DYNAMICS OF THE MAGNETIZED CHROMOSPHERE

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BACKGROUND

The chromosphere essentially consists of ionized (partiall
plasma extending over the height range 500 - 2000 k
(above τ_{5000}=1) that corresponds to about 10 pressu
scale heights;

Below a height of about 1500 km, the chromosphere
essentially isothermal (there is a fine balance betwee
heating by mechanical energy and radiative losses);

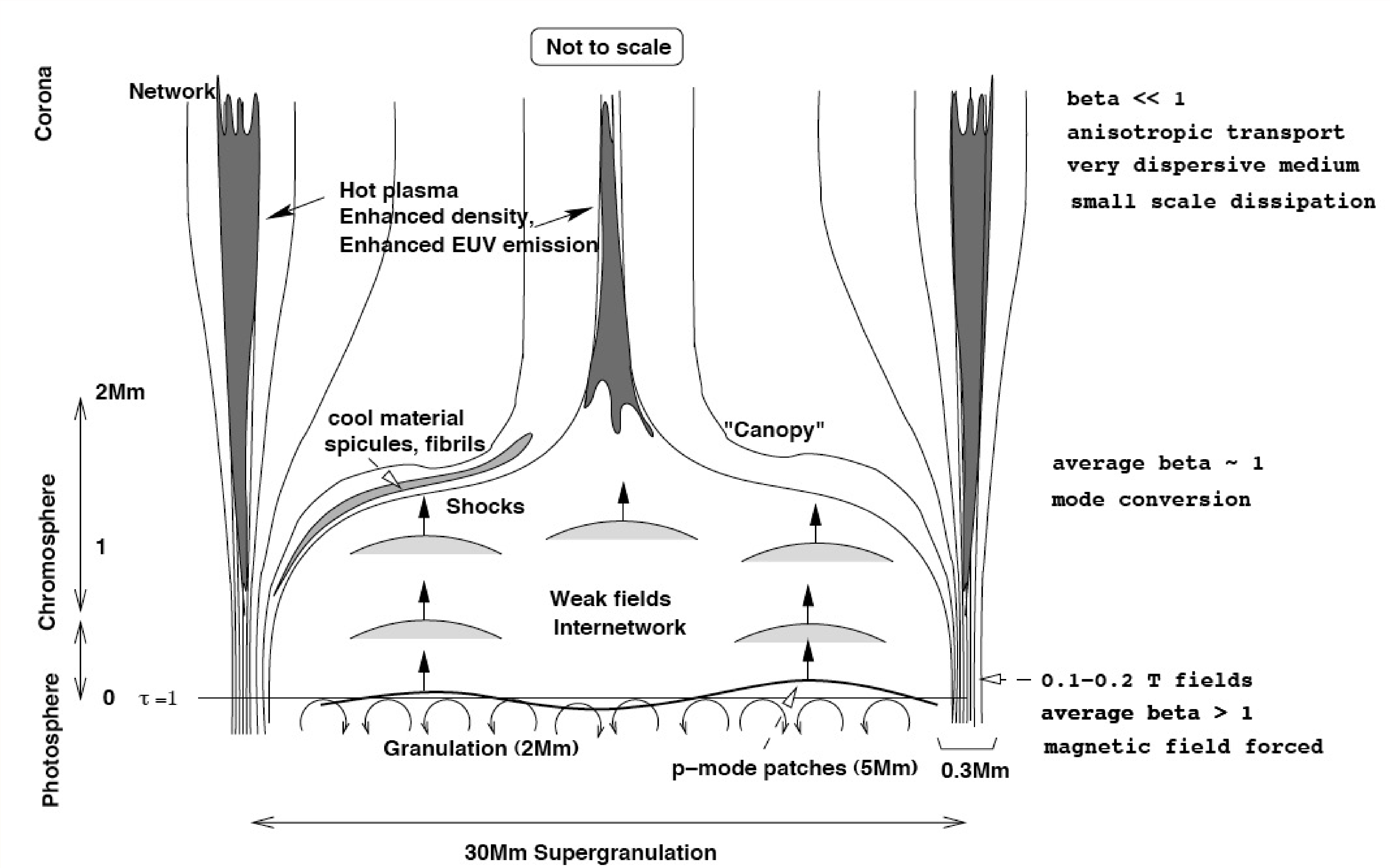
Above 1500 km, the observed properties are strong
influenced by the presence of the magnetic field (β << 1
The β =1 surface (which is not necessarily uniform b
varies with height) provides a natural separation of th
atmosphere into magnetic and non-magnetic regions.

Strong magnetic elements occur at the cell boundarie
and constitute the *magnetic network*. Vertical tubes
pressure equilibrium with the outside medium expar
upward to conserve magnetic flux. From a low filling facto
(< 1%) in the photosphere the tubes spread to 15% in th
layers of formation of the emission features in the H and
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.

The internetwork consists of intermittent bright feature
called cell grains showing emission in the violet K_{2v} and H
peaks, that appear in spectroheliograms as bright patche
(1"-2") lasting less than a minute which reappear at 2-
minute intervals in the same place. The average period
about 3 min (Rutten & Uitenbroek 1991).

CARTOON OF THE CHROMOSPHERE



Schematic figure depicting the structure of the solar chromosphere in a region with unipolar magnetic field (from Livingston and Harvey 1971).

IMPORTANT ISSUES

What are the physical processes that contribute to the dynamics and heating of the chromosphere? Can we observationally identify the sources of wave excitation?

How is the the magnetic field structured - in particular what is the field geometry in the network and internetwork regions? Where is the magnetic canopy located?

What mechanisms contribute to chromospheric fine structure (mottles, fibrils and spicules)?

Is the chromosphere thermally bifurcated - are there cool pockets as suggested by the presence of CO?

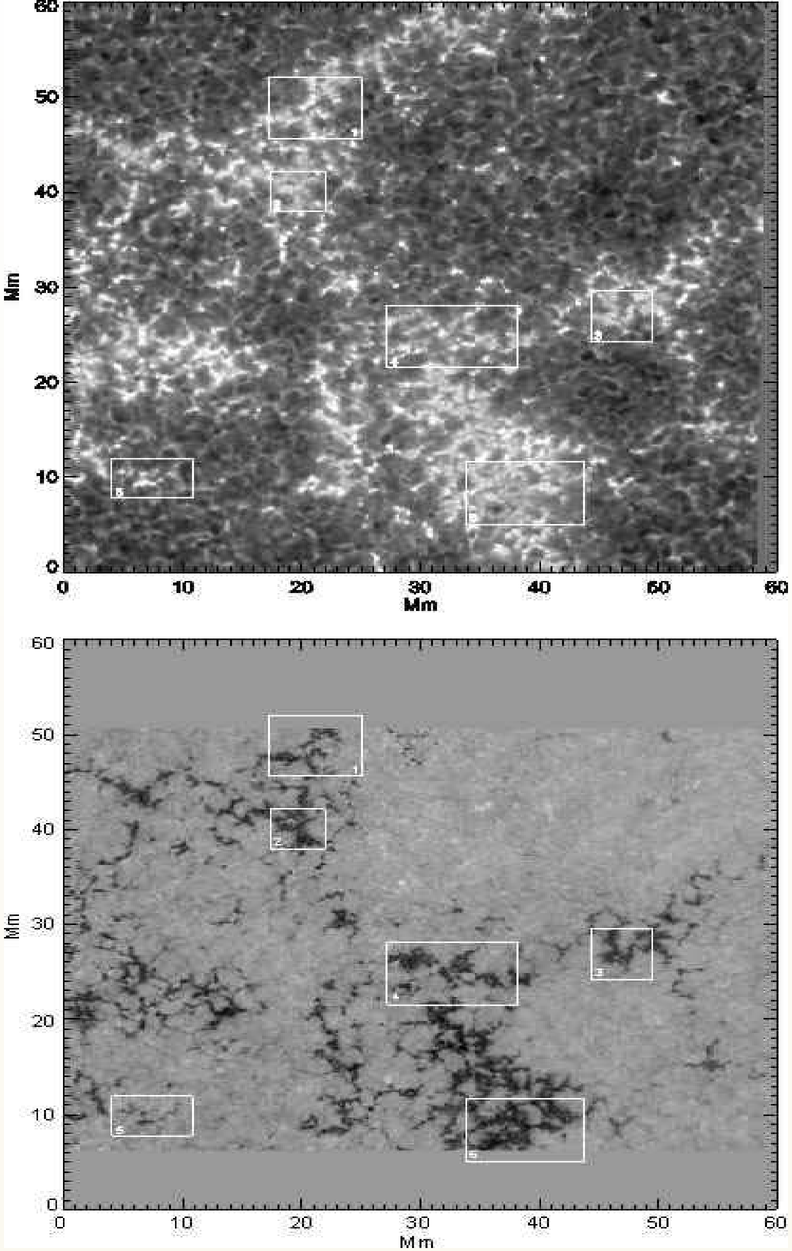
MAGNETIC NETWORK

Canonical picture: The magnetic network consists of vertic magnetic fields clumped into elements or flux tubes with fie strengths in the kilogauss range and diameters of the order of 10 km or less at their *footpoints* located in the photosphere;

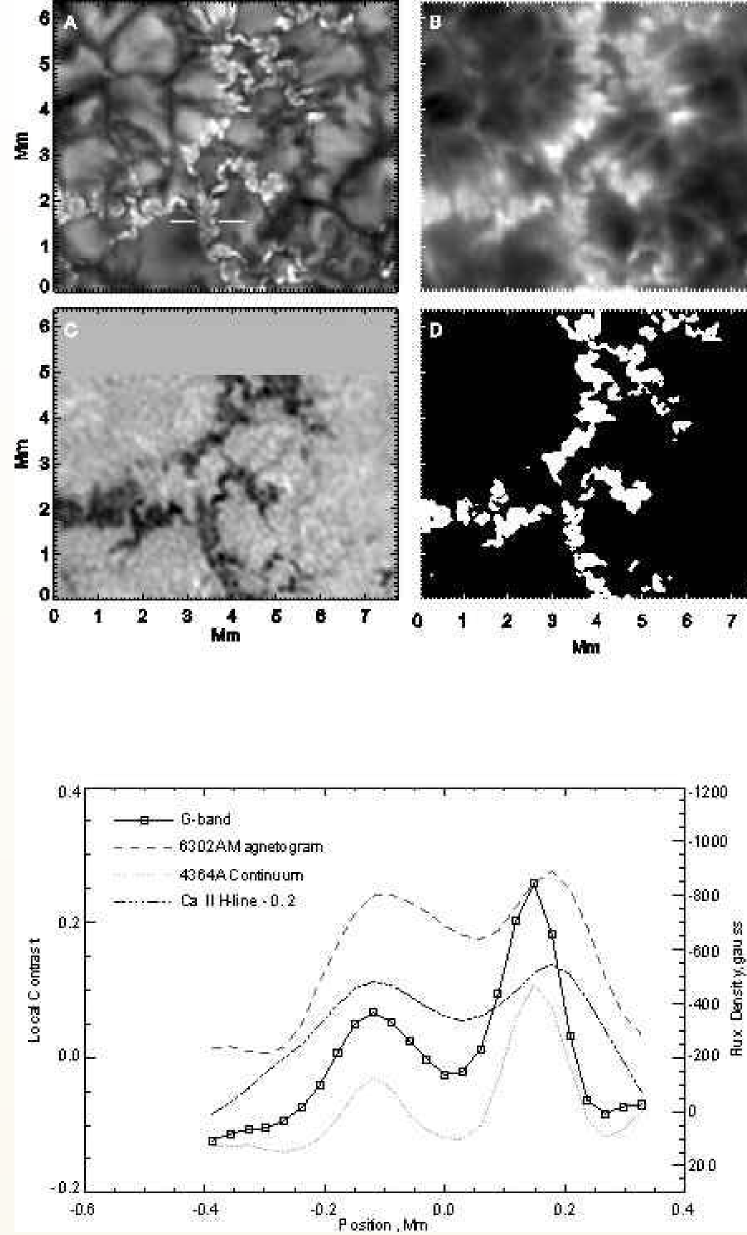
Magnetic elements can be identified with bright points in G-bar (4305 Å) images (e.g. Muller 1994, Berger et al. 1995, 1998, 2004 which are co-spatial with Ca II and TRACE (UV) structures (Rutte 1999);

High resolution observations suggest that these network bright poin (NBPs), located in intergranular lanes, are in a highly dynamic state, due to the buffeting effect of random convective motions (e. Muller et al. 1994; Berger & Title 1996);

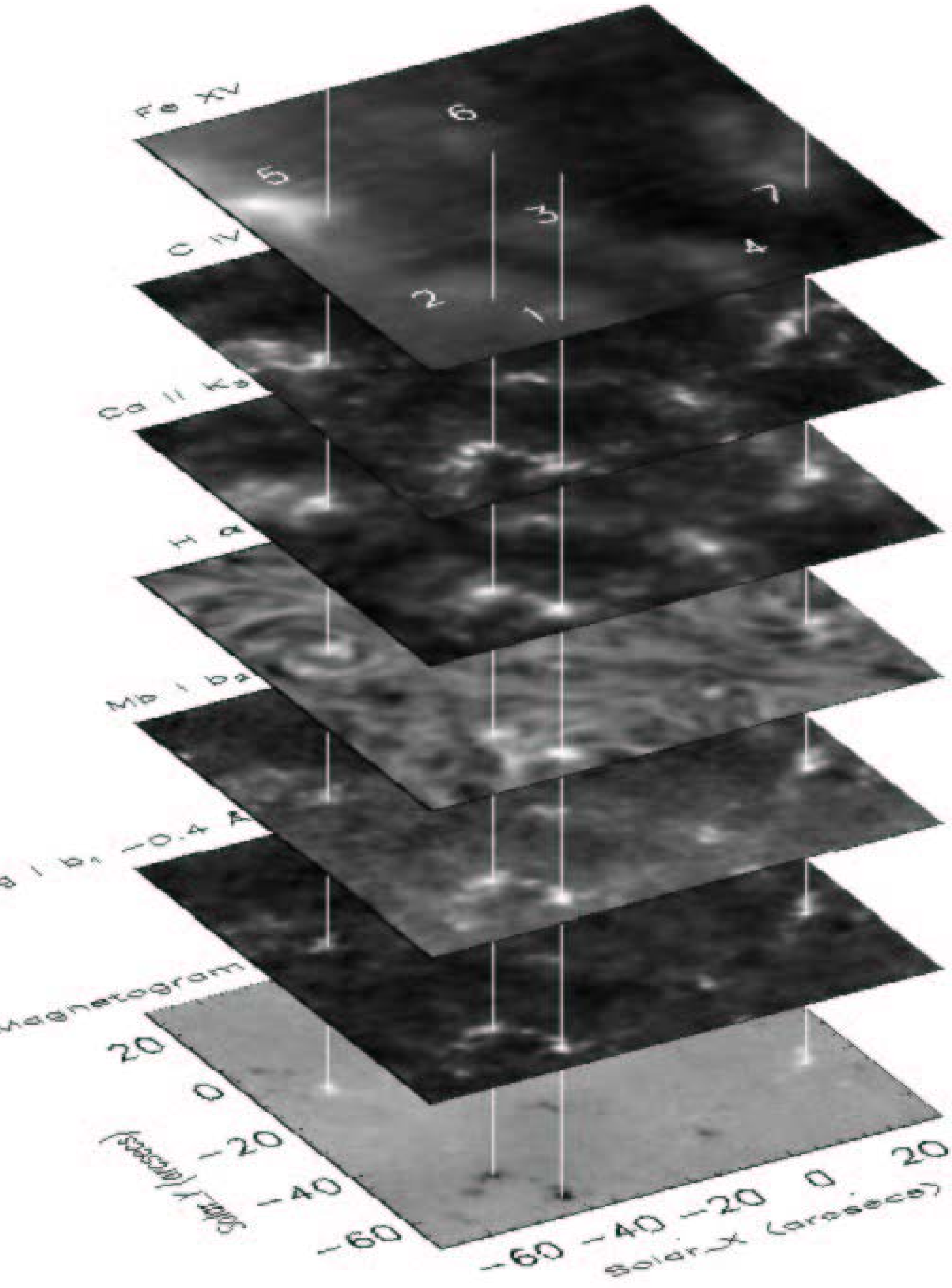
New observations (e.g. Berger et al. 2004 and Rouppe van der Voo et al. 2005) allow the magnetic structures to be examined with resolution of 0.1” in strong field areas indicating elongated “ribbon and circular “flowers”.



mnant AR 10365 at heliographic S7 E4 (μ = 0.99)
p: Ca II (396.8 nm) H-line bandpass; Bottom: SOUP
lar Optical Universal Polarimeter) Fe I 630.5 nm
gnetogram (Berger et al. 2004)



Top: Enlargement of Box 1 from a) G-band filtergram,
b) Ca II H-line filtergram, c) Fe I 630.25 magnetogram
Binary mask of the G-band emission in panel a).
Bottom: Intensity plot along the white lines shown in



Time averaged data of a 100"
100" field of view in the coror
(EIT 284Å), transition regio
(CIV 1500Å) and th
chromosphere. The bottom pl
is the corresponding magnet
gram. The vertical lines sho
four stable NBPs. Th
chromospheric NBPs have
one to one spatial correlatio
with the photospheric magnet
field and exist throughout th
transition region and the coror
(after McAteer et al. 2003)

DYNAMICS

The buffeting action of convective motions on magnetic flux tubes w generate various wave modes that can propagate in to the higher layers of the atmosphere and produce interesting effects such as mode conversion near the β=1 surface (Rosenthal et al. 2002, Bogdan et al. 2003);

Observations from the ground in Ca II H and K lines (e.g. as Lites e al. 1993) well as from space (Curdt & Henzel 1998, Hansteen et al. 2000) show that the chromosphere in the magnetic network of the quiet Sun oscillates with periods of around 7 min, which may be a signature of the kink mode cutoff period (Kalkofen 1997, Hasan & Kalkofen 1999);

New insights in to the physical processes occurring in and outside magnetic flux tubes comes from recent simulations such as those in 2-D by Rosenthal et al. (2002), Bogdan et al. (2003), Hasan et al. (2005) and in 3-D by Vogeler et al. (2005), Schaffenberger et al. (2005) and Carlsson & Bogdan (2006).

ENERGY SOURCE FOR HEATING NBPs

Kink waves generated inside flux tubes by the buffeting action granules (Choudhuri et al 1993; Hasan & Kalkofen 1999) or turbule motions (Huang, Musielak & Ulmschneider 1995);

Longitudinal waves generated either by pressure fluctuations insi flux tubes (Ulmschneider et al. 1991); or through nonline conversion of kink waves (Hasan et al. 2003);

Torsional (Alfvén) waves generated inside flux tubes (Nob Musielak & Ulmschneider 2004);

Acoustic waves, generated in the field-free atmosphere surroundi the flux tubes, that can penetrate into the tubes;

Acoustic-like waves generated at the interface of flux tubes and th ambient medium that also penetrate into the flux tubes.

MODEL OF A NETWORK ELEMENT

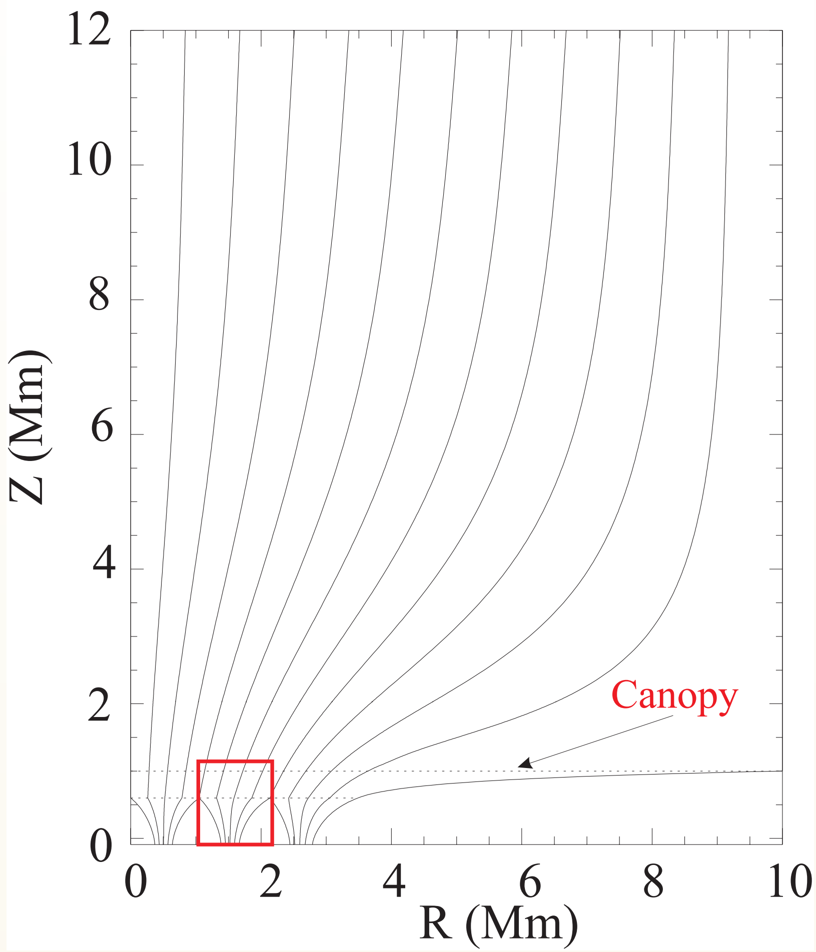
he network field structure consists of three distinct regions:

Photospheric region up to about 600 km, consisting of individua flux tubes, with a typical diameter of about 100 km in the low photosphere. The flux tubes are rooted in intergranular lanes and are separated from one another by about the diameter of a granule (~ 1000 km). The tubes expand upward and merge with thei neighbours at a height of about 600 km;

Lower chromosphere (600-1000 km) where the merged network flux element expands laterally over the surrounding supergranula cell centre and overlying field free chromosphere;

Upper chromosphere (1000-12000 km), the fully merged magneti field fills the available volume. At larger heights the field expands primarily in the vertical direction and becomes practically uniform However, at lower heights (1000-2000 km), the field strength varies significantly with horizontally position and the field strength above the tubes is much larger than that above the supergranular cel centre.

MODEL OF A NETWORK ELEMENT

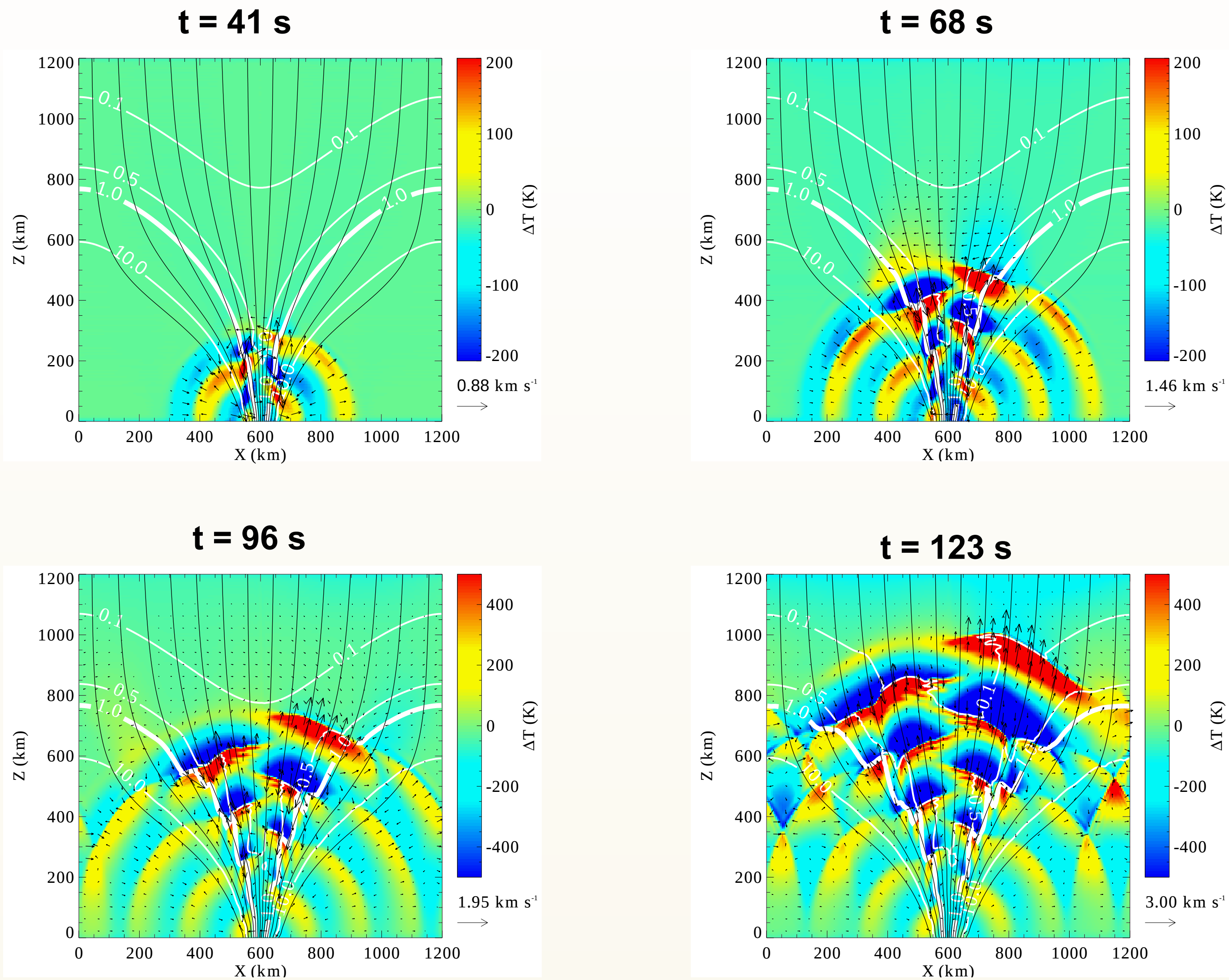


twork element (typical flux tube ~ 3 10^{19} Mx) as a collection of smaller flux tubes spatia parated from each other in the photosphere. Neighbouring tubes within the network eleme rge into a monolithic structure at a height of about 600 km. The outer edge of this tube form *gnetic canopy*. A second merging occurs when neighbouring network elements come togethe anopy height (after Cranmer and van Ballegoiijen 2004).

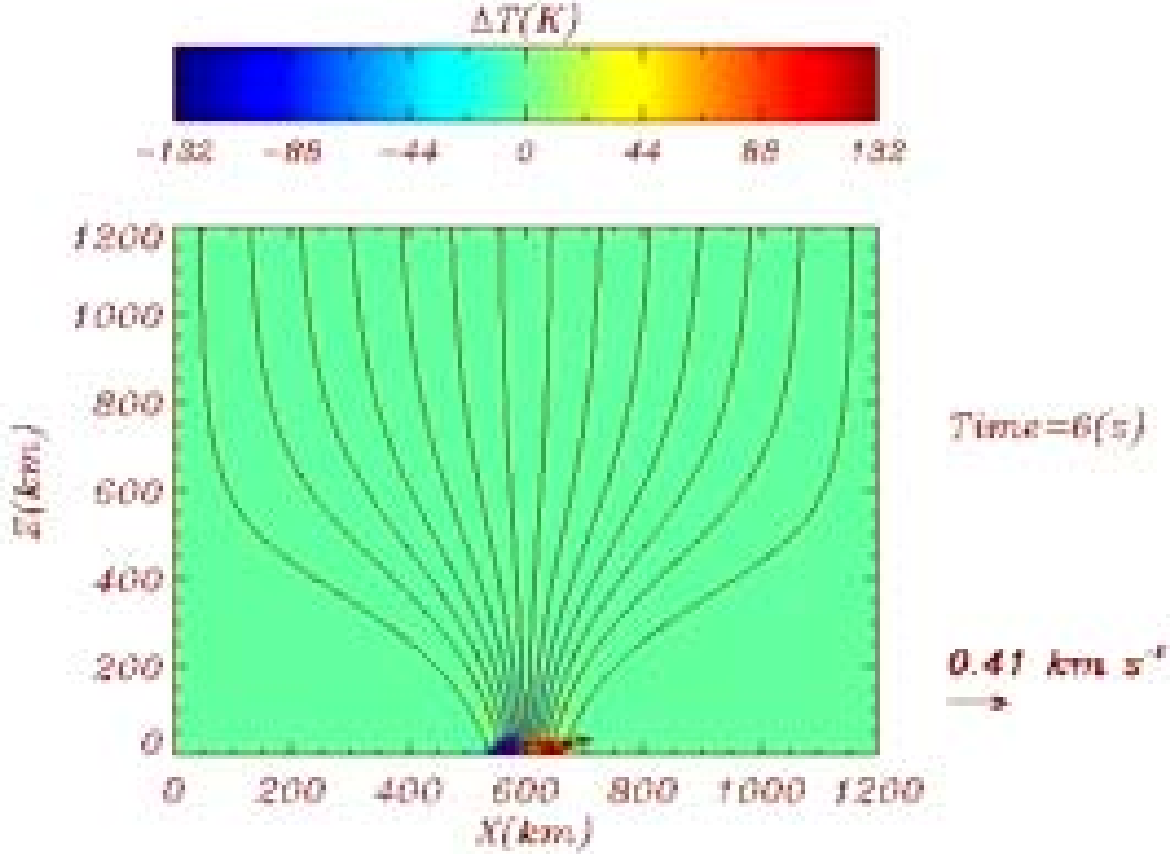
PARAMETERS ON THE TUBE AXIS & AMBIENT MEDIUM

	Tube Axis		Ambient Medium	
Variable	Base	Top	Base	Top
Temperature	4800 K	8200 K	4800 K	8200 K
Sound speed	7.1 km s^{-1}	12 km s^{-1}	7.1 km s^{-1}	12 km s^{-1}
Alfvén speed	11 km s^{-1}	92 km s^{-1}	0.3 km s^{-1}	52 km s^{-1}
Magnetic field	1400 G	100 G	70 G	100 G
β **(ratio of gas to magnetic pressure)**	0.5	0.02	600	0.06

Flow pattern and Temperature perturbation: *Periodic excitation*



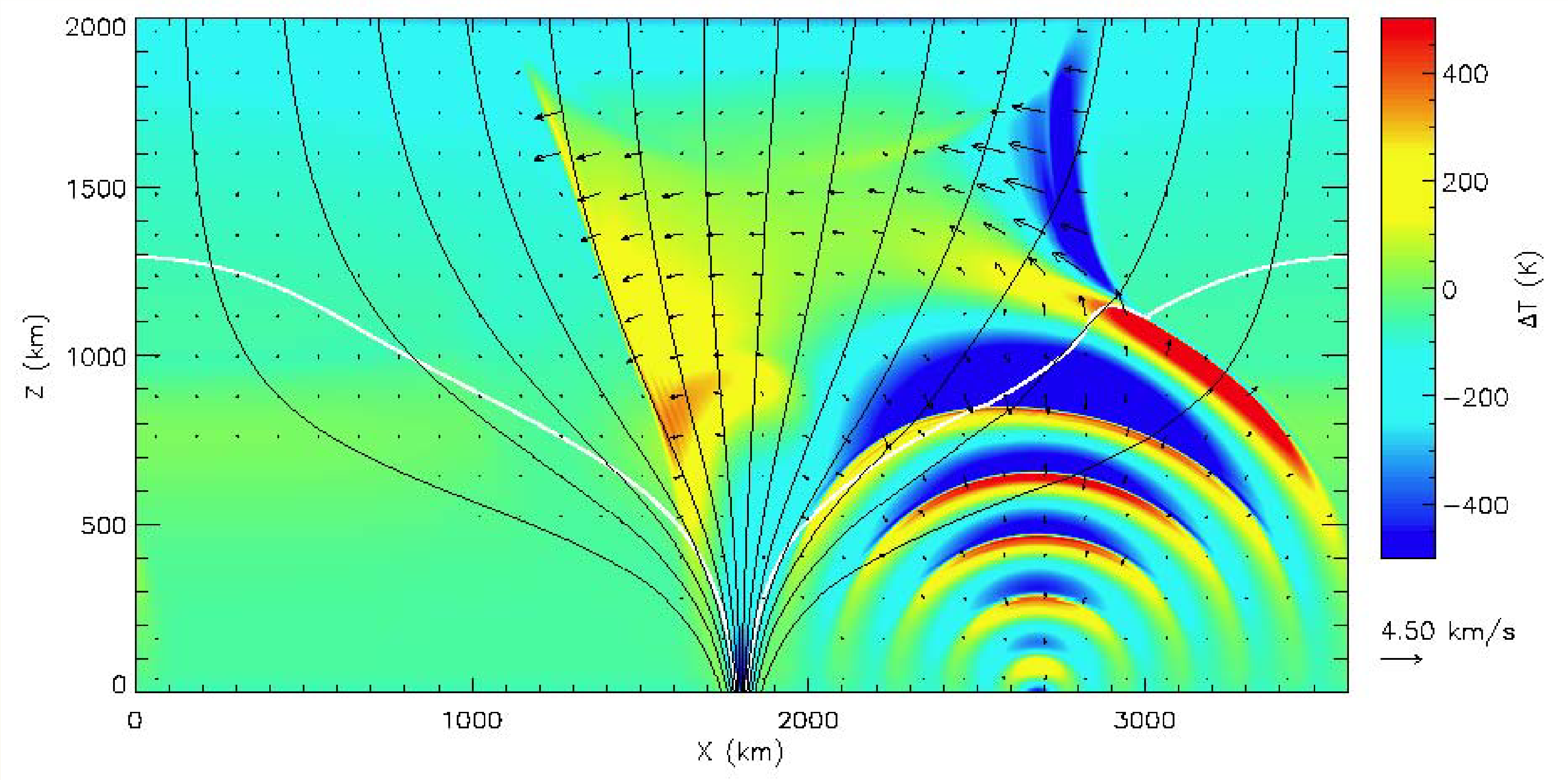
w pattern (arrows) and ΔT at a) 41 s, b) 68 s, c) 96 s and d) 123 s in a network element due to a horizontal periodic motion at the er boundary with an amplitude of 750 m s^{-1} and a wave period P=24 s. Thin black curves denote the field lines and white curves contours of constant β – the thick white curve corresponds to β=1 (from Hasan et al. 2005).



ΔT(K)
-132
-88
-44
0
44
88
132
Z(km)
1200
1000
800
600
400
200
0
X(km)
0
200
400
600
800
1000
1200
Time=6(s)
0.41 km s⁻¹

INTERACTION OF AN ACOUSTIC WAVE WITH A FLUX TUBE

t = 135 s



ow pattern (arrows) and ΔT at 123 s due to a localised vertical periodic motion at at x = 2700 km and z=0 he lower boundary) with an amplitude of 750 m s^{-1} and a wave period P=24 s. Thin black curves denote the agnetic field lines and the thick white curve corresponds to β=1 (Hasan and van Ballegooijen 2006)

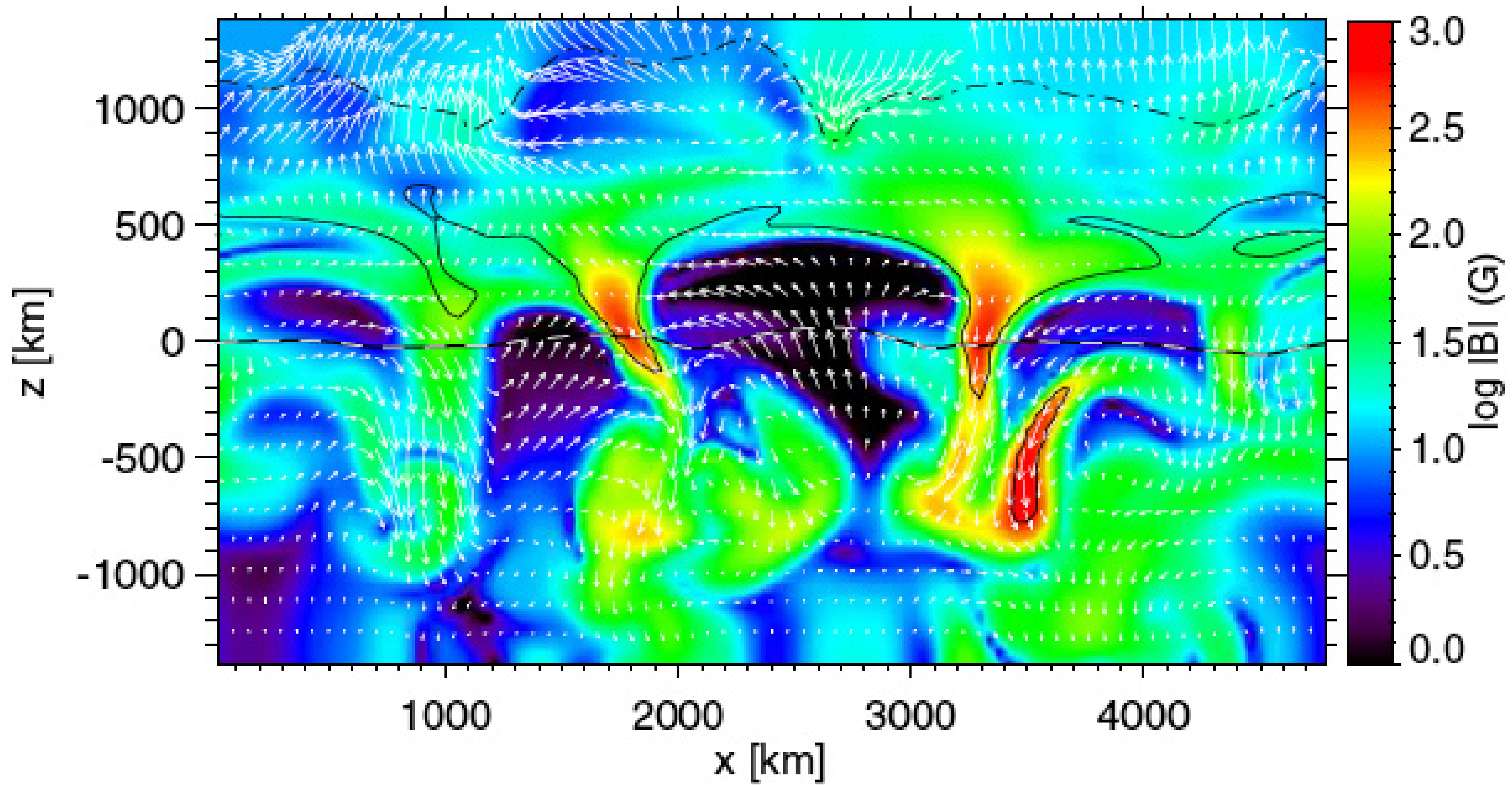
DISCUSSION

Horizontal motion of the flux tube at the lowe
boundary is a source of acoustic waves at th
interface, and in the ambient medium the
propagate isotropically;

Away from the axis (where $\beta \geq 1$), the compressior
and decompressions of the gas generate acoust
like modes (180° out of phase on opposite sides c
the tube axis) that are guided along the field lines;

These waves steepen with height and heat th
upper atmosphere of the flux tube;

3-D SIMULATION OF THE CHROMOSHERE



apshot of a vertical section through the 3-D computational domain showing log |B| (colou
ded) and velocity vectors projected on the vertical plane (white arrows). The black and
ite dashed curve shows optical depth unity and the dot-dashed and solid black contours
pict $\beta = 1$ and 100 surfaces respectively (from Schaffenberger et al. 2005)

SOME OUTSTANDING PROBLEMS

What is the nature of the internetwork magnetic field?

A substantial portion of the magnetic flux on the solar surface is in weak form (e.g. Meunier, Solanki & Livingston 1998):

Magnetic flux in quiet regions increases exponentially with spatial resolution - from 1 G for 2”-3” to around 20 G at 0.5” (Sanchez Almeida et al. 2003);

Hanle depolarization signals are consistent with a turbulent magnetic field in the internetwork - perhaps due to turbulent component of the solar dynamo;Is there a variation with the solar cycle? Indications are that the variation (if any) is weak;

Do K_{2V} grains correlate one-to-one with an enhanced magnetic field?

How are spicules formed and what are their properties?

- Chromospheric emission (H_α or He I) from the limb comes from spicules;
- Spicules are believed to originate in the magnetic network, but th field strength and geometry associated with the spicule channel i unknown (Trujillo Bueno et al. use Hanle and Zeeman effects to estimate ($B \sim 10$ G at a height of 2000 km inclined at about 35º t the vertical);
- P-mode photospheric oscillations with 5 min. periods can propagate into the corona (guided along an inclined flux tube tha has a higher acoustic cutoff period), where they form shocks, which drive chromospheric spicules (de Pontieu, Erdelyi & Jame 2004);
- Oscillations associated with spicules might be due to kink waves excited by the impact of granules on their footpoints (Kukhianidze et al 2005).

IMPLICATIONS FOR FUTURE STUDIES

Observations as well as simulations reveal that magnetic structur need to be resolved to an accuracy better than 0.1”. Neither th present space missions such as SOHO or TRACE (1” resolutio Hinode (0.2” resolution) nor future (SDO) have this capability;

Large aperture ground-based telescopes at sites equipped wi adaptive optics and located at sites with good seeing off considerable promise;

High time cadence observations (<1 s) especially in the UV (ne 1600 A) would be required to carefully study the presence of hig frequency oscillations in the chromosphere;

Polarimetric measurements with a high sensitivity (a few Gauss) the magnetic field and its inclination over a large field of view;

Distribution of the magnetic structures over the network ar internetwork regions - determination of the filling factor and als geometry of the magnetic canopy;

Spectroscopic measurements using temperature sensitive lines demarcate the thermal structure of the chromosphere and cros correlate with the magnetic observations.

THANK YOU