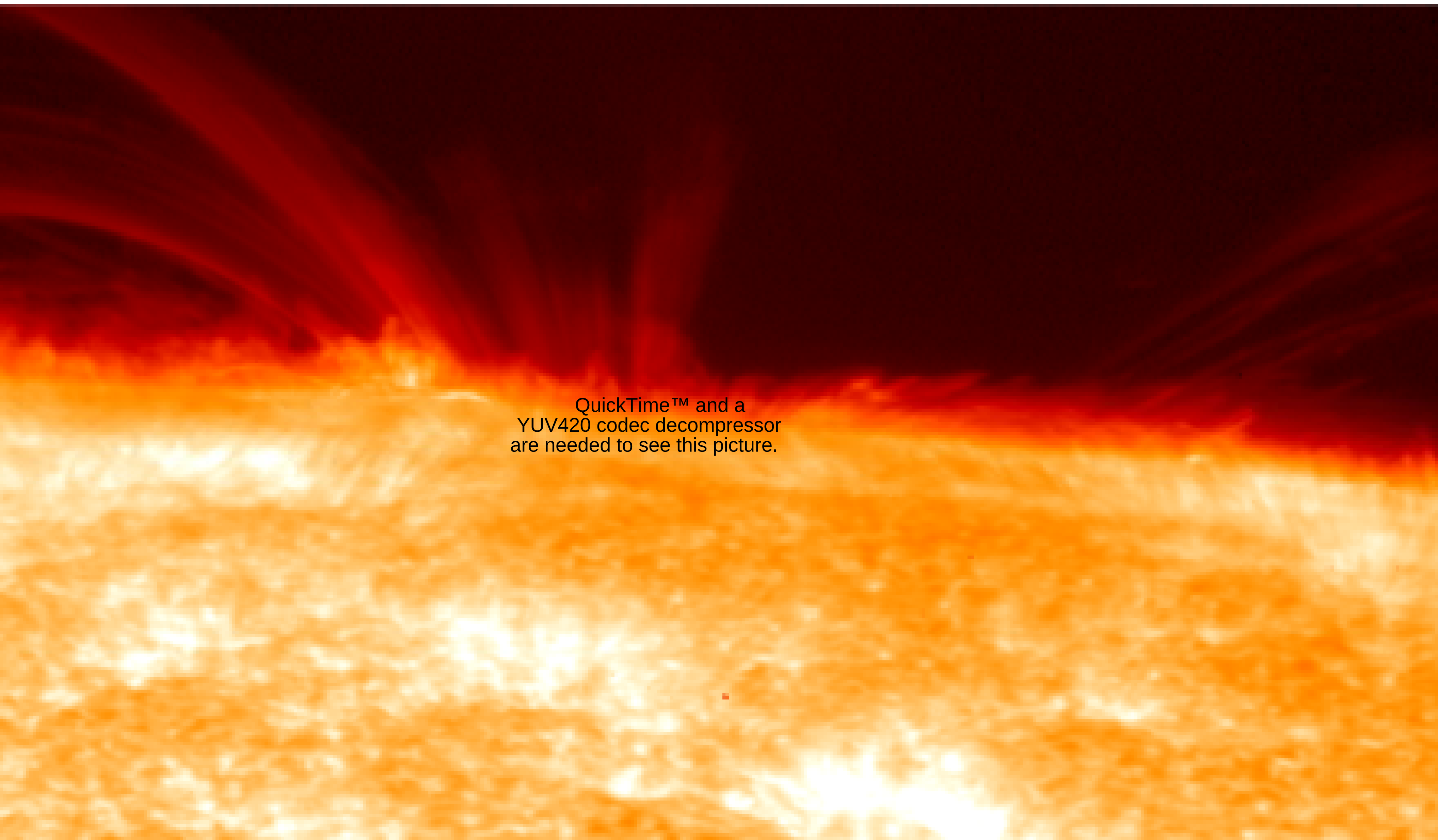
VAL3C



Mg II k line
k3
k2
k1
Ca II K line
K3
K2
K1
Hα (core)
Hα (wing)
3 cm
1cm
3 mm
1 mm
600 μm
300μm
150μm
50μm
T(10^3 K)
Lα(center)
Lα(peak)
H (70 nm)
H (90.7 nm)
Lα(1Å)
Lα(5Å)
C (109.8 nm)
Si(152.4 nm)
Fe, Si (157.5 nm)
Si (168.1 nm)
30
20
10
8
6
4
2500
2000
1500
1000
500
0
h (km)


NET RADIATIVE COOLING RATE (ergs cm^{-3}s^{-1})
+10^{-1}
+10^{-2}
+10^{-3}
+10^{-4}
-10^{-4}
-10^{-3}
-10^{-2}
He II λ30.4
k
h
K
H
HYDROGEN
He (50.4 nm)
Ca II λ393.3 K
λ396.8 H
λ854.2
λ849.8
λ866.2
Mg II λ279.5 k
λ280.2 h
TOTAL
K
h
k
H$^-_{ff}$
H$^-_{bf}$
He λ58.4
Si II λ181.6
b
D
Mg (162.2)
Si (168.1 nm)
Fe (157.5+176.8 nm)
Si (152.4 nm)
HYDROGEN
Mg λ285
λ518 b
Na λ589+λ589.6 D
-5.25
-5.20
-5.15
-5
-4
-3
-2
LOG m (g cm^{-2})

Ca II H as seen with Hinode

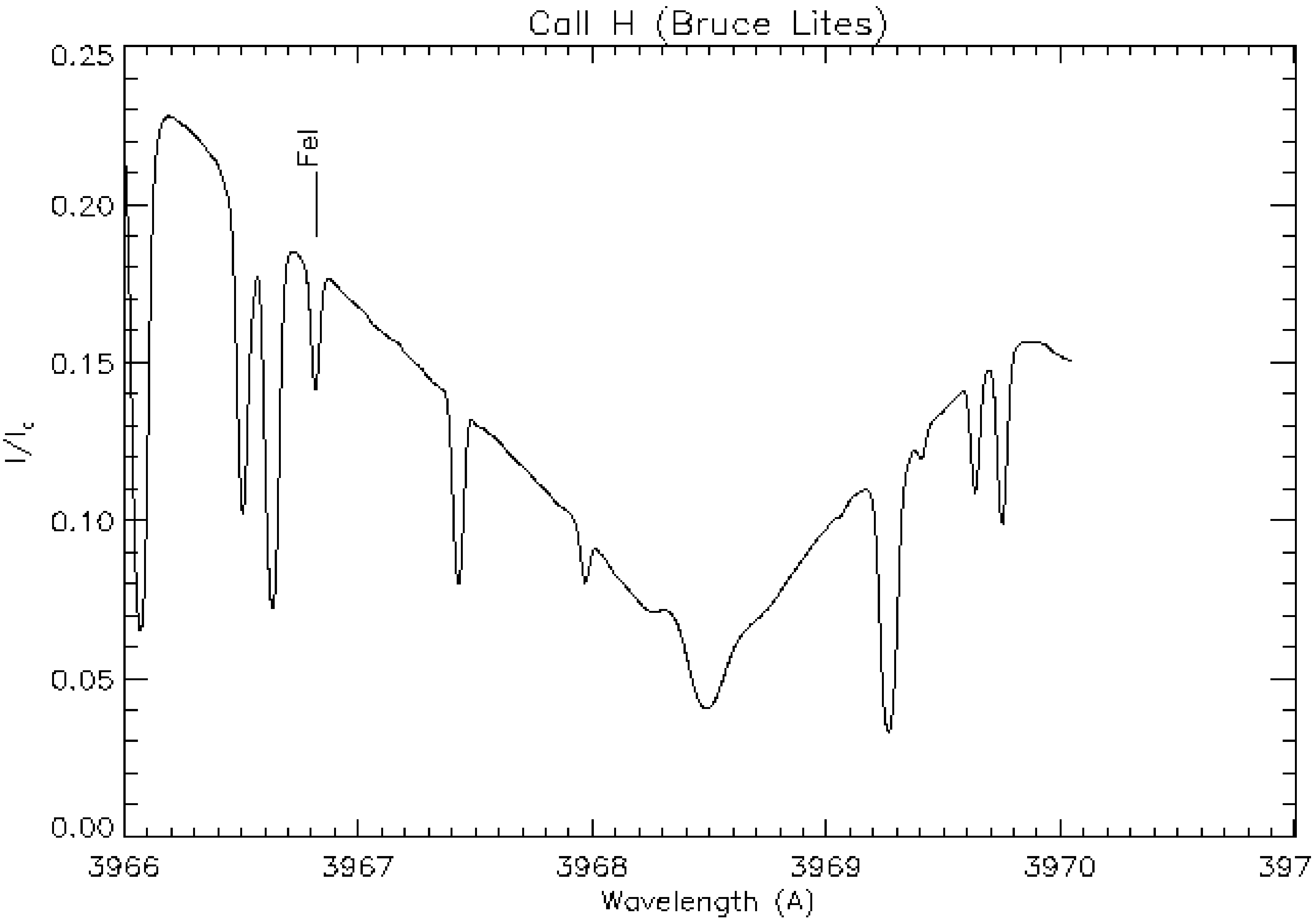


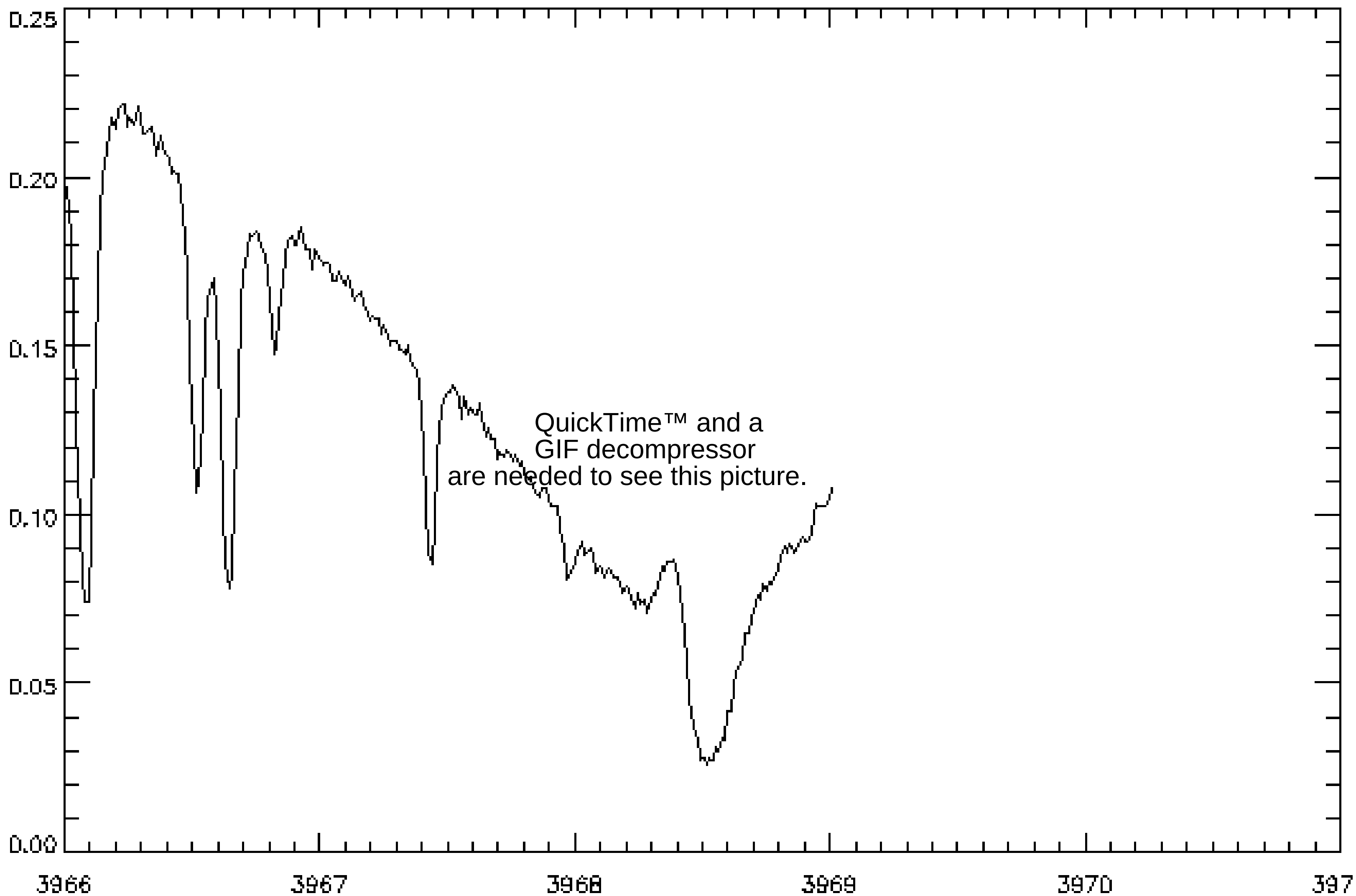
Chromospheric structure and oscillations

$$\frac{\partial^2 Q}{\partial t^2} - c_s^2 \frac{\partial^2 Q}{\partial z^2} + \omega_a^2 Q = 0$$

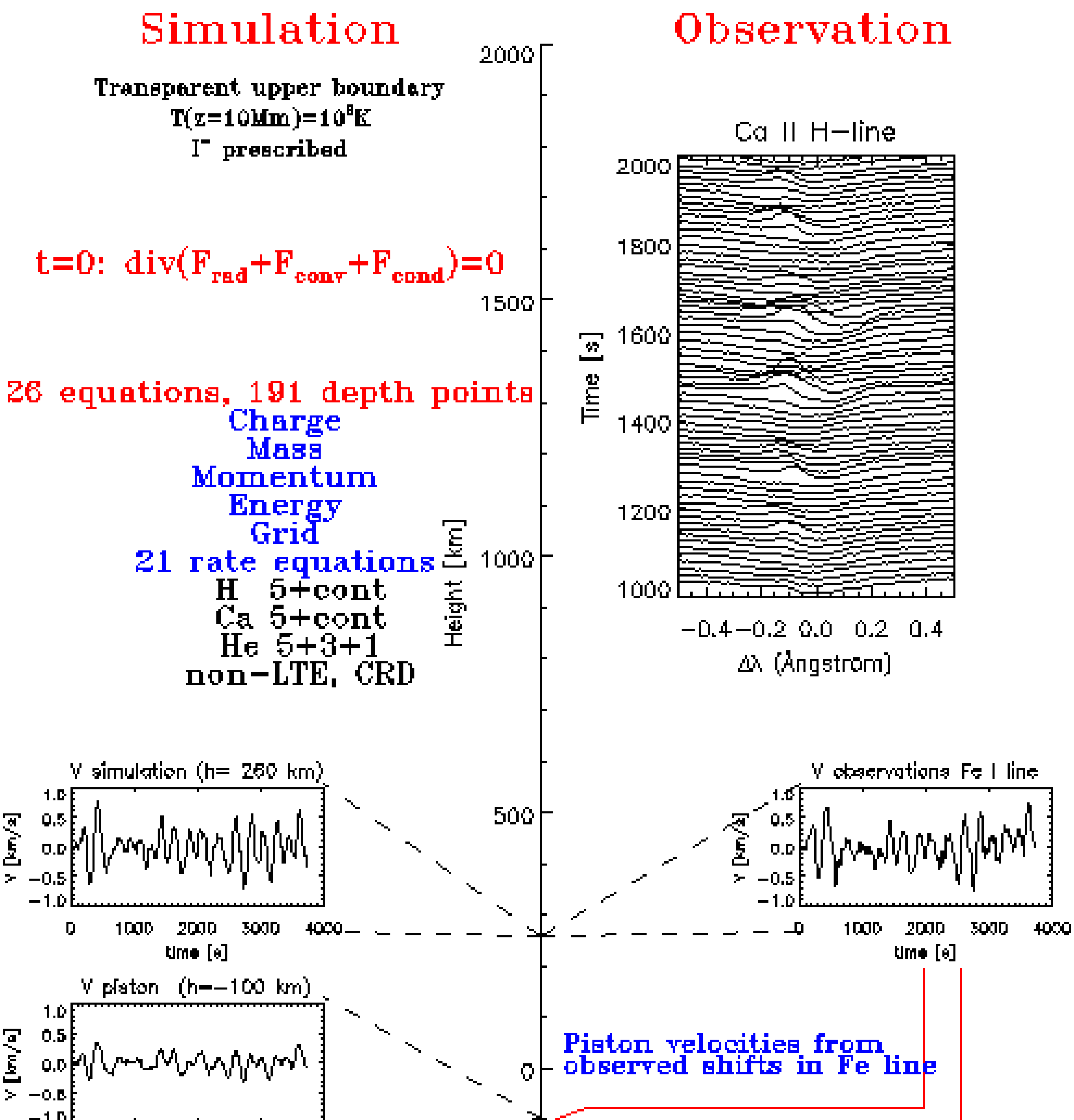
$$Q \equiv \rho_0(z)^{1/2} u, \quad \omega_a \equiv c_s/2H_p$$

The internetwork chromosphere may perhaps be considered as a gravitationally stratified isothermal slab. In which case we may combine the linearized mass, momentum and energy equations.

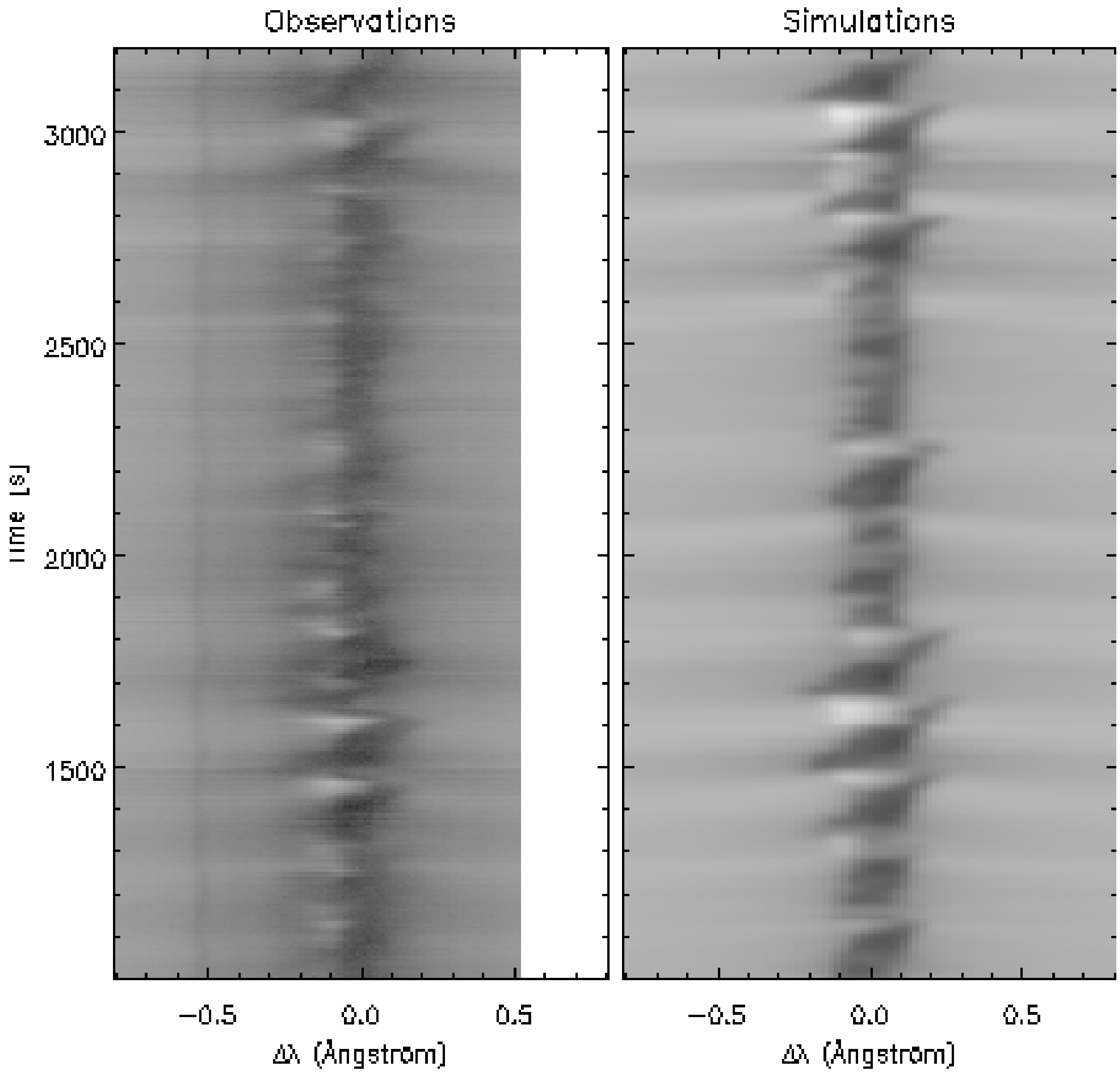

CaII H (Bruce Lites)
FeI
I/I_c
0.00
0.05
0.10
0.15
0.20
0.25
3966
3967
3968
3969
3970
3971
Wavelength (A)


0.25
0.20
0.15
0.10
0.05
0.00
3966
3967
3968
3969
3970
3971
QuickTime™ and a
GIF decompressor
are needed to see this picture.

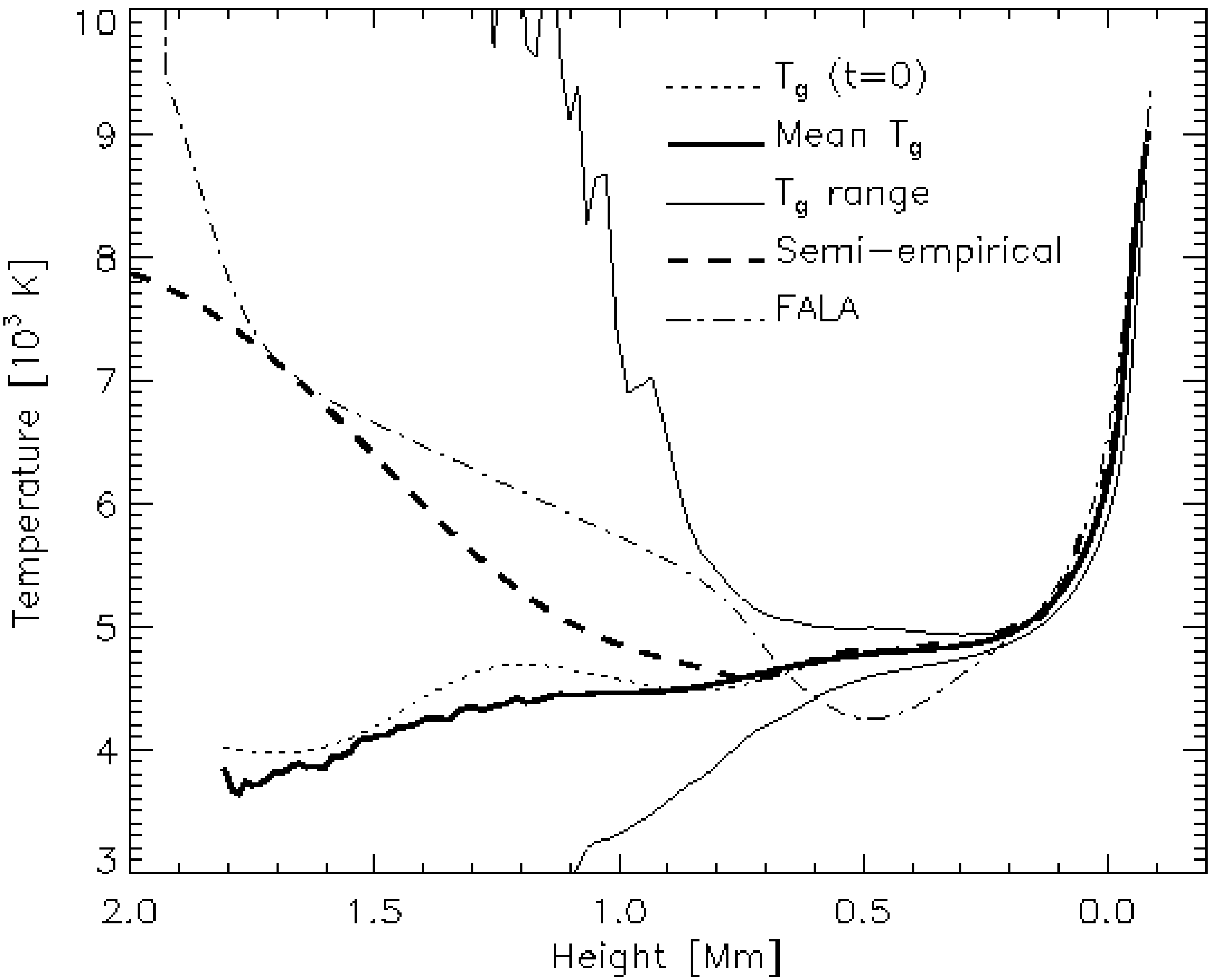
1D non-LTE simulation



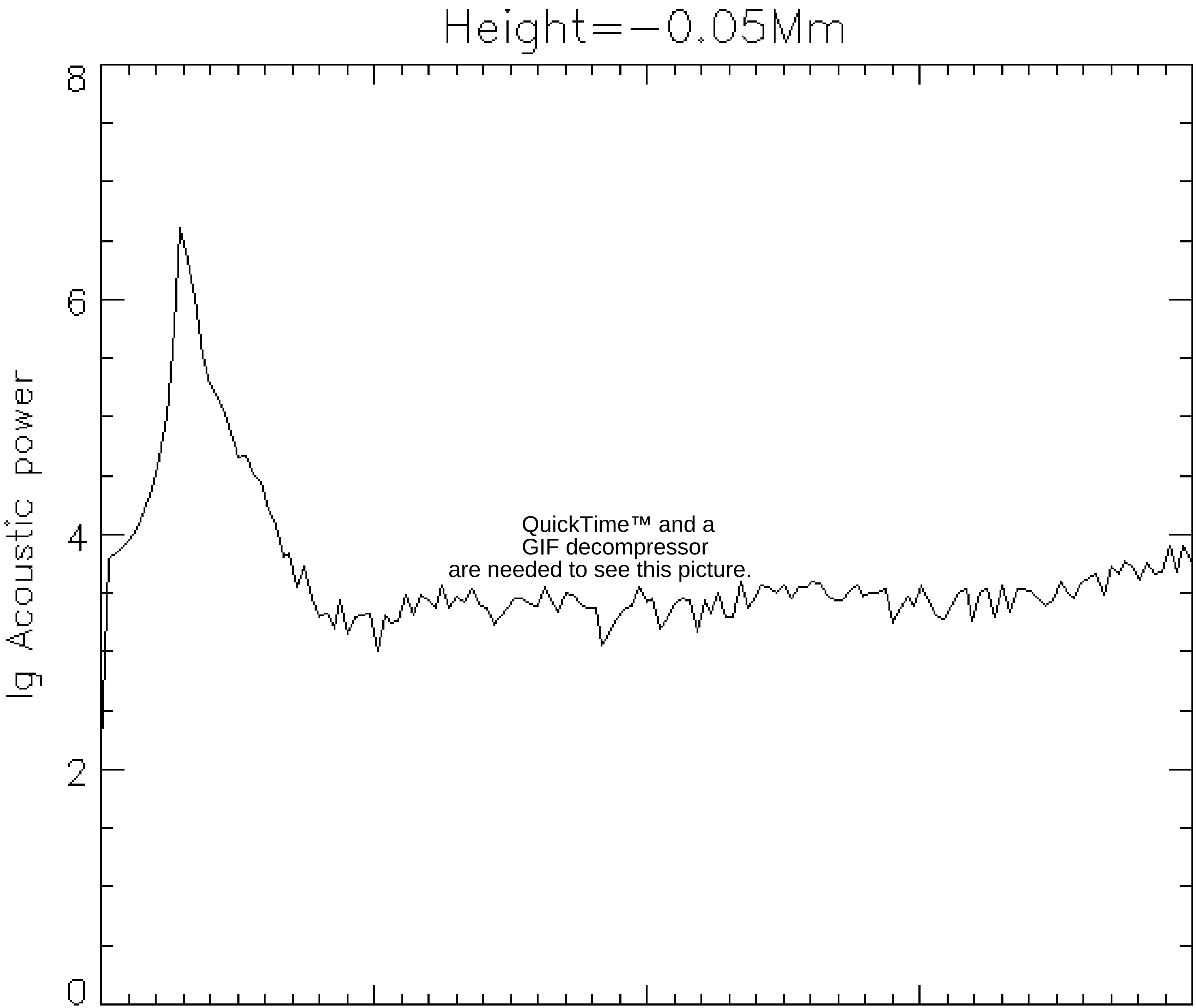
Ca II H-line intensity



Semi-empirical equivalent



Wave energy flux as function of height



What have we learnt?

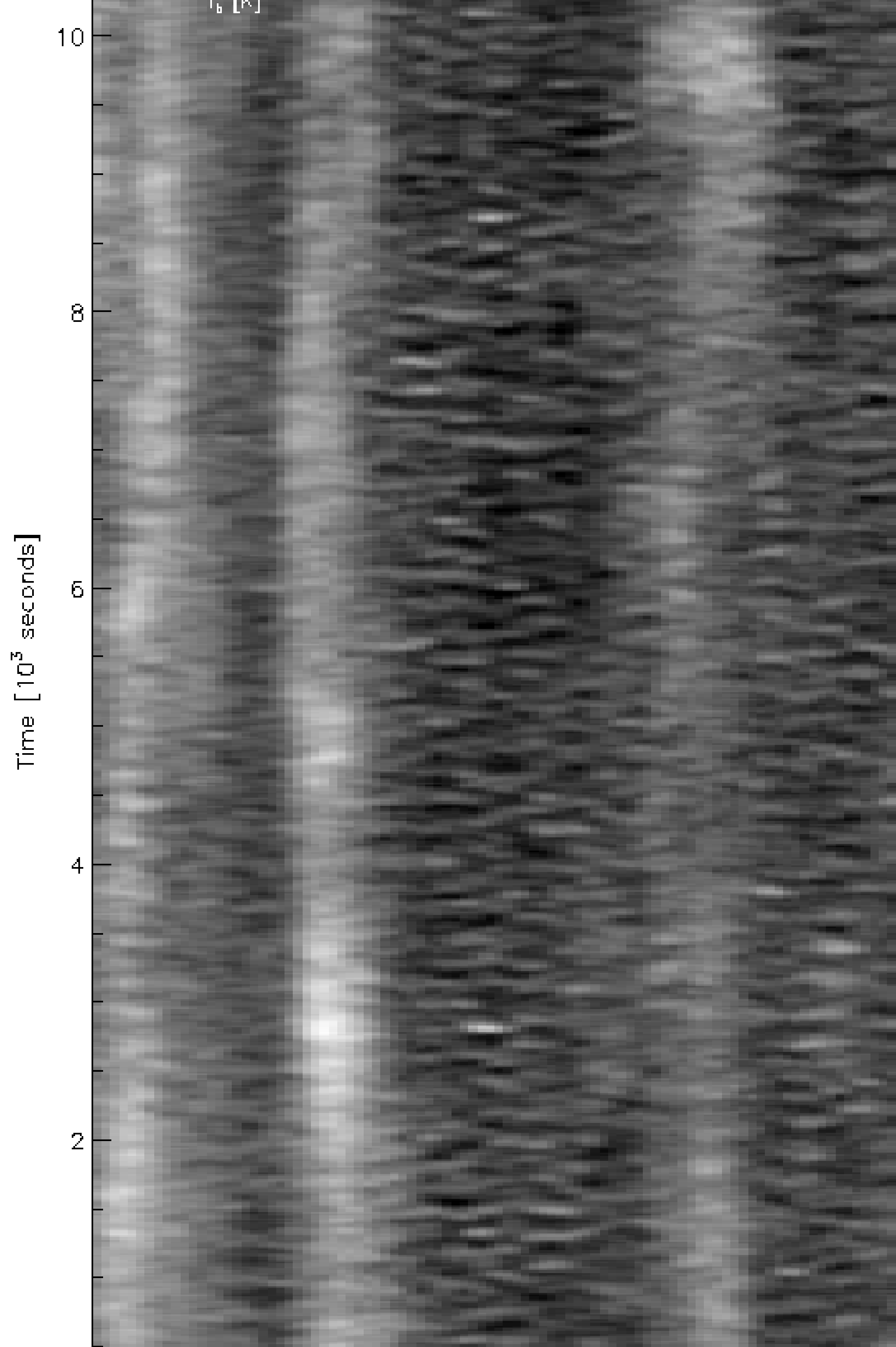
- Ca II grains explained by acoustic waves
    - only way to get strong blue-red assymetry is through a strong velocity gradient
- 3 min waves present already in photosphere
- Non-magnetic chromosphere very dynamic. There may be no temperature rise.
- Slow rates important for hydrogen ionization and energy balance in chromosphere
- Acoustic waves not enough to explain mid-upper chromosphere in internetwork

d speed with periods of
r 3 min/5 mHz

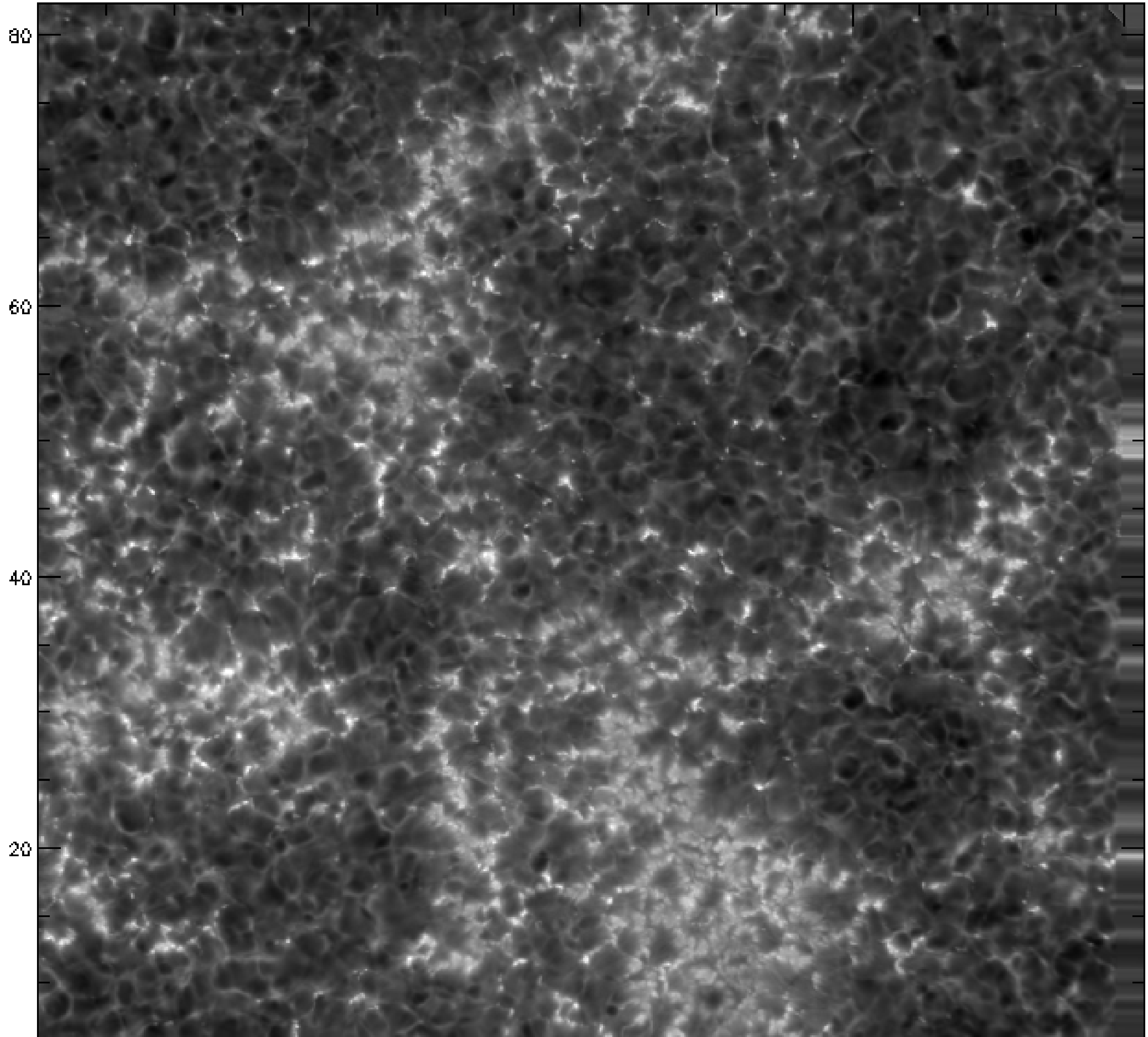
edicted by "Carlsson-Stein"
type models
ol. 397, no. 1, p. L59-L62)

l also observed at greater
nts in the atmosphere...
støl et al, 2000 (ApJ Volume 531,
, pp. 1150-1160)

ever... the Sun has magnetic
and more!!!



The chromospheric network



Network and inter-network

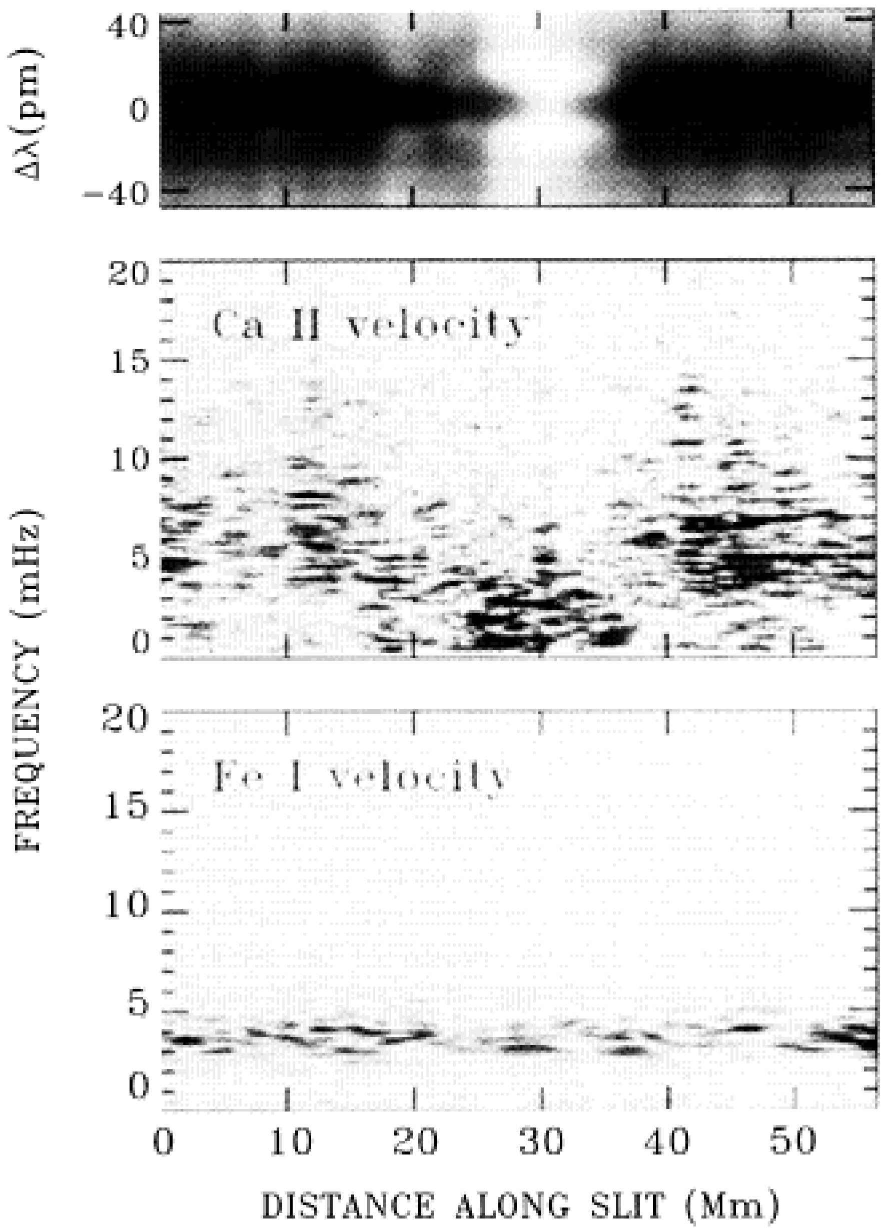
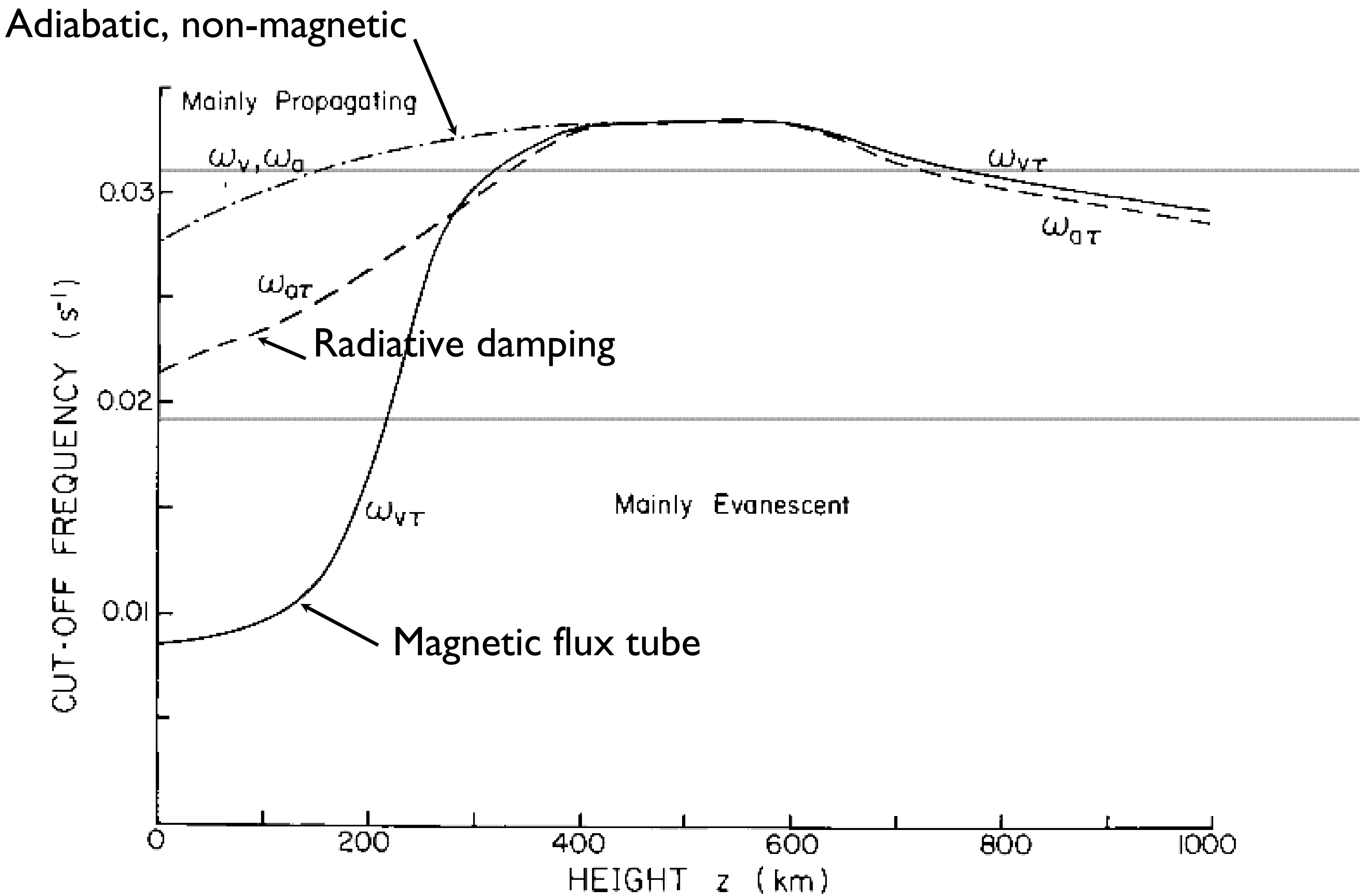
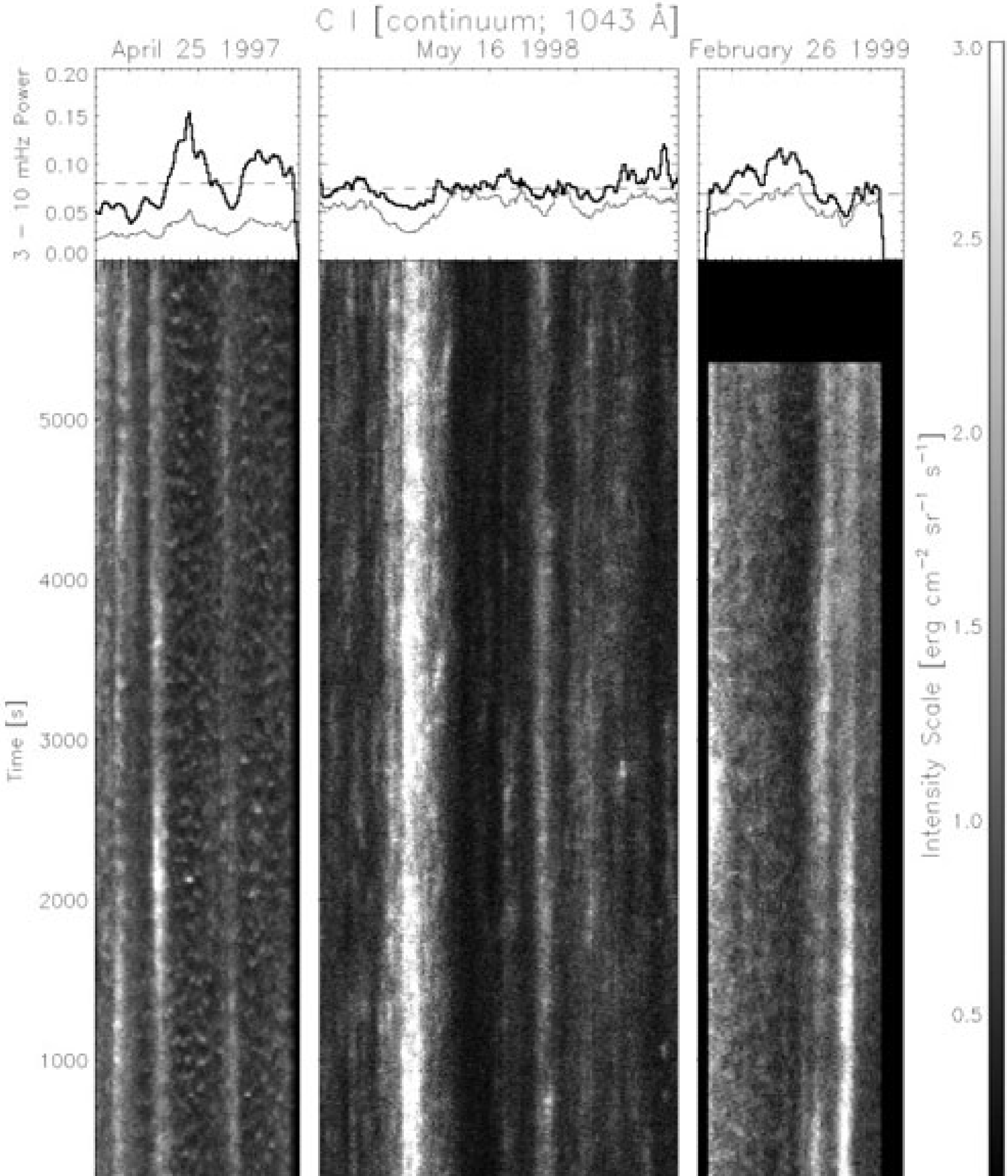


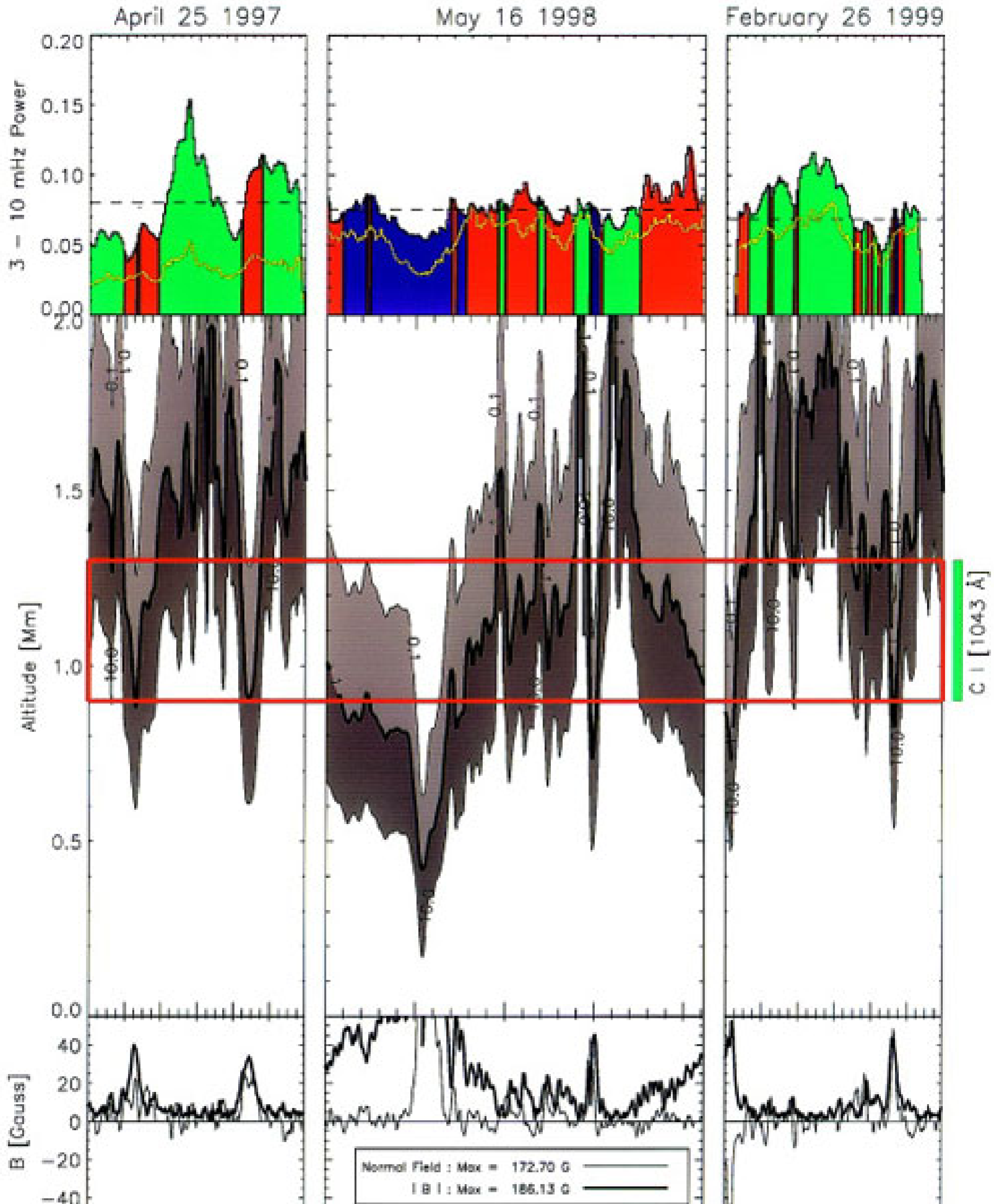
FIG. 4.—The top panel displays the time-averaged Ca II H profile as a function of spatial position. The bright K_2 bands in the middle reveal the segment of network covered by the slit. The middle and bottom panels show the power in the Doppler velocity fluctuations of Ca II H_3 and Fe I 396.682 nm, respectively, as a function of frequency of oscillation and spatial position along the slit. Darker gray-scale shading corresponds to higher power in the bottom two panels. These and subsequent power spectra are presented only out to $f = 20$ mHz, whereas the Nyquist frequency is at $f = 100$ mHz. However, all power spectra are featureless at the frequencies not shown.

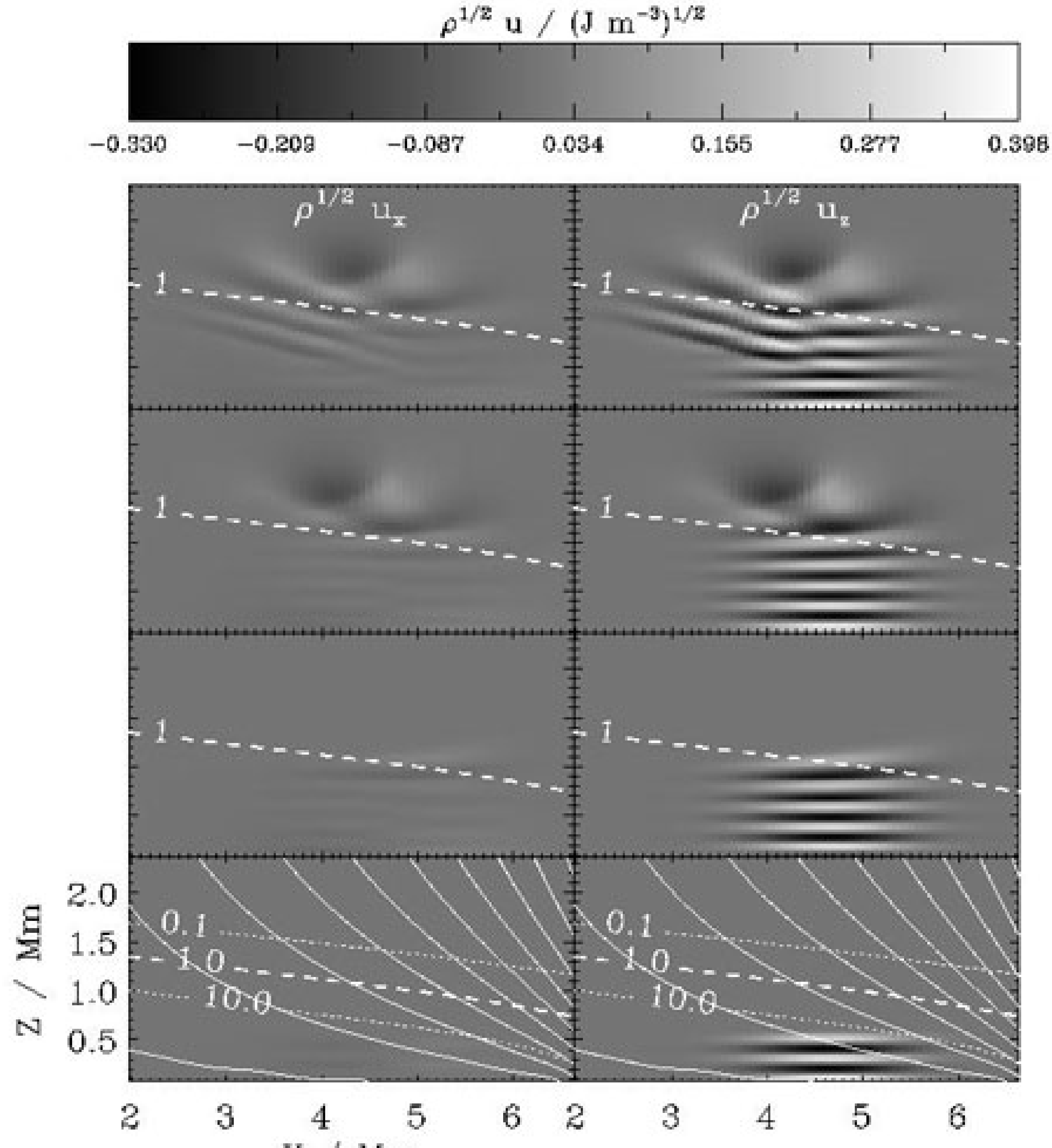


Roberts, 1983, Solar Physics 87,77

(McIntosh et al., 2001, ApJL 548, 237)

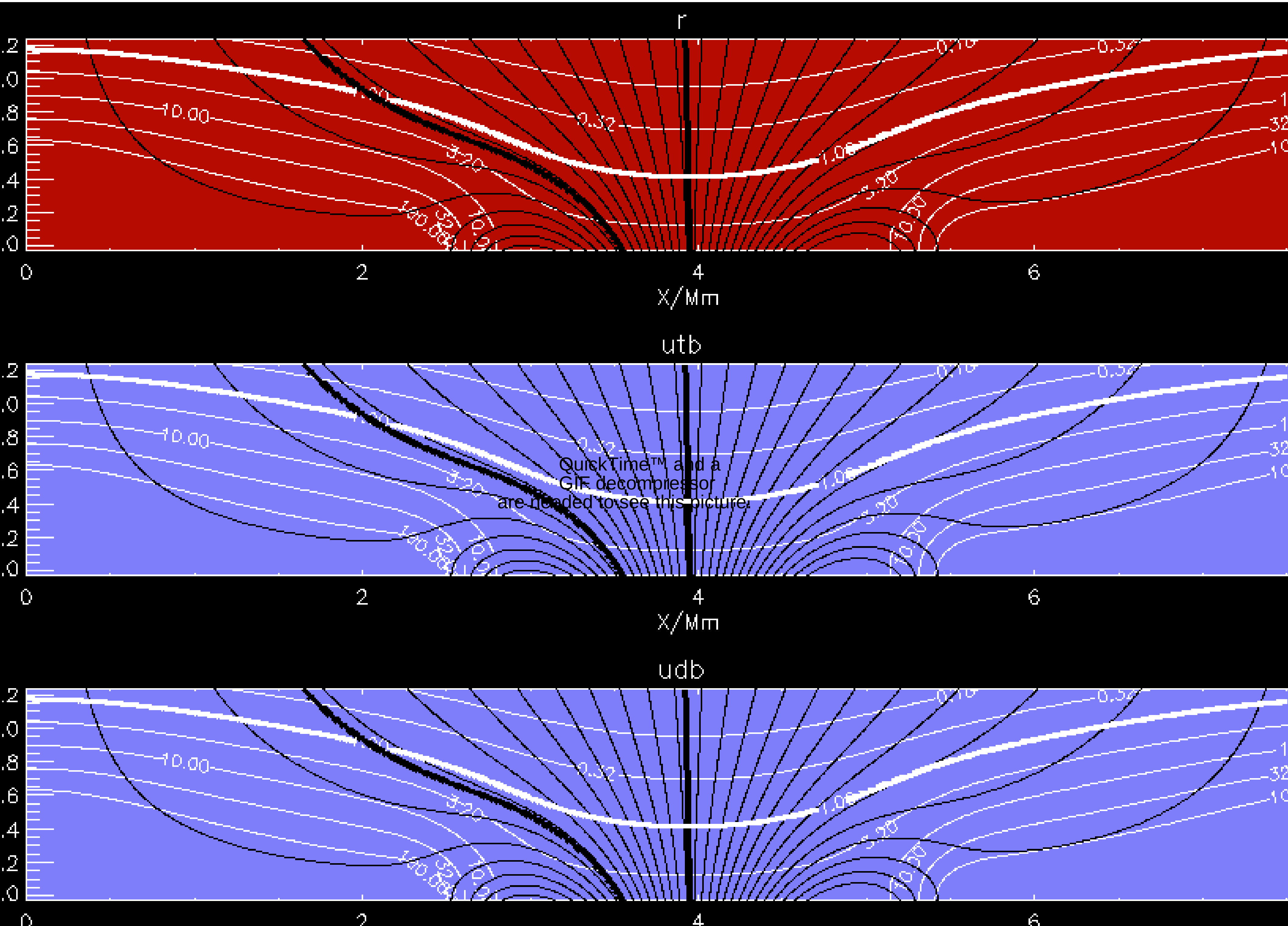



April 25 1997
May 16 1998
February 26 1999
3 – 10 mHz Power
Altitude [Mm]
B [Gauss]
C I [1043 Å]
Normal Field : Max = 172.70 G
| B | : Max = 186.13 G

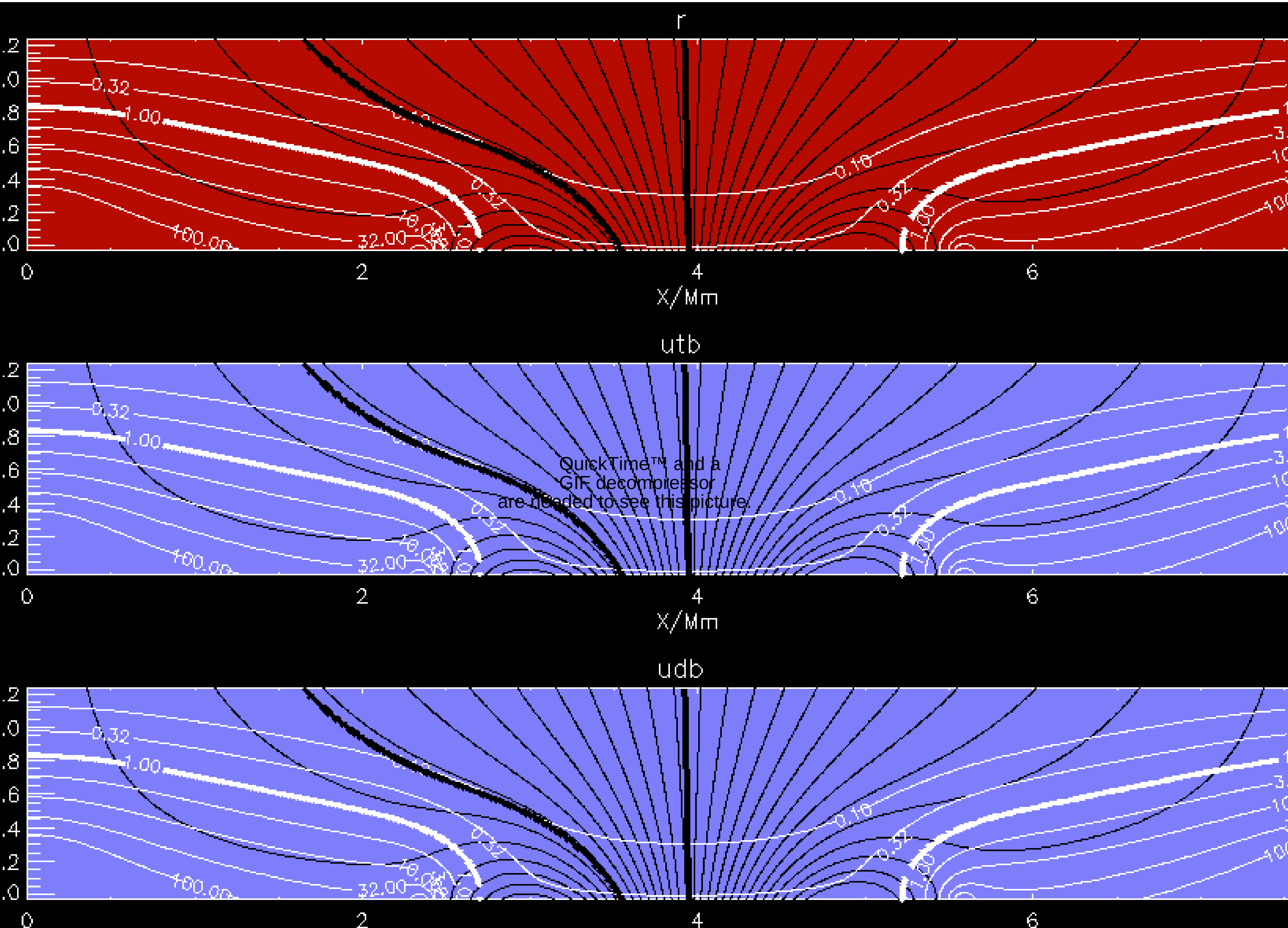


$\rho^{1/2}$ u / (J m^{-3})$^{1/2}$
−0.330
−0.209
−0.087
0.034
0.155
0.277
0.398
$\rho^{1/2}$ u_x
$\rho^{1/2}$ u_z
1
0.1
1.0
10.0
Z / Mm
2.0
1.5
1.0
0.5
2
3
4
5
6

Weak field - vertical driving

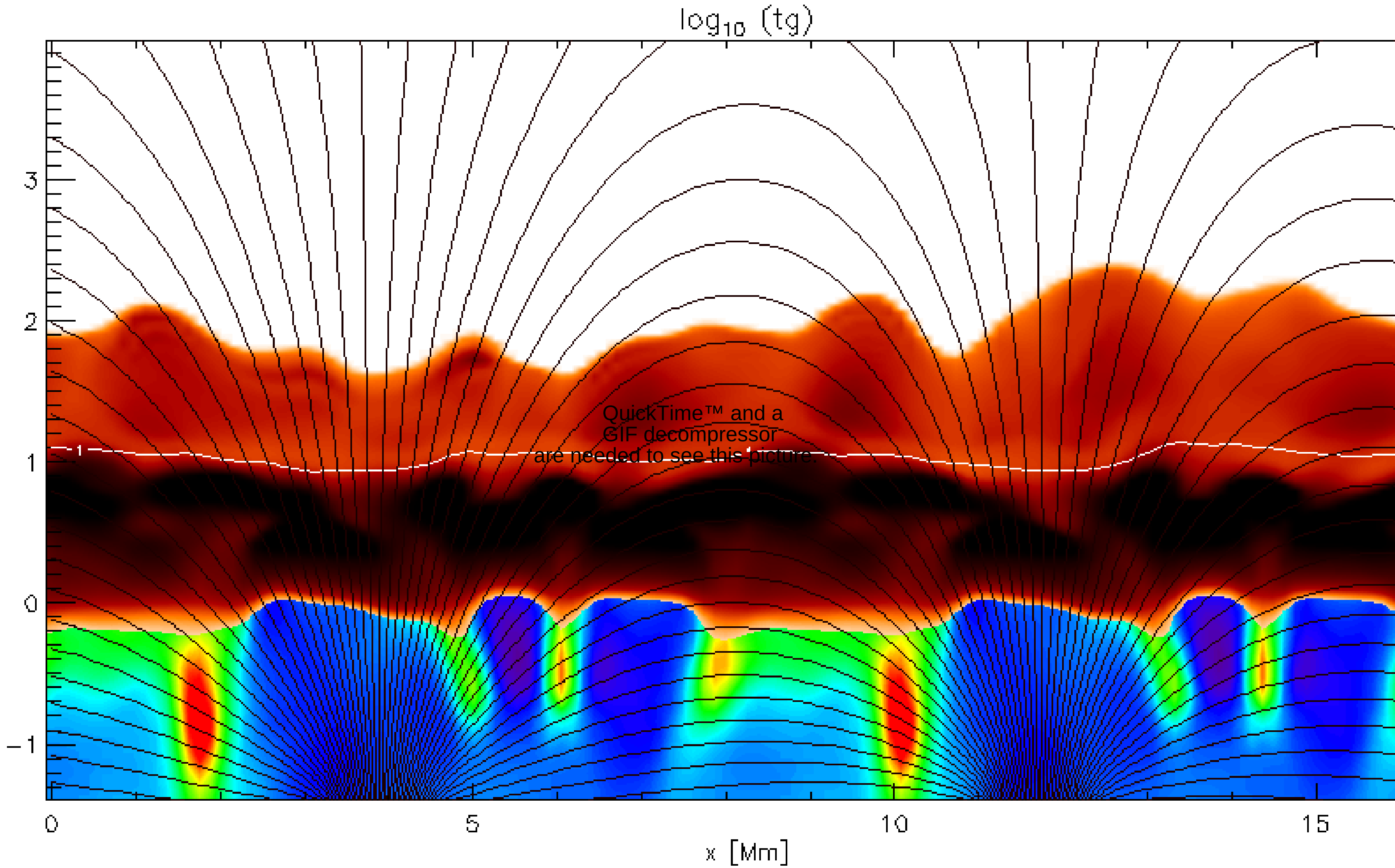


Strong field - vertical driving

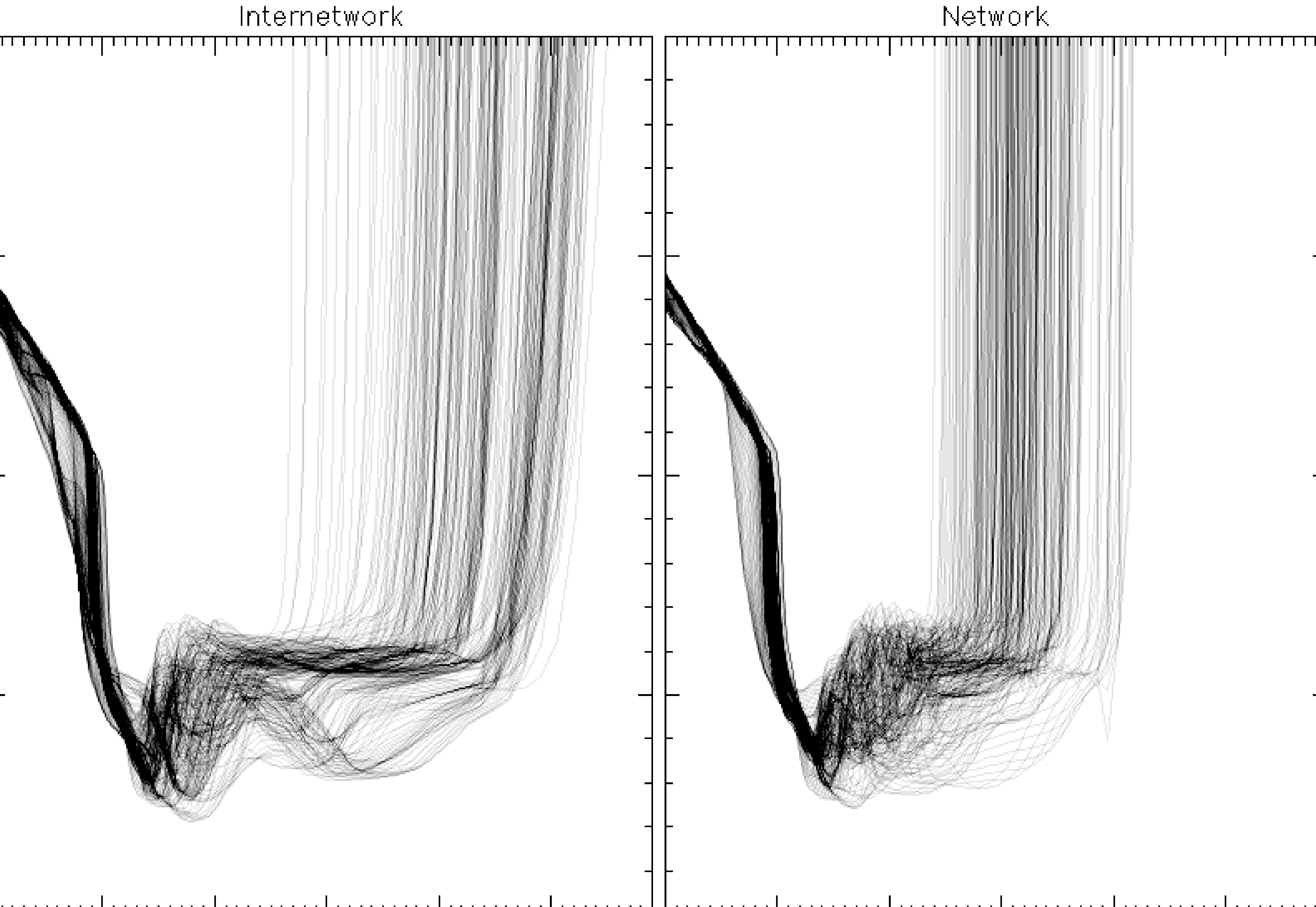


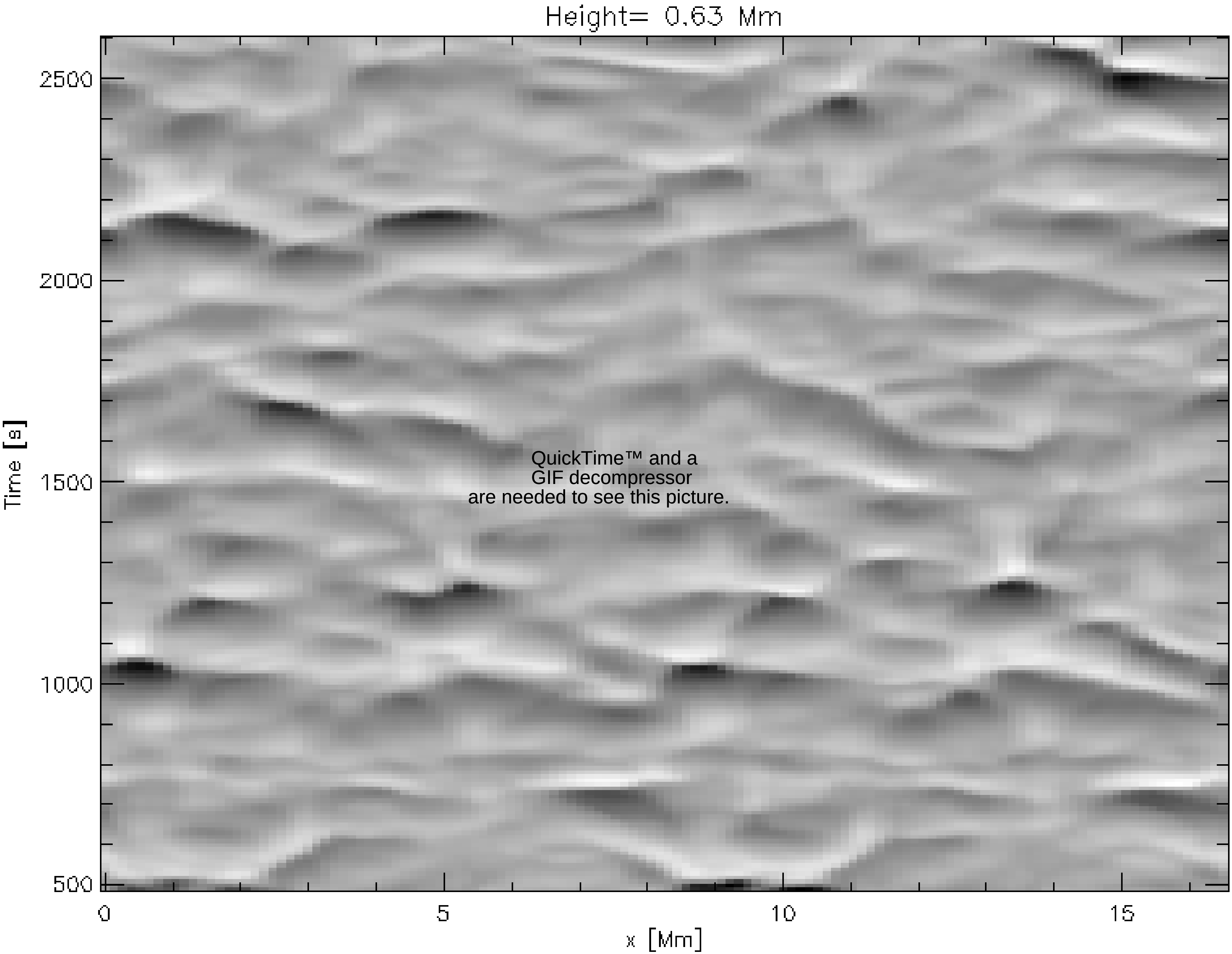
- Be aware of regions surrounding place where observations are obtained
    - Observation made in high or low beta plasma?
    - Closest approach of magnetic canopy
    - Where magnetic field at measurement site connects to photosphere
- Location of wave source and dominant state of polarization
    - Proximity may not be overriding factor...
- Understand that as many as three wave modes are moving information and energy

2D version



log10 (tg)
QuickTime™ and a
GIF decompressor
are needed to see this picture.
3
2
1
0
−1
0
5
10
15
x [Mm]

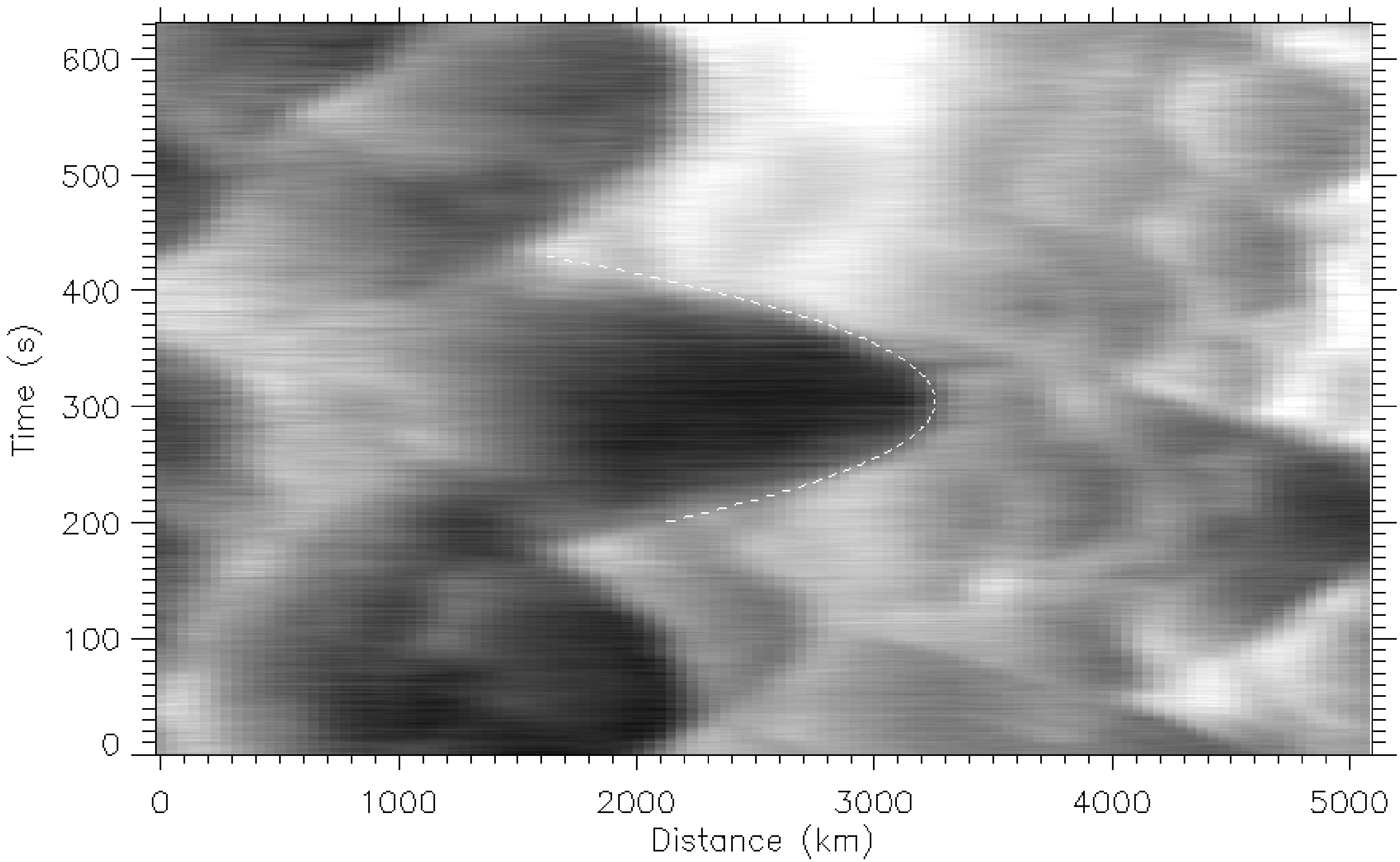

Internetwork
Network


Height= 0.63 Mm
Time [s]
2500
2000
1500
1000
500
x [Mm]
0
5
10
15
QuickTime™ and a
GIF decompressor
are needed to see this picture.

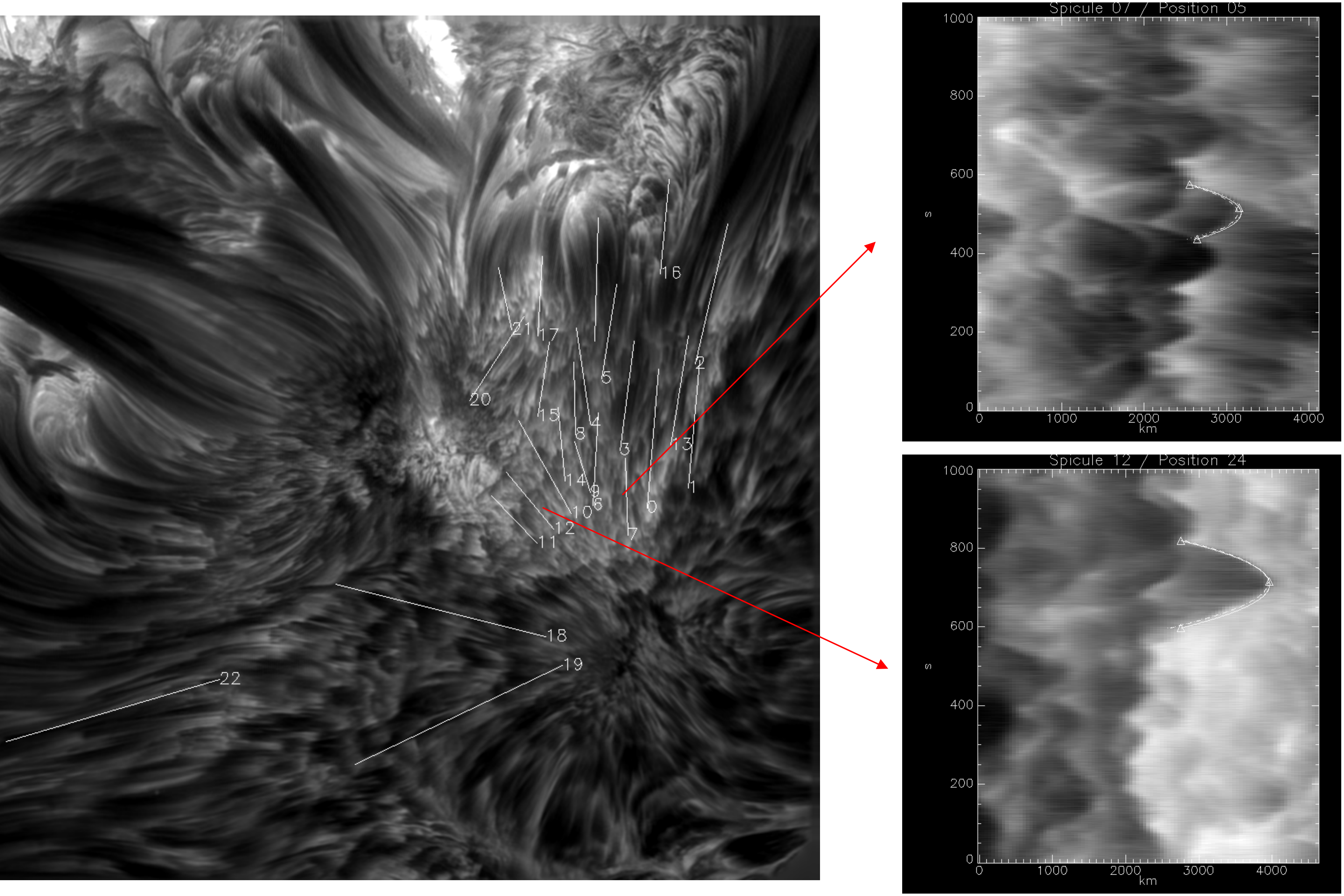
QuickTime™ and a
H.264 decompressor
are needed to see this picture.

Diffraction limited (0.2”), Ha linecenter at 1 s cadence, from 8:50 to 10:10 UT, m=0.78 (S8 E37)

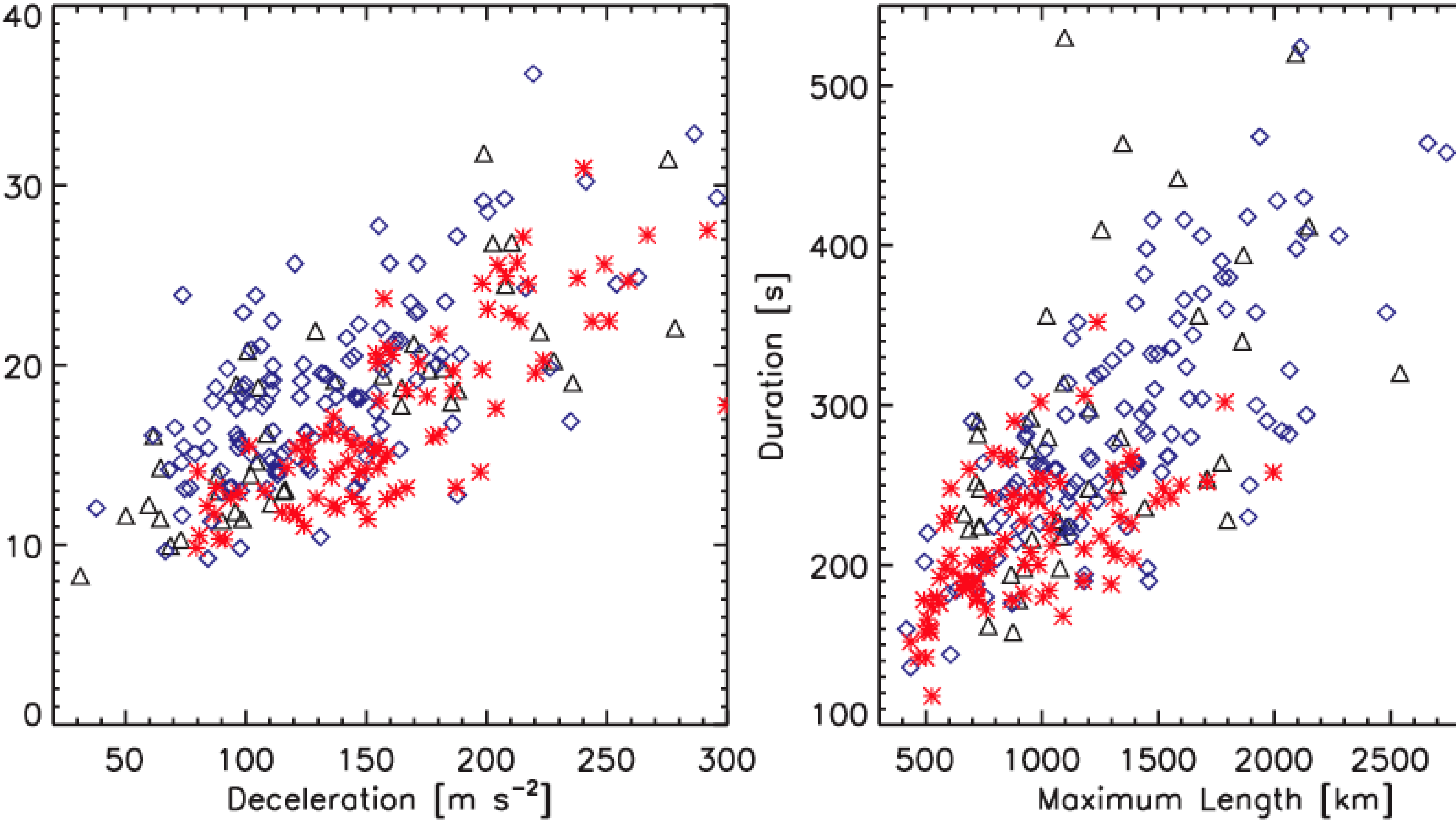
The life of a Dynamic Fibril



Dynamic Fibril Analysis

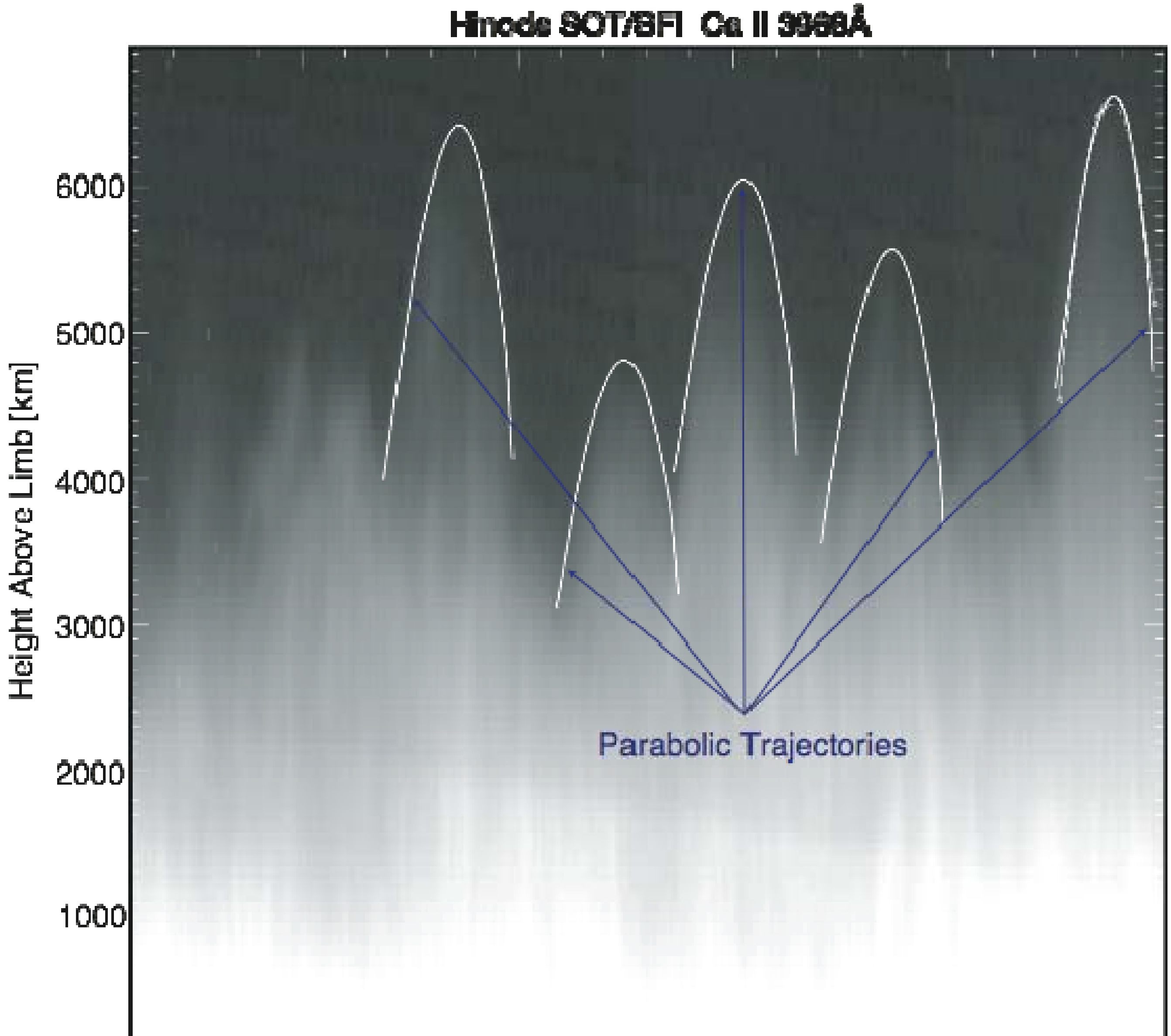


- Tracking 257 individual dynamic fibrils: Most follow a parabolic



- On average (but with large spread):
- Fast DFs are decelerated the most, and long DFs live the longest

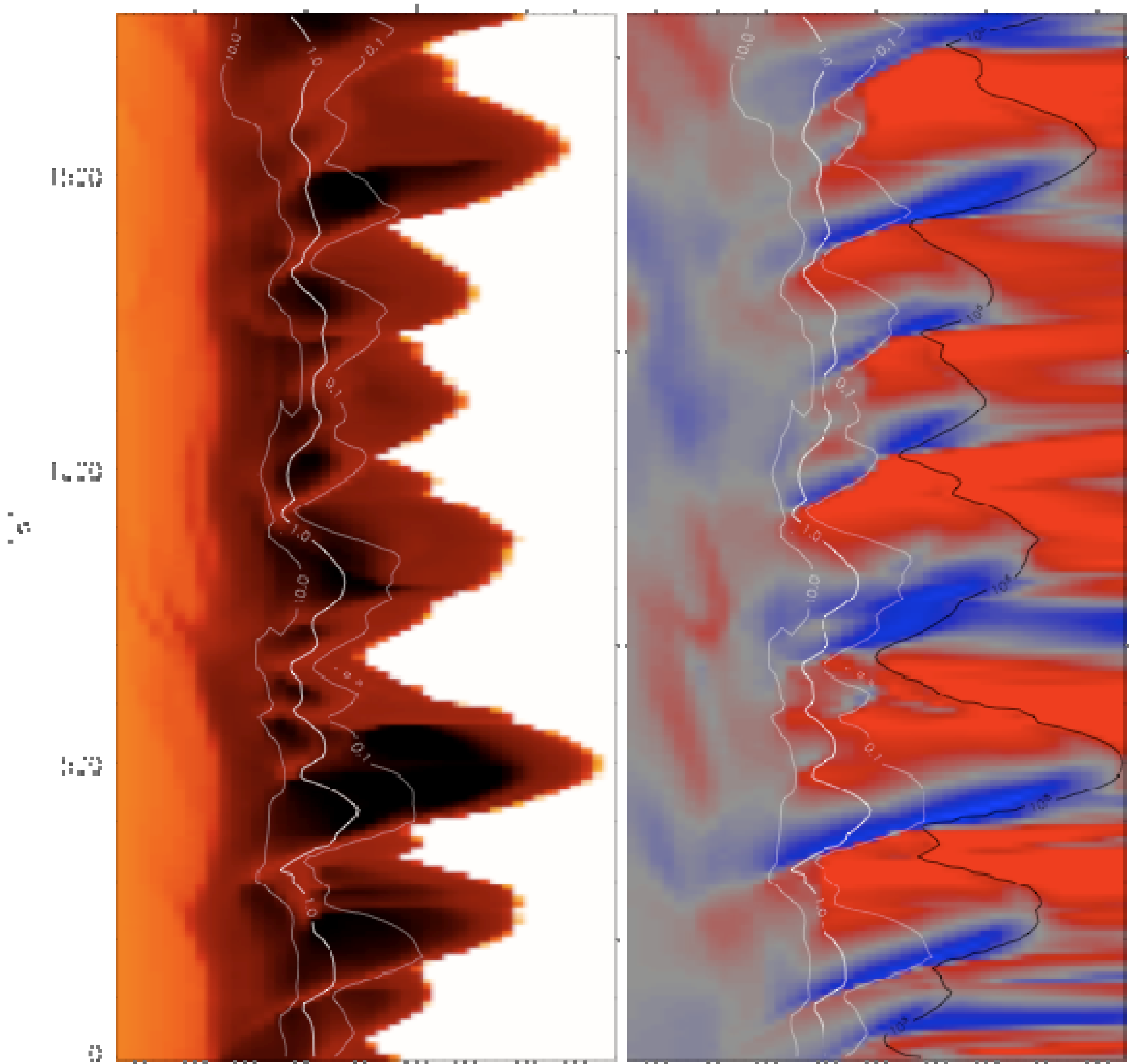
Parabolas in Ca II H as observed with Hinode



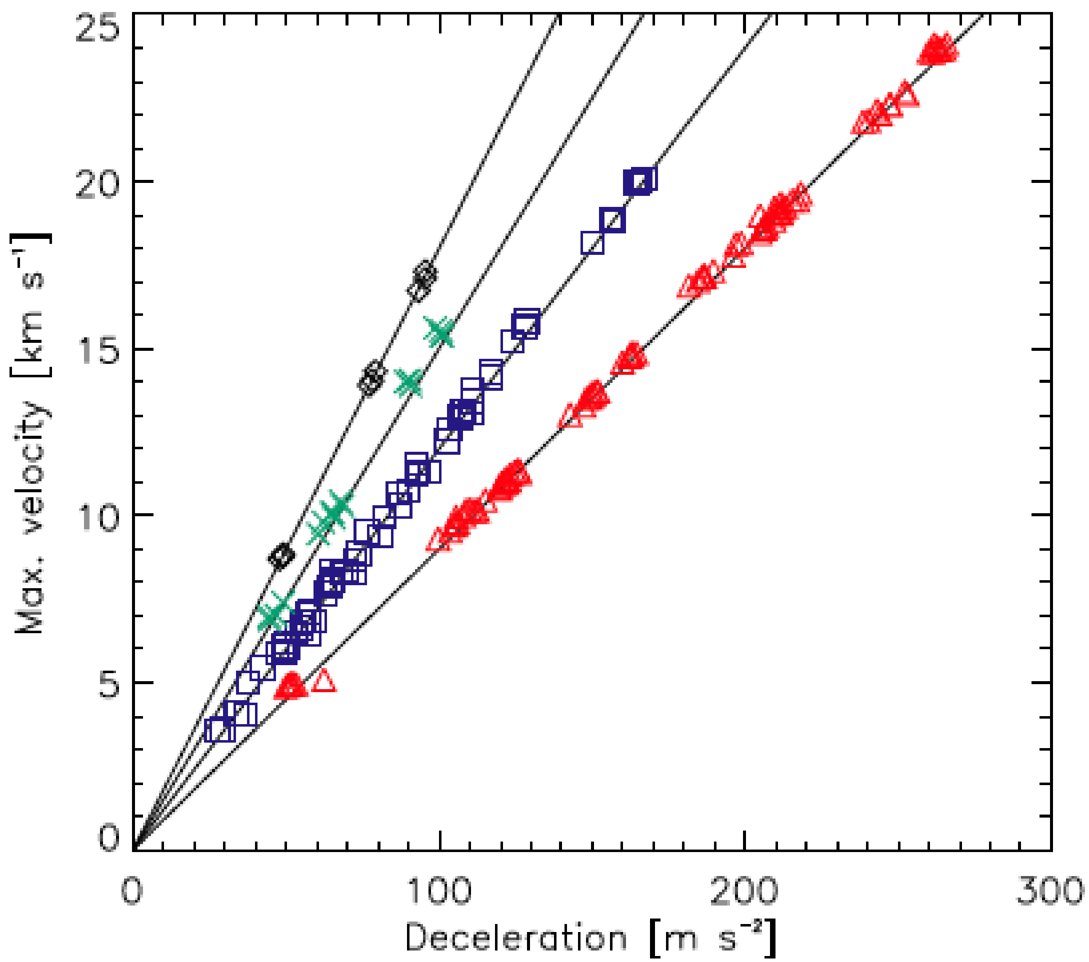
Simulations: inclined field

QuickTime™ and a
Foto - JPEG decompressor
are needed to see this picture.

Simulated log Tg and uz

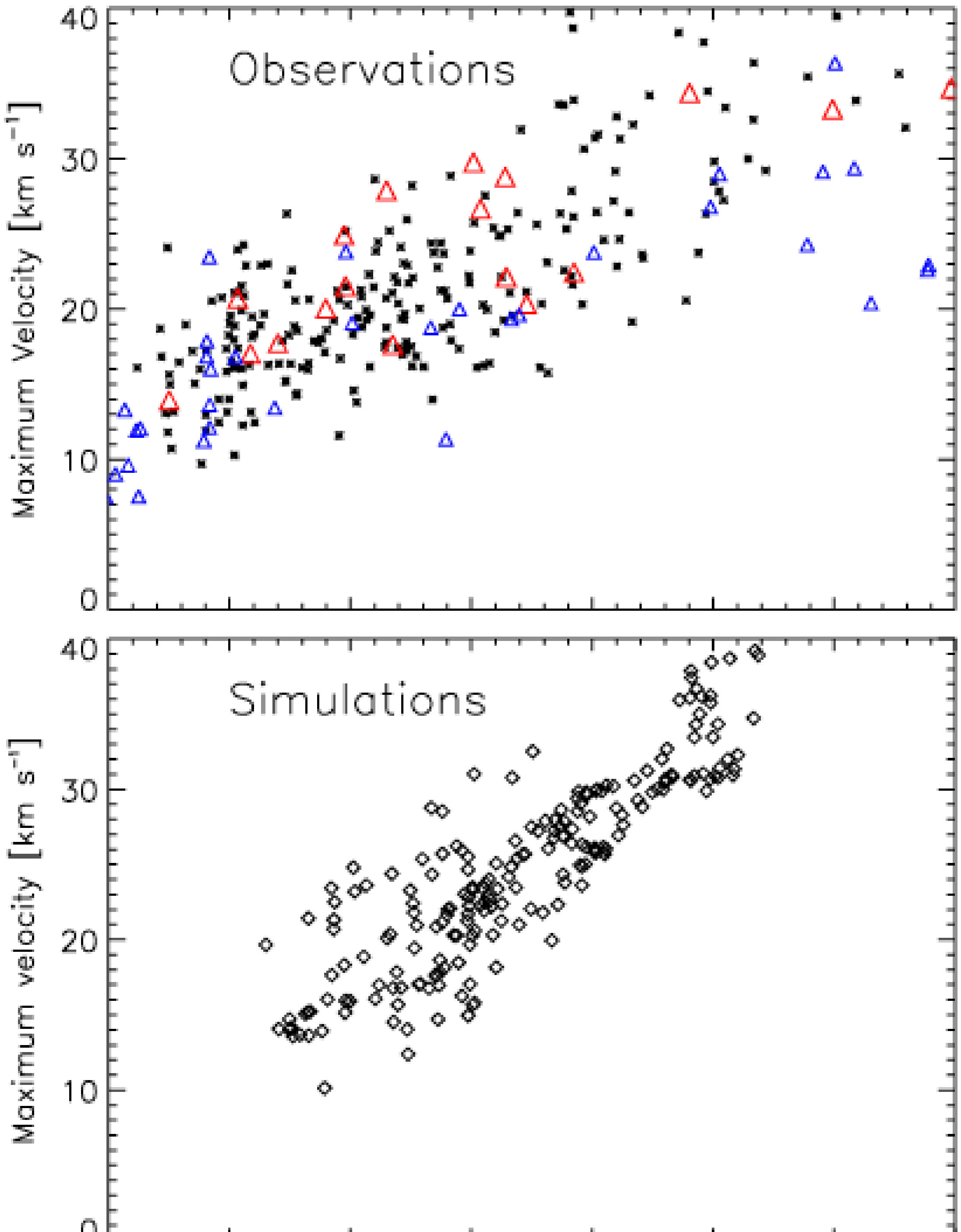


How can waves give correlation between deceleration and max velocity?

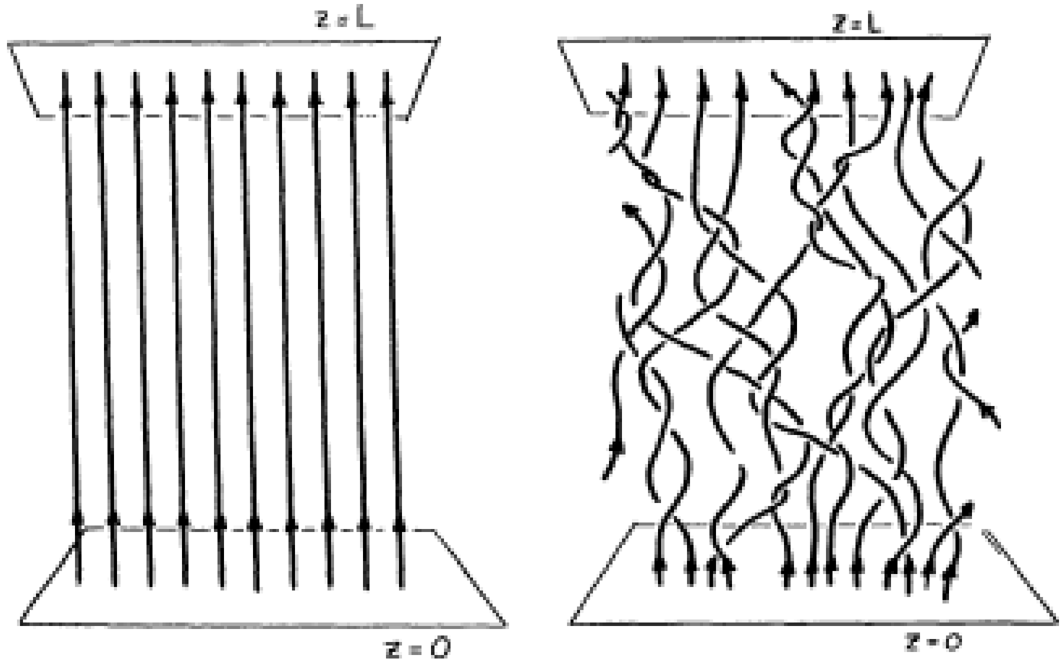


Deceleration given by $d = \frac{v_{max}}{P/2}$

velocity/deceleration



Coronal Heating



(a) (b)

Fig. 2. (a) A sketch of the initial uniform magnetic field B_0 through $0 < z < L$. (b) A sketch of the continuous field of equation (2).

Parker, E.N., 1991, Reviews in Modern Astronomy, p 1-17

Coronal heating questions

- AC or DC?
- Constant or episodic?
- How is energy flux thermalized?
- Need continual injection of new magnetic flux?
- Robust diagnostics that can separate various scenarios?

Nano-, micro-, and milliflares

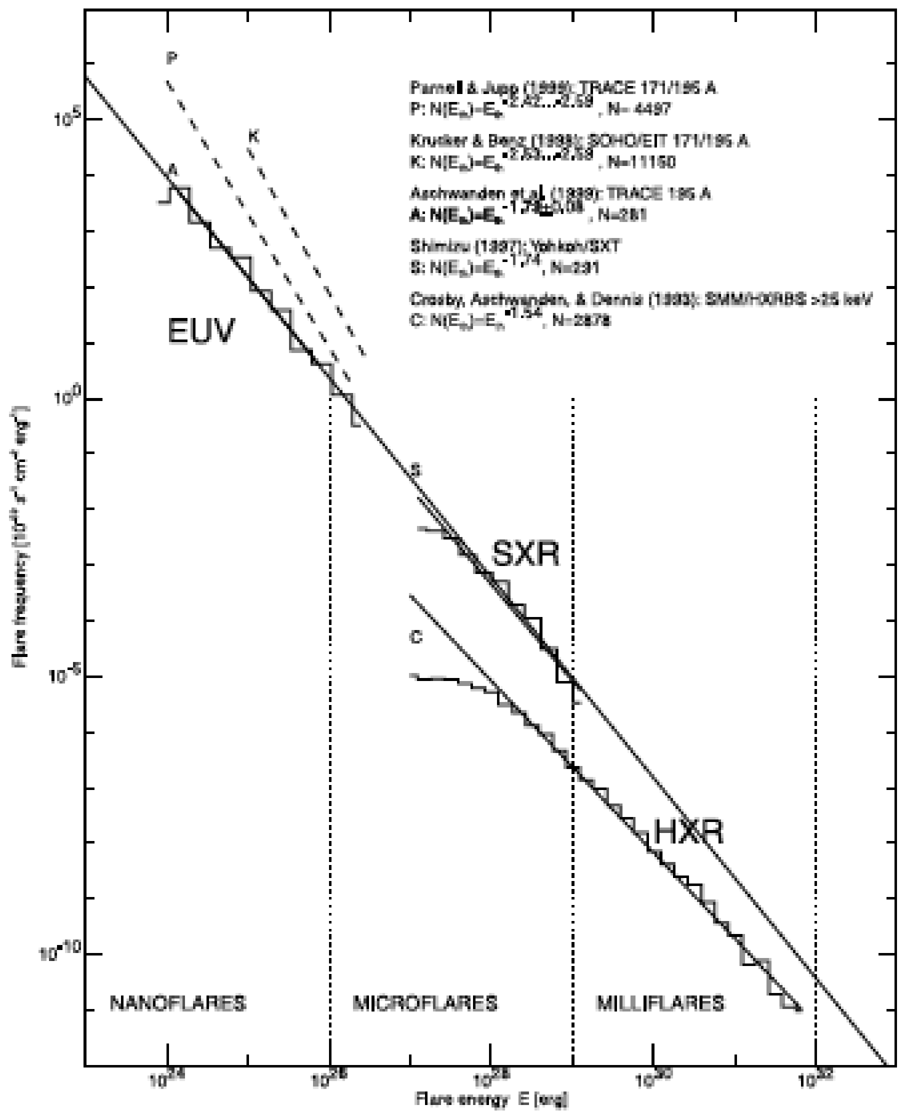


FIG. 10.—Composite flare frequency distribution in a normalized scale in units of 10^{-50} flares per time unit (s^{-1}), area unit (cm^{-2}), and energy unit ($ergs^{-1}$). The diagram includes EUV flares analyzed here (A), from Krucker & Benz (1998), from Parnell & Jupp (2000; with the steeper slope of -2.4 referring to a constant column depth, while the flatter slope of -2.0 refers to the same flare loop model as used here), the distribution of transient brightenings in SXR (Shimizu 1997) and HXR (Crosby et al. 1993). All distributions are specified in terms of thermal energy $E_{th} = 3n_e k_B T_e V$, except for the case of HXR flares, which is specified in terms of nonthermal energies in greater than 25 keV electrons. The slope of -1.8 is extended over the entire energy domain of 10^{24}–10^{32} ergs, yielding also a thermal energy estimate for the HXR flares.

Aschwanden et al., 2000, ApJ 535,

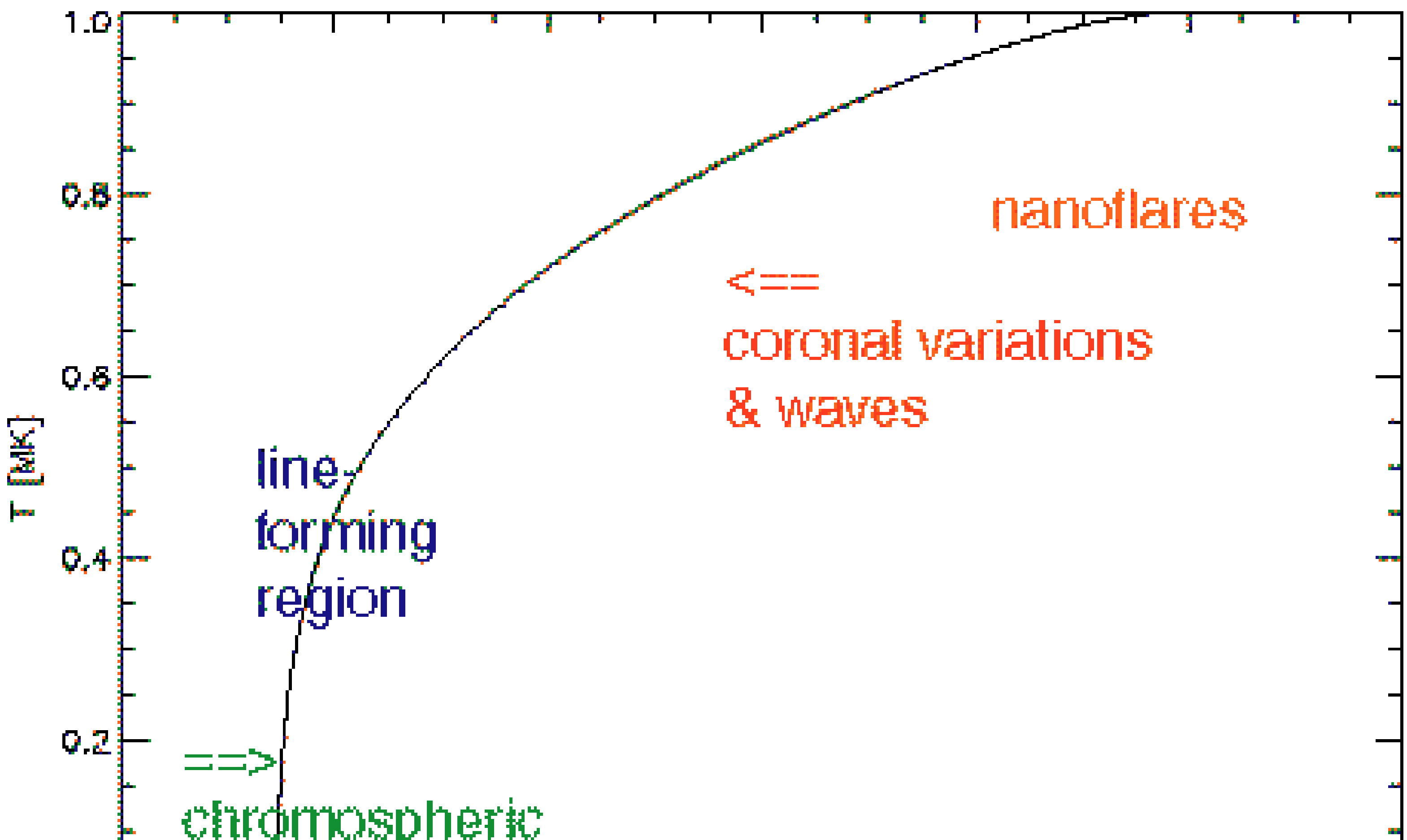
Why is the corona 1 MK?

- Temperature set by balance of energy gains and losses
- Possible coronal energy losses are radiation, conduction, and solar wind acceleration
  - Radiative losses given by $n_\mathrm{e} n_\mathrm{H} f(T_\mathrm{e})$
  - Conduction given by $-\kappa_0 T_\mathrm{e}^{5/2} \dfrac{dT_\mathrm{e}}{dz}$
- Efficiency of conduction poor at low T, efficiency of radiation poor at low n

Transition Region Structure

$$F_c \approx \text{constant} \approx 100\ W/m^2$$

$$F_c = \kappa_0 T^{5/2} \frac{dT}{dz}$$



Line emission from the optically thin Transition Region

$$I_\nu = \frac{h\nu}{4\pi}\int_0^s n_u A_{ul} ds = \frac{h\nu}{4\pi}\int_0^s n_l C_{lu} ds$$

$$n_l = \frac{n_l}{n_i}\frac{n_i}{n_H} = \frac{n_l}{n_i} A_i n_H$$

$$C_{lu} = n_e C_0 T_e^{1/2} \exp\left(-\frac{h\nu}{kT_e}\right)\Gamma_{lu}(T_e)$$

$$\begin{aligned} I_\nu &= \frac{h\nu}{4\pi} A_i C_0 \int_0^s n_e n_H g(T_e) ds \\ &\propto E(T_e) \equiv \int_{\Delta T} n_e n_H (ds/dT_e) dT_e \end{aligned}$$

The differential emission measure (DEM)

164 WARREN Vol. 157

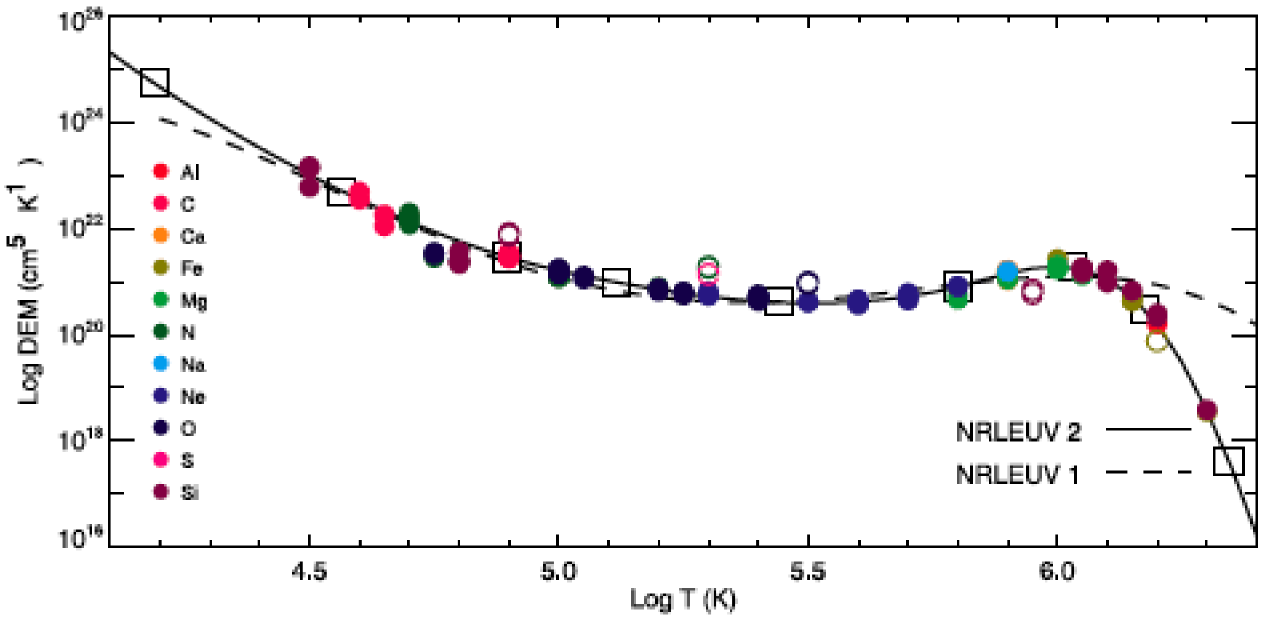
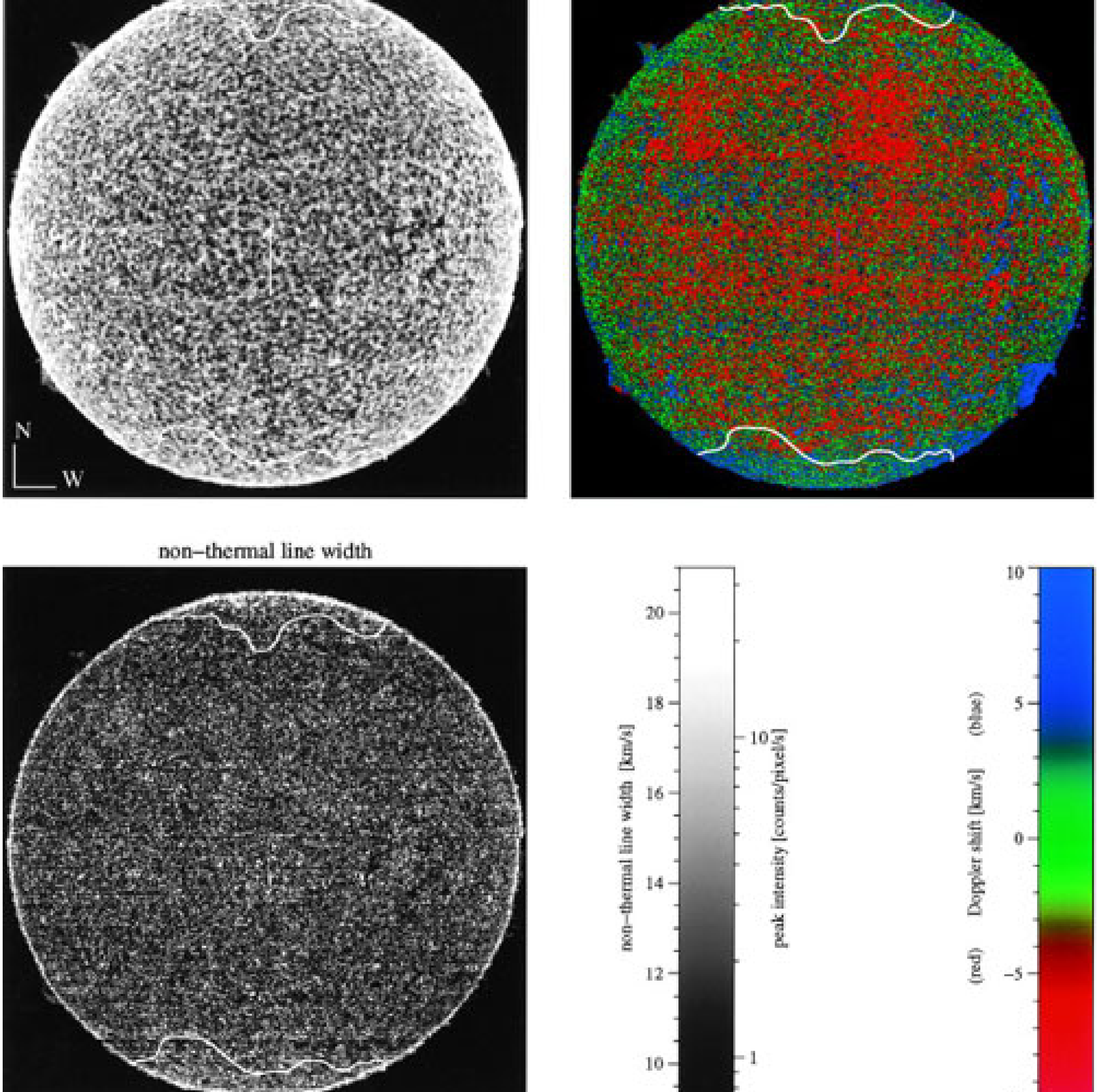


Fig. 13.—Quiet-Sun differential emission measure. Distributions derived from both Harvard *Skylab* (*dotted line*) and *SOHO* (*solid line*) observations are shown. The circles represent the ratio of the observed to calculated radiance scaled by the emission measure at the temperature that maximizes the product of the radiant power density and the emission measure. Lines not used in the emission measure analysis are shown with open circles. The open squares represent the positions of the spline knots.

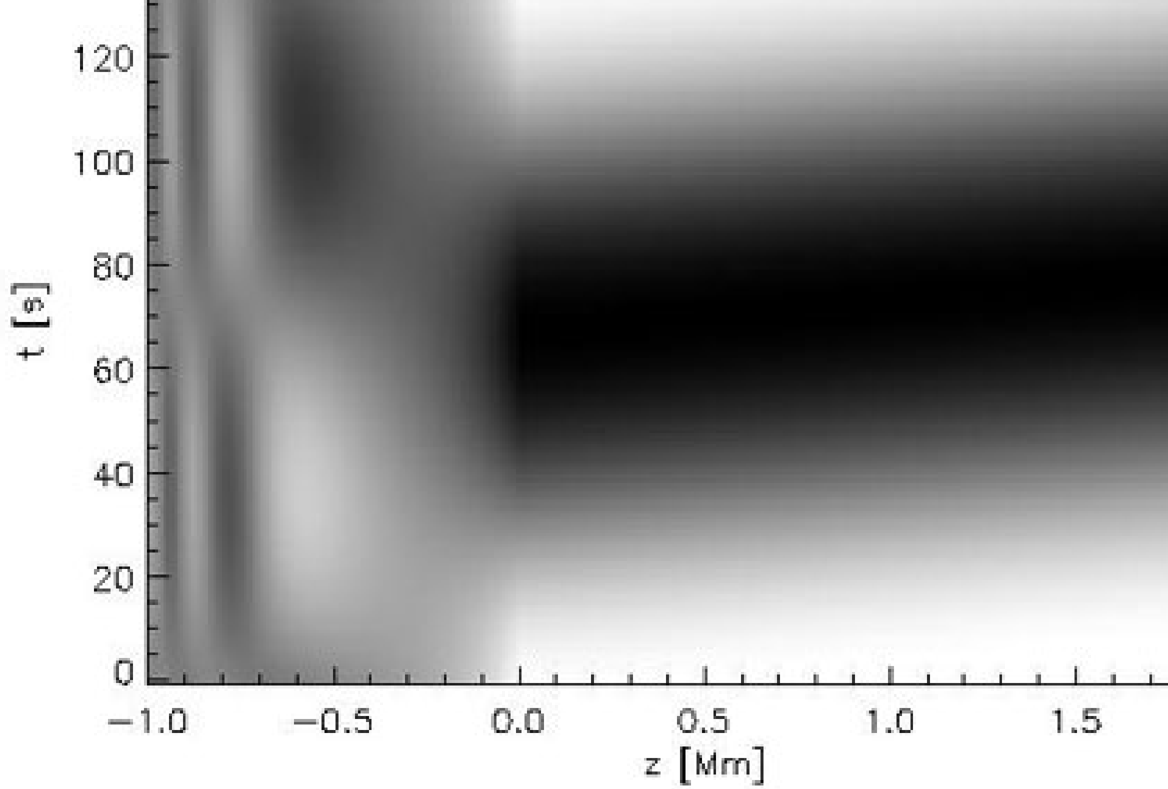
Warren, 2005, ApJSS 157, 147

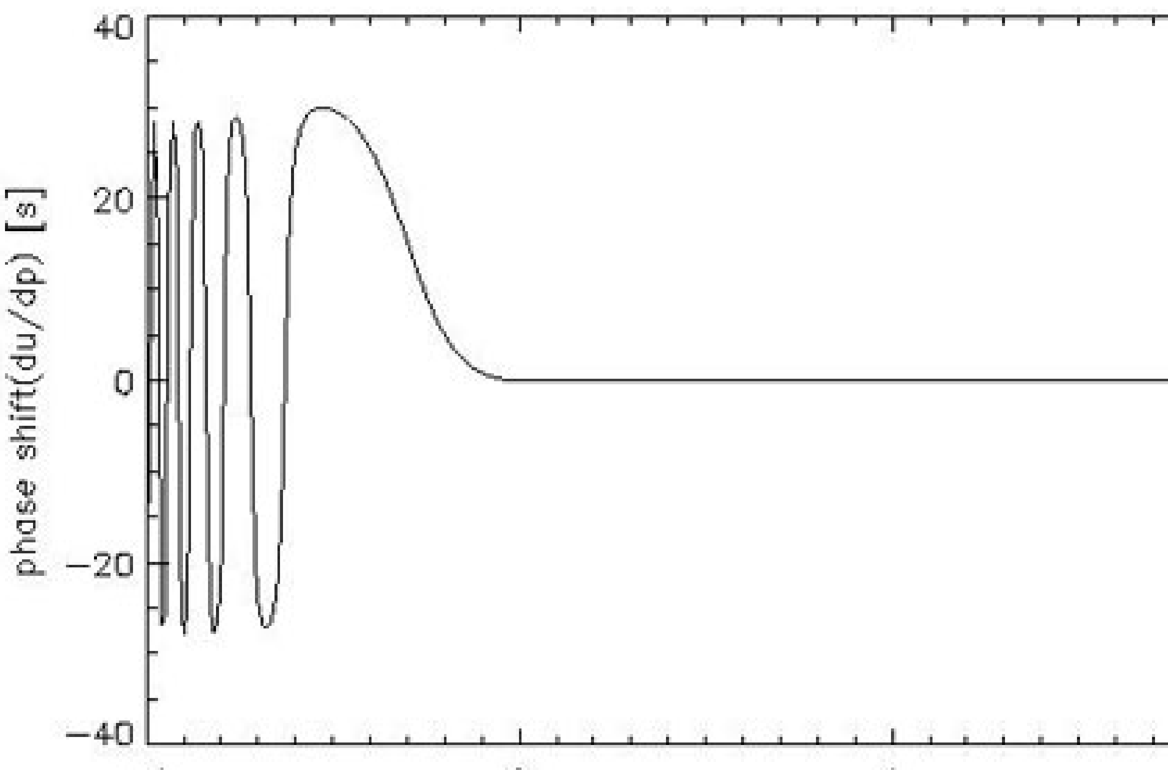

N
W
non−thermal line width
20
18
16
14
12
10
non−thermal line width [km/s]
10
1
peak intensity [counts/pixel/s]
10
5
0
−5
(red) Doppler shift [km/s] (blue)

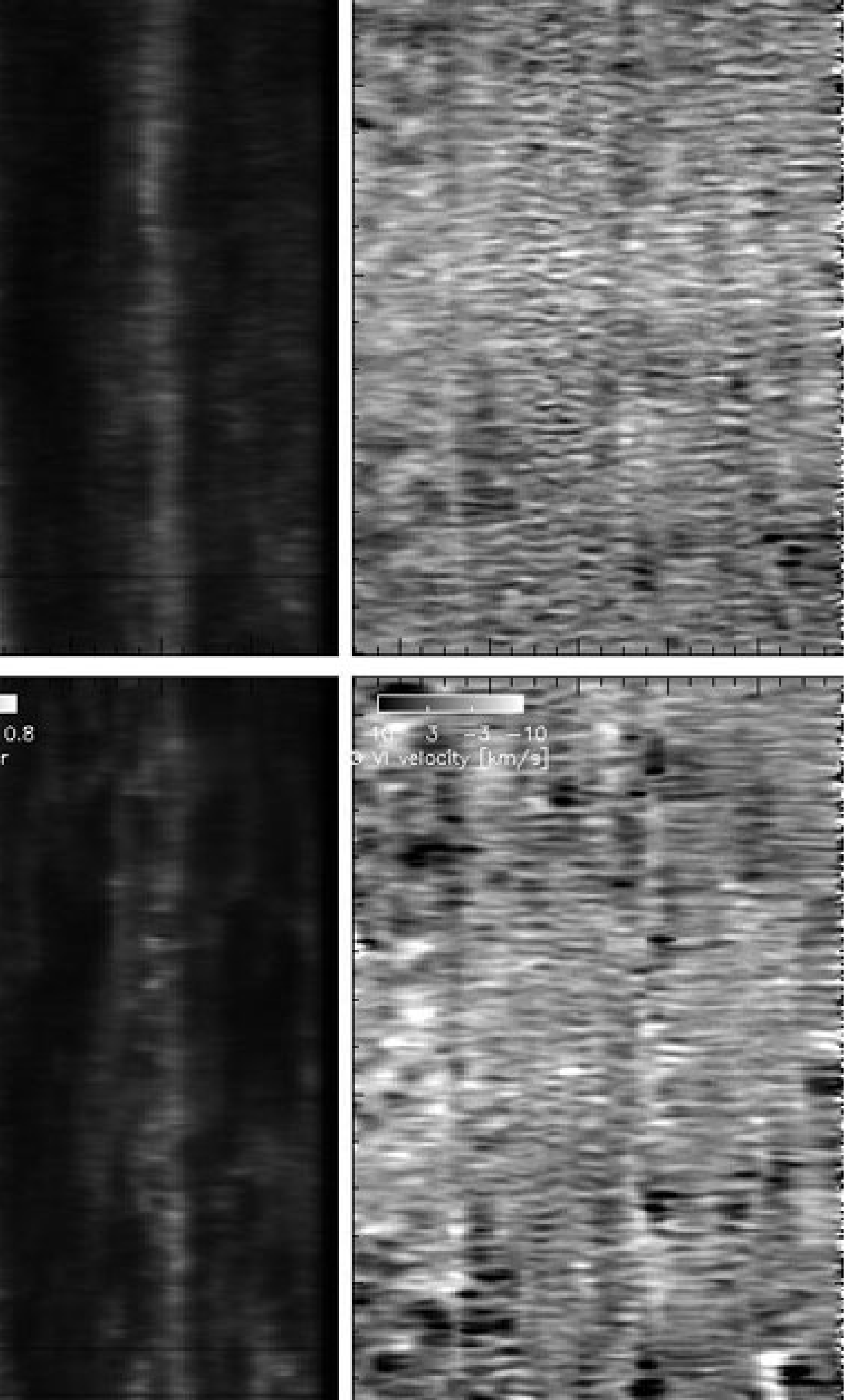
mperature gradient

oustic wave will partially
oximately 50% of the wave
y) reflect off the expected
tion region temperature
nt

tion will lead to phase shifts
en line shifts and the line
ities







show that...

the 5-10 mHz oscillations can be followed up into the (upper) tran region

the oscillations are best seen in th shift, but are also present as varia the line intensity

Wikstøl et al, 2000
(ApJ Volume 531, Issue 2, pp. 1150-1160)

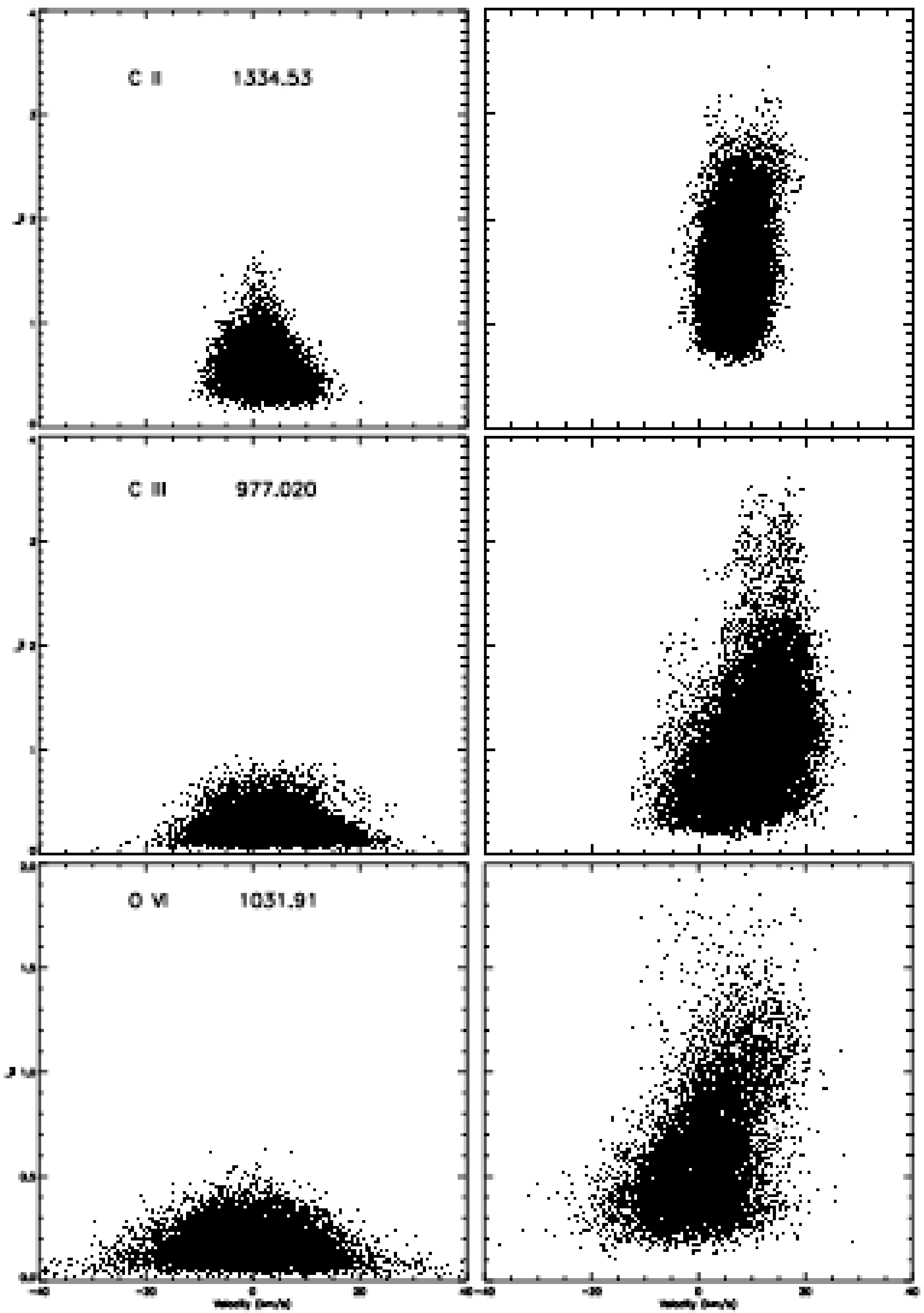
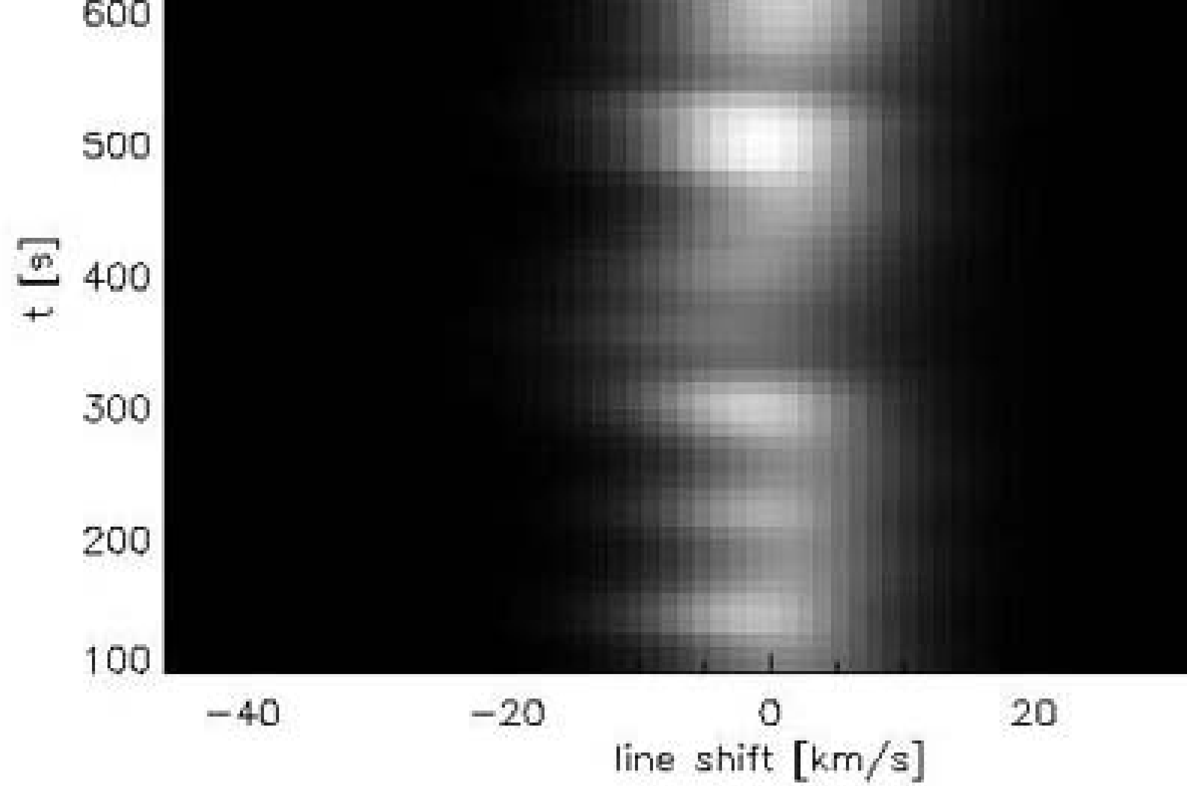


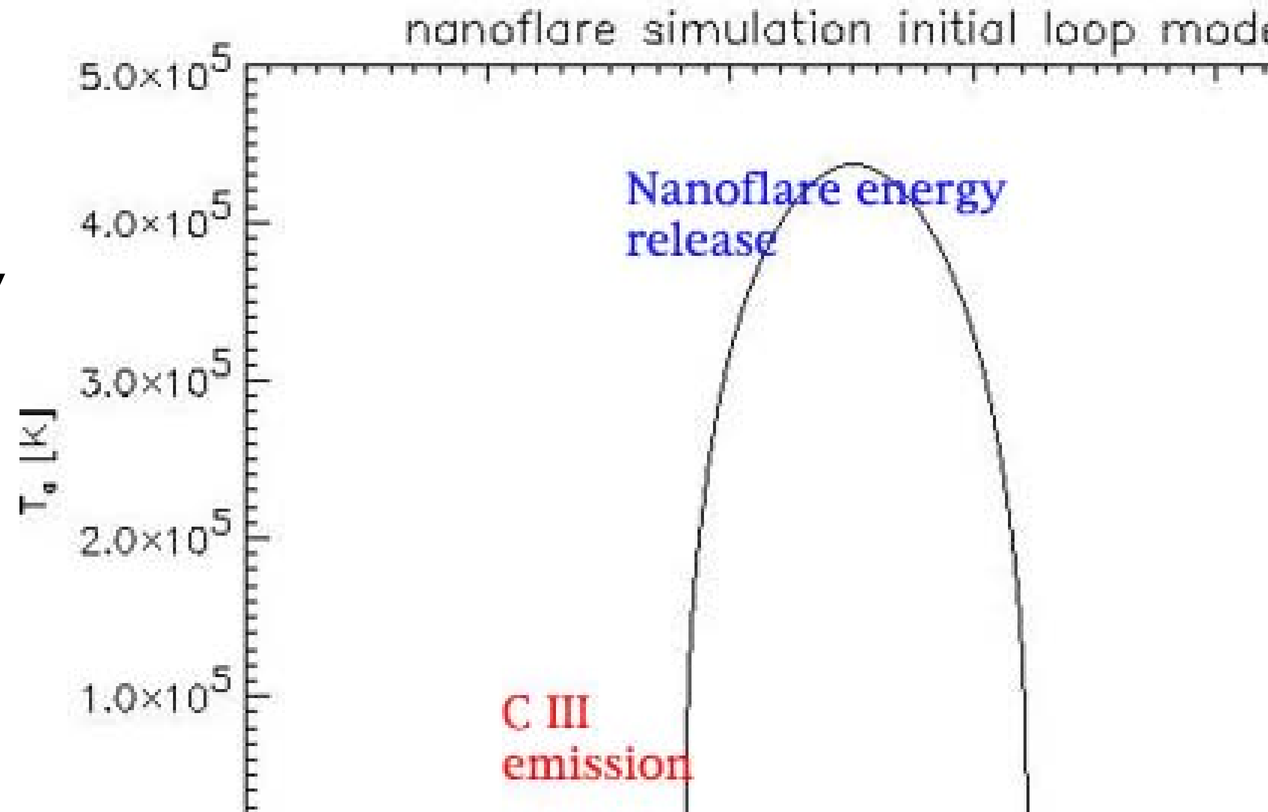
Fig. 11. Total line intensity versus line shift for C II 1334Å, C III 977Å, and O VI 1032Å. Cell interior positions in the left panels and network positions in the right panels.

t, episodic events in the
a should leave a trace in
tion region emission

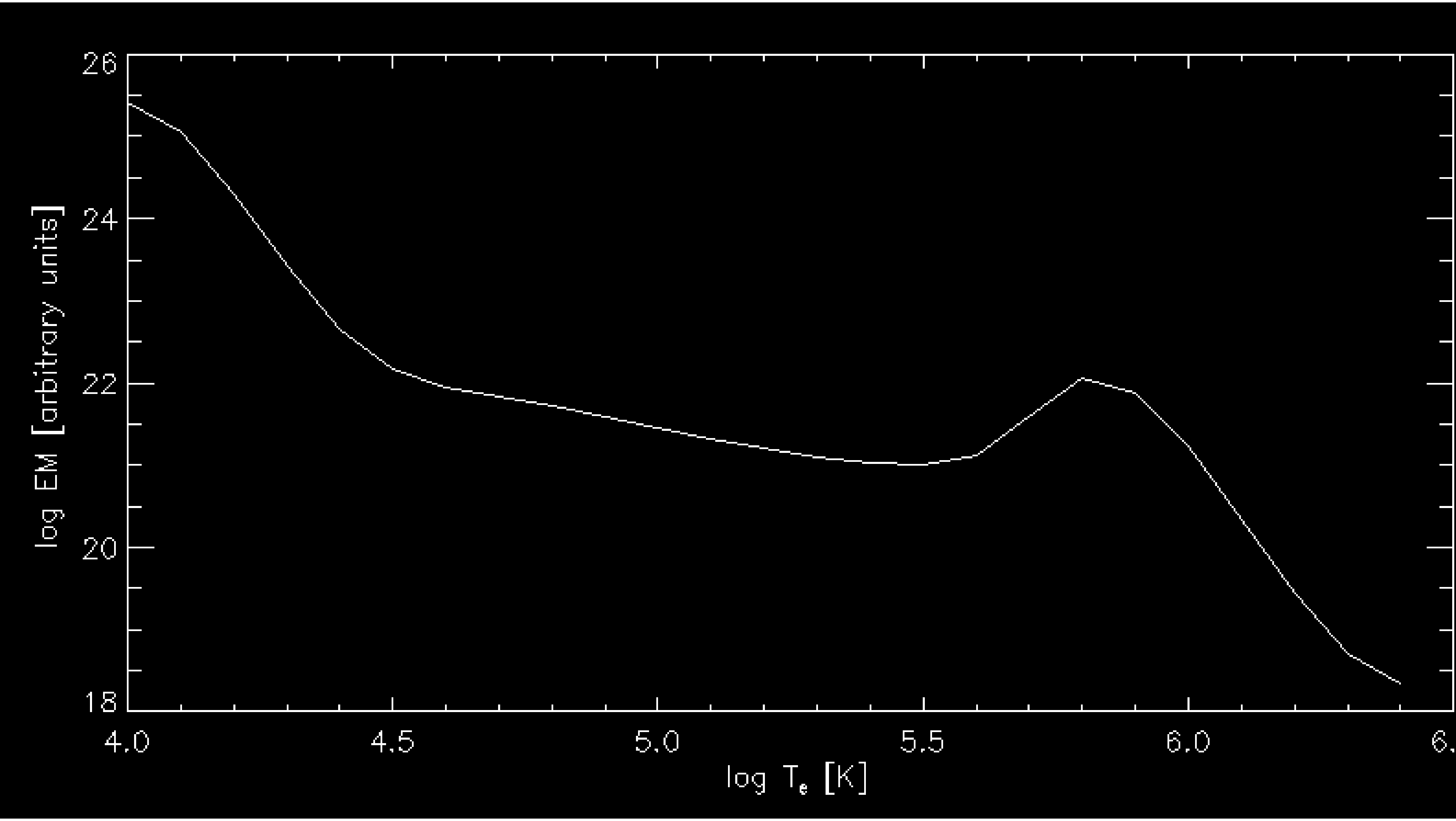
tion region jets, turbulent
s and blinkers?

rhaps a “natural
quence” of episodic
g; gas is heated quickly
ools slowly as predicted by
& Holzer 1982 and
ps shown by Peter &
sen 2005

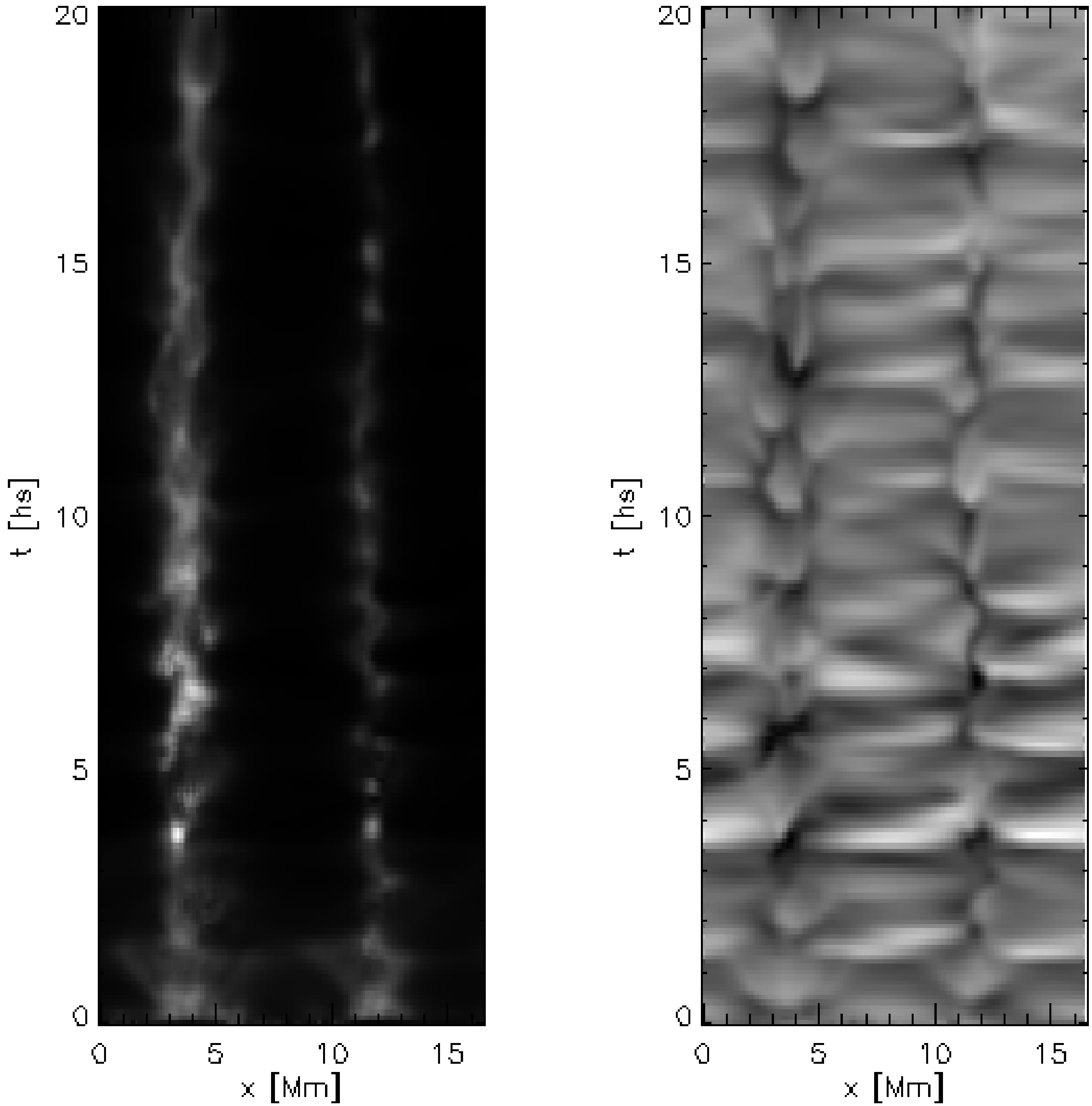




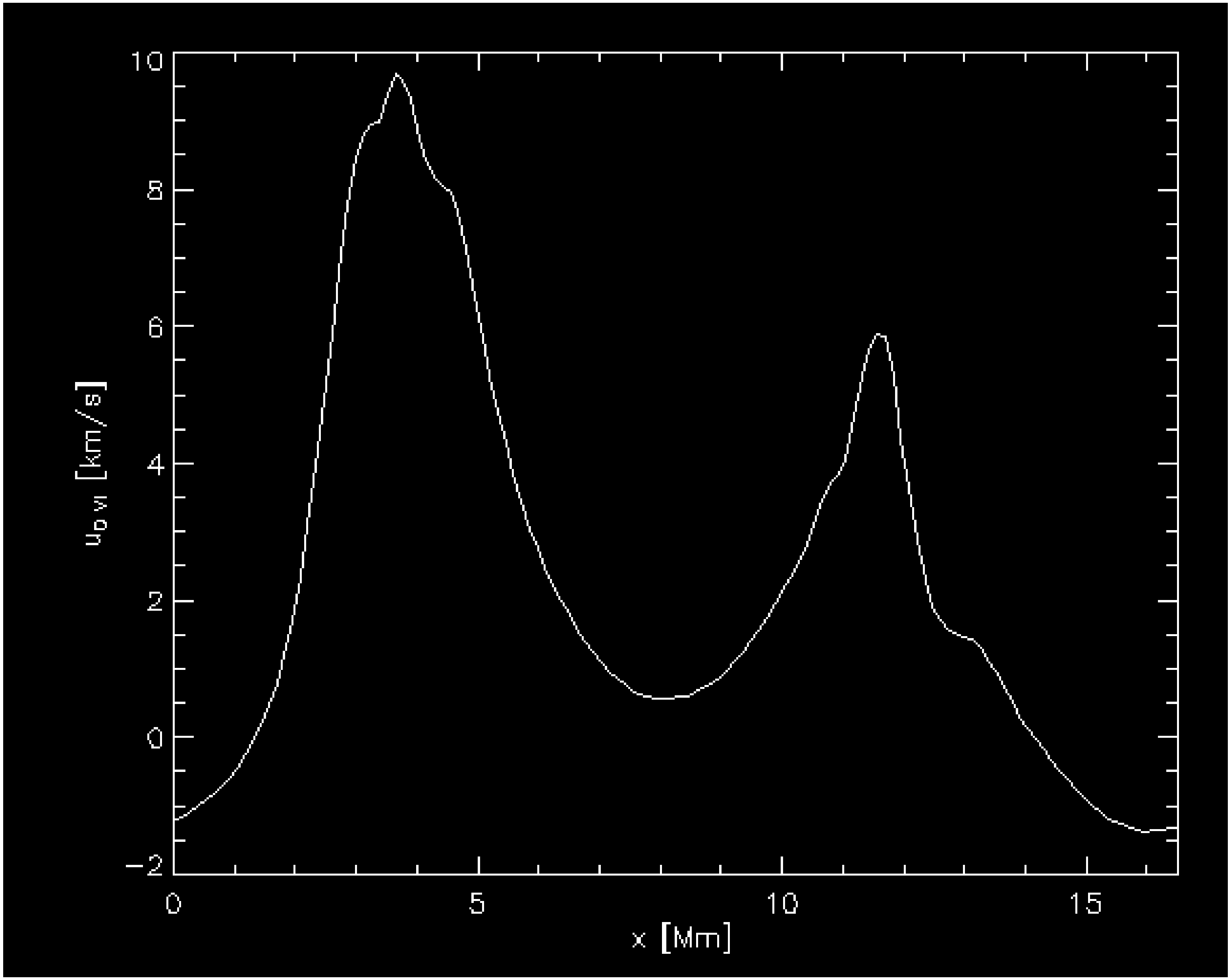
3d Model DEM



O VI 103.4 nm intensity and velocity



Average O VI 103.7 nm Velocities



3d convection zone to coronal modeling

- Corona is high temperature and low beta
  - thermal conduction dominates the energy equation
  - heat flows along the field in low beta plasma
- Convection zone & photosphere is high beta
  - Coronal dynamics and energetics are a result of forcing by the lower regions of the atmosphere
  - Driving term in energy equation is radiation
- Chromosphere (and TR) are intermediate

The MHD equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$\frac{\partial e}{\partial t} + \nabla \cdot (e\mathbf{u}) + p\nabla \cdot \mathbf{u} = \nabla \cdot \mathbf{F}_r + \nabla \cdot \mathbf{F}_c + \eta j^2 +$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u} + \tau) = -\nabla p + \mathbf{j} \times \mathbf{B} - g\rho$$

some equation of state $e = \frac{1}{\dots}\frac{p}{\dots}$

Solution of the energy equation with conduction

- Numerical analysis severely strained by Courant condition - which with conduction scales as the grid size squared
- An implicit operator to solve diffusive part of operator
- Proceed by operator splitting
  - High order explicit method with Hyman time-stepping is used to solve MHD
  - Multigrid method is used to solve diffusive operator

Solution Strategy

$$\frac{\partial e}{\partial t} = \nabla \mathbf{F}_c = -\nabla \kappa_{\parallel} \nabla_{\parallel} T$$

a) Use Crank-Nicholson to discretize; compute explicit part of operator

b) Solve MHD part of operator by “usual” method

c) Update temperature by solving by multi-grid method

```
do it = 1, nstep
 if (heatflux) call init_heat_flux
 call mhd_timestep()
 if (heatflux) call heat_flux_mg
 ...
```

General considerations

Elliptic (and "elliptic like") operators can be solved by relaxation methods

$$\frac{{}^2\Phi}{x^2} = \frac{1}{h^2}\left(\Phi_{i+1,j} + \Phi_{i-1,j}\right) \qquad \frac{\partial^2\Phi}{\partial y^2} = \frac{1}{h^2}\left(\Phi_{i,j+1} + \Phi_{i,j-}\right.$$

which means solution converges by repeated averaging

$$\Phi_{i,j} = \frac{1}{4}\left(\Phi_{i+1,j} + \Phi_{i-1,j} + \Phi_{i,j+1} + \Phi_{i,j-1}\right)$$

e general idea is that Jacobi or Gauss - Seidel iteration is very goo
removing errors on the "small" scales and very bad at removing
rors on "large" scales.

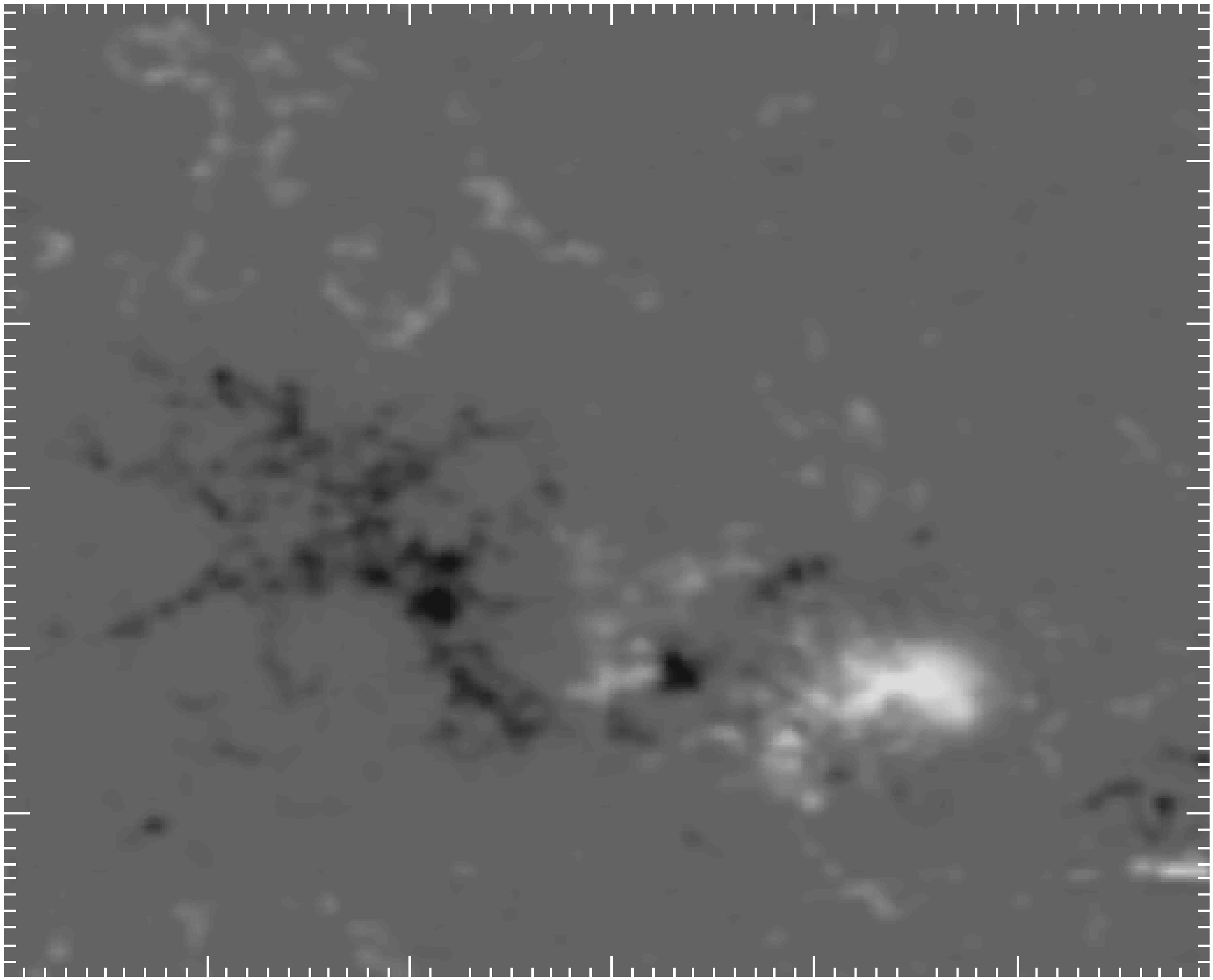
ltigrid methods work by converting large scales to small scales

- We use a V-cycle starting at original grid size h
  - at this finest grid level the solution is smoothed using a few Gauss-Seidel relaxation to smooth the high frequency errors
- The residual errors are injected into a coarser grid
- This process of smoothing and injection continues down to a the coarsest grid
- The solution interpolated back up to the finest grid
  - through a succession of intermediate smoothing and prolongation steps
- Injection and prolongation are obtained simply by bilinear interpolation.

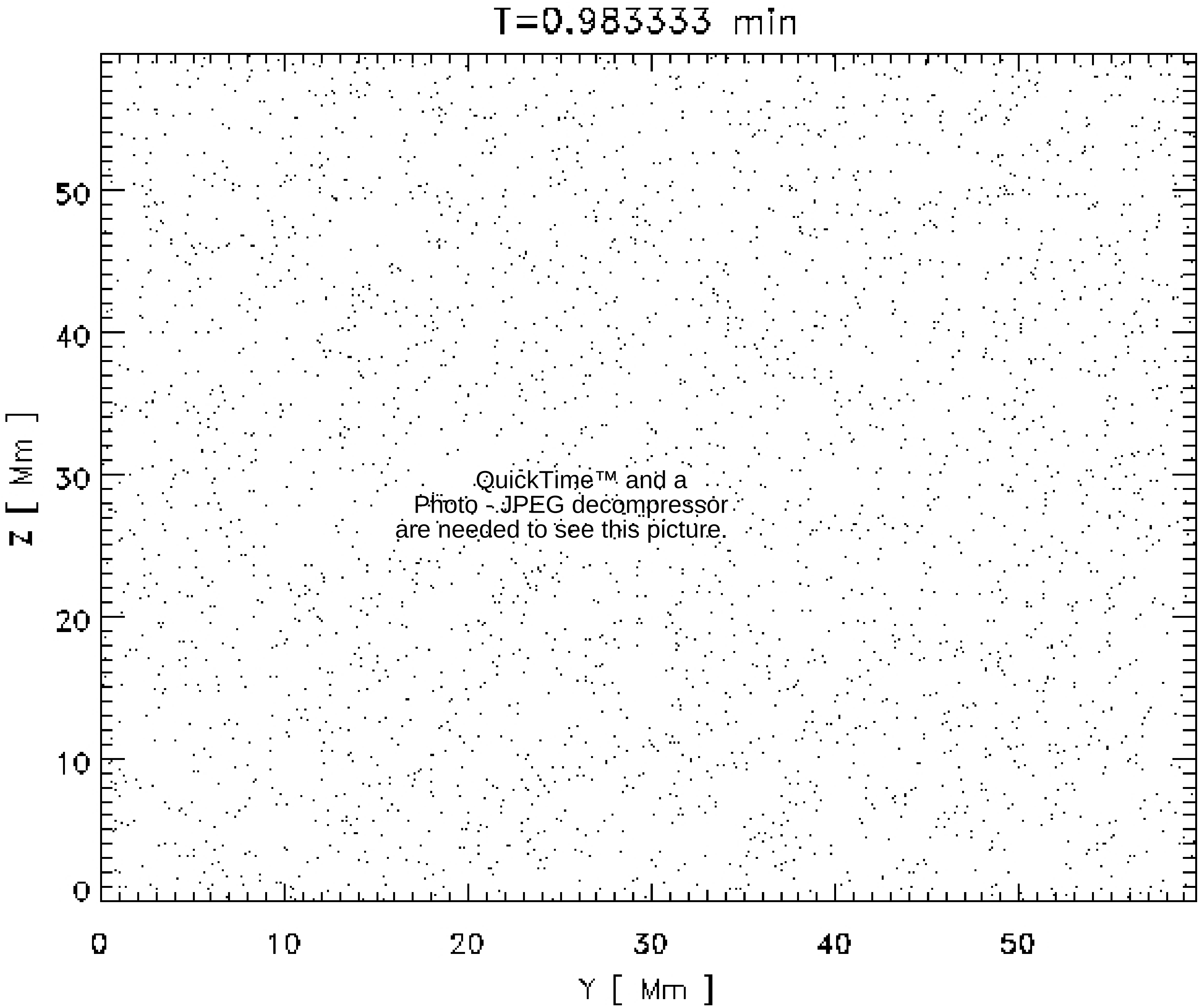
Multigrid methods originally by Brandt 1977
(Mathematics of Computation, vol 31, pp 333-390)

Originally coded by A. Malagoli, A. Dubey, F. Cattaneo "A Portable and Efficient Parallel Code for Astrophysical Fluid Dynamics"

Models with photospheric driving



Gudiksen & Nordlund, 2002, ApJ 572, L113
Gudiksen & Nordlund, 2005, ApJ 618, 1020



Driving based on observations & modeling at smallest scales

Trace 171Å emission

Gudiksen & Nordlund, 2002, ApJ 572,
Gudiksen & Nordlund, 2005, ApJ 618,

Heating via magnetic dissipation

$$Q_{\mathrm{Joule}} = \mathbf{E} \cdot \mathbf{J} \qquad\qquad \mathbf{J} = \nabla \times \mathbf{B}$$

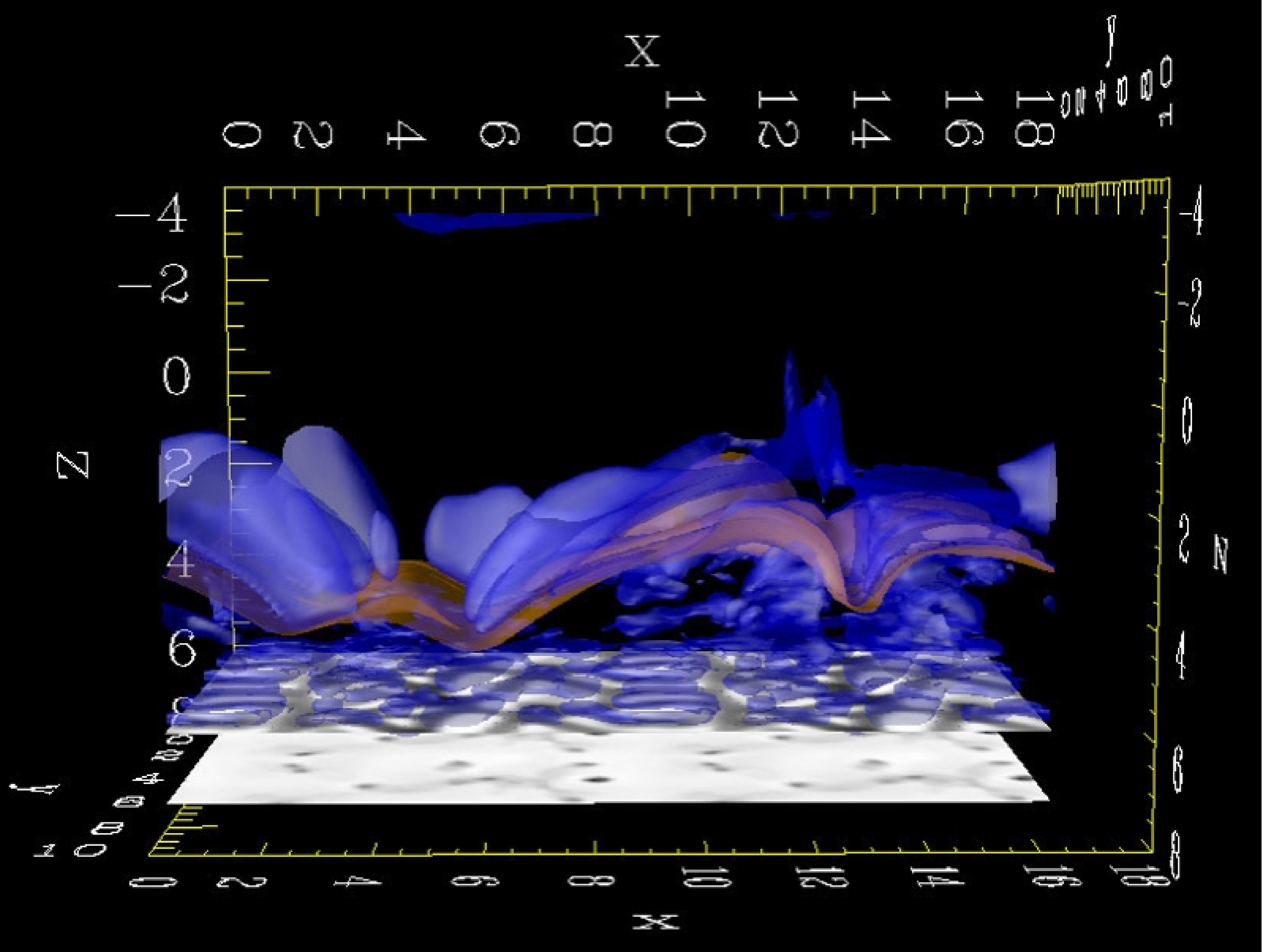
where the resistive part of the electric field is

$$E_x^{\eta} = \left\{ \frac{1}{2}(\eta_y^{(1)} + \eta_z^{(1)}) + \frac{1}{2}(\eta_y^{(2)} + \eta_z^{(2)}) \right\} J_x$$

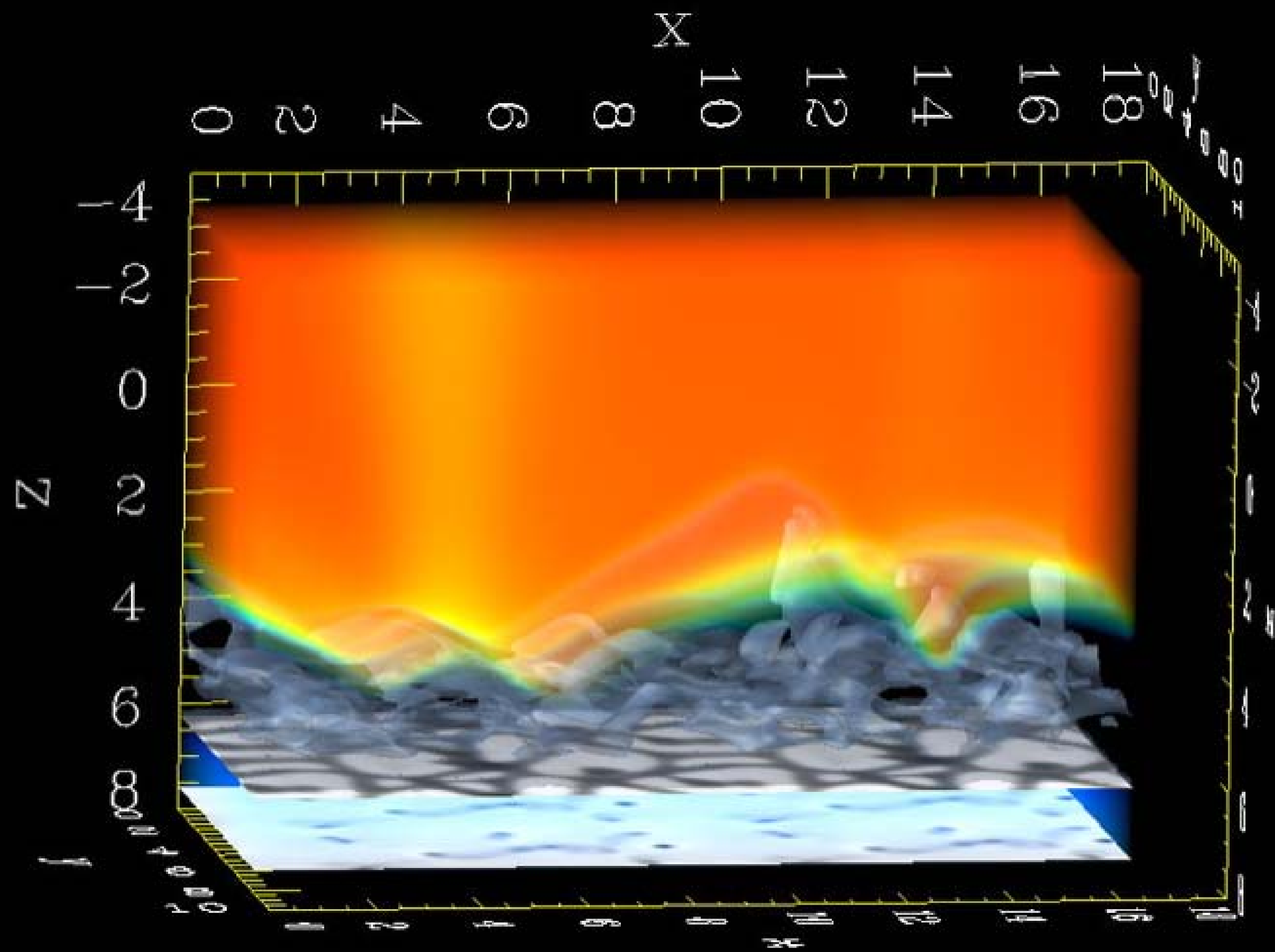
where the diffusivities are given by

$$\eta_j^{(1)} = \frac{\Delta x_j}{\mathrm{Pr}_M}(v_1 c_f + v_2 |u_j|)$$

$$\eta_j^{(2)} = \frac{\Delta x_j^2}{\mathrm{Pr}_M} v_3 |\nabla_{\perp} \cdot \mathbf{u}|$$



x
0 2 4 6 8 10 12 14 16 18
y
z
−4 −2 0 2 4 6


X
0
2
4
6
8
10
12
14
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Z
-4
-2
0
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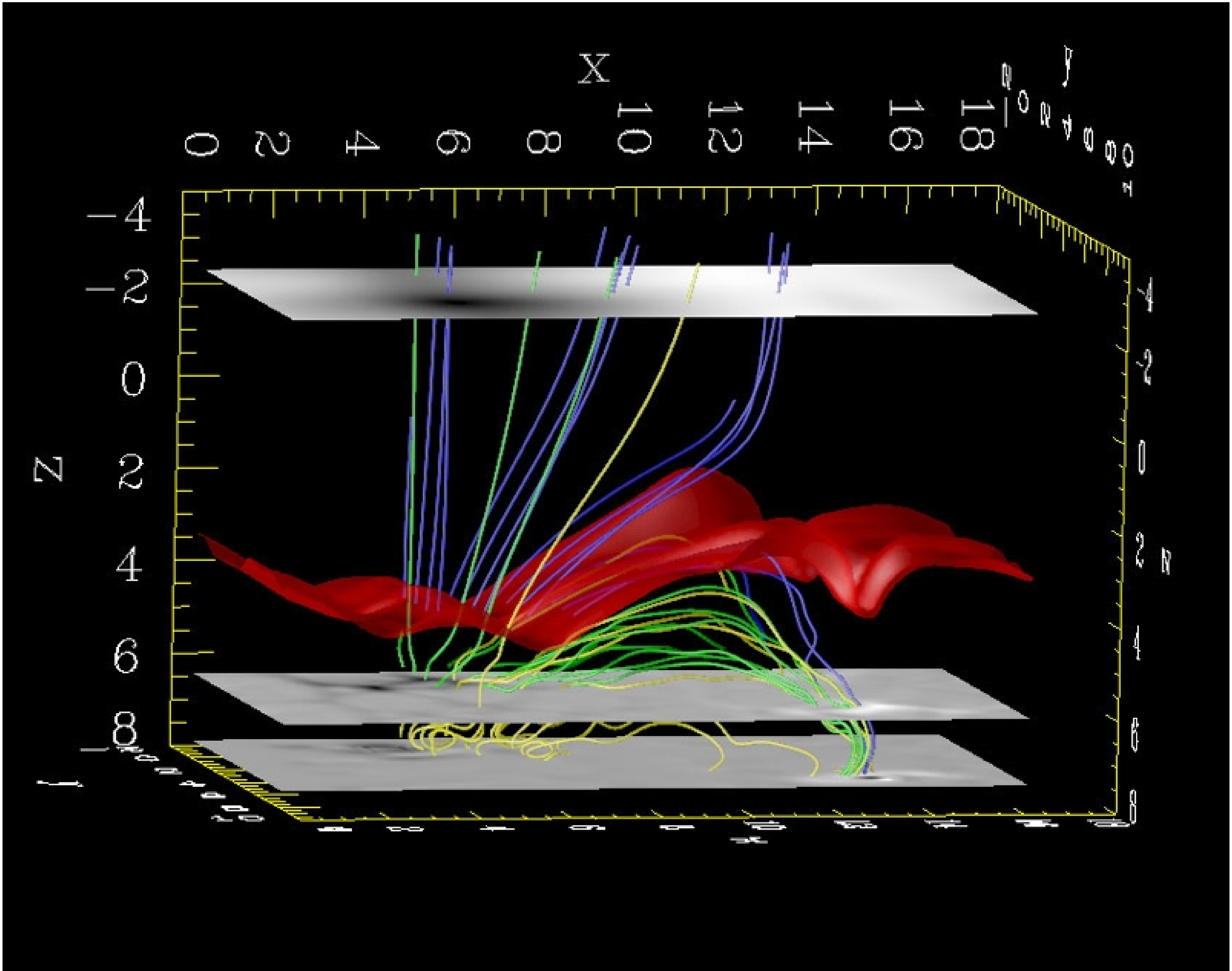
8

QuickTime™ and a
GIF decompressor
are needed to see this picture.


X
0 2 4 6 8 10 12 14 16 18
Z
−4 −2 0 2 4 6 8

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

QuickTime™ and a
Photo - JPEG decompressor
are needed to see this picture.

O6 O VI 103.1 nm

QuickTime™ and a
GIF decompressor
are needed to see this picture.

O VI 103.1 nm

QuickTime™ and a
GIF decompressor
are needed to see this picture.

realistic 3D simulations

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Photo - JPEG decompressor
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Red field

Colorin
tempera
(red=chromo
reen/blue

Hansteen &

- It seems we have a promising hypothesis...
    - How do we test it?
    - Peter Cargill's cat can reproduce TRACE images...
- ...it would be interesting to investigate
    - variations in the field strength
    - variations in the initial field topology
    - do we need to introduce new flux?
    - is there any interaction between waves and dissipation?
    - etc

- Our treatment of microscopic physics is wrong
  - Does it matter? Galsgaard & Nordlund 1996 claim “No”
- Thermalization
  - via particle acceleration (Turkmani et al.)
  - via highly episodic scale phenomena (Velli & co.)
- Is there a difference between chromospheric and coronal heating?
- What about open magnetic regions?