

# DYNAMICS OF CHROMOSPHERES

SIRAJ HASAN  
INDIAN INSTITUTE OF ASTROPHYSICS  
BANGALORE, INDIA

# BACKGROUND

- ▶ The quiet chromosphere consists of magnetic and non-magnetic regions. Although magnetic fields are found everywhere on the Sun they are dynamically unimportant in the interior of supergranulation cells.
- ▶ Strong magnetic elements occur at the cell boundaries and constitute the “magnetic network”. Vertical tubes in pressure equilibrium with the outside medium expand upward to conserve magnetic flux. From a low filling factor ( $< 1\%$ ) in the photosphere the tubes spread to 15% in the layers of formation of the emission features in the H and K lines of ionized calcium (at a height of 1 Mm) and to 100% in the so-called “magnetic canopy”.
- ▶ The remaining quiet Sun outside the network is called the internetwork, sometimes also referred to as cell interior.

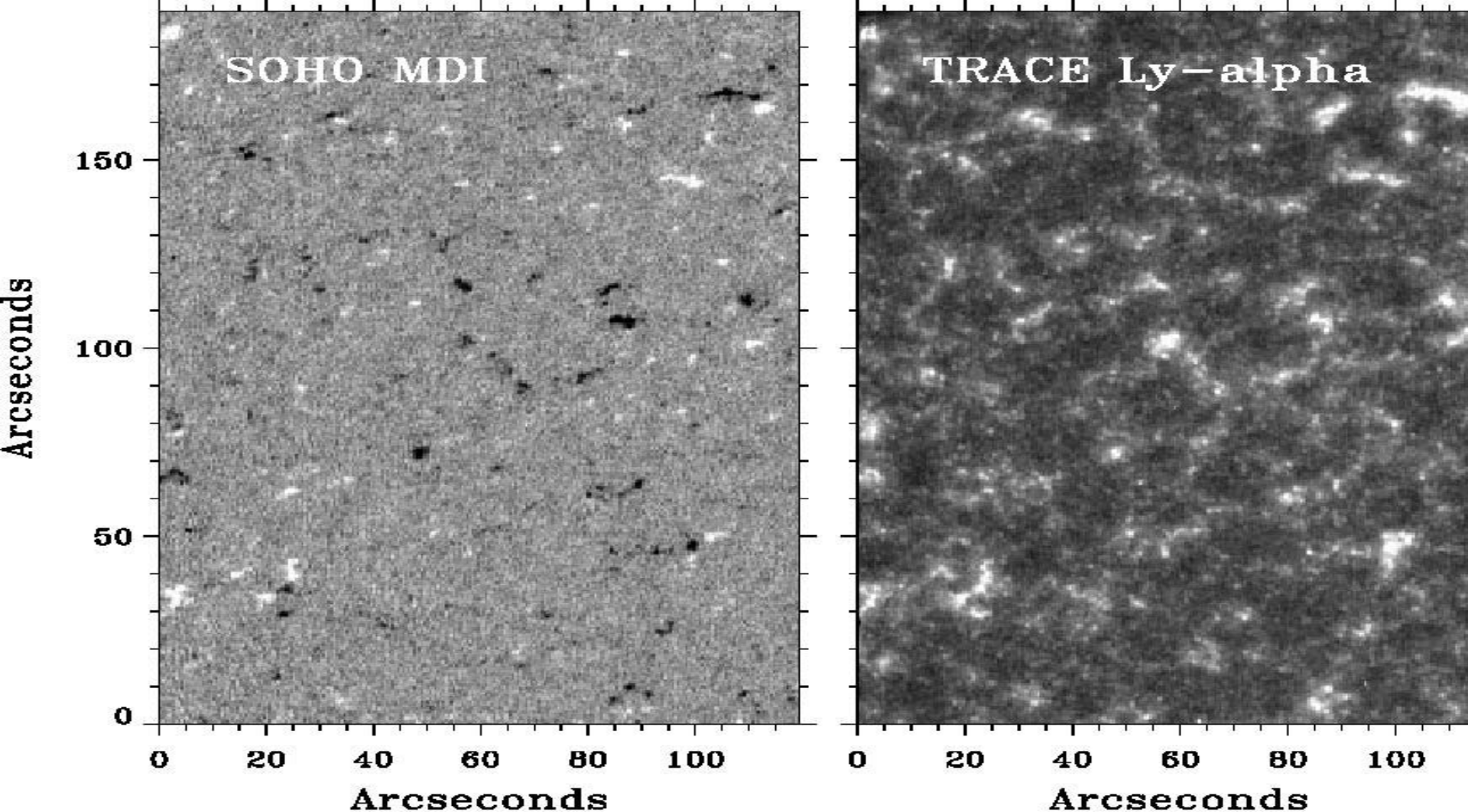


Figure 1. Part of an MDI magnetogram and a co-aligned part of a simultaneous TRACE Ly $\alpha$  filtergram. The chromospheric emission pattern at right corresponds closely with the photospheric magnetic field pattern at left, irrespective of polarity, except for the small-scale background graininess which is dominated by noise at left and by acoustic oscillation patterns at right. Data taken on June 14, 1998, reduced by C.J. Schrijver and H.J. Hagenaar.

# INTERNETWORK

- ▶ The internetwork consists of intermittent bright features called “cell grains” showing emission in the violet  $K_{2v}$  and  $H_{2v}$  peaks, that appear in spectroheliograms as bright patches (1"-2") lasting less than a minute which reappear at 2-4 minute intervals in the same place. The average period is about 3 min (Rutten & Uitenbroek 1991).
- ▶ Strong magnetic elements occur at the cell boundaries and constitute the “magnetic network”. Vertical tubes in pressure equilibrium with the outside medium expand upward to conserve magnetic flux. From a low filling factor ( $< 1\%$ ) in the photosphere the tubes spread to 15% in the layers of formation of the emission features in the H and K lines of ionized calcium (at a height of 1 Mm) and to 100% in the so-called “magnetic canopy”.
- ▶ The remaining quiet Sun outside the network is called the internetwork, sometimes also referred to as cell interior.

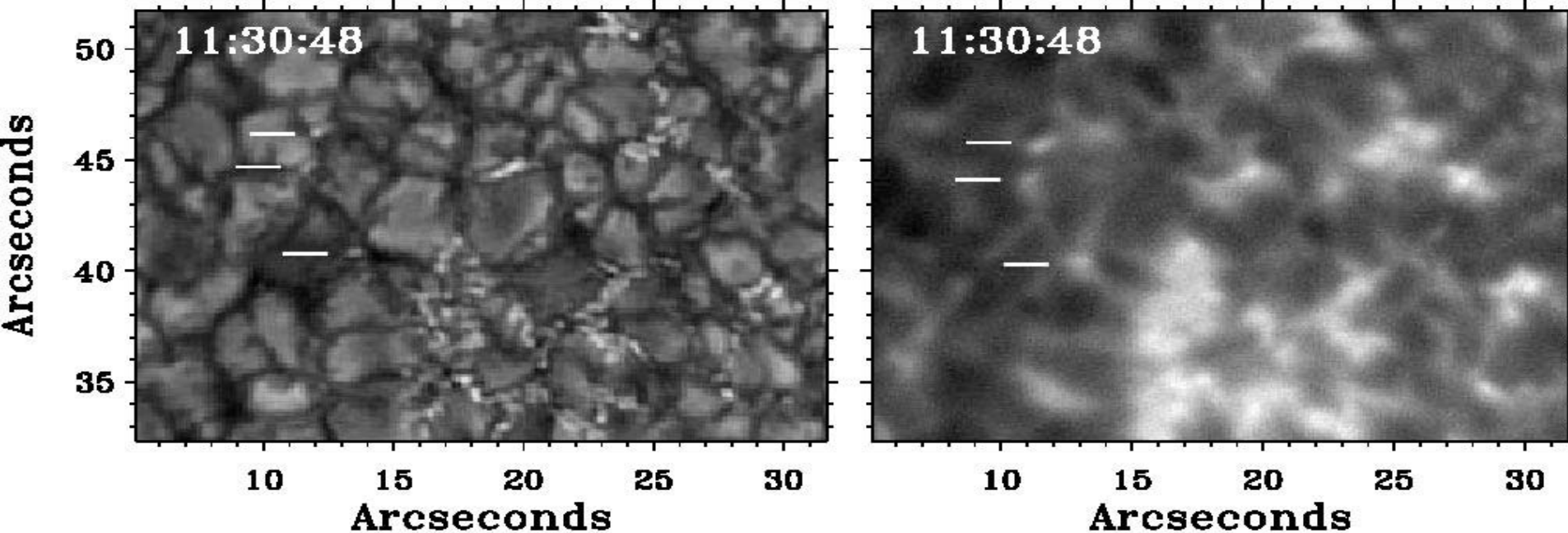


Figure 6. Left: part of a high-resolution (0.2 arcsec) G-band filtergram (bandpass  $10 \text{ \AA}$  FWHM) from a sequence taken by R.A. Shine with the Swedish Vacuum Solar Telescope at La Palma, restored using phase-diverse speckle sampling by Löfdahl et al. (1998) and analyzed by Berger et al. (1998a, 1998b). Right: simultaneous Ca II K filtergram (bandpass  $3 \text{ \AA}$  FWHM) of the same area, non-restored. The diffuse patches of Ca II K network emission overlie clusters of tiny filigree grains. The three marked isolated features might be classified as  $K_2V$  internetwork grains (“cell flashes”) in a single Ca II K image such as this one, but when the two image sequences are displayed as movies these features are seen to represent “persistent flashers” that show up intermittently, tracking the disappearing and reappearing filigree grains underneath. From Lites et al. (1999).

- ▶ Recent observations resolve the diagnostic diagram into traditional 5-min.  $p$ - mode ridges and pseudo-ridges with higher frequencies (upto 11 mHz) (Harvey et. al. 1993, 1995; Steffens et al. 1995; Krijger et al. 2002).
- ▶ Space-based observations (TRACE & SUMER) show that:
  - ▶ There is a broad power peak in the range 3-10 mHz for internetwork oscillations;
  - ▶ In the upper chromosphere, oscillations are coherent over patches with diameters of 3"-8";
  - ▶ There appears evidence for the existence of upward propagating waves that occasionally drive oscillations in the overlying transition region.

# *NATURE OF OSCILLATIONS*

- ▶ Standing acoustic waves in a chromospheric cavity with the lower and upper boundaries respectively at the temperature minimum (lower boundary) and transition region region respectively (Mein and Mein 1976, Leibacher and Stein 1981). Observational support for this interpretation comes from the observed  $180^\circ$  phase jump in the Na D<sub>1</sub> line (Fleck and Deubner 1989) and from linear calculations (Steffens et al. 1997).
- ▶ 1-D radiation hydrodynamic simulations using observations of the Doppler velocity of a photospheric Fe I line as the input for the velocity at the lower boundary (Carlsson & Stein 1994): A comparison of the simulated and observed H line intensity profiles as functions of wavelength and time shows broad agreement in the signature feature for the simulated bright points. This model established that calcium bright points are caused by propagating acoustic waves and the intermittent formation of shocks.

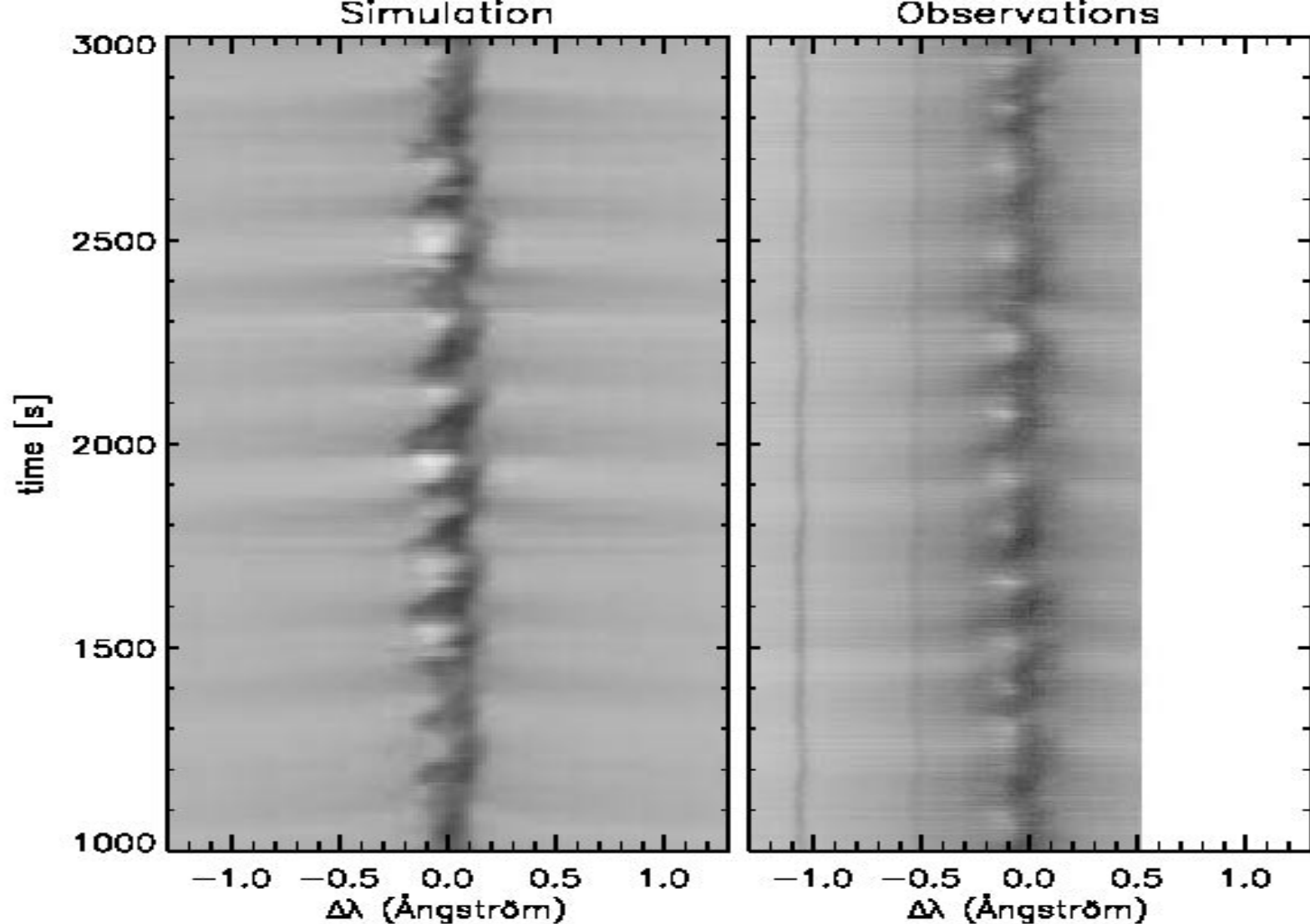
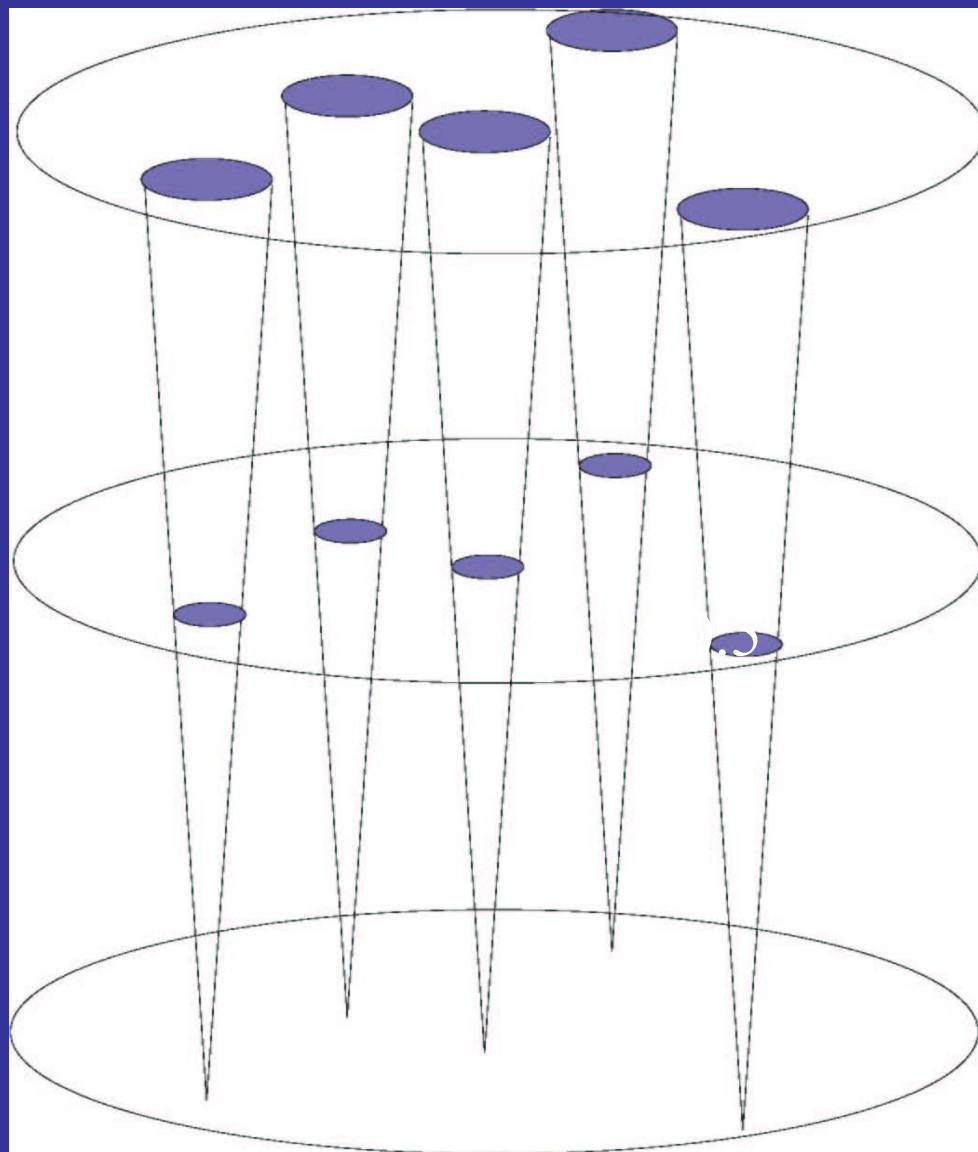


Figure 3. Comparison between observed (right) and computed (left) spectral evolution of the Ca II H core for a quiet-sun internetwork location. The simulation matches the repetitive line-center shifts, dark “whisker” contractions and bright  $H_{2V}$  “grain” occurrences quite well. Cover illustration of proceedings edited by Carlsson (1994).

- ▶ The main properties of the oscillations can be understood from an analysis of the 1-D linearized hydrodynamic equations, which reveals that their 3-min. character can be interpreted simply as the response of the atmosphere at the acoustic cutoff frequency  $\omega_A$  (Fleck & Schmidt 1991, Kalkofen et al. 1994). The solution actually consists of two contributions; the exciting wave with frequency  $\omega$  and an oscillation with frequency  $\omega_A$ , which decays asymptotically with time  $t$  as  $t^{-3/2}$ .
- ▶ The 1-D simulations of CS produce a good fit with observations of the velocity shifts seen in  $H_3$ , but the  $H_{2V}$  intensity at maximal brightness appears to be too high by an order of magnitude. The excess intensity in  $H_{2V}$  is possibly due to the topology of wave propagation in bright-point oscillations, which the model assumes to be in the form of plane waves, rather than in the form of spherical waves, where the energy spreads horizontally in upward propagation (Kalkofen et al. 2002).

# TOPOLOGY OF THE SUPERGRANULATION CELL INTERIOR



$z = 2 \text{ Mm}$ ,  $d = 3''\text{-}8''$ ,  $f = 0.5$   
(SUMER)

$z = 1 \text{ Mm}$ ,  $d \sim 2 \text{ Mm}$ ,  $f = 0.1$   
(H<sub>2</sub>V)

$z = 0.5 \text{ Mm}$ ,  $d \sim 1 \text{ Mm}$ ,  $f = 0.03$   
(1600 Å)

$z = 0$ ,  $d \sim 0.1 \text{ Mm}$ ,  $f = 10^{-3}$   
(K line)

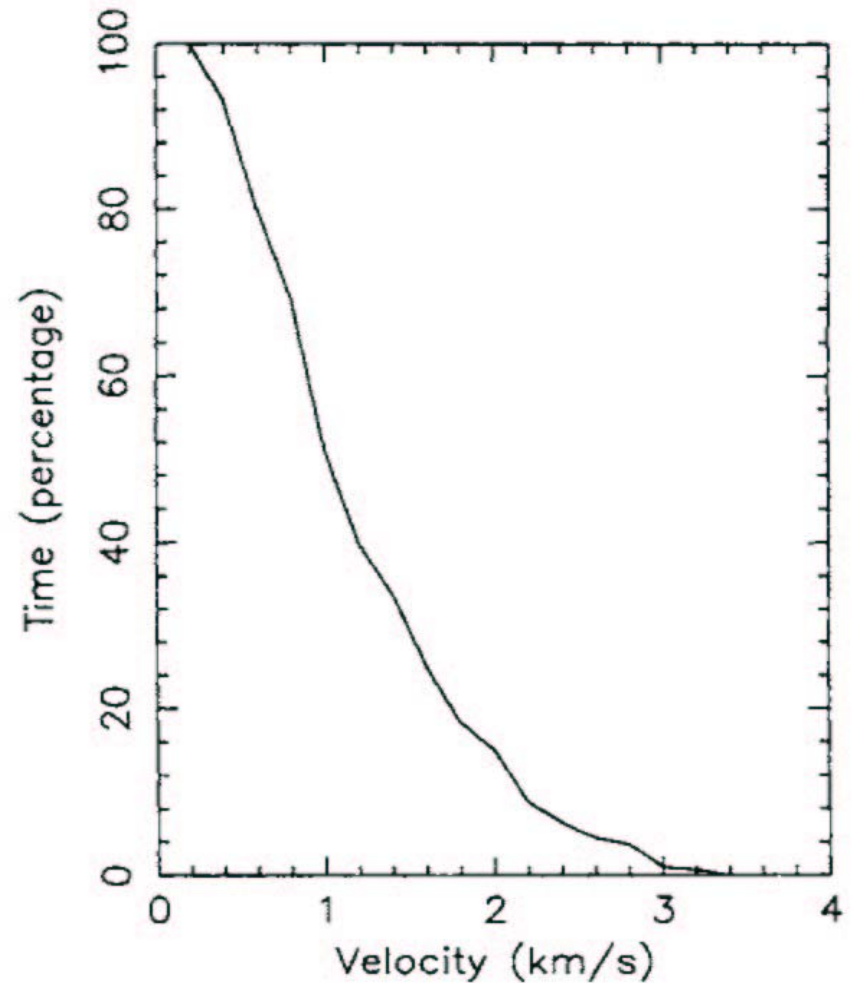
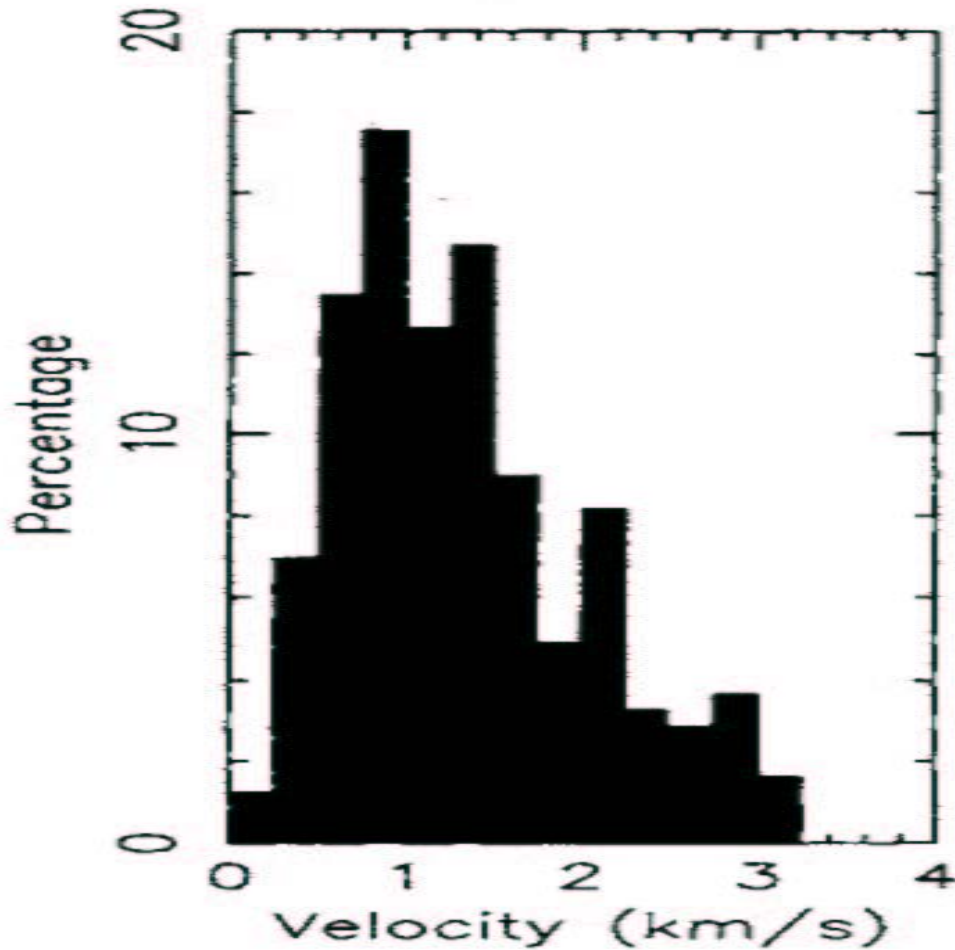
Spherical waves emanating from point sources  
within the cell interior with 30 Mm diameter  
(after Kalkofen 2002)

- ▶ This spreading is apparent in the size of the area disturbed by the shock that varies from 100 km in the photosphere, to 0.5-1 Mm at the base of the chromospheres (Foing & Bonnet 1984), to 2-3 Mm in the layer of formation of the  $H_{2V}$  emission peak (Cram & Damé 1983) and 3"-8" at a height of 2 Mm (Carlsson et al. 1997).
- ▶ Assuming a propagation channel in the form of a cone with opening angle  $90^\circ$ , the channel expands by a factor of more than 3 and the area by 10. Thus, the energy, which in the CS simulations is contained in vertical columns, is reduced by horizontal spreading by a factor 10, which leads to a better agreement with observations.

# MAGNETIC NETWORK

- ▶ The magnetic network consists of vertical magnetic fields clumped into elements or flux tubes with field strengths in the kilogauss range and diameters of the order of 100 km (e.g. Frazer & Stenflo) at their *footpoints* located in the photosphere.
- ▶ Magnetic elements can be identified with bright points in G-band (4305 Å) images (e.g. Muller 1994, Berger et al. 1995, 1998), which are co-spatial with Ca II and TRACE (UV) structures (Rutten 1999).
- ▶ High resolution observations suggest that these network bright points (NBPs), located in intergranular lanes, are in a highly dynamical state, due to the buffeting effect of random convective motions (e.g. Muller 1983; Muller et al. 1994; Berger & Title 1996; van Ballegooijen et al. 1998).
- ▶ A histogram of the velocities of NBPs measured by Muller et al (1994) shows a mean speed of  $1.4 \text{ km s}^{-1}$  but there were several instances of motions with speeds as high as  $3 \text{ km s}^{-1}$ .

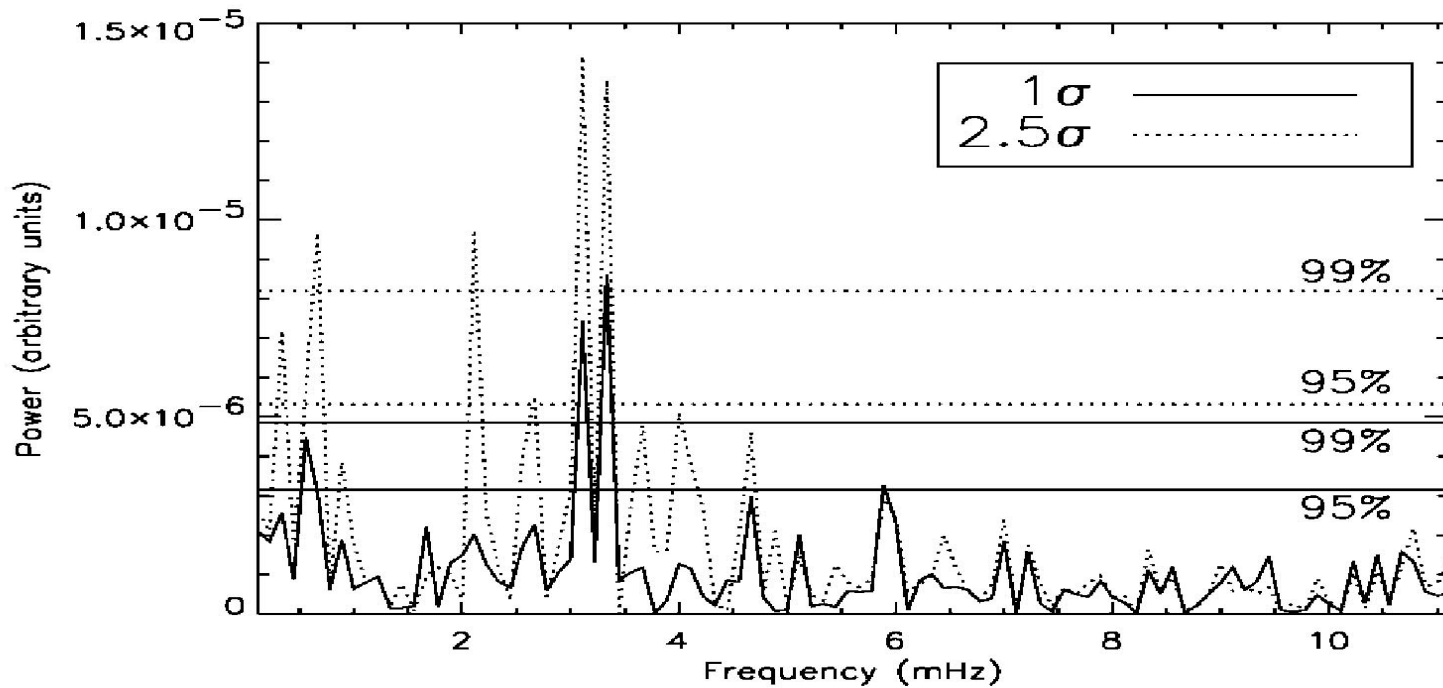
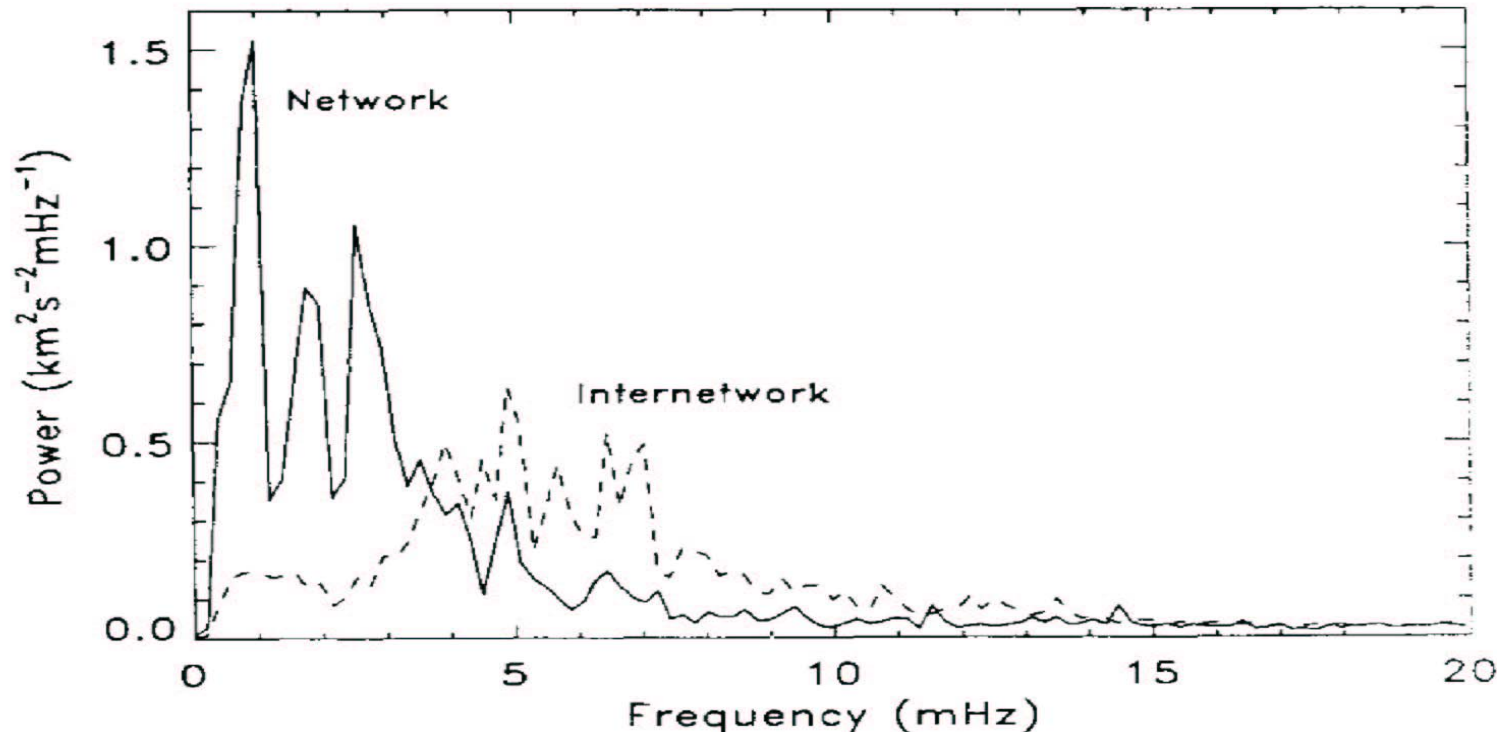
# HISTOGRAM OF VELOCITIES COMPUTED ALONG NETWORK TRAJECTORIES (AFTER MULLER '94)



Calculation for 245 values: Mean=1.3 km s<sup>-1</sup>, standard deviation 0.70 km s<sup>-1</sup>

Percentage of times a given granule moves faster than a given velocity

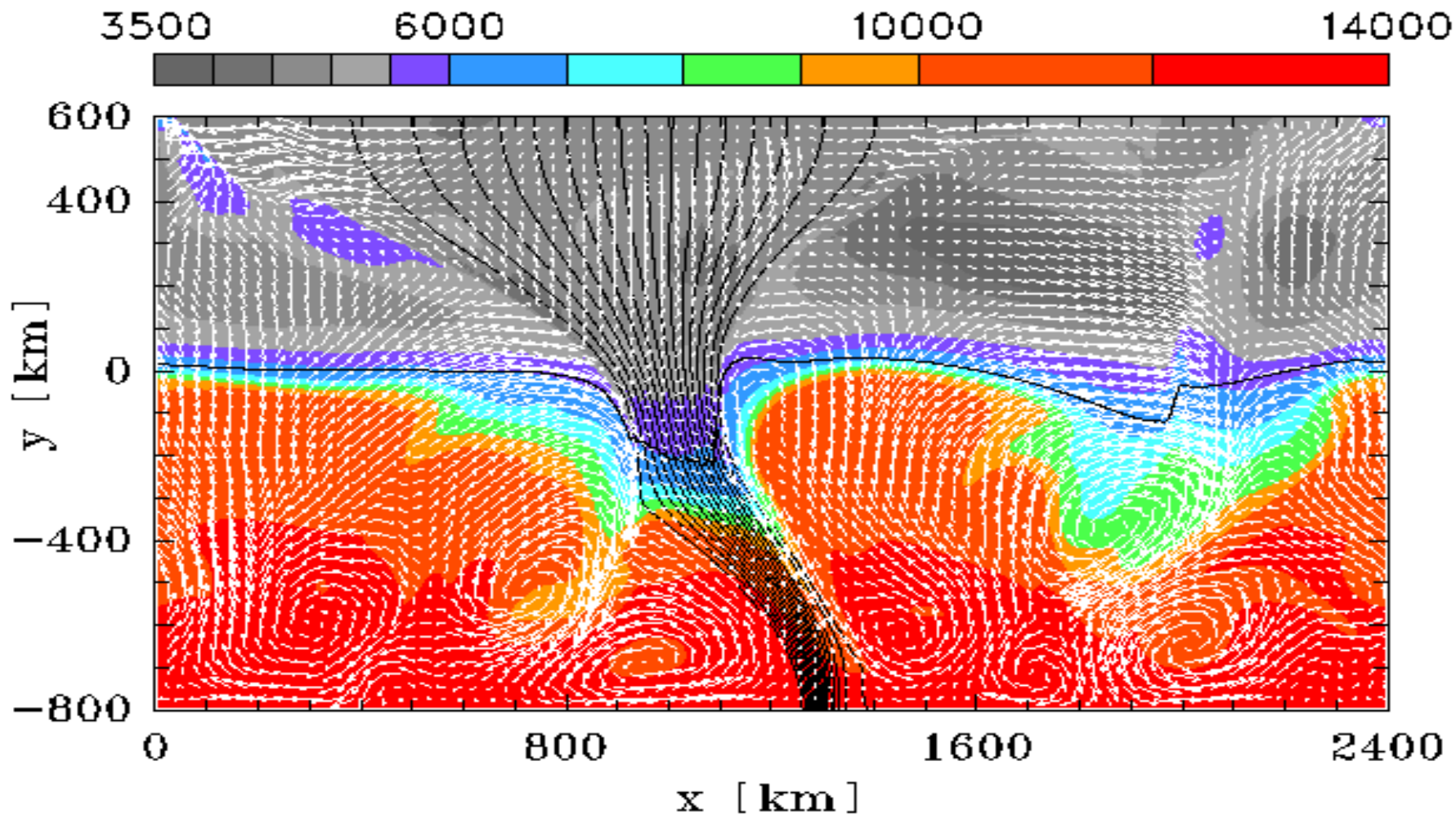
- ▶ Ground-based observations of the Ca II H and K lines, which are formed in the low chromosphere, reveal that the chromosphere in the magnetic network of the quiet Sun oscillates with periods of around 7 min. (e.g. Lites et al. 1993), in contrast to the internetwork which exhibits oscillations at higher frequencies. Recent observations by McAteer et al. (2002) suggest the presence of multiple peaks in the power spectrum with periods in the 4-15 min. range.
- ▶ Space observations have also confirmed the above picture and the absence of significant power in oscillations with frequencies above 3 mHz (Judge et al. 1997, Curdt & Henzel 1998, Hansteen et al. 2000).
- ▶ There appears evidence for upward propagating waves within the network (Curdt & Henzel 1998, Henzel & Curdt 1999).



## ***THEORETICAL ASPECTS***

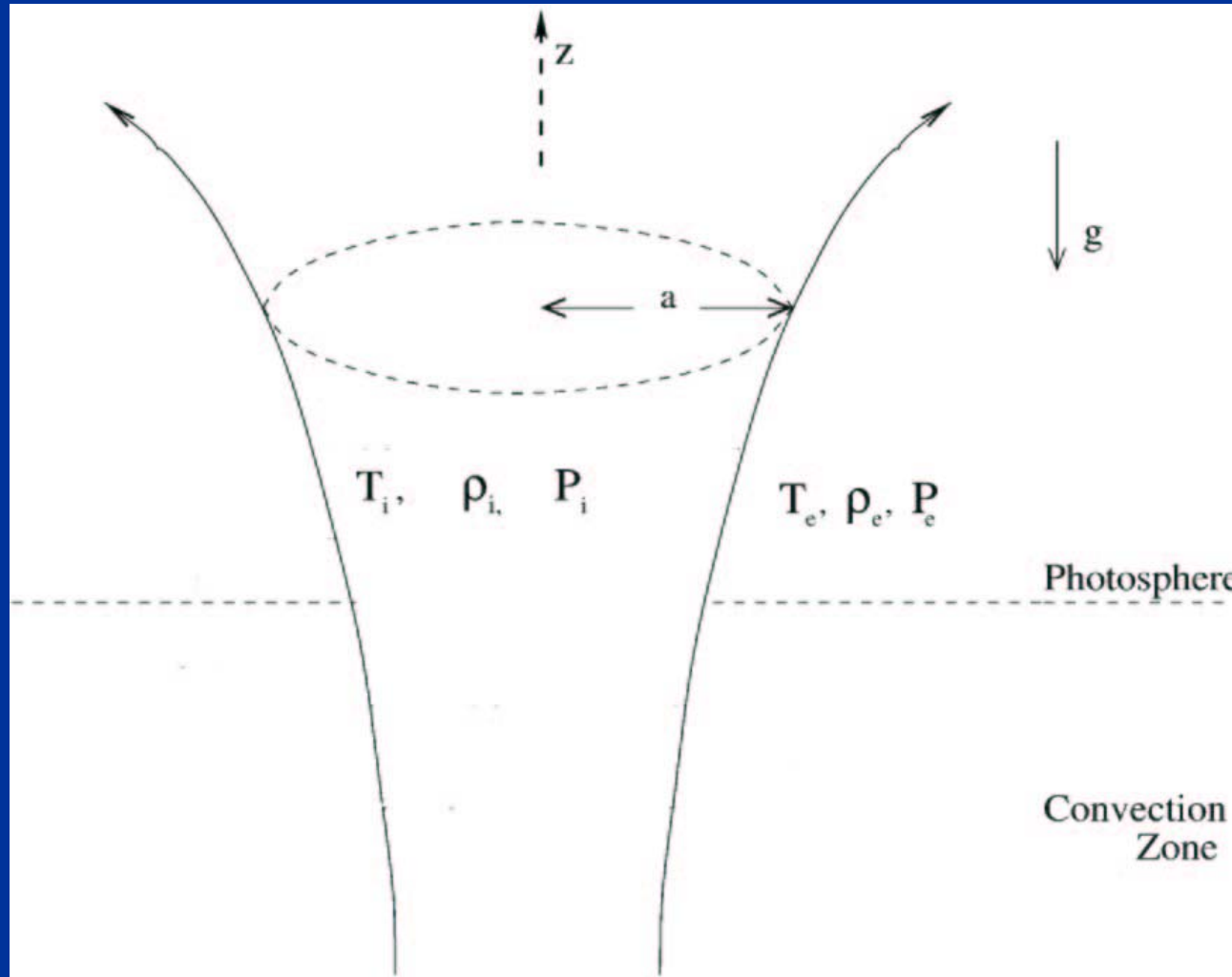
- ▶ The magnetic field in the network can be idealized in terms of thin isolated vertical flux tubes which fan out with height, due to the decrease in pressure with height. A ``thin" flux tube can support *sausage* or longitudinal oscillations and *kink* or transverse oscillations.
- ▶ The earliest studies on MHD wave excitation used extensions of the Lighthill (1952) mechanism (Osterbrock 1961; Musielak & Rosner 1987; Collins 1989, 1992). More recently, Musielak et al (1989, 1995), Huang et al. (1995) and Ulmschneider & Musielak (1998) examined the generation of longitudinal and transverse waves in a flux tube through turbulent motions in the convection zone.

- ▶ An alternative scenario, based on the observations of Muller (1994), is that the excitation of transverse (kink) waves occurs through the footpoint motions of magnetic elements (Choudhuri, Auffret & Priest 1993). Rapid motions with velocities larger than  $2 \text{ km s}^{-1}$  can excite transverse oscillations which carry adequate energy for coronal heating;
- ▶ Calculations show that transverse waves get converted to longitudinal waves in the chromosphere (Ulmschneider et al. 1991; Zhugzhda et al. 1995); the latter can easily dissipate through shock formations and contribute to heating the atmosphere;
- ▶ Many numerical simulations of dynamical effects associated with the interaction of magnetic fields and convection have been carried out (e.g. Nordlund & Stein 1989, 1990; Nordlund et al. 1992; Steiner et al. 1998). The simulations of Steiner et al. clearly show the bending of flux sheath through the buffeting action of granules. This interaction can excite MHD oscillations in the magnetic element which can propagate upwards and heat the chromosphere and corona (Spruit 1981; Ulmschneider et al. 1999).



The convective flow of gas in the photosphere sweeps magnetic lines of force into narrow tubes of magnetized material. In such flux tubes the field reaches a strength of 2000 G. The tubes are permanently pressed and shaken; they do not settle to a steady equilibrium. Along the tubes, MHD waves transmit energy into the upper part of the atmosphere (after Steiner et al. 1998)

# FLUX TUBE IN EQUILIBRIUM WITH THE AMBIENT MEDIUM



Pressure balance:

$$p_i + \frac{B^2}{8\pi} = p_e$$

For an isothermal atmosphere:

$$p = p_0 e^{-z/H}$$

$$B = B_0 e^{-z/2H}$$

Flux conservation:

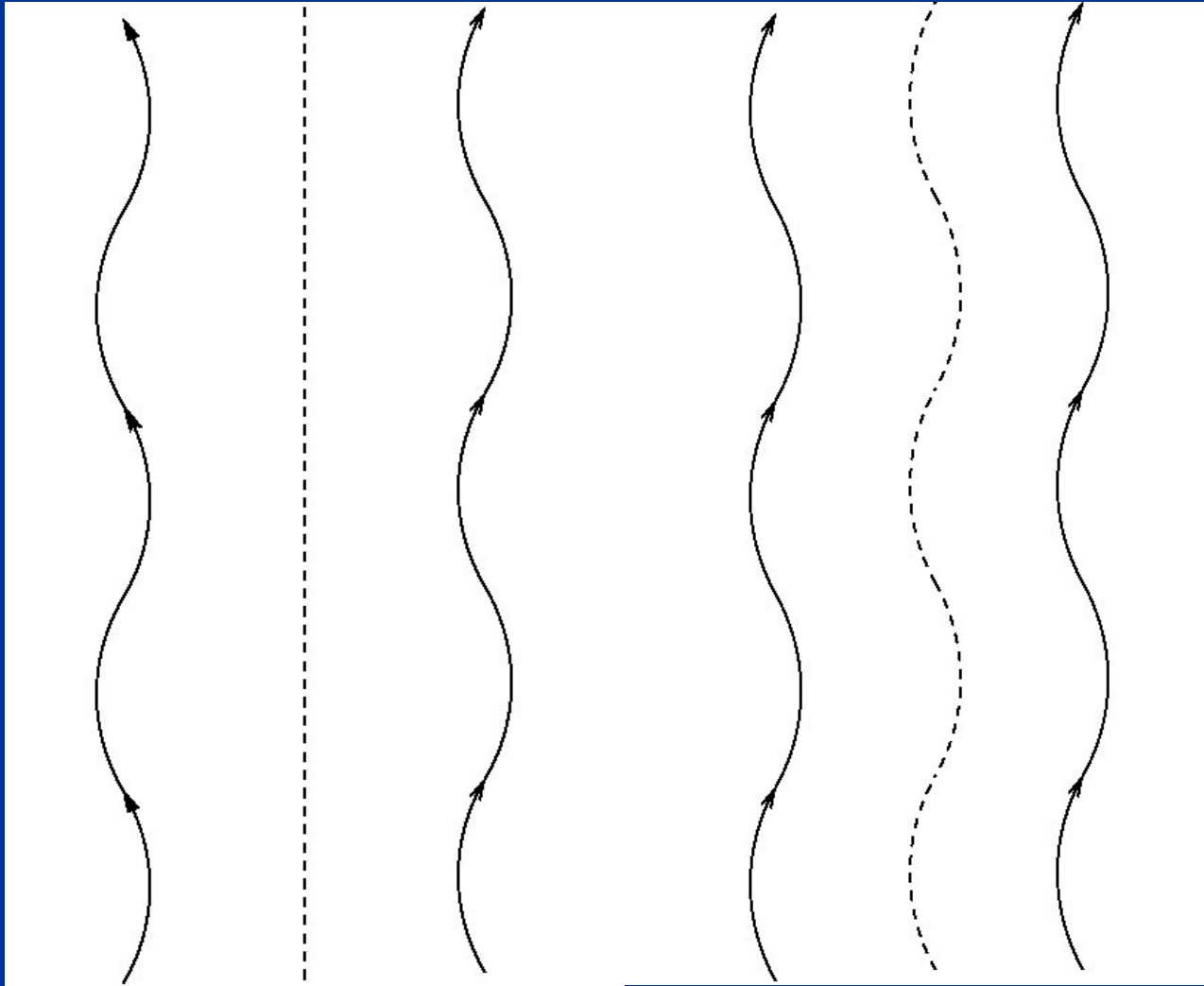
$$A = A_0 e^{z/2H}$$

Flux tube extending vertically through the photosphere and convection zone

# PERTURBATIONS IN A FLUX TUBE

Sausage mode

Kink mode



$$\omega^2 = c_\lambda^2 k^2 + \omega_\lambda^2$$

$$\omega^2 = c_\kappa^2 k^2 + \omega_\kappa^2$$

## *Linear 1-D Model*

Consider a vertical thin isothermal flux tube. The linear oscillations of this tube are given by a Klein-Gordon equation of the form:

$$\frac{\partial^2 Q_\alpha}{\partial t^2} - c_\alpha^2 \frac{\partial^2 Q_\alpha}{\partial z^2} - \omega_\alpha^2 Q_\alpha = F_\alpha$$

where  $Q_\alpha = \xi_\alpha e^{-z/4H}$ ,  $\xi_\alpha$  is the Lagrangian displacement,  $H$  is the scale height ( $\alpha = \lambda, \kappa$  for longitudinal & transverse waves). The waves have the following dispersion relation:

$$\omega^2 = \underset{\substack{\uparrow \\ \text{tube speed}}}{c_\alpha^2} k^2 + \underset{\substack{\uparrow \\ \text{cutoff frequency}}}{\omega_\alpha^2}$$

## *Typical parameters*

Sound speed:  $C_s = 6.6 \text{ km s}^{-1}$

Plasma beta:  $\beta = 0.3$  ( $B \approx 1600 \text{ G}$  at  $z = 0$ )

Tube speeds are:

$$C_\kappa = 5.7 \text{ km s}^{-1} \text{ (transverse waves)}$$

$$C_\lambda = 5.9 \text{ km s}^{-1} \text{ (longitudinal waves)}$$

Cutoff periods are:

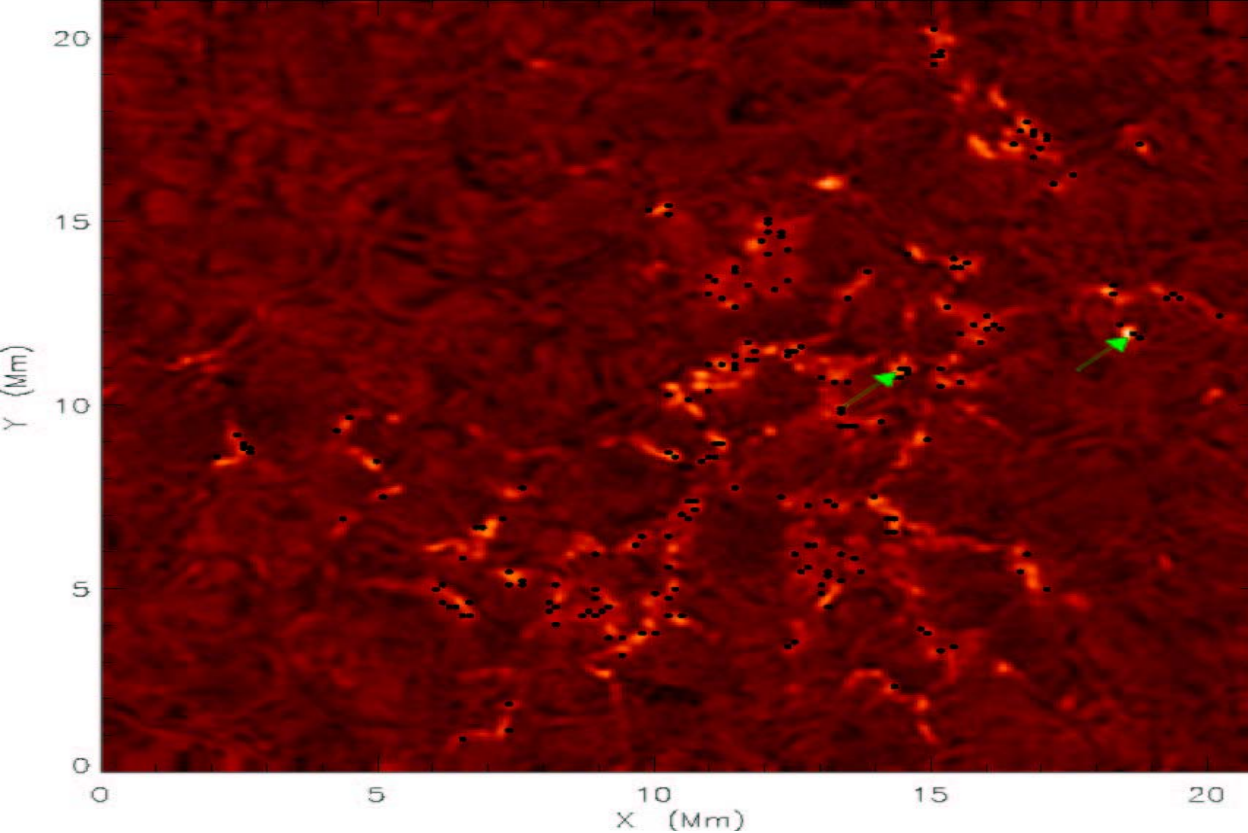
$$P_\kappa = P_a \sqrt{2\gamma(1+2\beta)} \approx 7 \text{ min. (transverse waves)}$$

$$P_\lambda = P_a \sqrt{(60+50\beta)/(63+48\beta)} \approx 3 \text{ min. (longitudinal waves)}$$

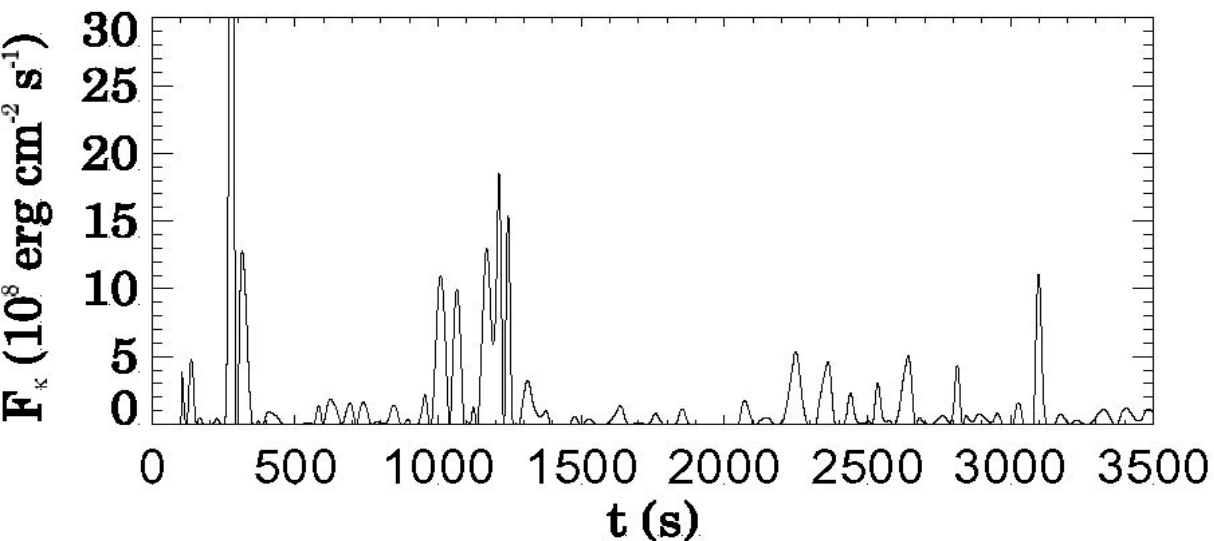
where  $P = 4\pi H/c_s = 180 \text{ s}$  is the acoustic cutoff period.

## *SUMMARY OF LINEAR RESULTS*

- ▶ The generic behaviour is the same for transverse and longitudinal wave excitation: the buffeting action of a granule on a flux tube impulsively excites a pulse that travels away from the source region (with the kink or longitudinal tube speed). After the passage of the pulse, the atmosphere oscillates at the cutoff period of the mode, with an amplitude that slowly decays in time.
- ▶ The initial pulse carries most of the energy ---- subsequently the atmosphere oscillates as a whole in phase, without energy transport. The wave period observed in the magnetic network is interpreted as the cutoff period of transverse waves, which leads naturally to an oscillation at this period (typically in the 7 min. range).
- ▶ Velocities in transverse and longitudinal waves excited by granules are comparable in magnitude for typical values of  $\beta$  ( $\beta \ll 1$ ). However, the vertical energy flux in transverse waves is an order of magnitude larger than that in longitudinal waves for network field strengths. (N.B. The displacements and velocities in the flux tube scale linearly and the energy fluxes scale quadratically with the applied external velocity.)



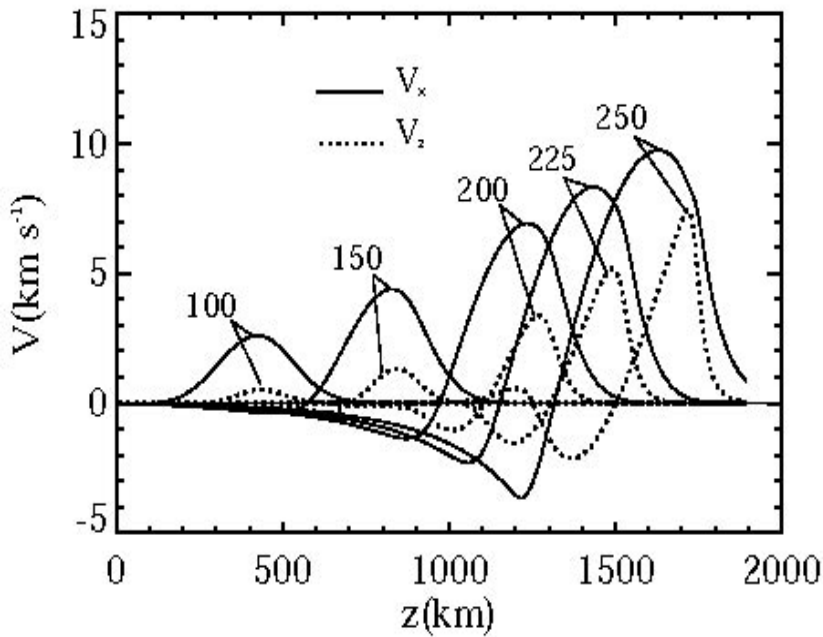
Difference between G band and continuum images obtained at the Swedish Solar Observatory on Oct. 5, 1995. Black corks are tracers for tracking NBPs (after van Ballegooijen et al. 1998).



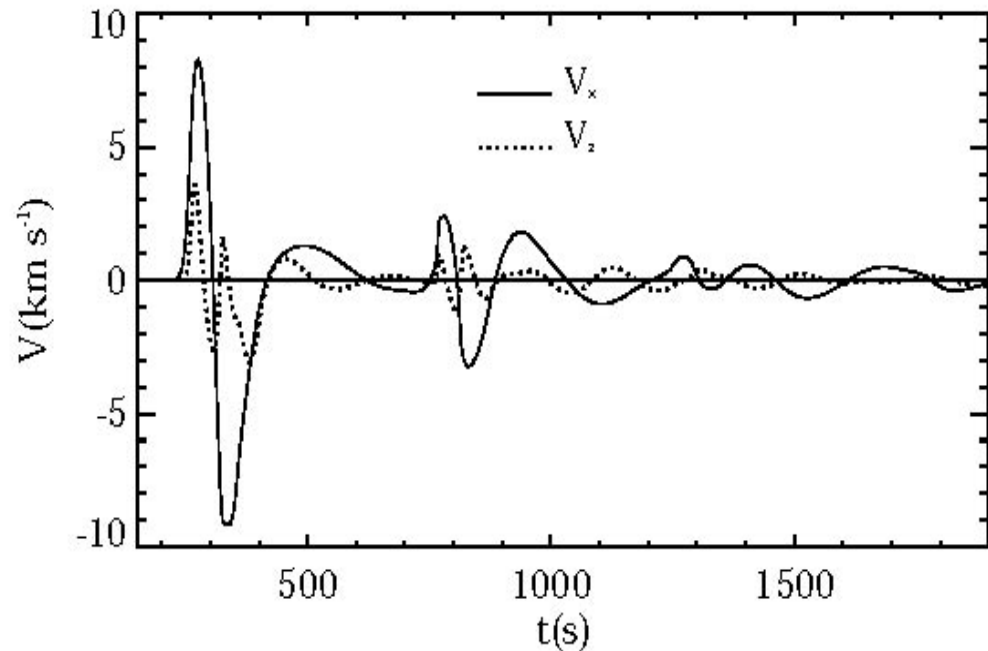
Time variation of the vertical energy flux in a single flux tube at a height of 750km generated due to footpoint motions taken from observations (after Hasan et al. 2000).

# *NONLINEAR ANALYSIS*

Nonlinear effects become important in the chromosphere, where the velocity amplitudes become comparable with the tube speed, leading to an efficient coupling of the kink and longitudinal modes.



(a)



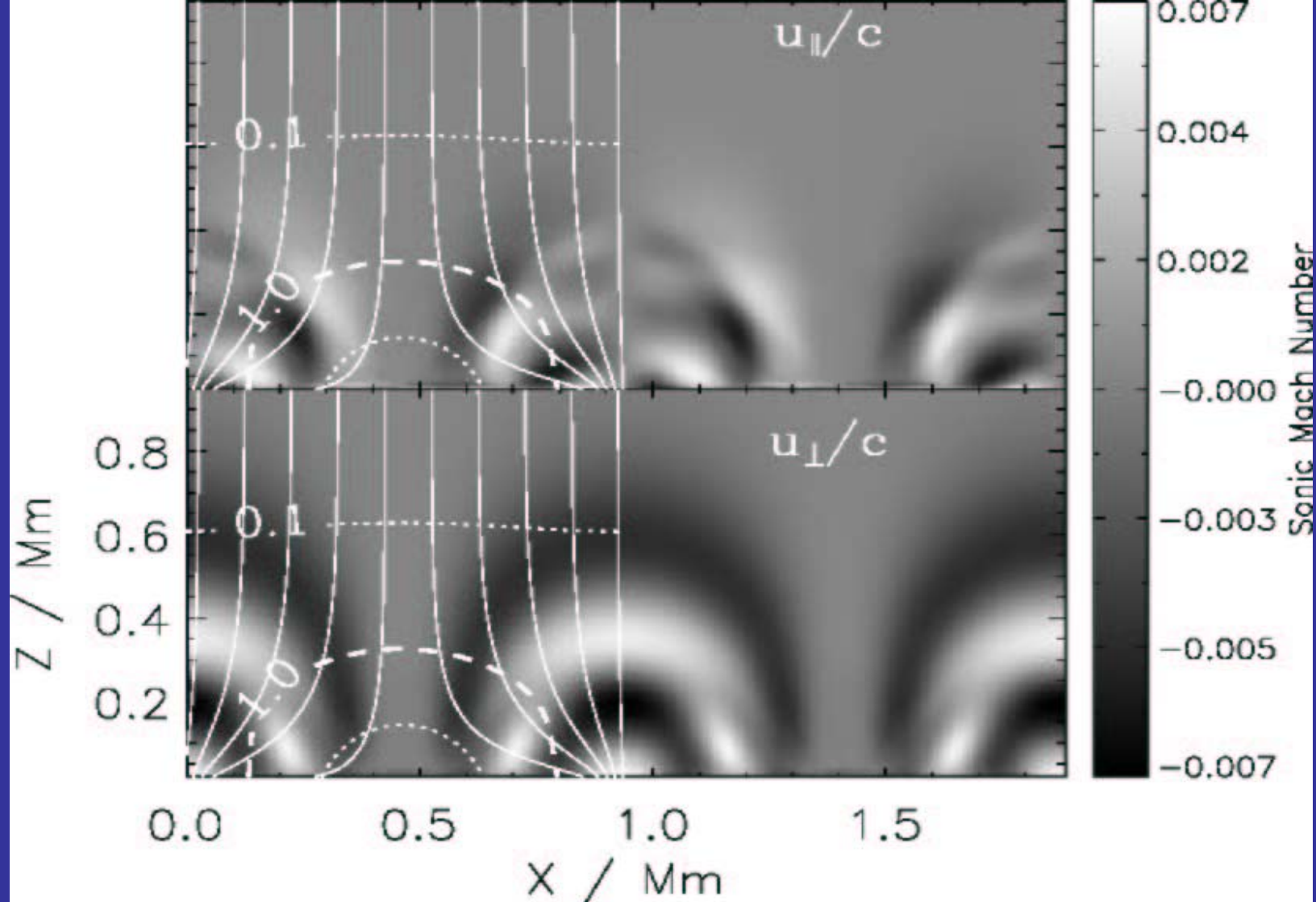
(b)

A horizontal motion is applied impulsively at the base, due to which a transverse wave is generated. Due to nonlinear coupling, a longitudinal wave is generated. After the passage of the impulse, the two modes get decoupled and generate motions at their respective cutoff frequencies (after Hasan et al. 2002)

## ***SUMMARY OF NONLINEAR RESULTS***

- ▶ When the transverse velocities are significantly less than the kink wave speed, there is essentially no excitation of longitudinal waves. However, at heights where the two become comparable, longitudinal wave generation becomes efficient.
- ▶ A large transverse pulse generates a longitudinal wave through mode coupling (similar to Hollweg et al. 1982; Mariska & Hollweg 1985; Cargill et al. 1997 for the coupling of torsional Alfvén waves with longitudinal waves).
- ▶ After the passage of the pulse, “wakes” are generated, that represent *decoupled kink and longitudinal waves* oscillating at their respective cutoff frequencies.
- ▶ Transverse waves lose energy to longitudinal waves through mode coupling.. The fractional energy in longitudinal motions increases rapidly at first with the forcing transverse velocity at the base, before eventually saturating to a value when there is almost equipartition of energy between the two modes.

- ▶ Large amplitude longitudinal waves are generated in the upper photosphere and form shocks in the chromosphere. Chromospheric heating occurs due to shock dissipation of the longitudinal waves. (e.g. Zhugzhda et al. 1995).
- ▶ Additional heating can occur through the resistive dissipation of Pederson currents generated due to slow longitudinal MHD waves (Goodman 2000).
- ▶ Multidimensional calculations are needed to overcome the limitations of the thin flux tube approximation. Recently, 2-D MHD simulations have been carried out (e.g. Cargill et al. 1997, Rosenthal et al. 2002) to understand wave propagation in more realistic geometries. Cargill et al. focused on Alfvén waves, whereas Rosenthal et al. examined the nonlinear solutions corresponding to magneto-acoustic waves.



Snapshot showing velocity parallel (top panel) and transverse (lower panel) to the magnetic field in a simulation of waves in an open magnetic field configuration by shaking the lower boundary horizontally at 42 mHz. The velocity is shown as a fraction of the local sound speed (after Rosenthal et al. 2002).

## SUMMARY

- ▶ The dynamics of the internetwork is dominated by the grain phenomenon, which extends from the photosphere up to the transition region and exhibits oscillations in the 3 min. band.
- ▶ Grains are produced by acoustic waves and their brightening is caused by shocks.
- ▶ The 3 min. oscillations in grains are the response of the atmosphere at its cutoff period.
- ▶ The network exhibits low-frequency oscillations, typically with periods in the 7 min. band, excited through motions of flux tube footpoints.
- ▶ Network oscillations can be identified with kink (transverse) modes of flux tubes, where the dominant periods may correspond to the cutoff period of kink modes.
- ▶ Through nonlinear effects, transverse waves generate (compressive) longitudinal waves that can efficiently dissipate through shock formation and contribute to chromospheric heating.