Waves and Shocks in the Solar Atmosphere

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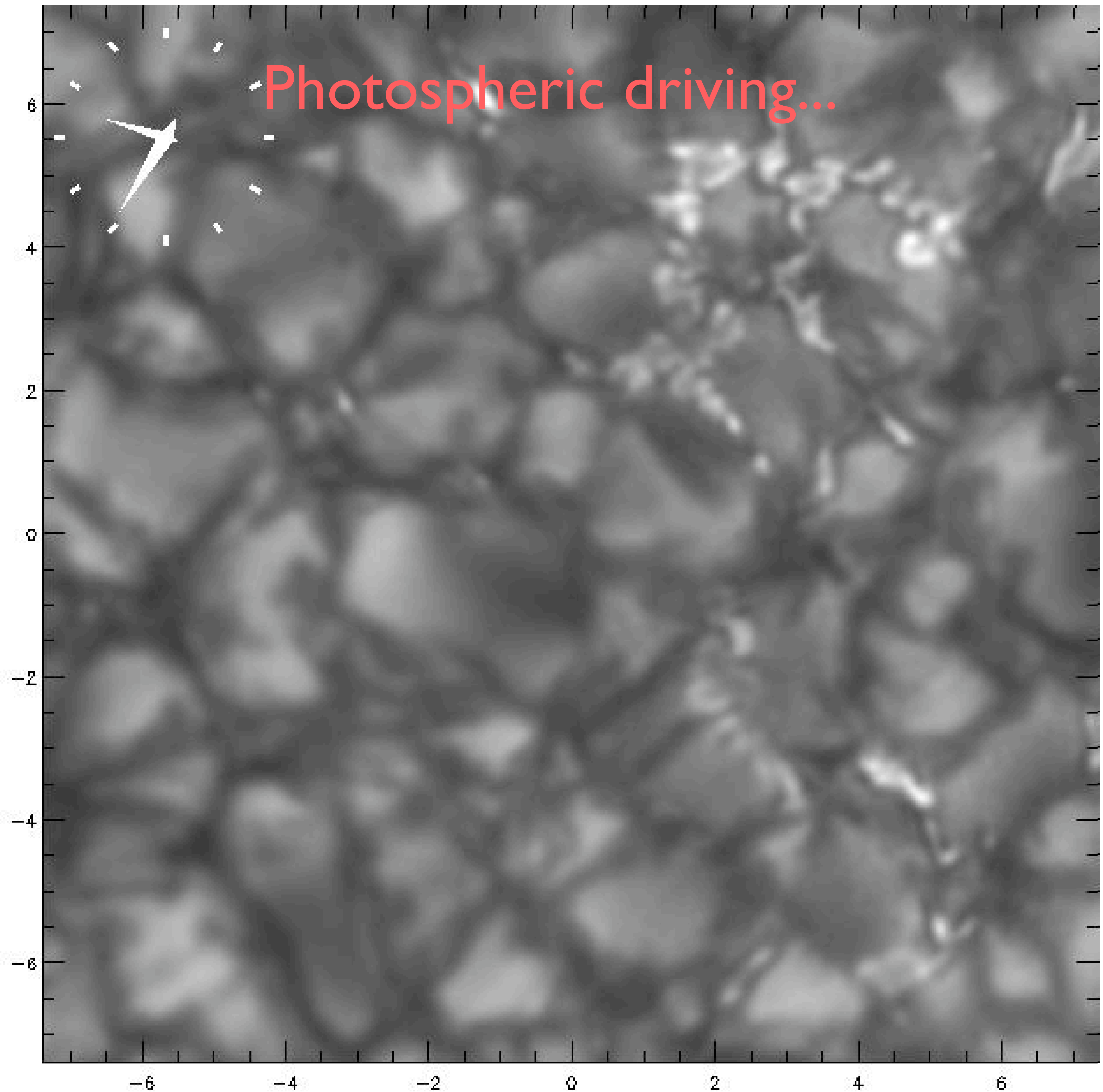
Kyoto, 9 November 2005


Photospheric driving...
6
4
2
0
−2
−4
−6
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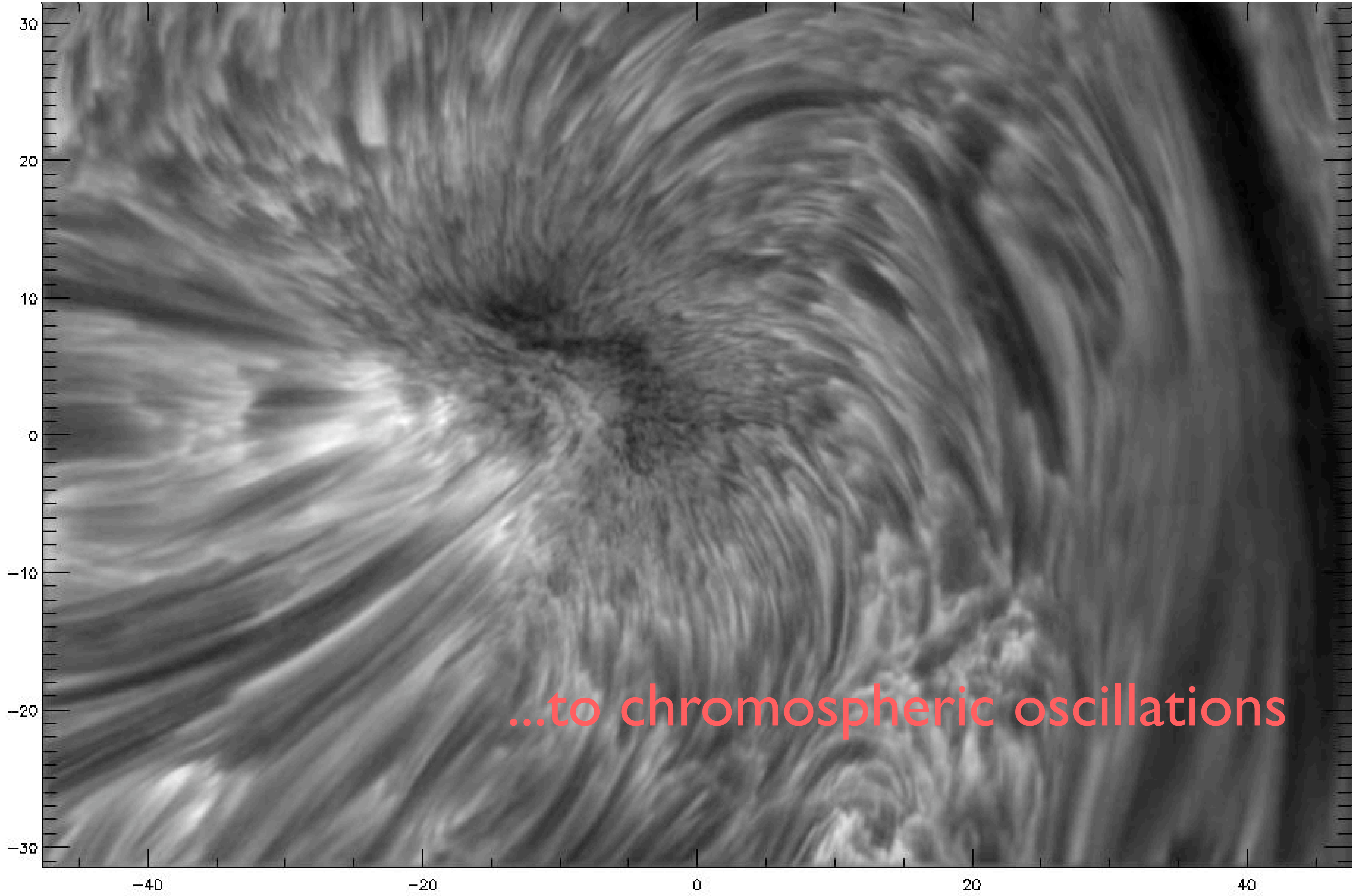
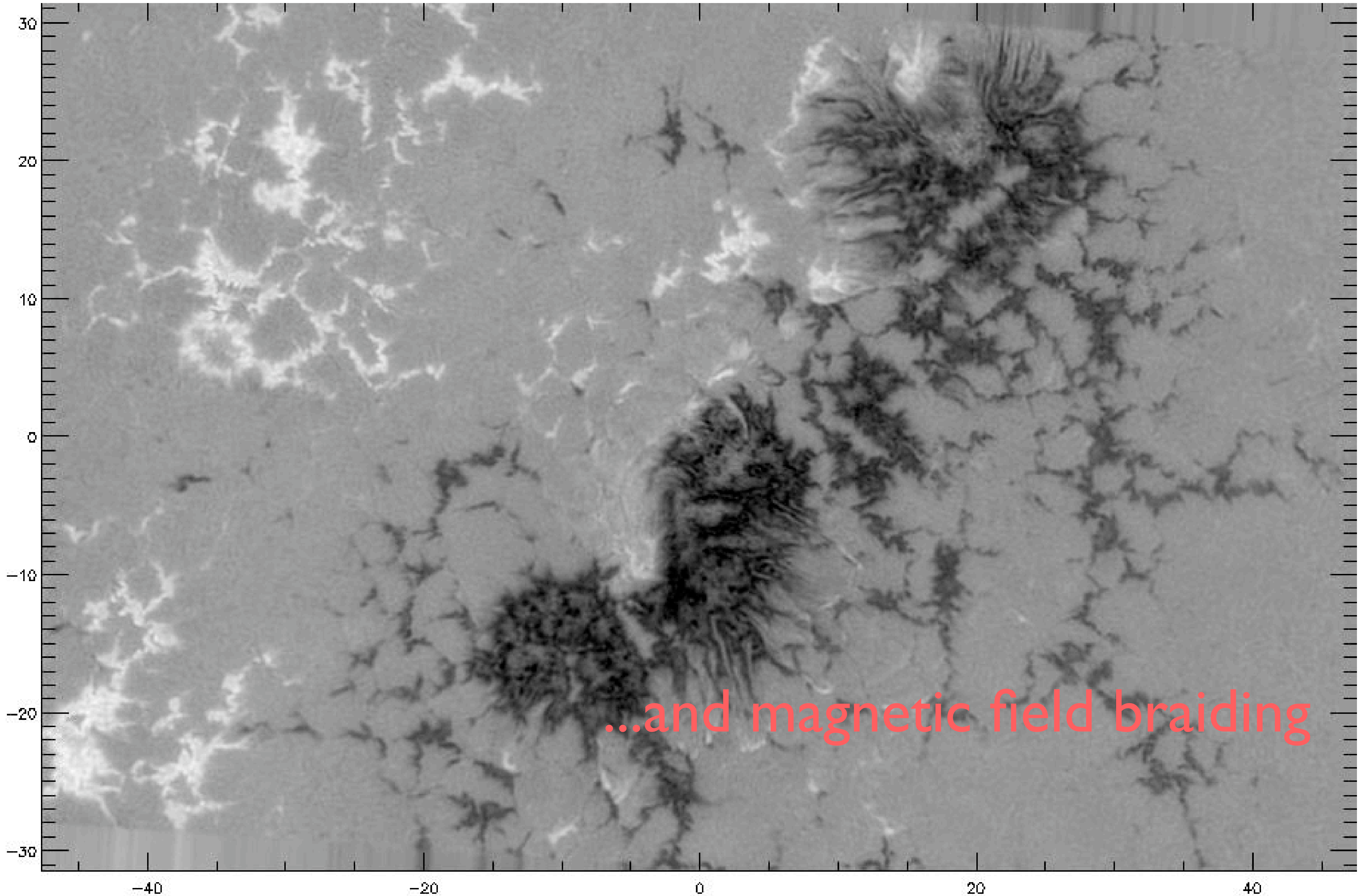
2
4
6

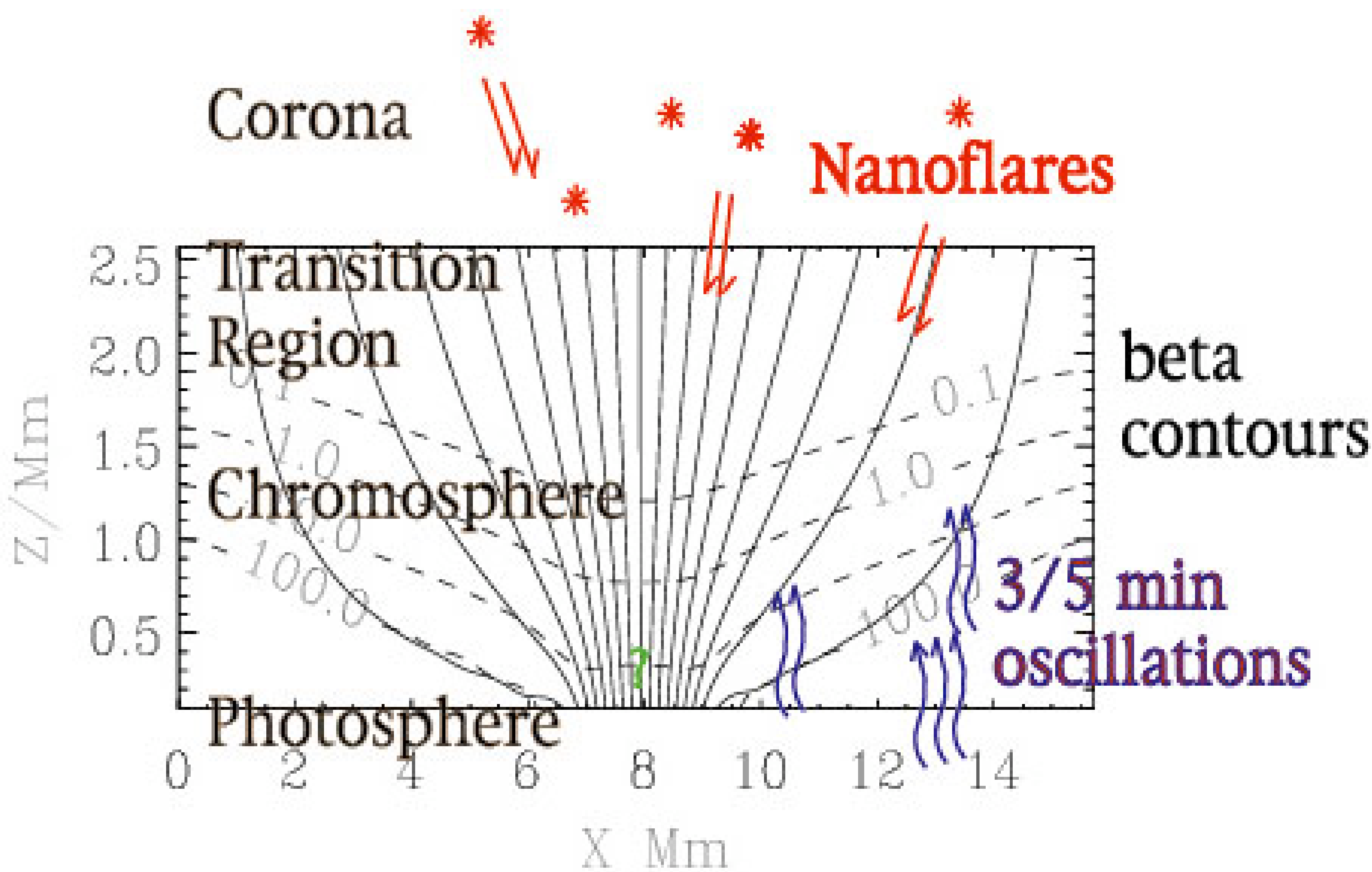
20 Aug 2004, H-alpha center



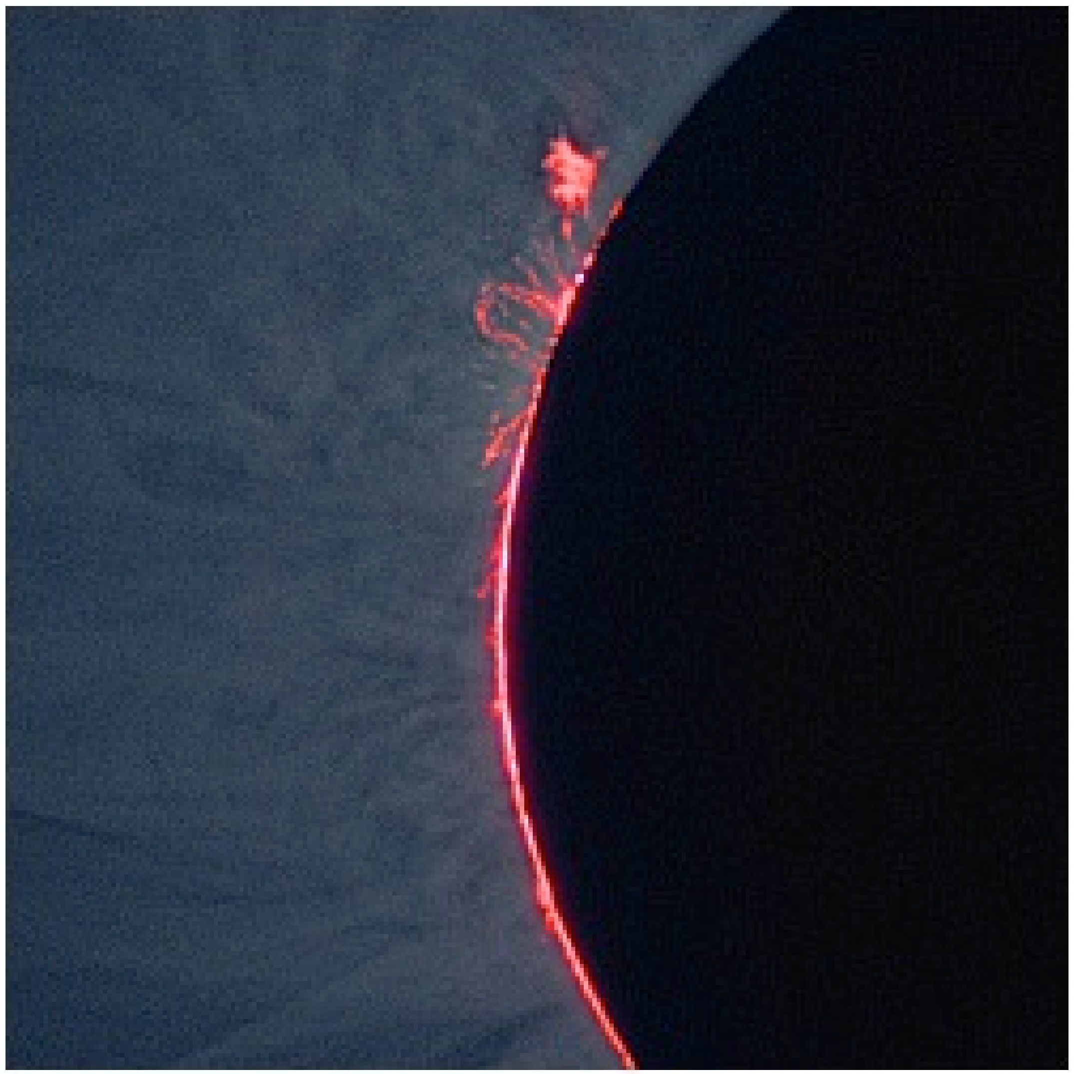
21 Aug 2004, Fe 6302 Magnetogram

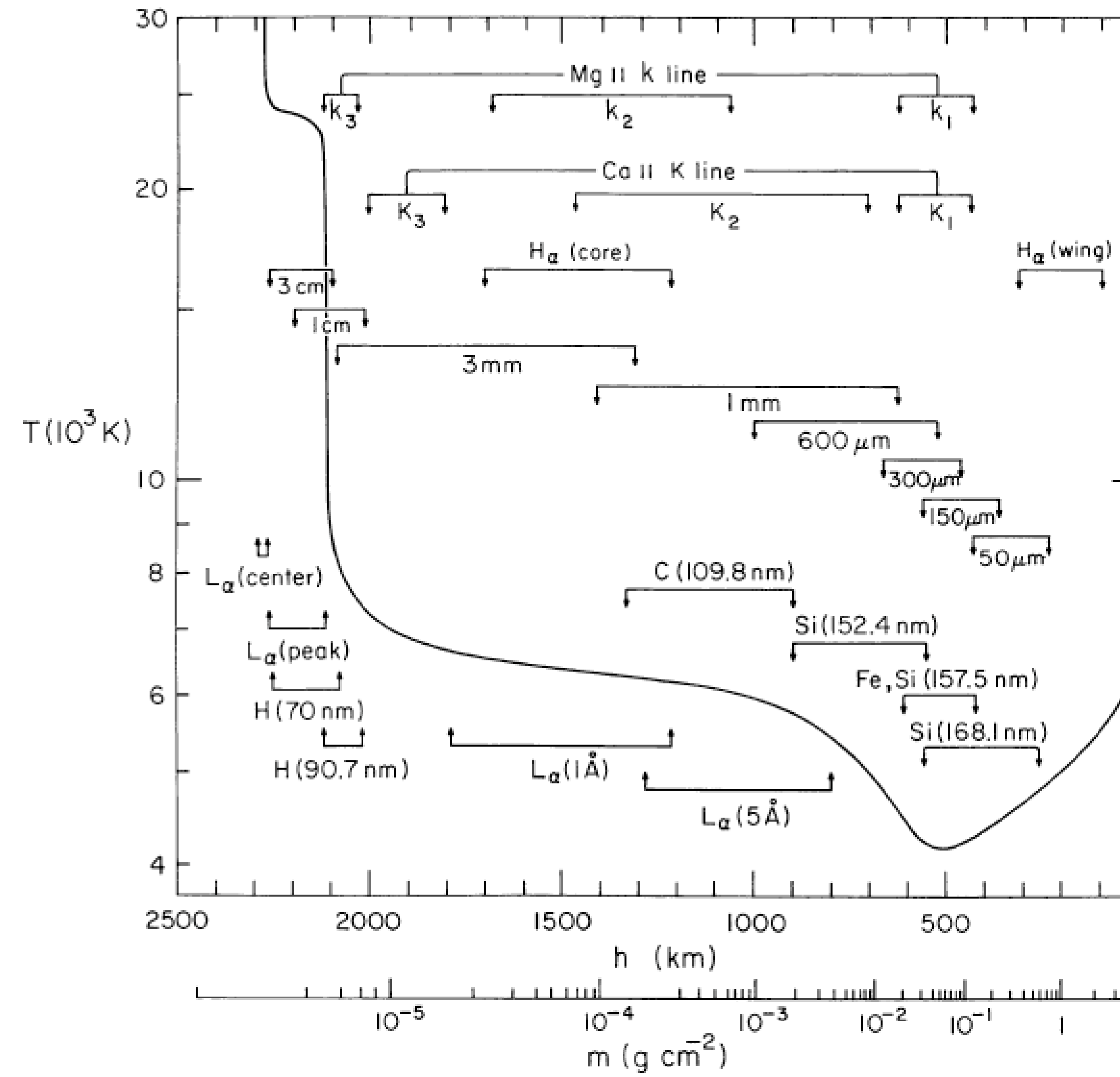


Solar atmospheric structure: Expected dynamics and energetics



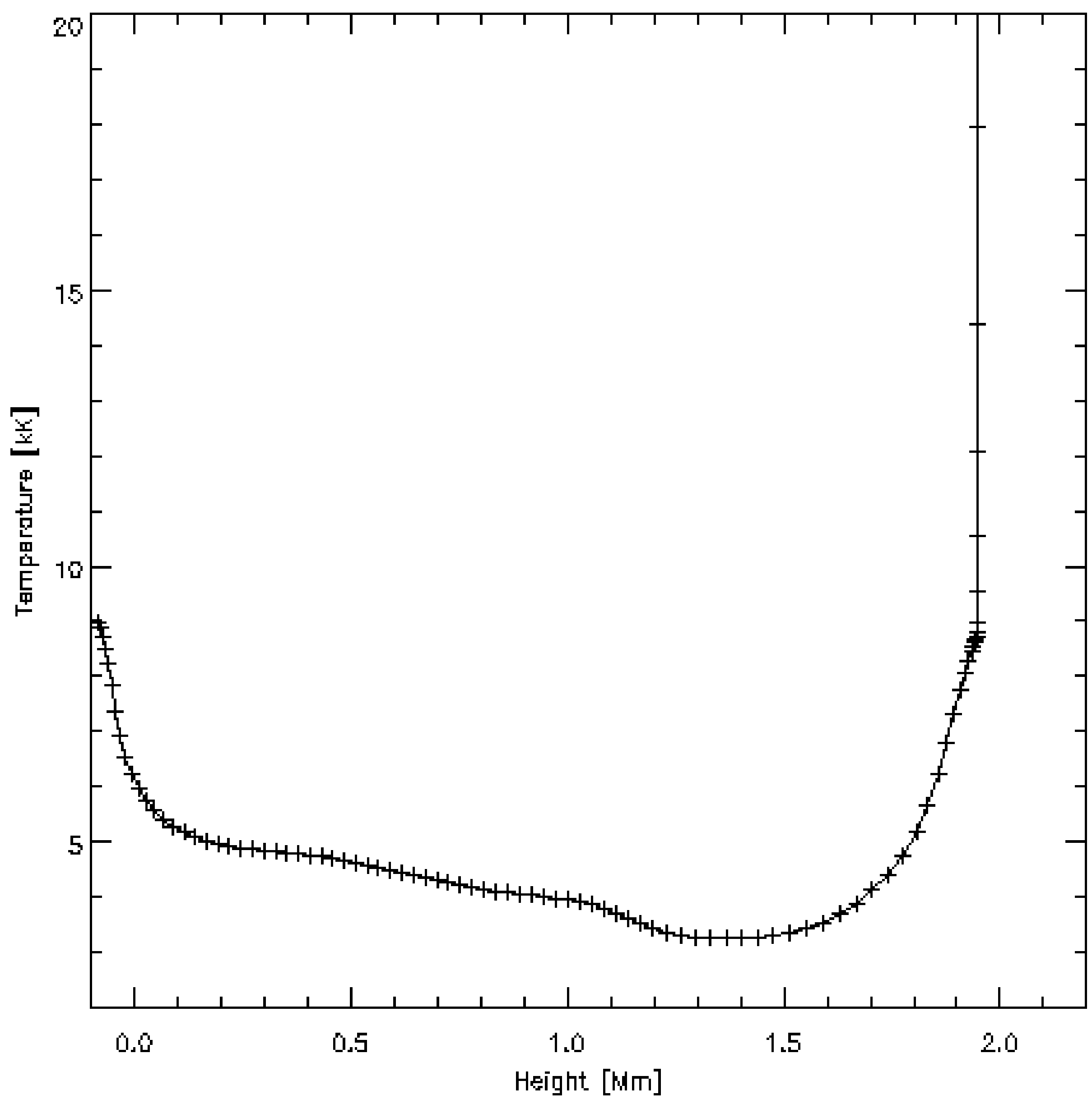
The chromospheric medium





...an isothermal slab through which waves propagate?

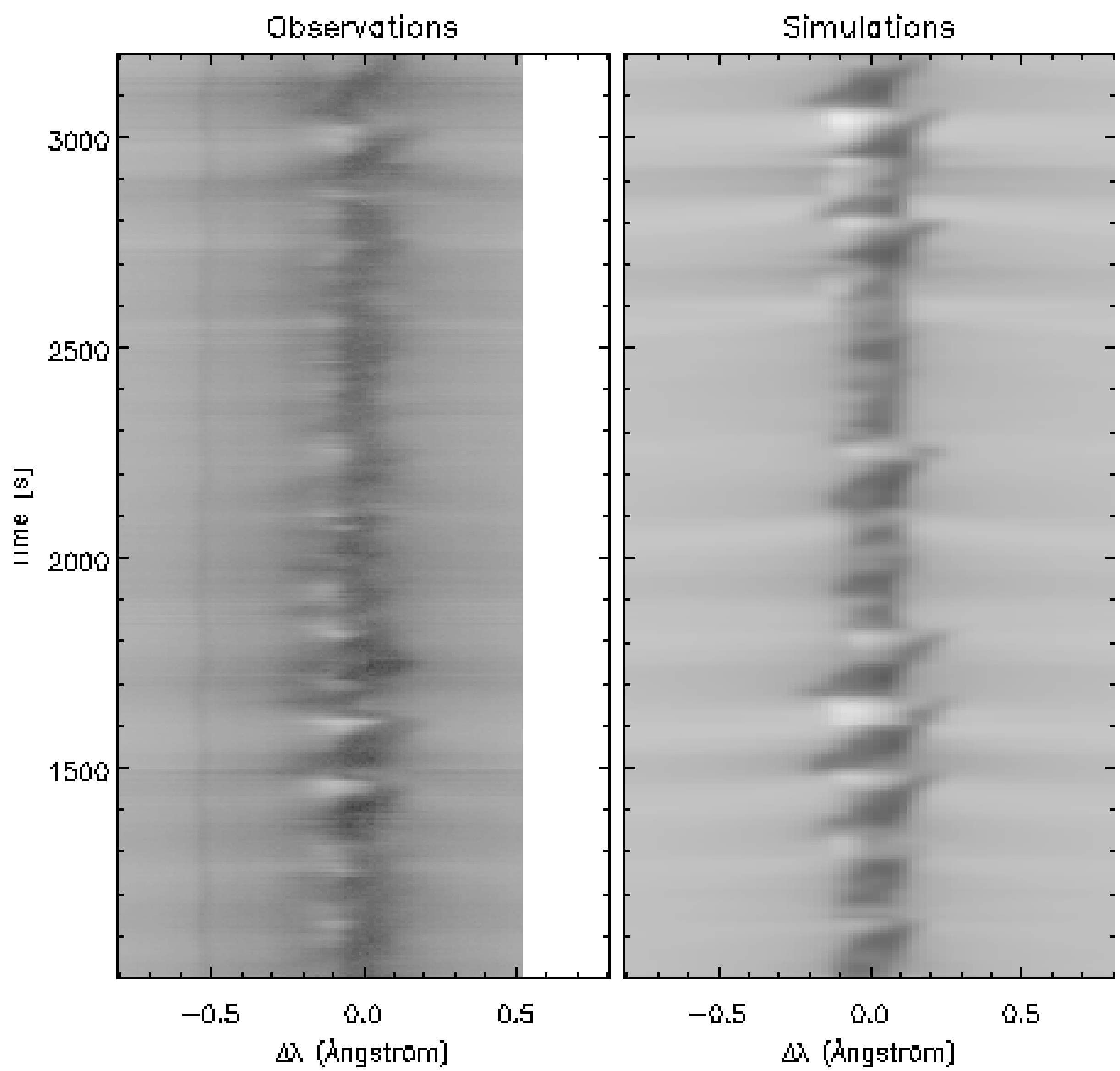
Acoustic waves driven by a photospheric piston



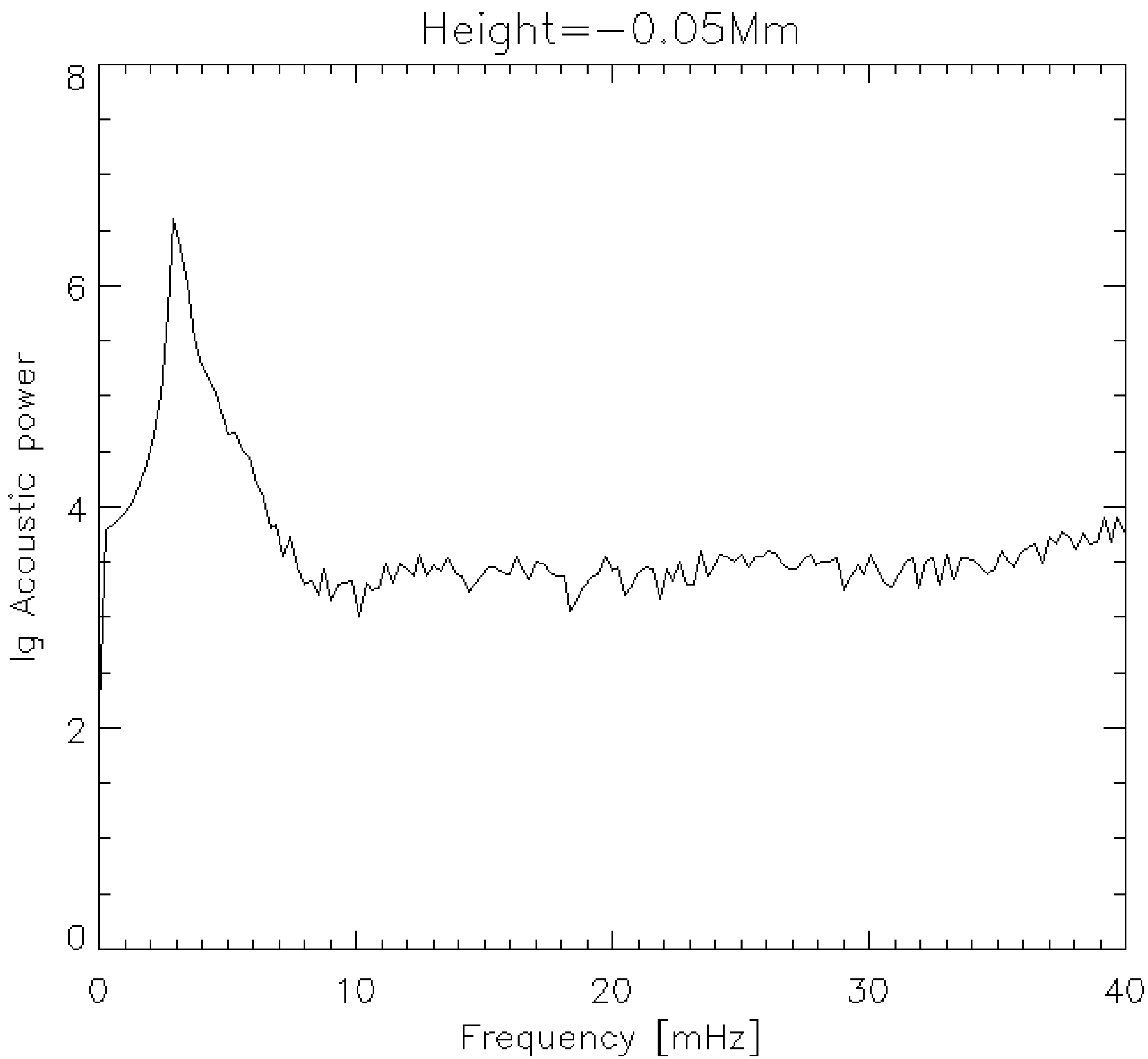
give waves of roughly 5 mHz

Carlsson & Stein (ApJ vol. 397, no. 1, p. L59-L62)

Ca II H-line intensity



Wave energy flux as function of height

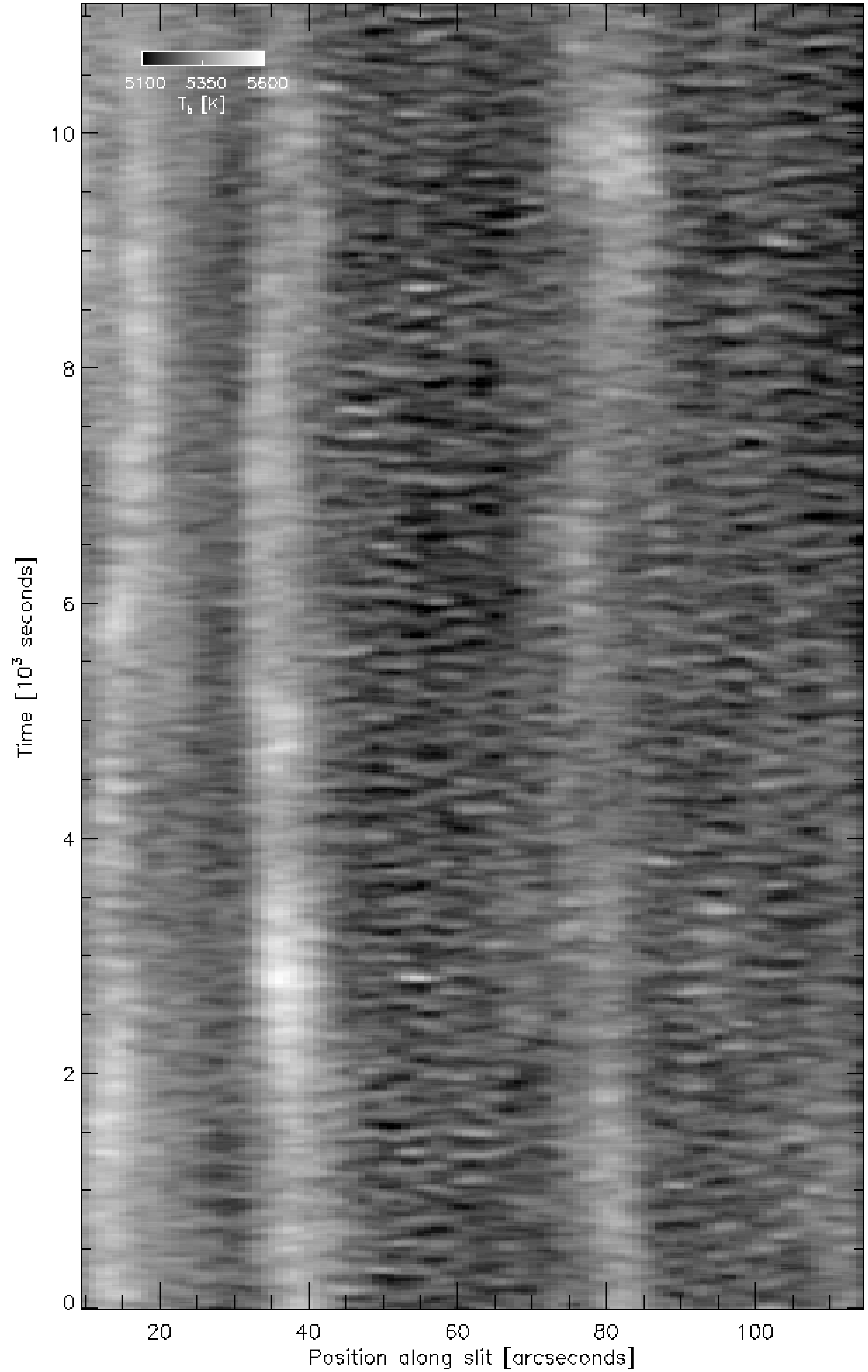


wave fronts that propagates at the sound speed with periods of order 3 min/5 mHz

as predicted by "Carlsson-Stein" 1992 type models
(ApJ vol. 397, no. 1, p. L59-L62)

...and also observed at greater heights in the atmosphere... Wikstøl et al, 2000
(ApJ Volume 531, Issue 2, pp. 1150-1160)

However... the Sun has a transition region, corona, magnetic fields and more!



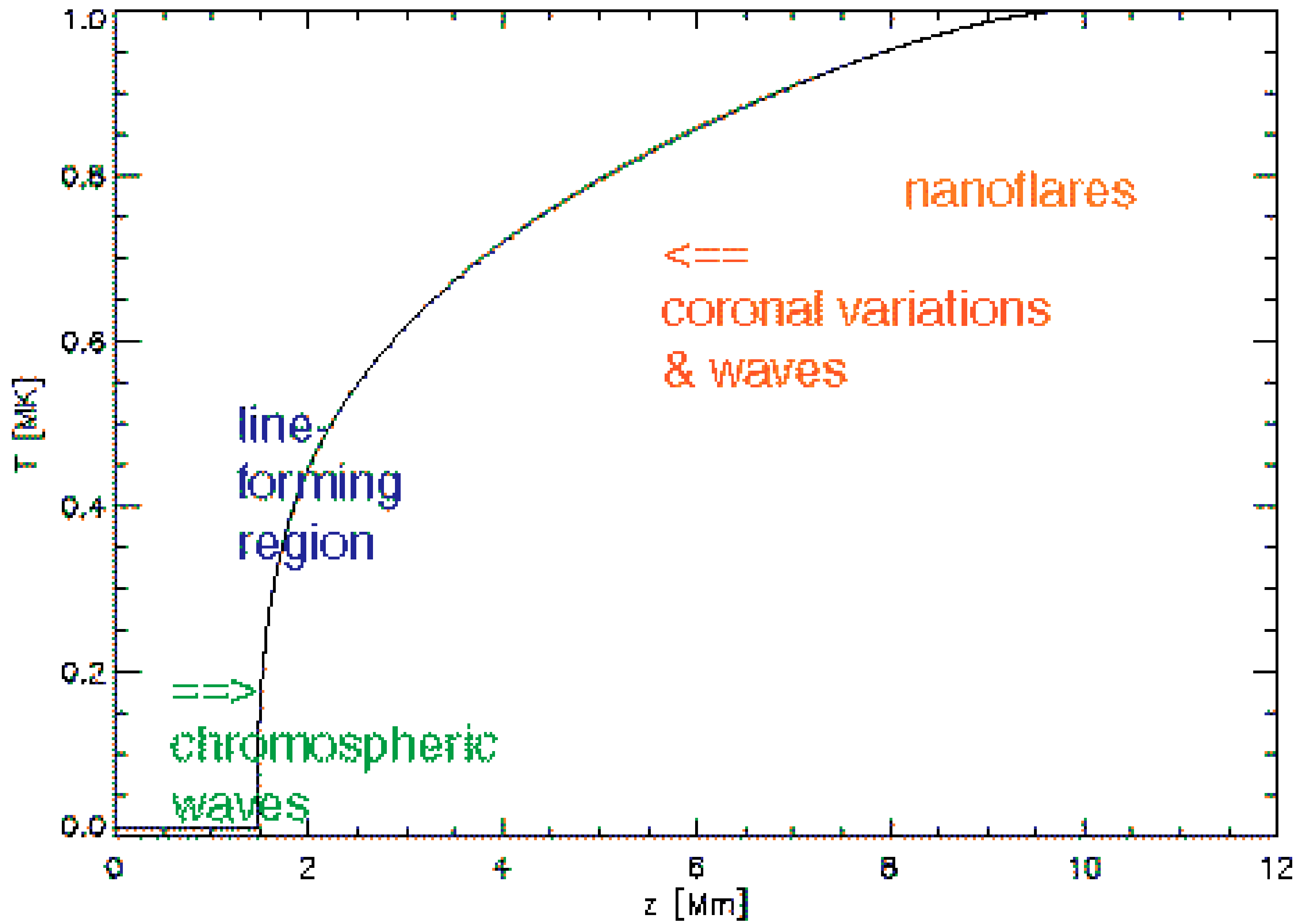
What have we learnt?

- Ca II grains explained by acoustic waves
  - only way to get strong blue-red asymmetry is through a strong velocity gradient
- 3 min waves present already in photosphere
- Non-magnetic chromosphere very dynamic. There may be no temperature rise.
- Acoustic waves cannot explain network chromospheric emission...
- ...nor indeed the inter-network background!

Transition Region Structure

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

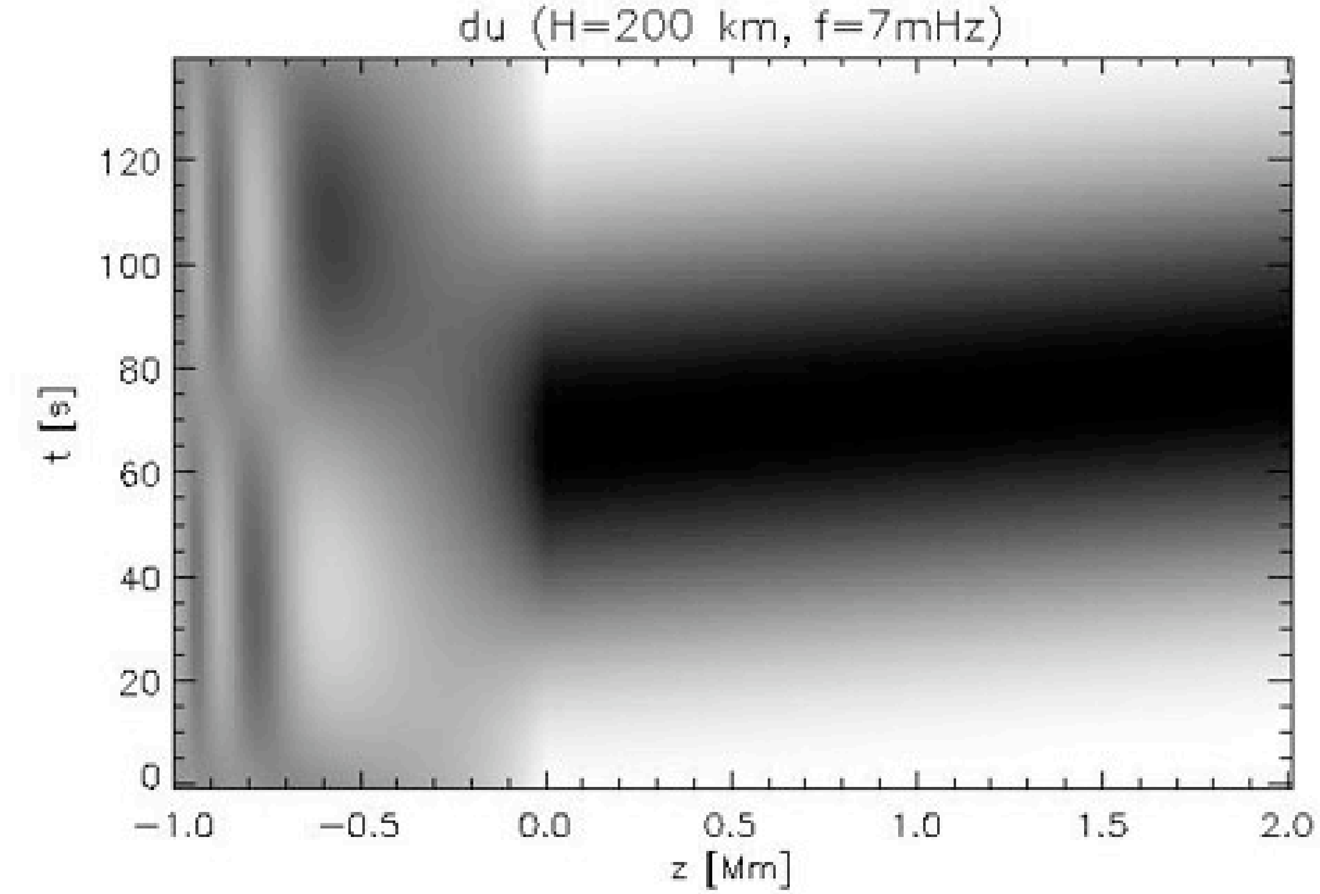
$$F_c = \kappa_0 T^{5/2} \frac{dT}{dz}$$

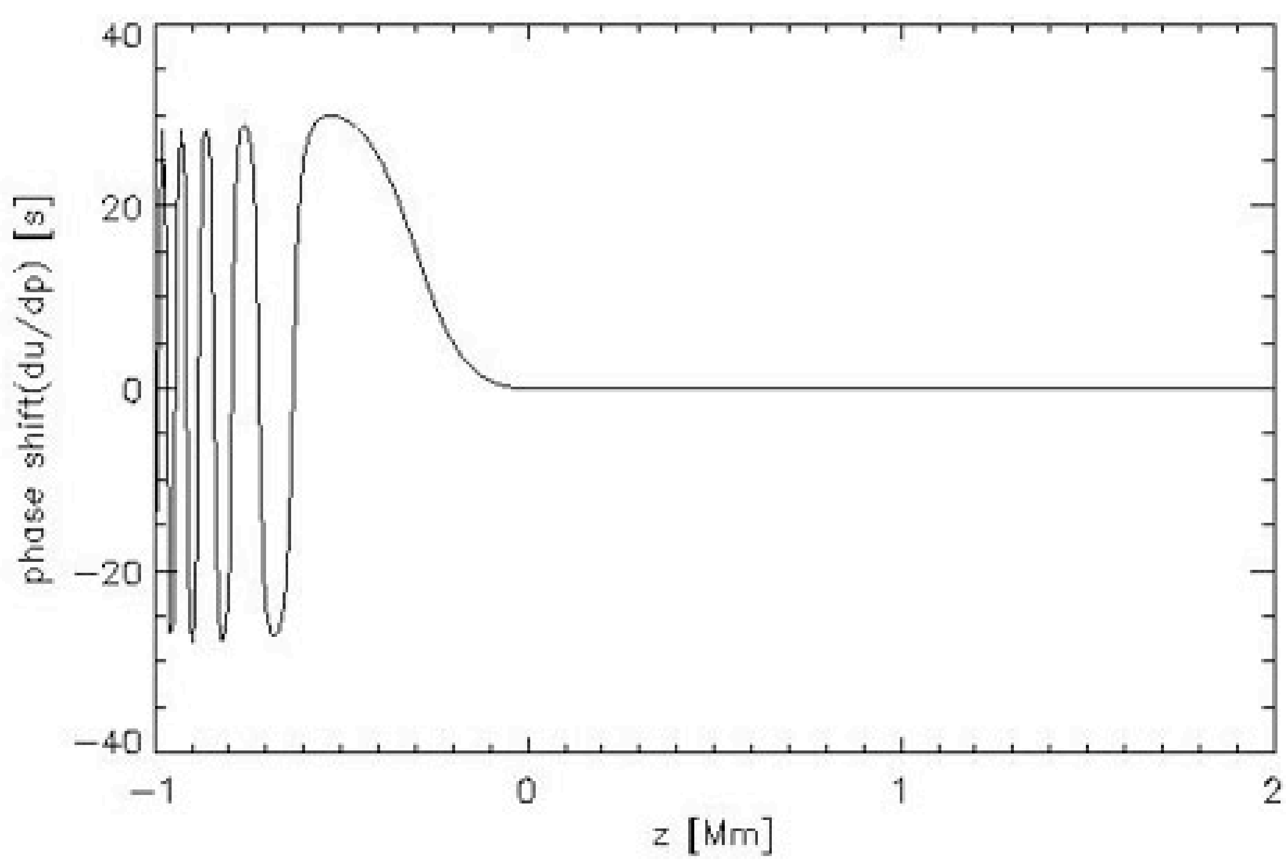


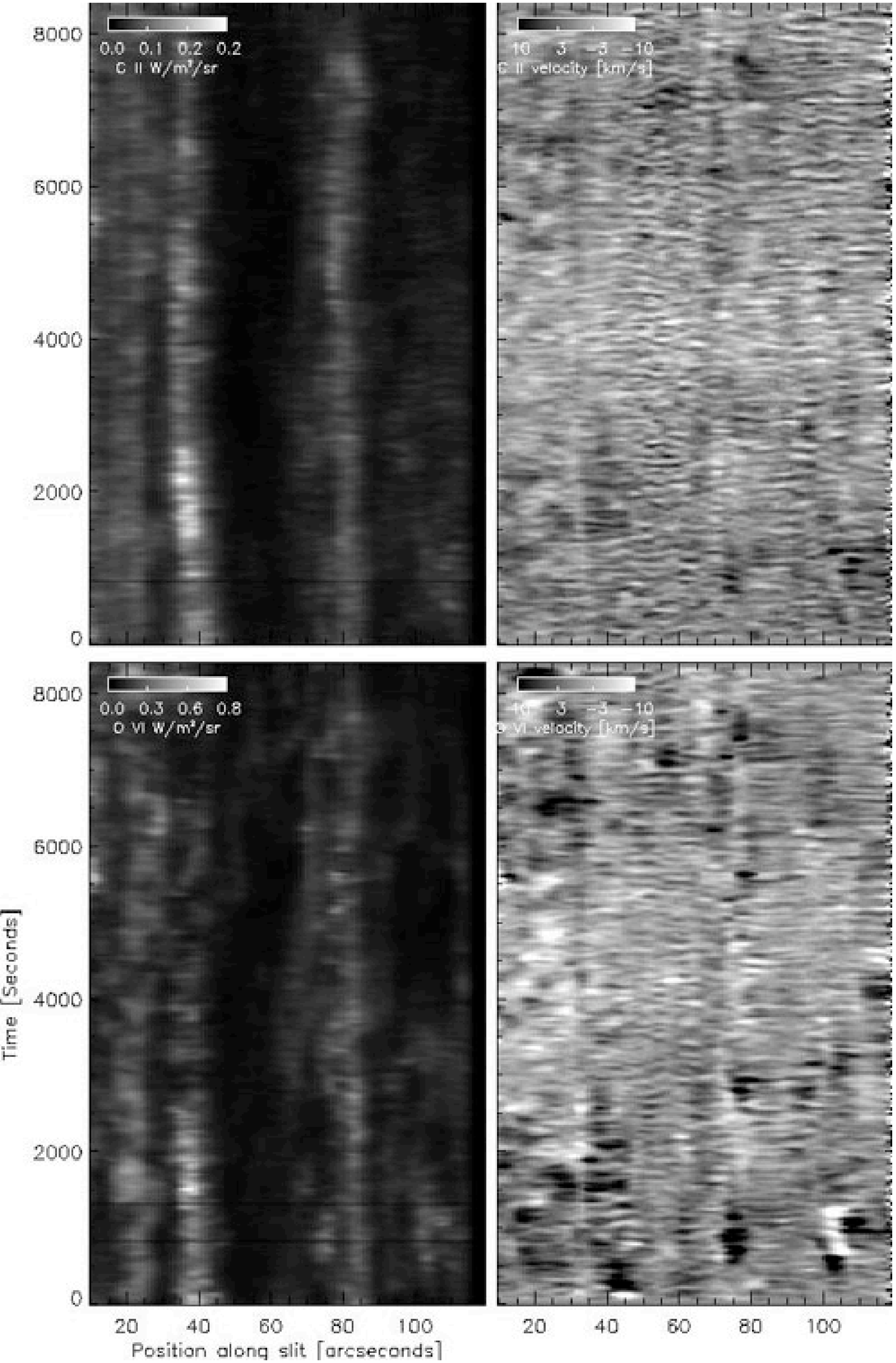
Reflections due the temperature gradient

an acoustic wave will partially (approximately 50% of the wave energy) reflect off the expected transition region temperature gradient

reflection will lead to phase shifts between line shifts and the line intensities







...and indeed observations show that...

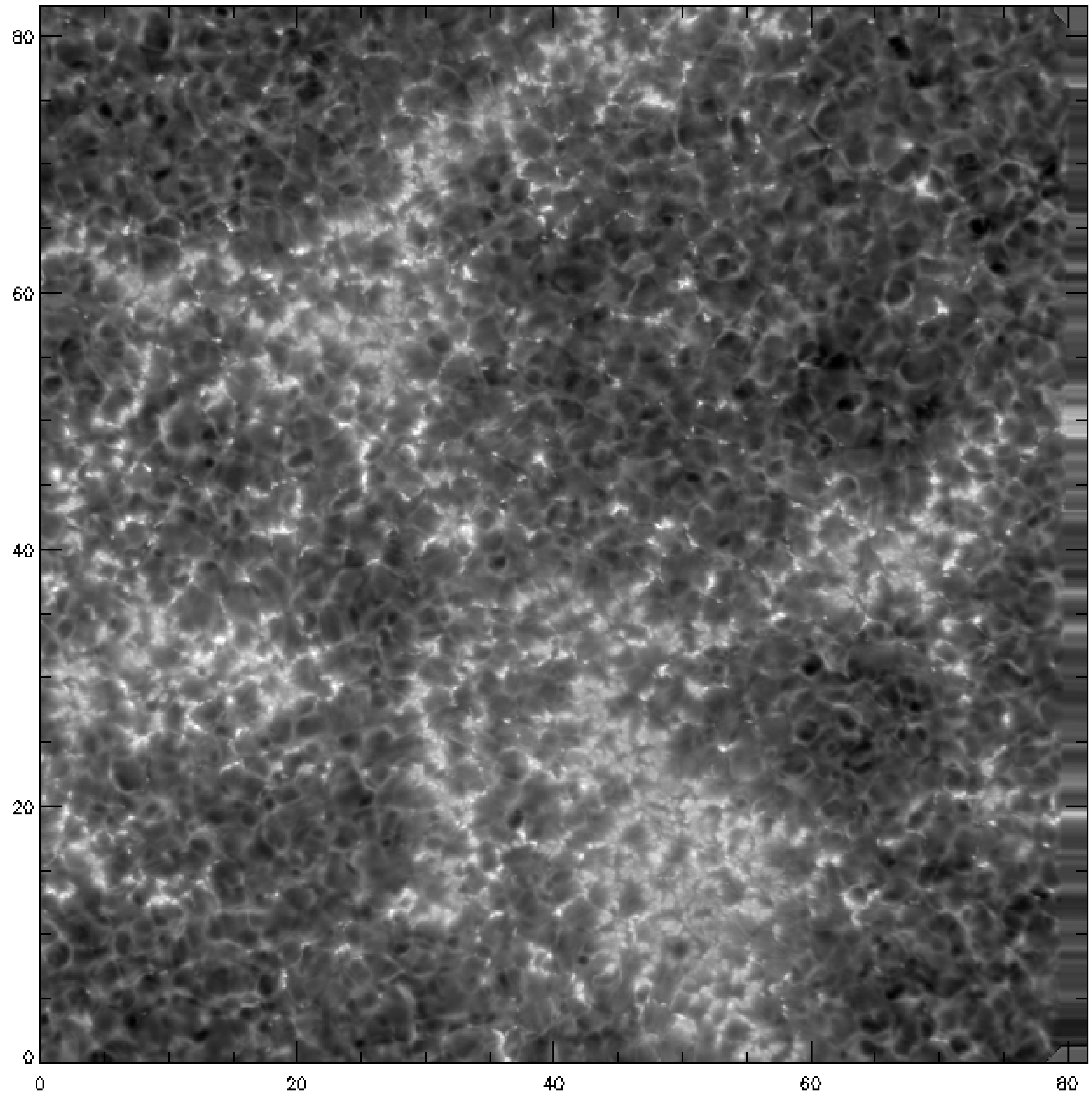
the 5-10 mHz oscillations can be followed up into the (upper) transition region

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

Wikstøl et al, 2000

(ApJ Volume 531, Issue 2, pp. 1150-1160)

The chromospheric network



Network and inter-network

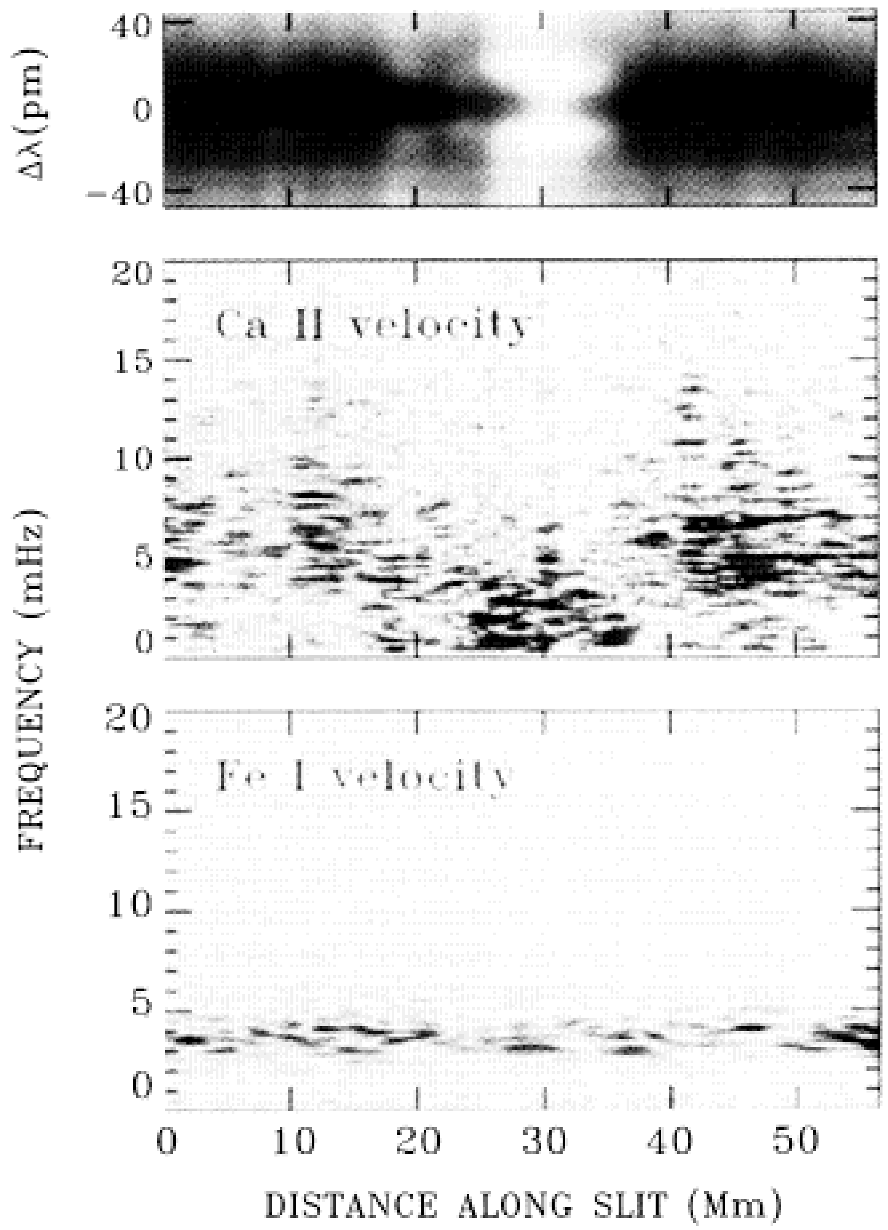
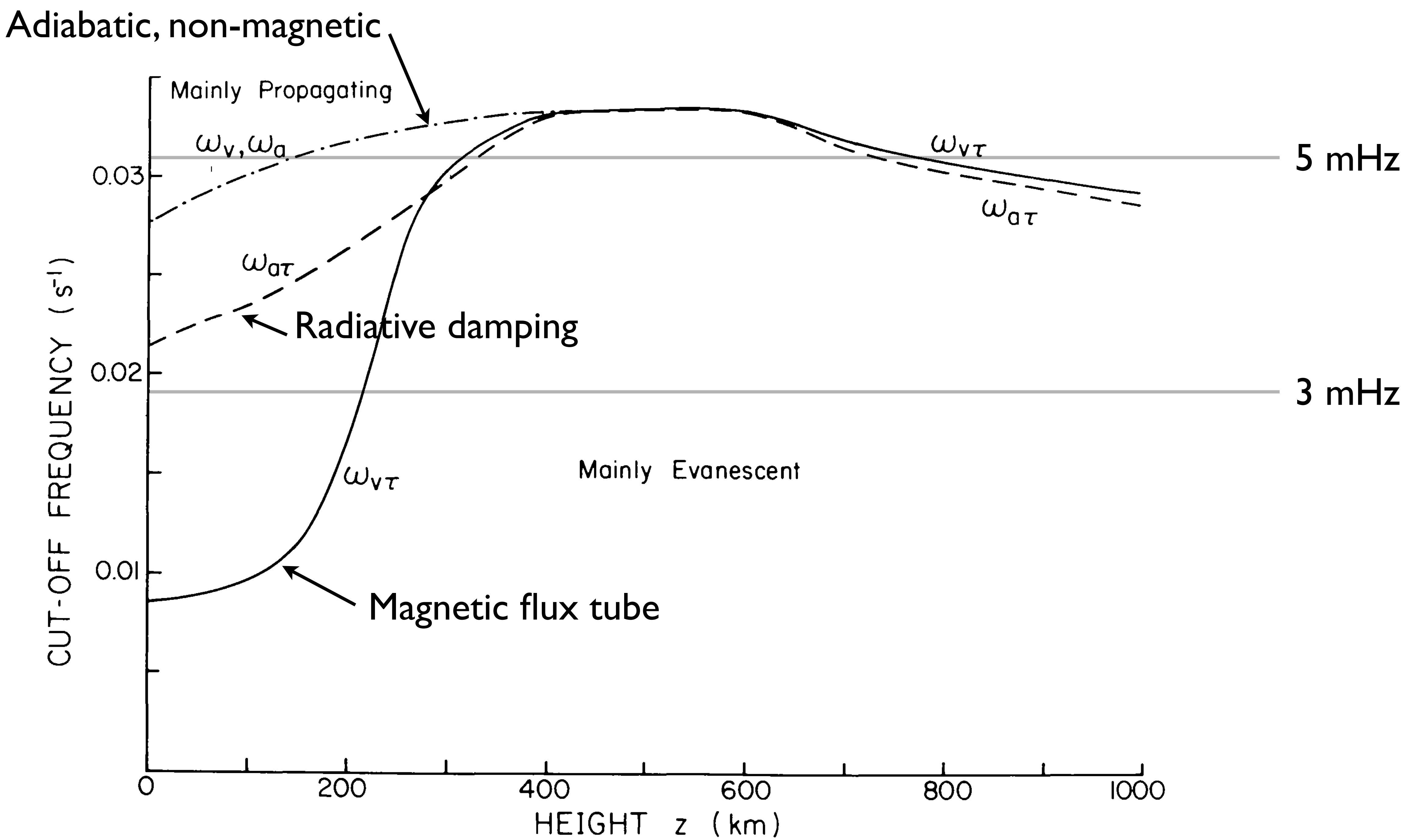


FIG. 4.—The top panel displays the time-averaged Ca II H profile as a function of spatial position. The bright K_2 bands in the middle reveal the segment of network covered by the slit. The middle and bottom panels show the power in the Doppler velocity fluctuations of Ca II H_3 and Fe I 396.682 nm, 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.

Lites, B. W., Rutten, R. J., & Kalkofen, W., 1993, ApJ 414, 345

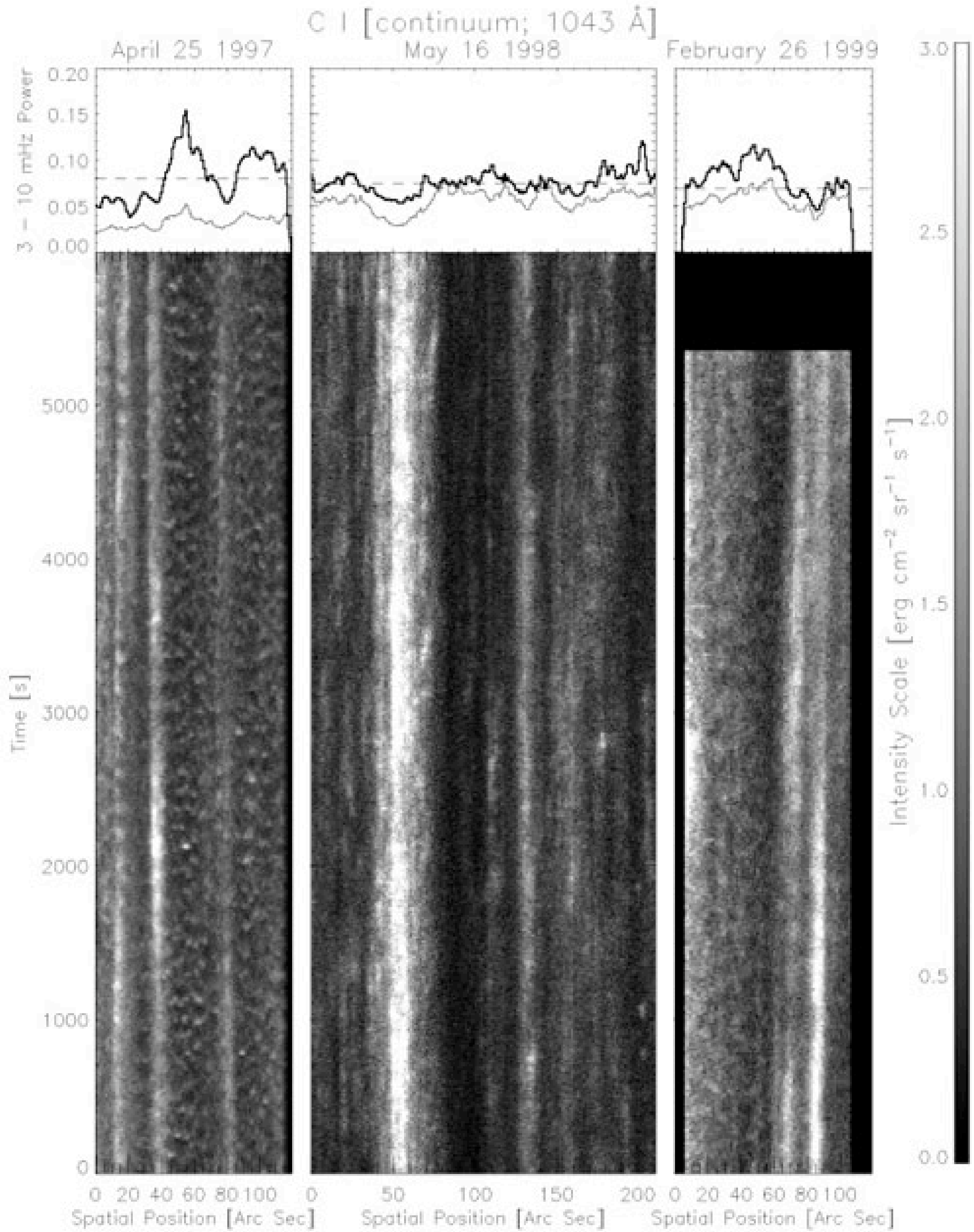
Cut-off frequency



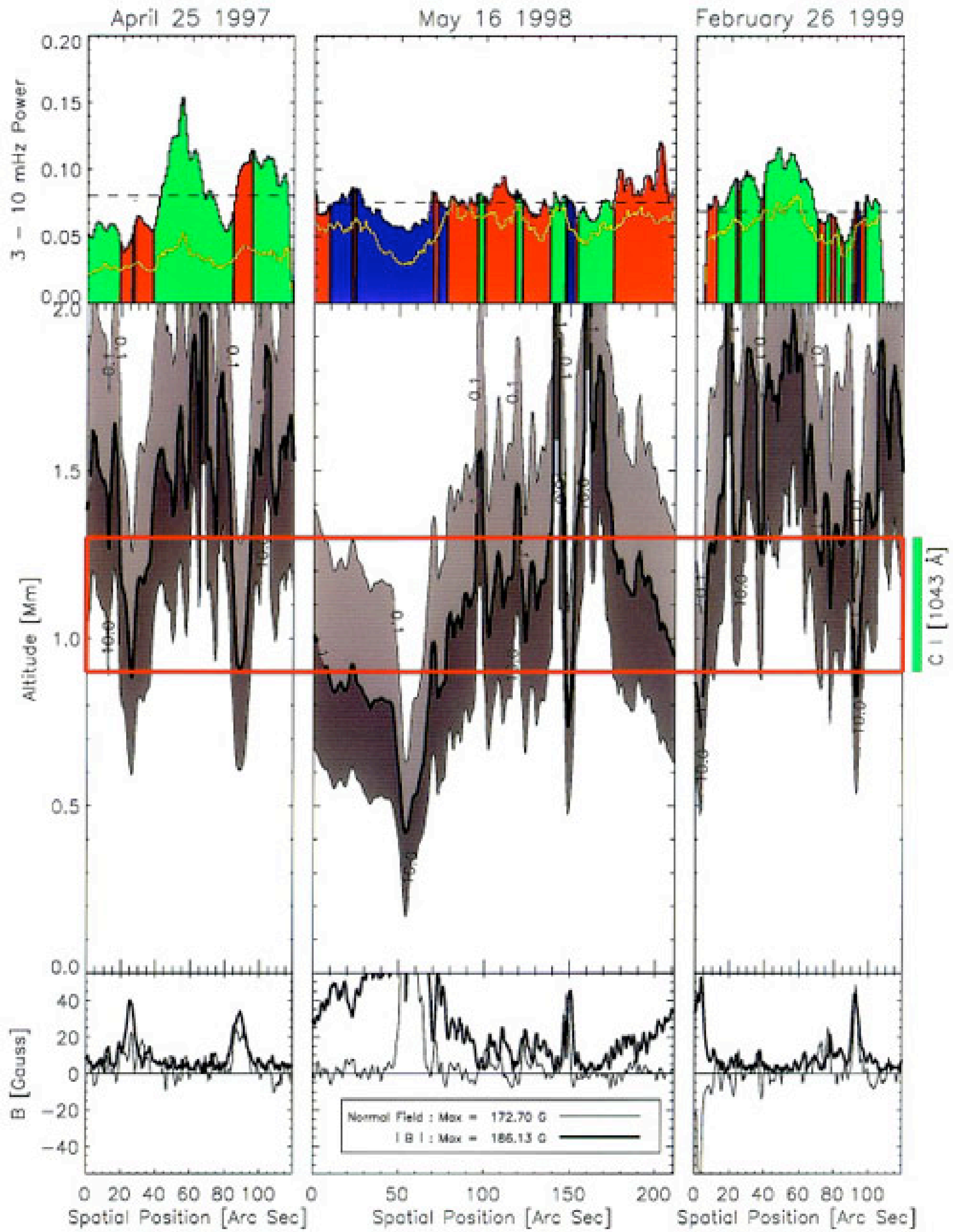
Roberts, 1983, Solar Physics 87,77

3 min/5 mHz oscillations not always visible!

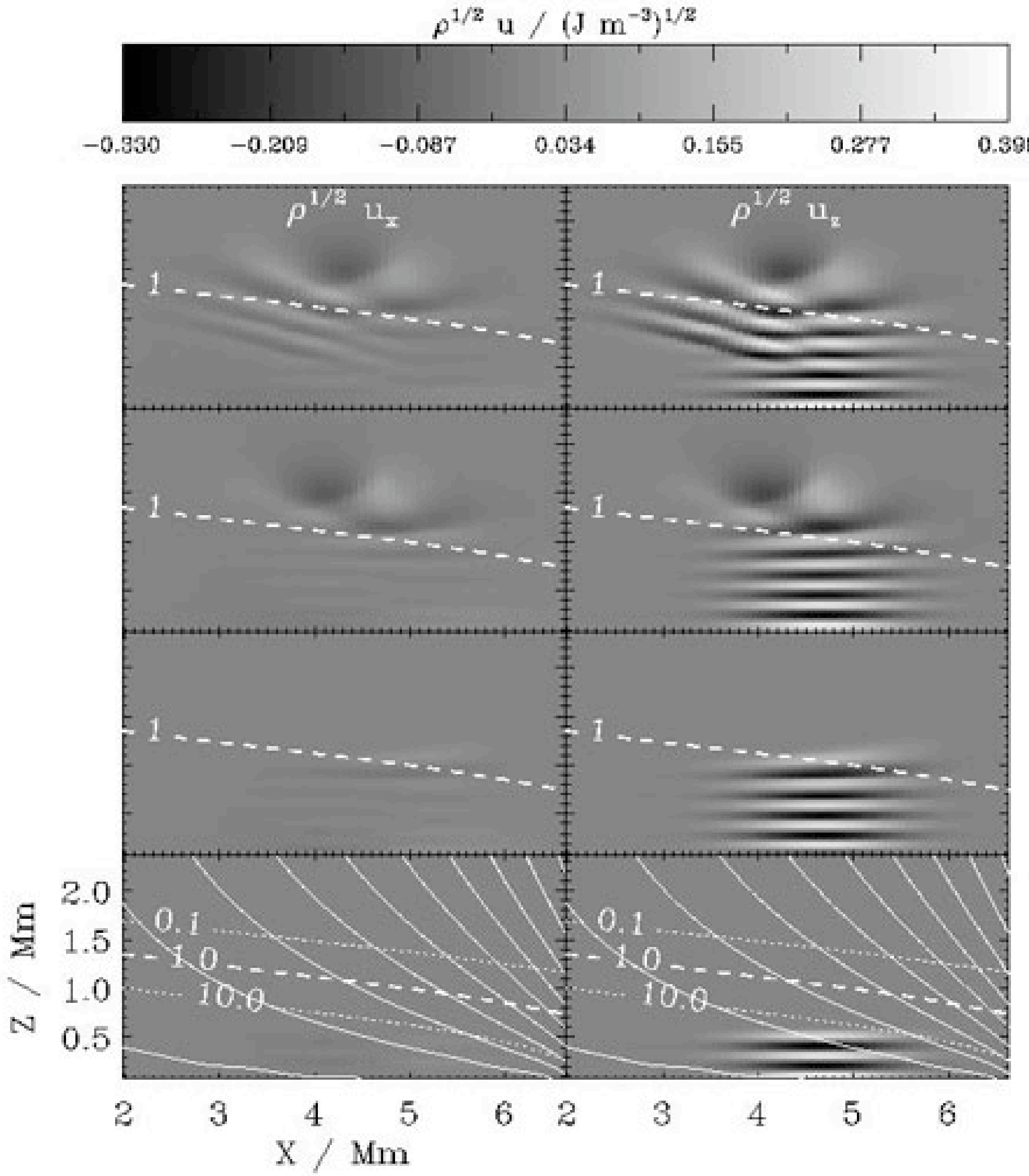
(McIntosh et al., 2001, ApJL 548, 237)



Relation with plasma beta or angle of B?

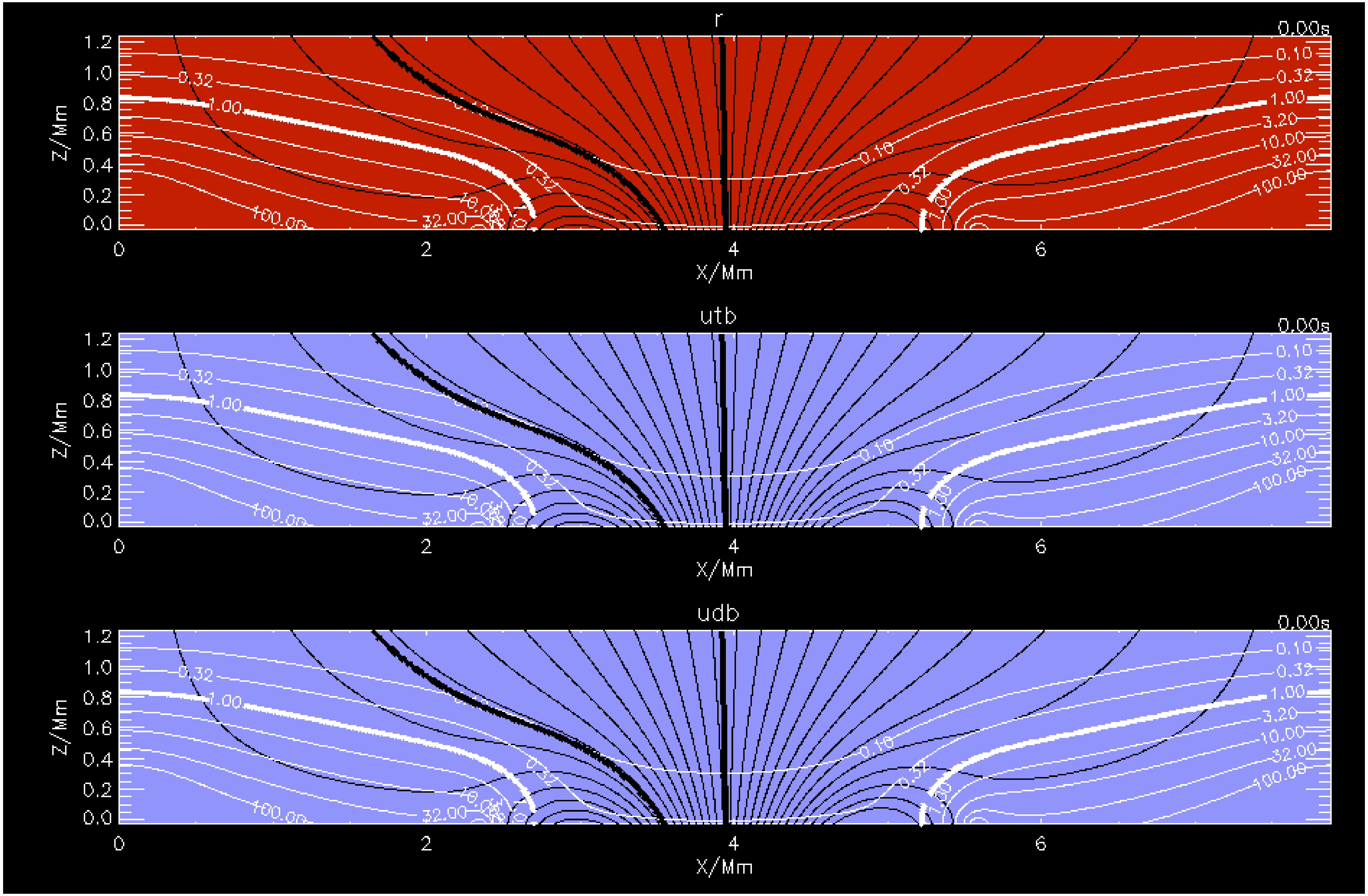


Wave reflection and refraction....



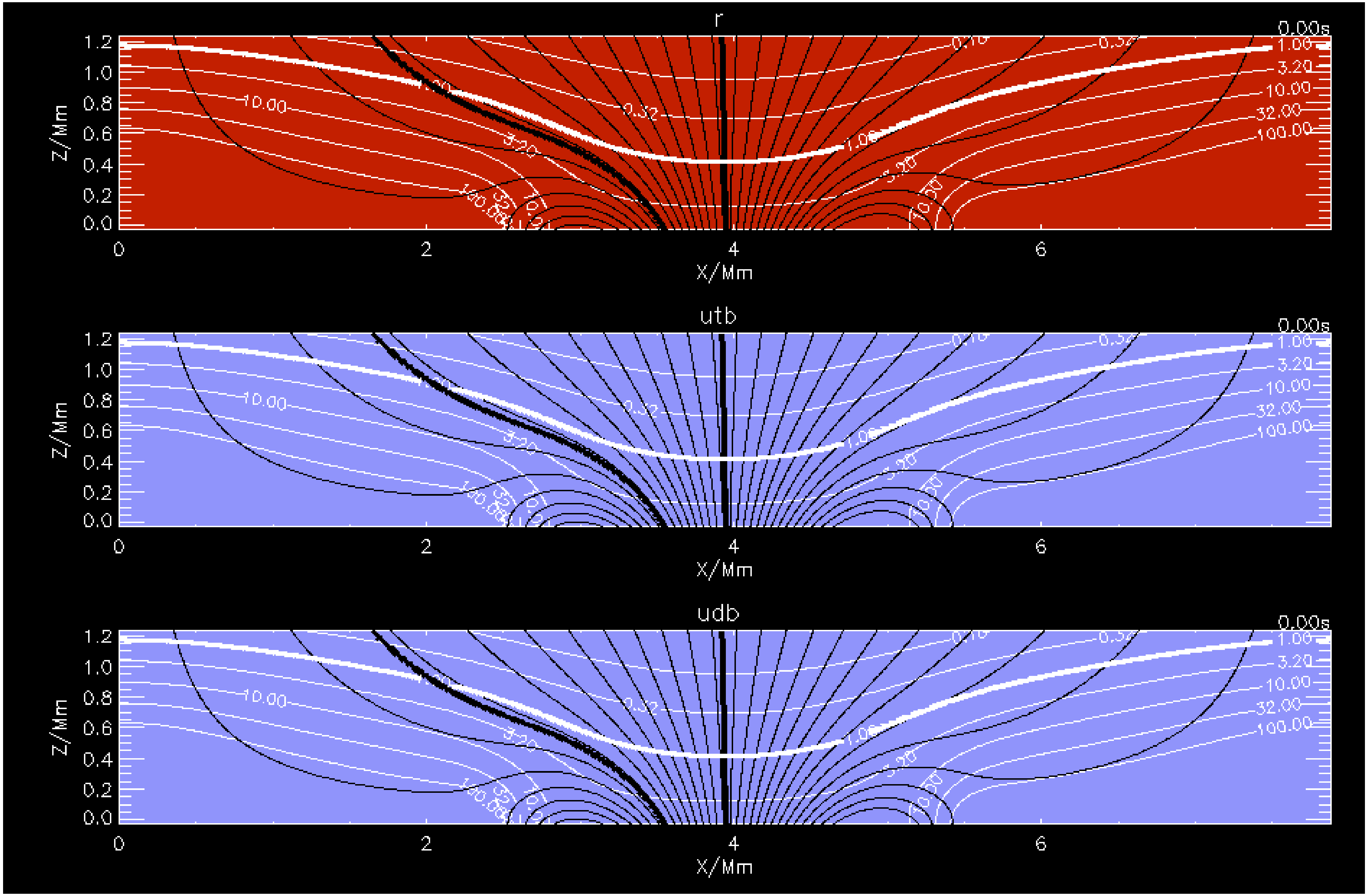
Rosenthal et al. 2002, ApJ 564, 508.

Strong field - vertical driving



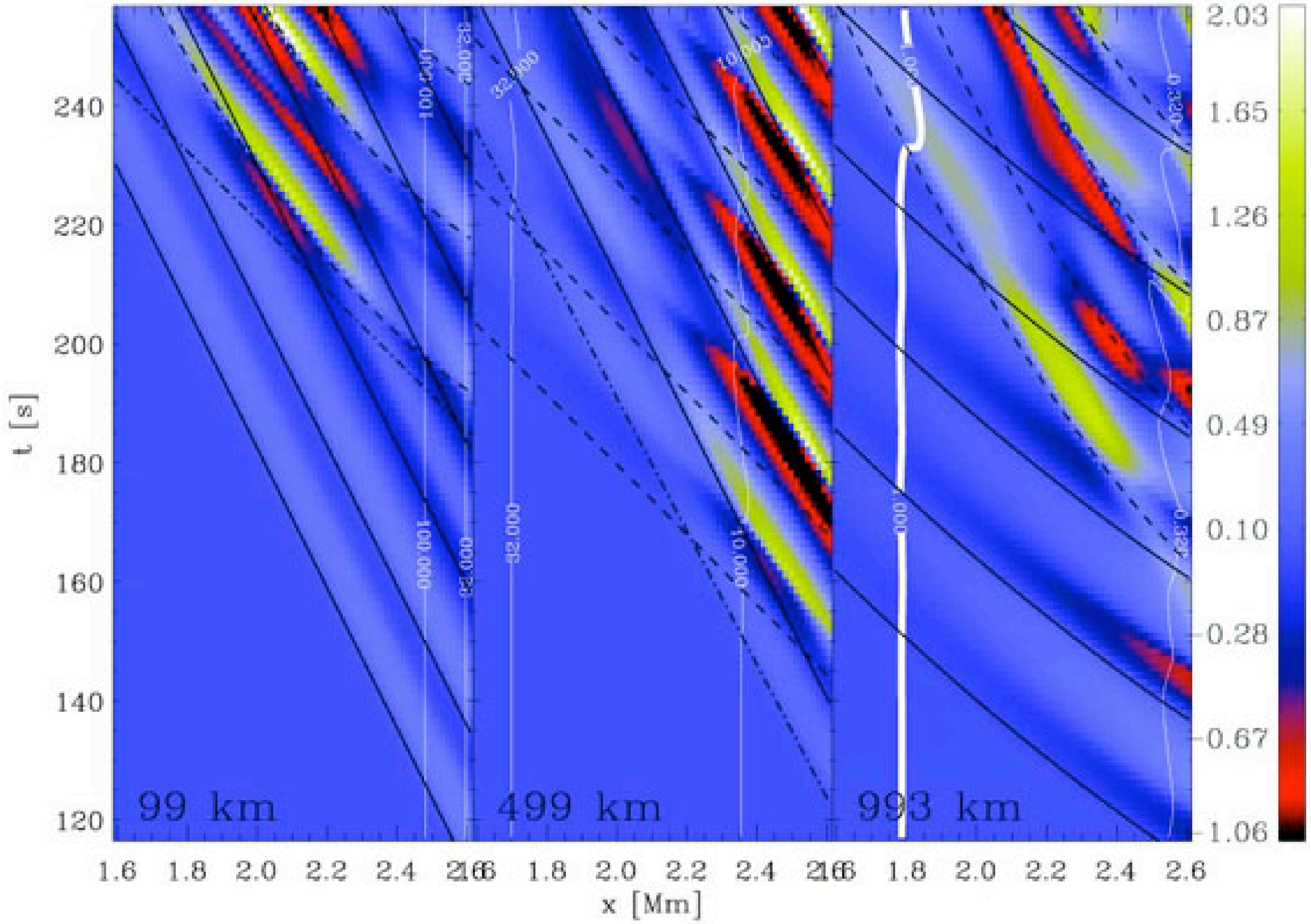
Bogdan et al. 2003, ApJ 599, 626.

Weak field - vertical driving



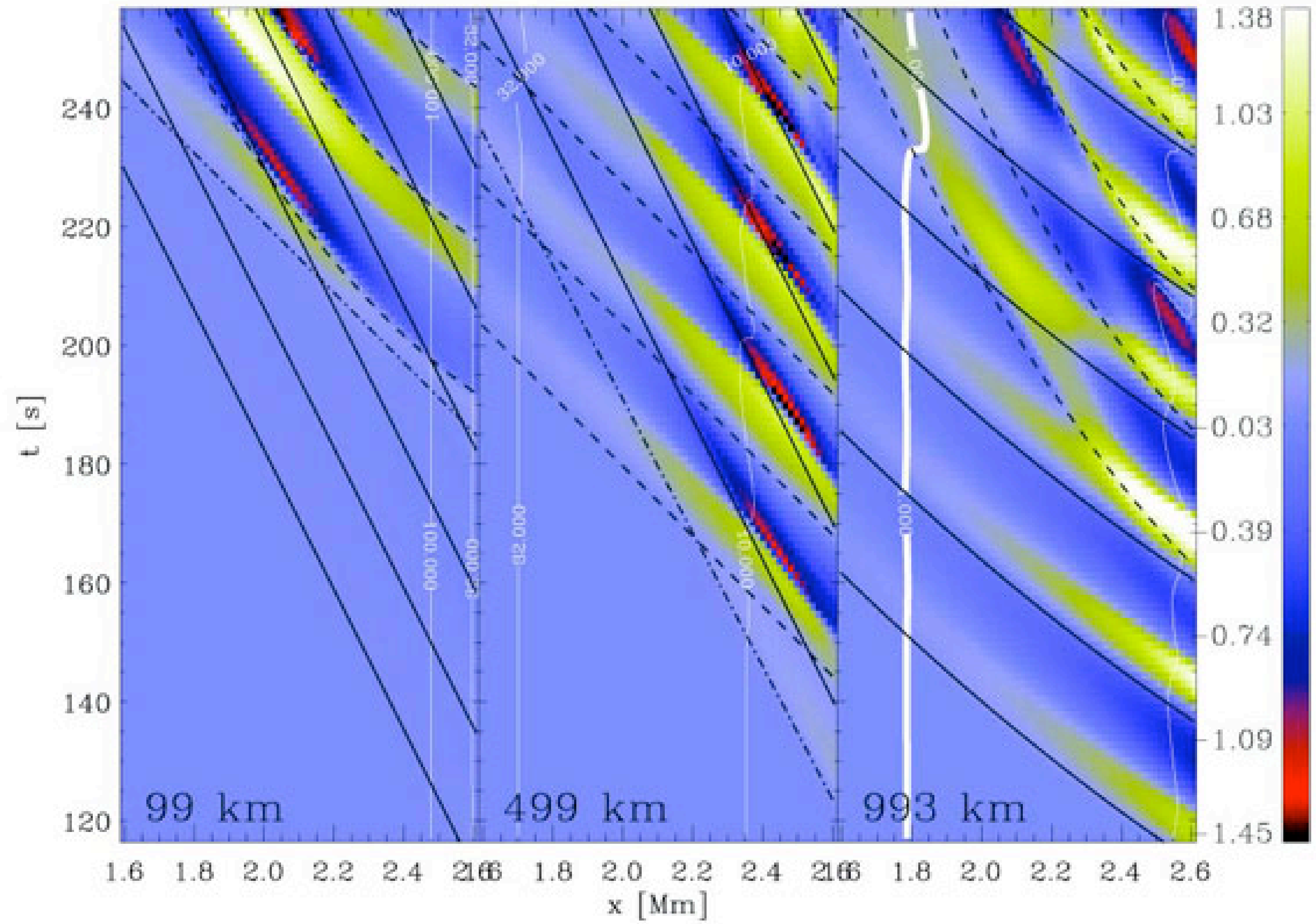
Bogdan et al. 2003, ApJ 599, 626.

“Intensity” signal at three heights



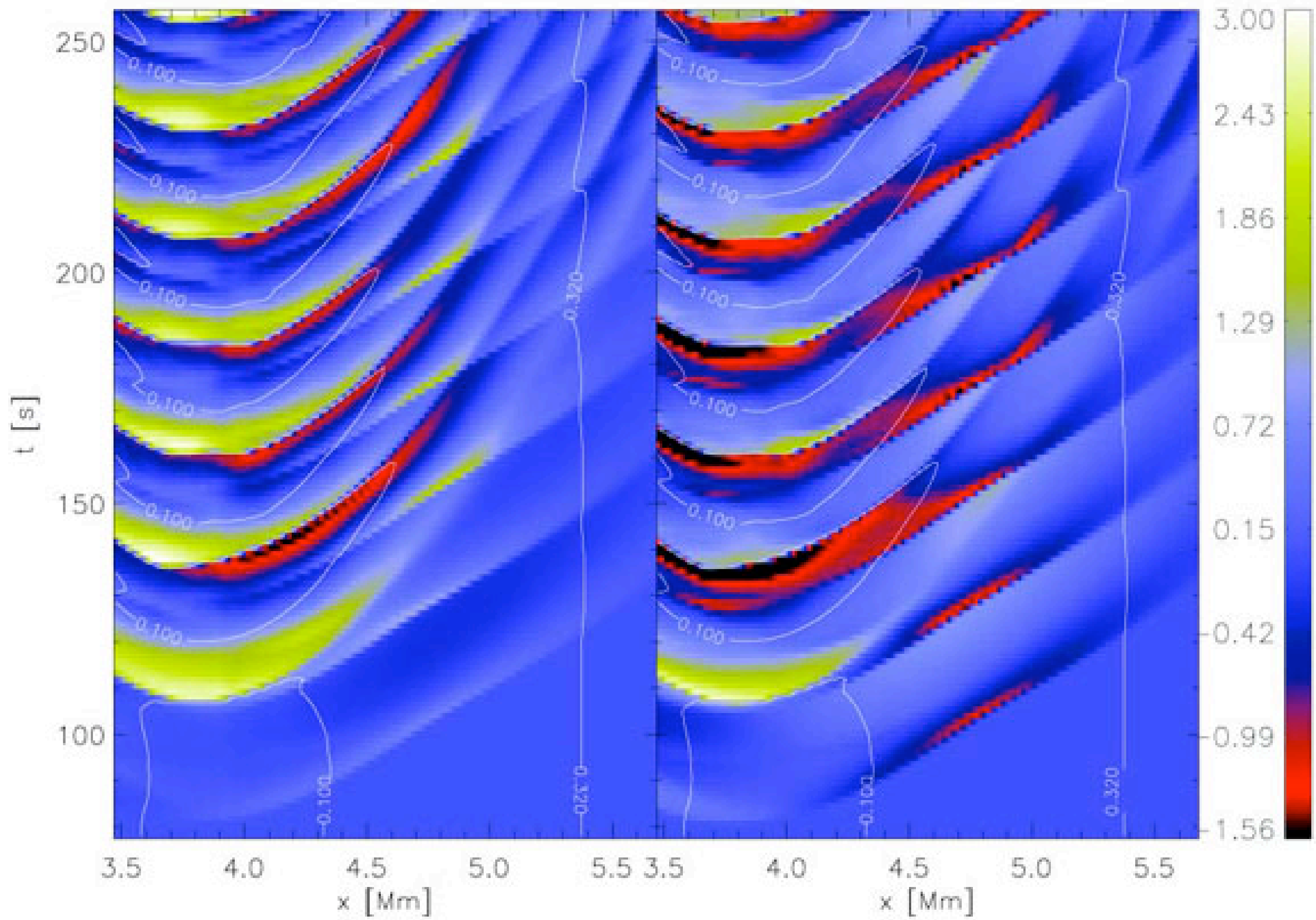
- 99 km - *two* fast mode wave trains
    - a) from piston b) downward propagating from canopy above
- 499 km - same two wave trains... both arrive at roughly the same time
- 993 km - looking mainly above canopy

“Doppler” signal at three heights



- 99 km - *two* fast mode wave trains
  - mode direct from piston essentially absent in Doppler signal
- 499 km - same two wave trains... both arrive at roughly the same time
- 993 km - looking mainly above canopy

Intensity and "Doppler" directly above piston



- 993 km - *two* interfering wave trains
  - Both generated 400 km below, where the piston generated high-beta fast waves interact with the canopy
  - no physical interactions between the modes at this height since beta is small, as are wave amplitudes
- The chromsphere is *not* well connected to the driving piston at the photosphere

Observational advice...

- 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
- Chromosphere is in general *not* well connected to photospheric piston

Network and Inter-network velocity statistics in the Transition Region

758 V.H. Hansteen et al.: Rapid intensity and velocity variations in solar transition region lines

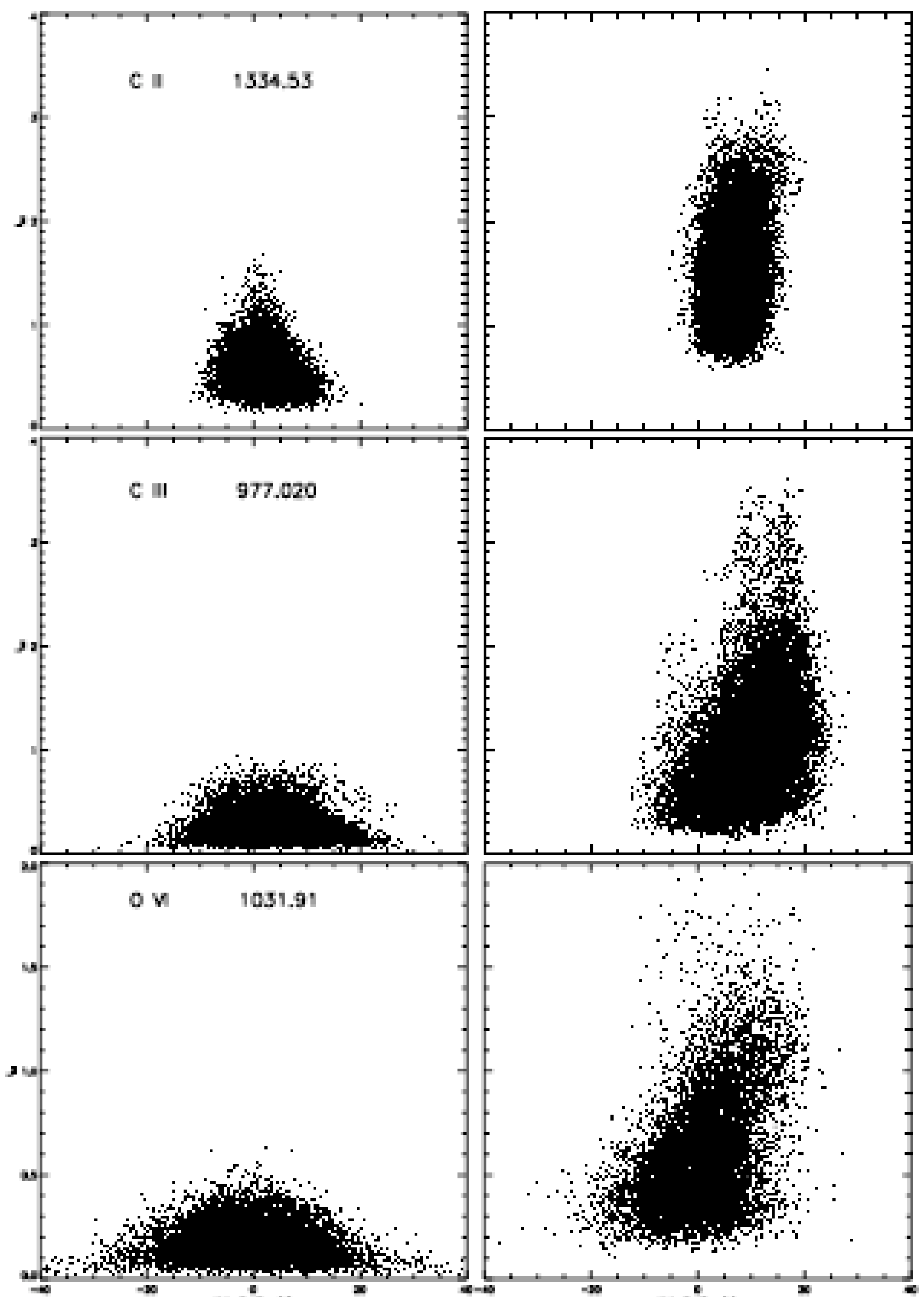
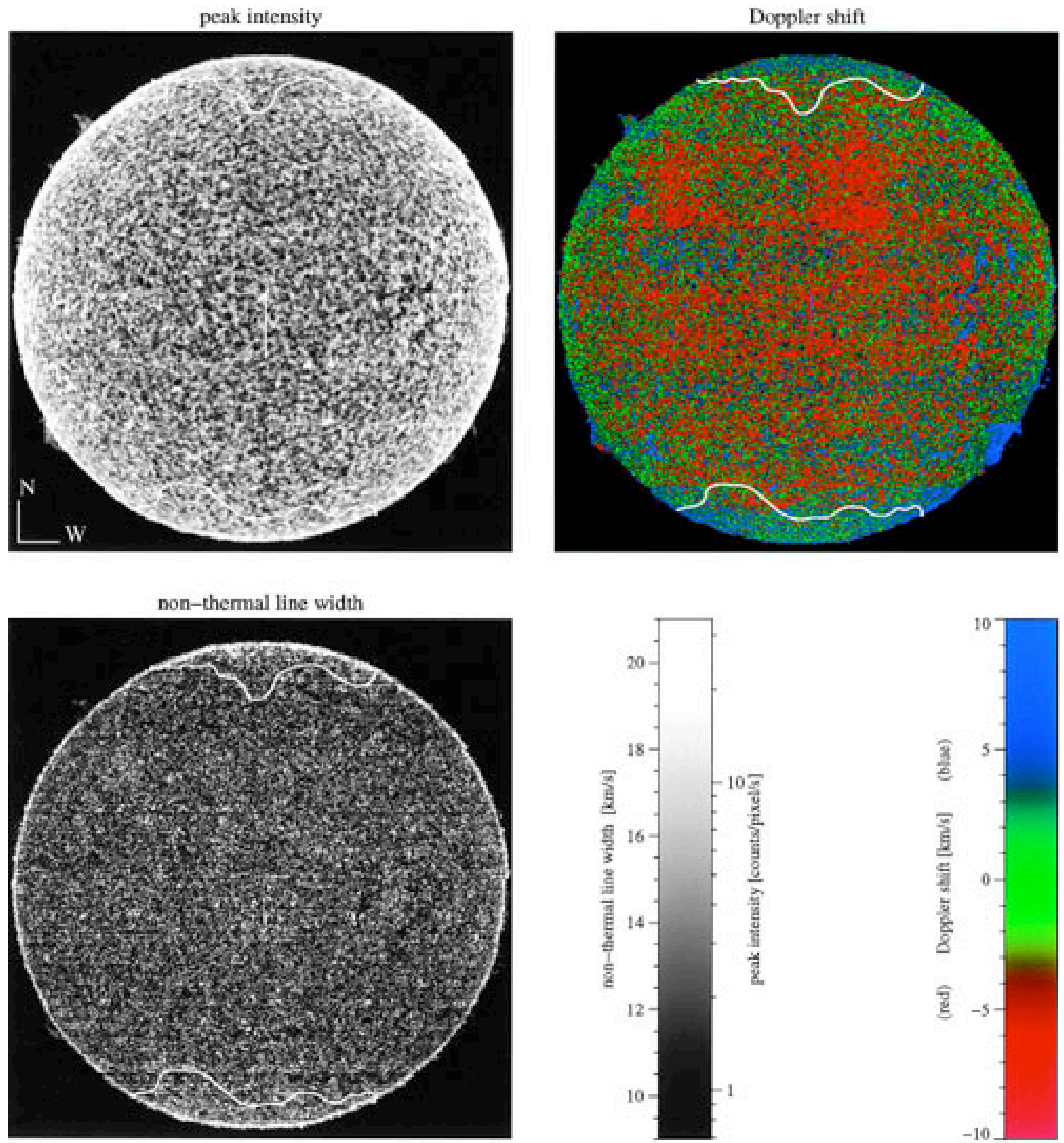


Fig. 11. Total line intensity versus line shift for C II 1334Å, C III 977Å, and O VI 1032Å. Cell interior positions in the left panels and network positions in the right panels.

Hansteen, Betta, Carlsson, 2000, A&A 360, 742



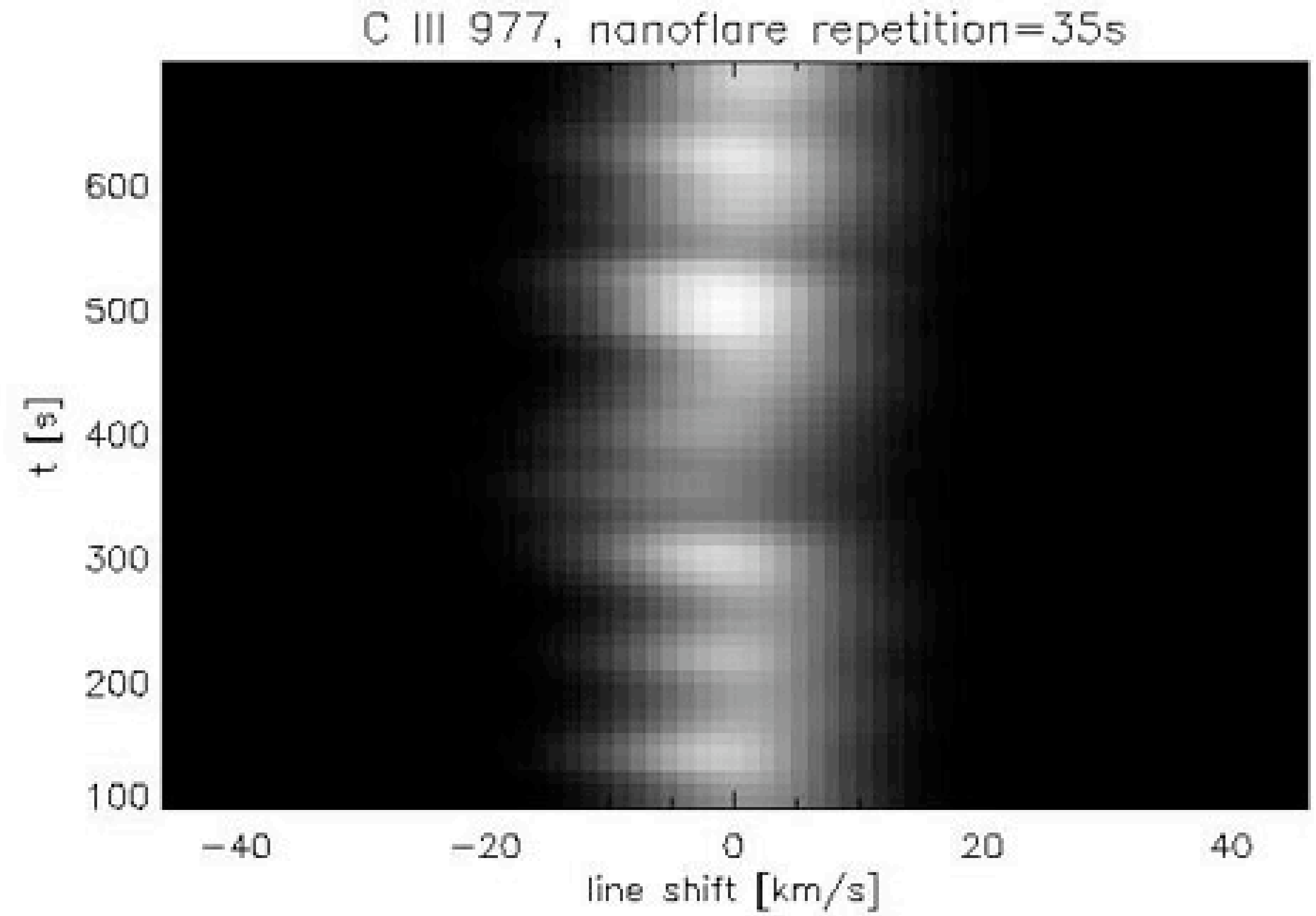
TR redshifts Peter 1999 (ApJ 516, 490)

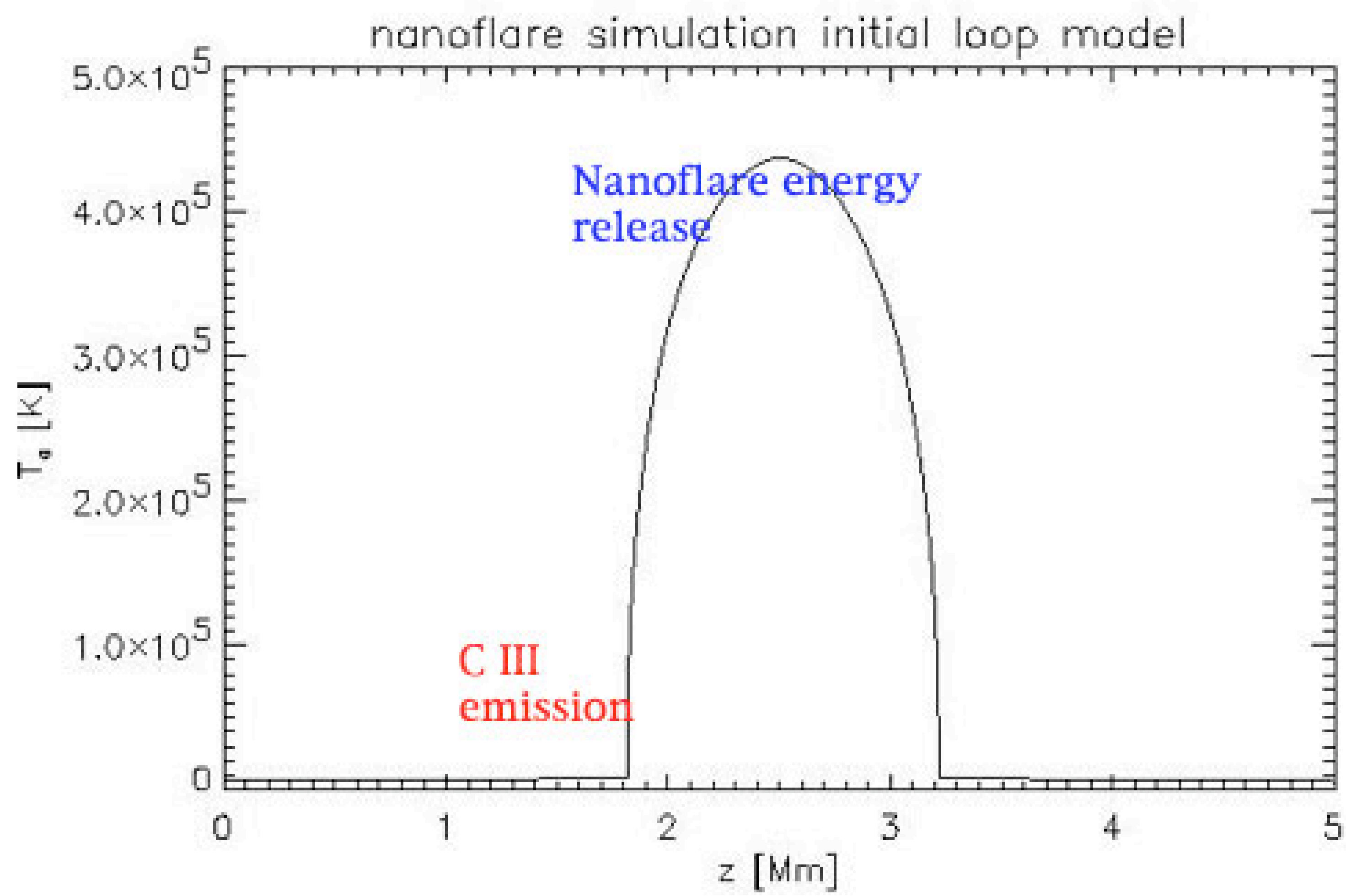
Coronal driving

violent, episodic events in the corona should leave a trace in transition region emission

transition region jets, turbulent events and blinkers?

or perhaps a "natural consequence" of episodic heating; gas is heated quickly but cools slowly as predicted by Athay & Holzer 1982 and perhaps shown by Peter & Gudiksen 2005?

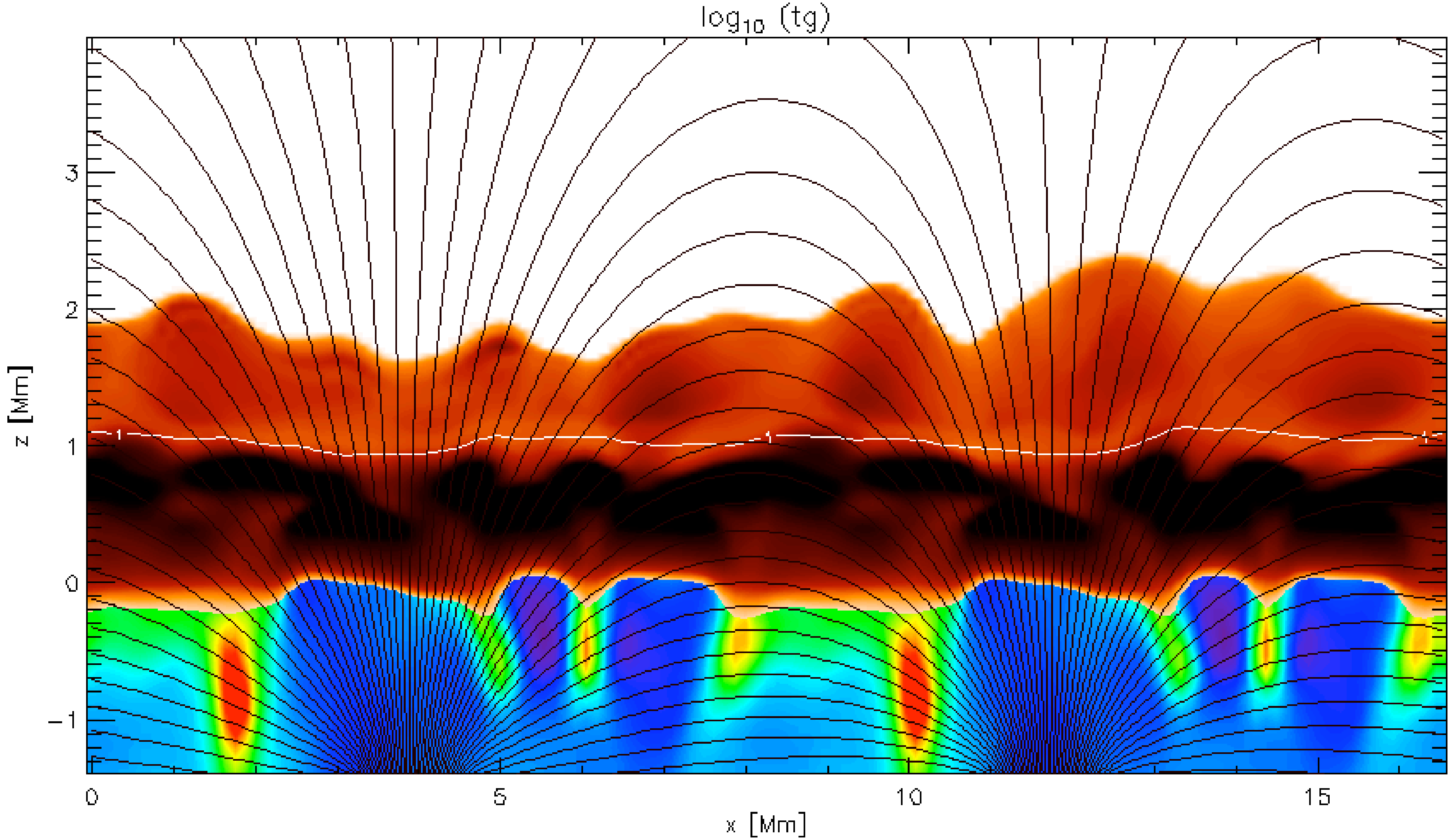




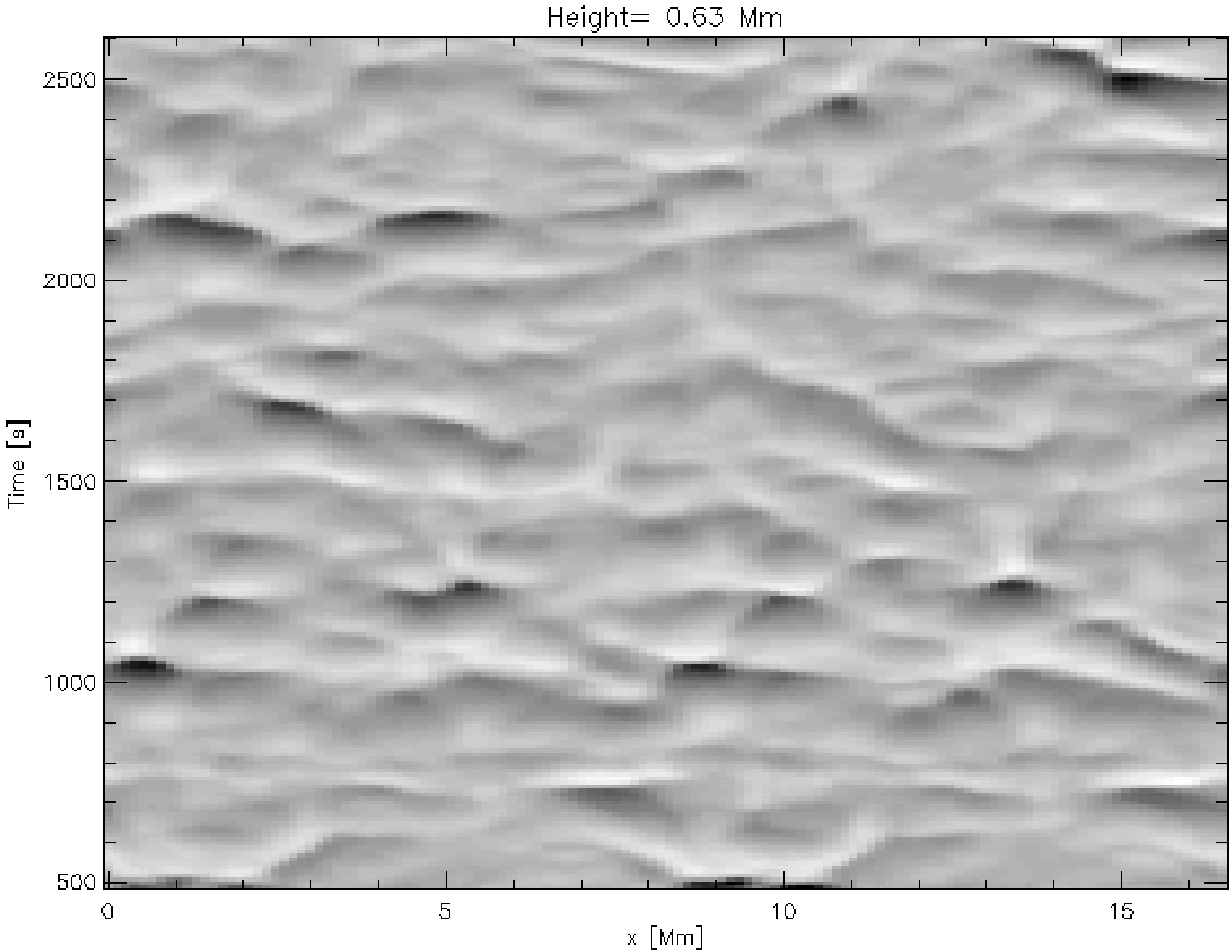
3d convection zone to coronal modeling

- 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

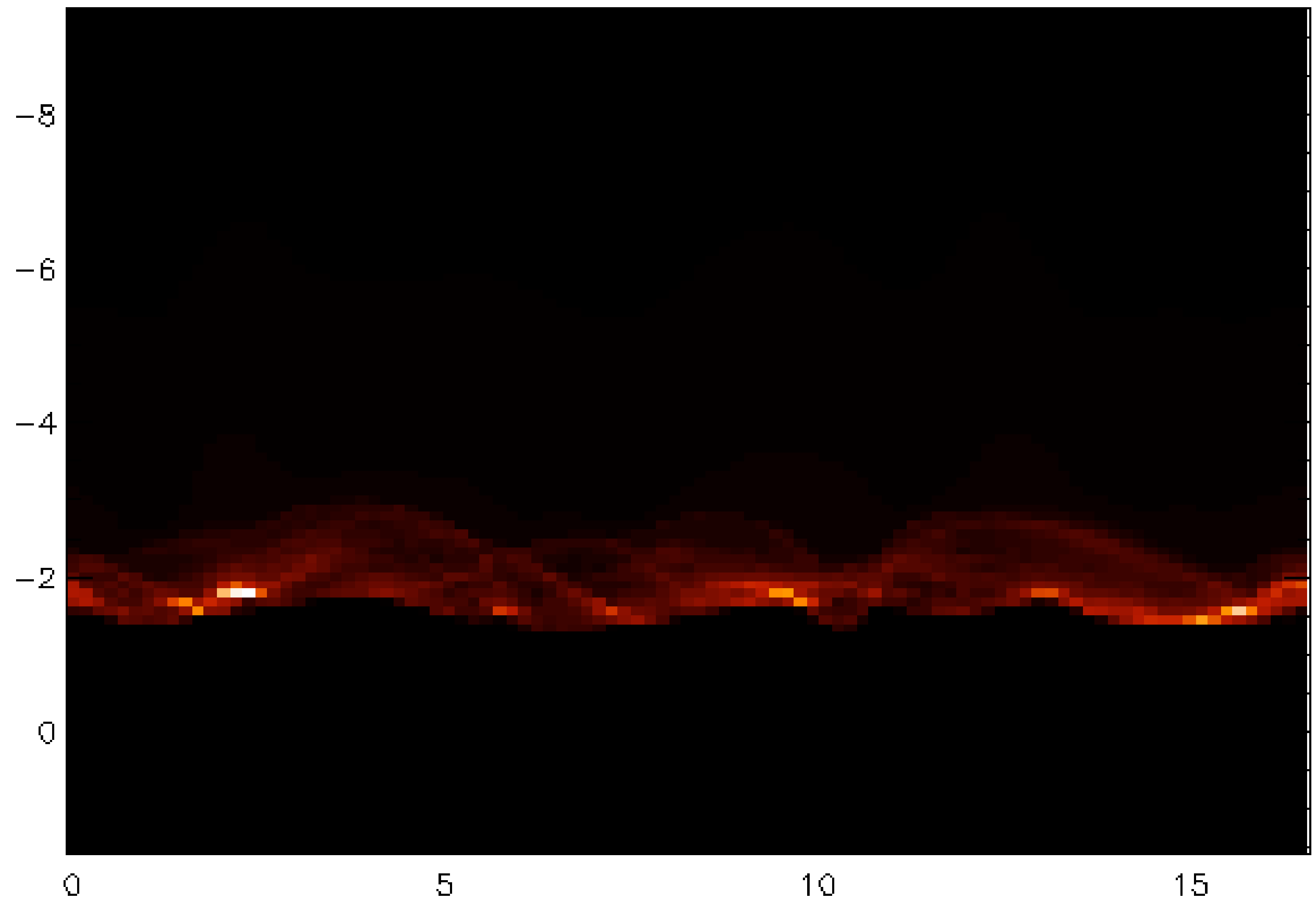
2D version



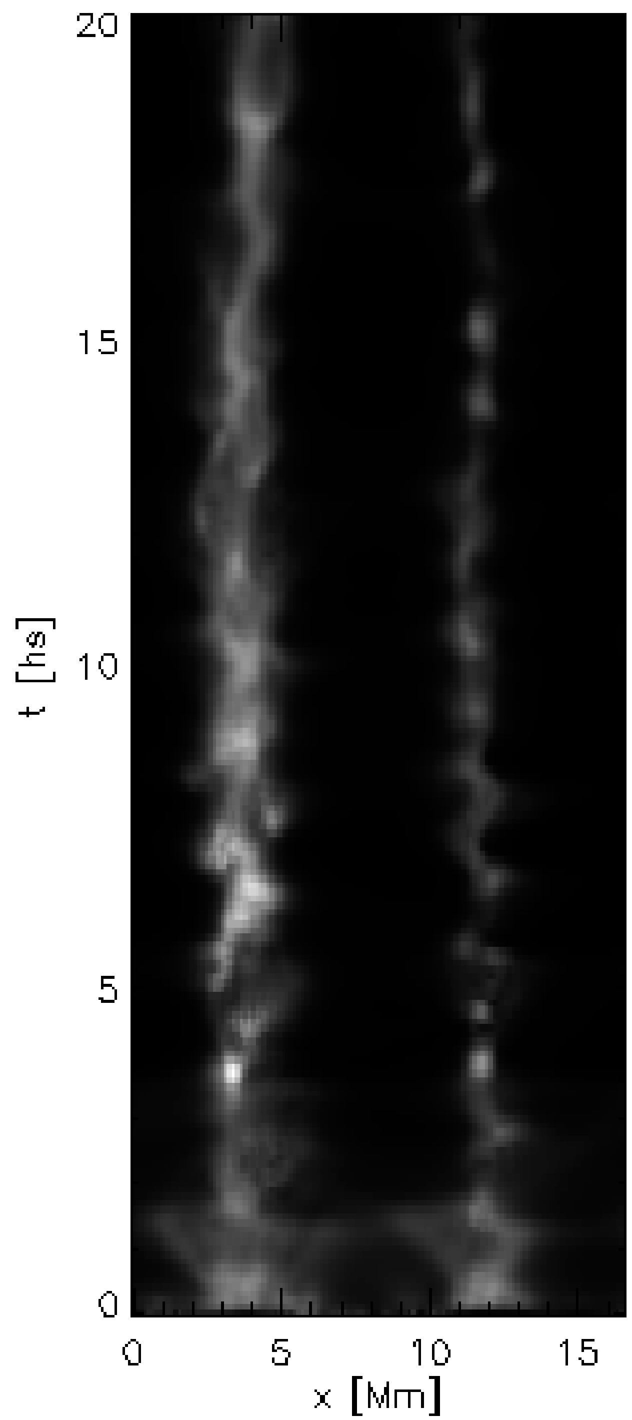
Waves

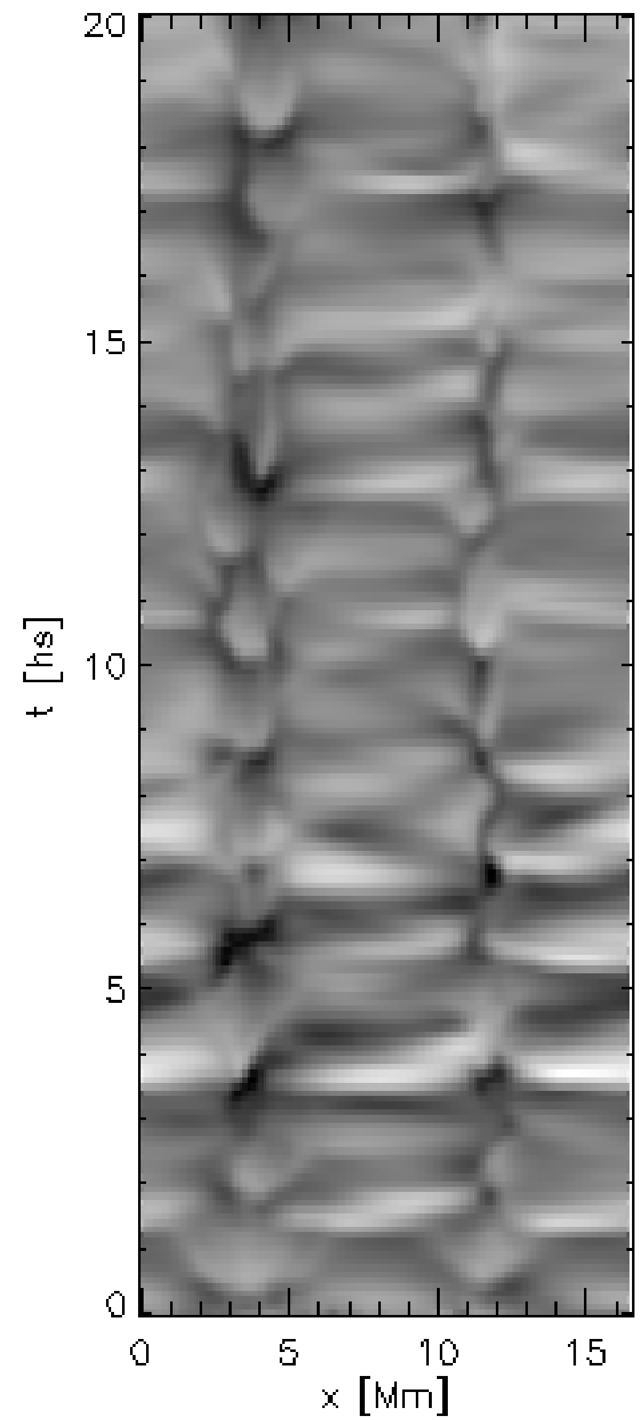


Transition region emission O VI 103.1 nm

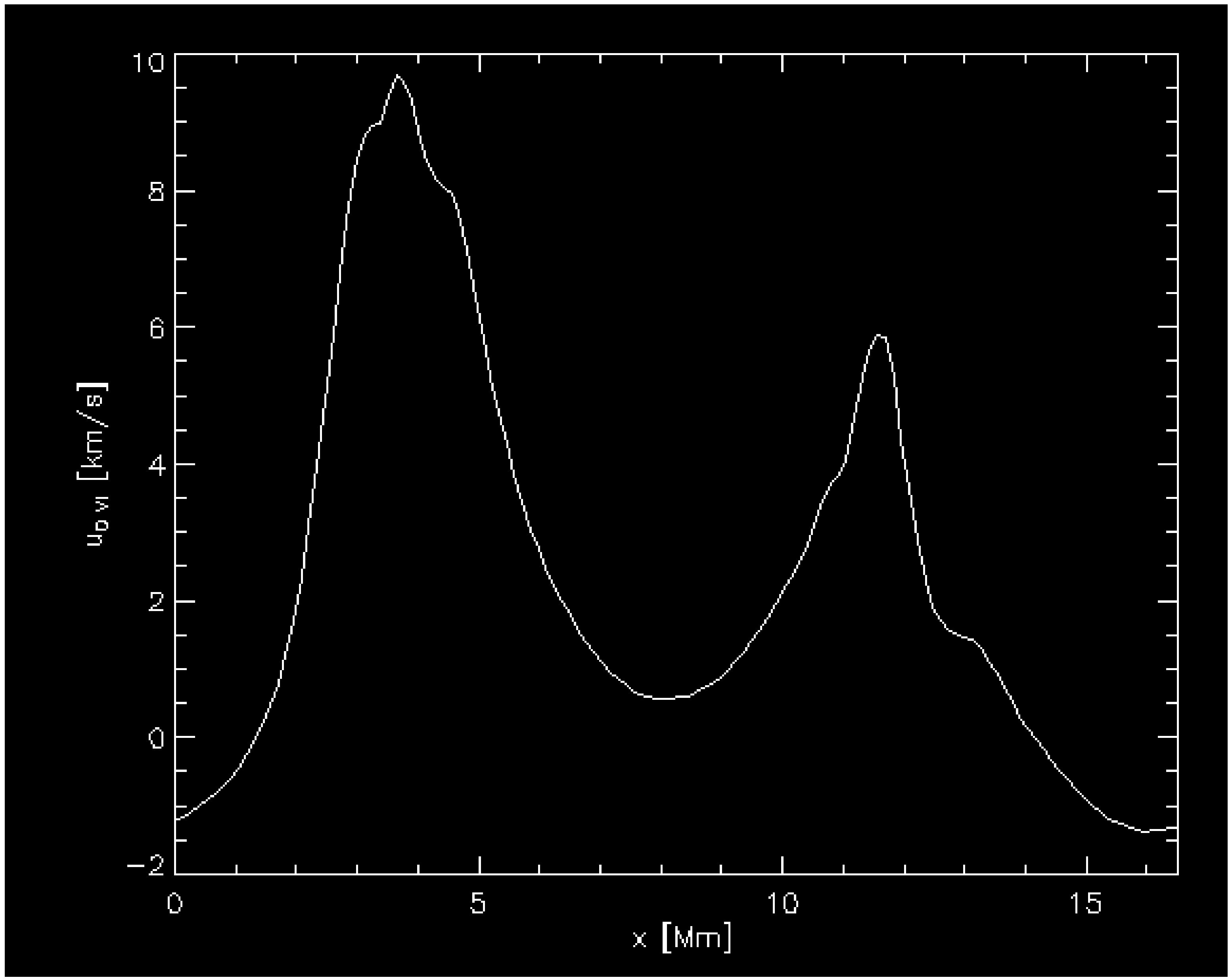


O VI 103.1 nm intensity and velocity





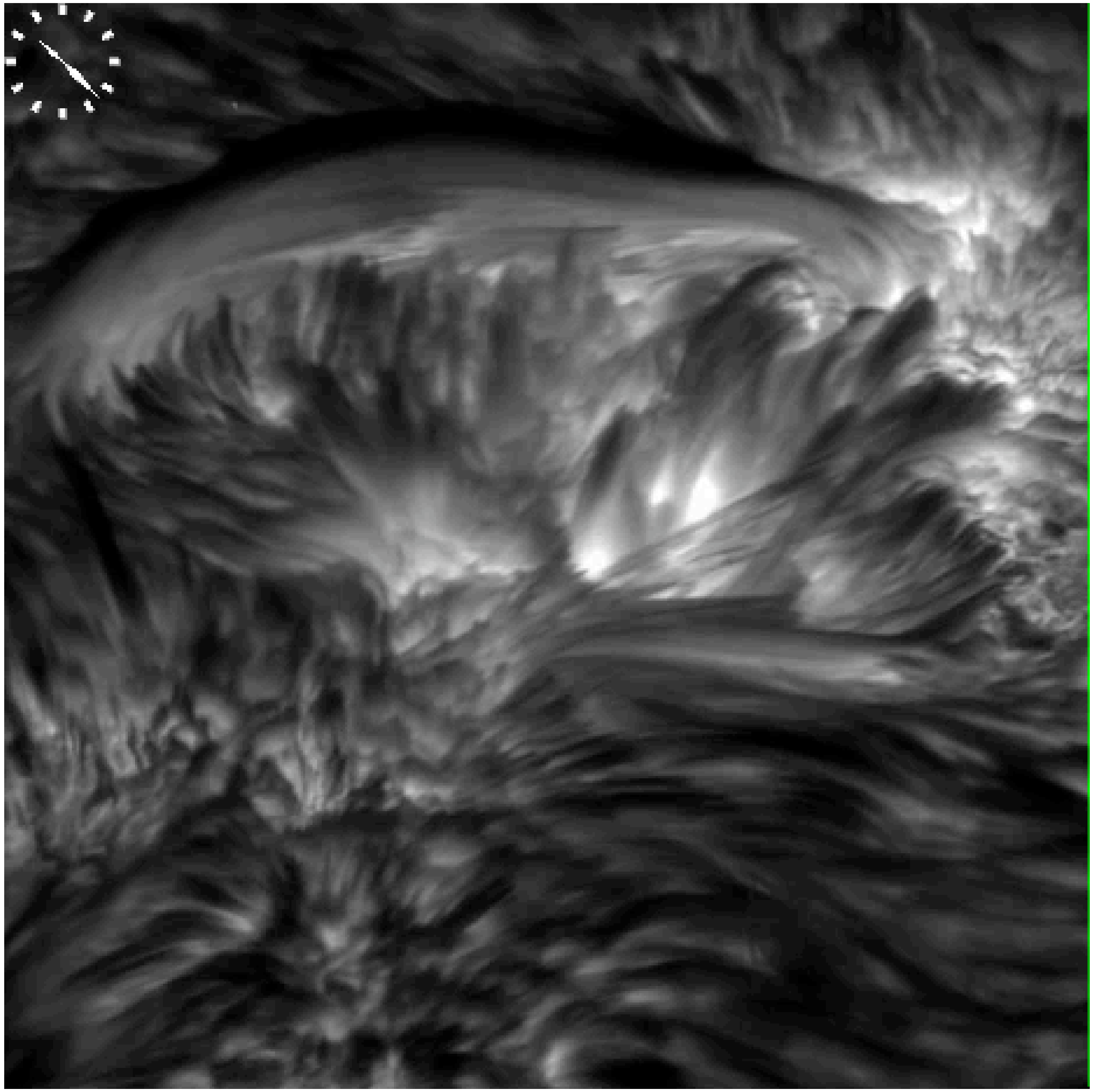
Average O VI 103.1 nm velocities



Conclusions (and Discussion...)

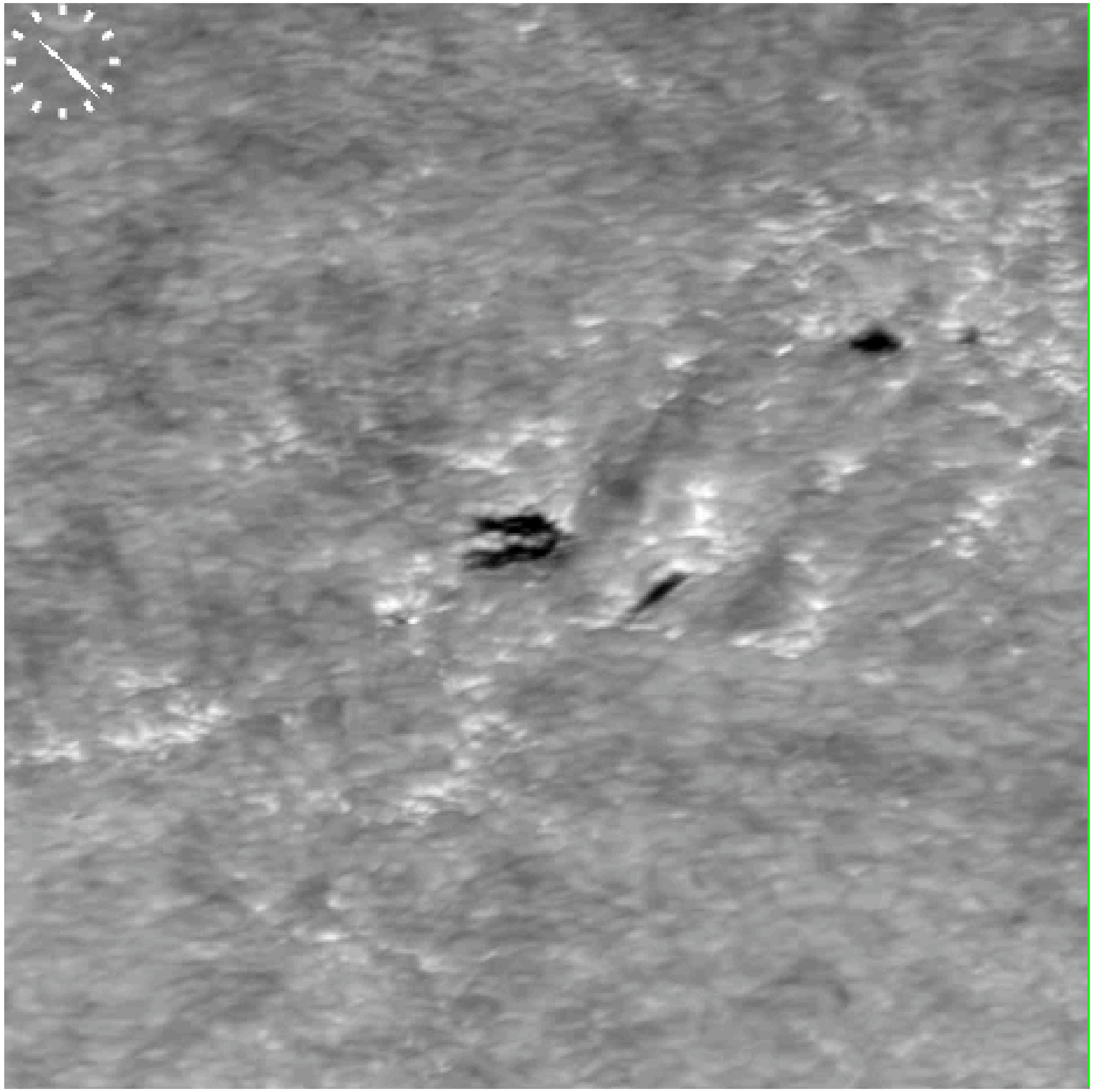
- Solar atmosphere pervaded by waves
  - generation from below in form of "3/5 minute" oscillations...
  - ...and from episodic phenomena higher in atmosphere
- Mode coupling and conversions in chromosphere
  - field topology important
  - ...as are observations from both sides of beta = 1
- This is a complicated problem!
  - Combination of high quality observations and forward modeling

H-alpha line center



Luc Rouppe van der Voort & Michiel van Noort, SST October 2005

“Broadband” H-alpha



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