CCMag, Lindau, Germany, August 30 - September 2, 2005

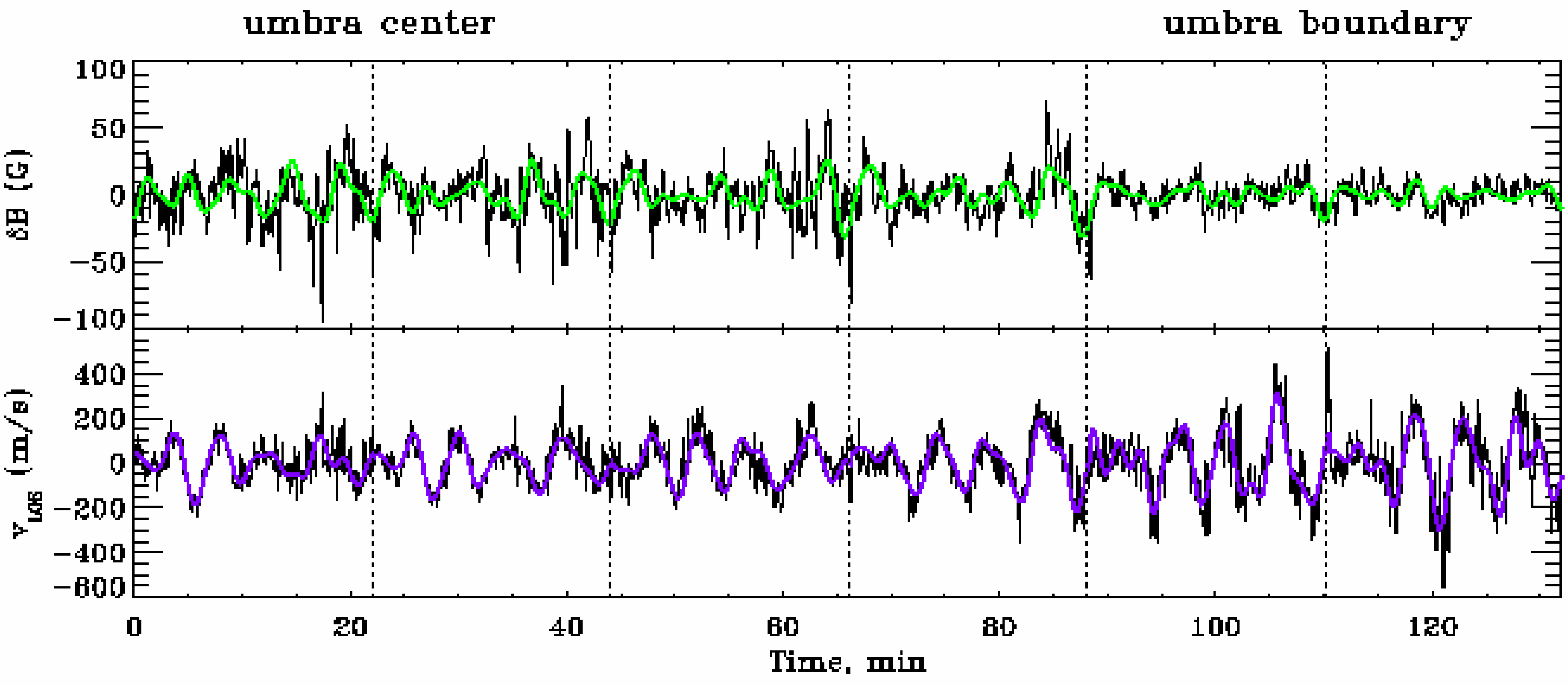
Simulations of magneto-acoustic waves in sunspots

Elena Khomenko(1,2), Manuel Collados(1)

Instituto de Astrofisica de Canarias, La Laguna, Spain;

Main Astronomical Observatory, Kiev Ukraine.

Motivation: photospheric oscillations

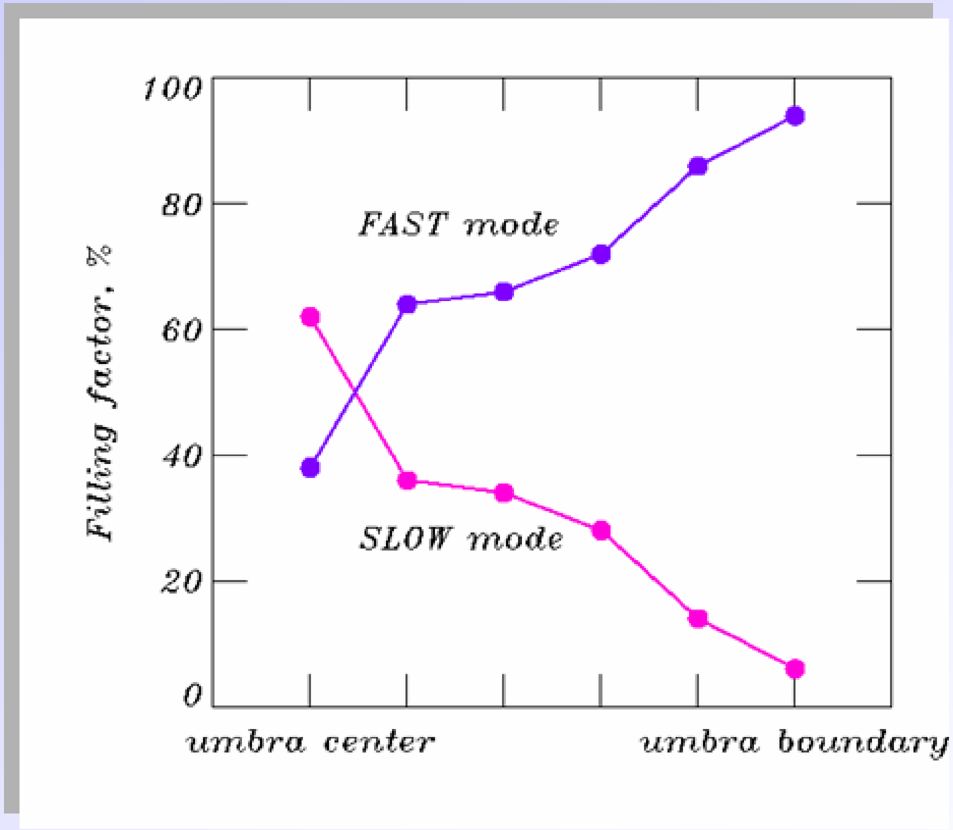


Bellot Rubio et al, 2000

•5-min velocity oscillations increase amplitude toward the umbra boundary.

•Magnetic field oscillations of ≈8 G

Motivation: photospheric oscillations



Khomenko et al, 2003

Slow (acoustic) mode →

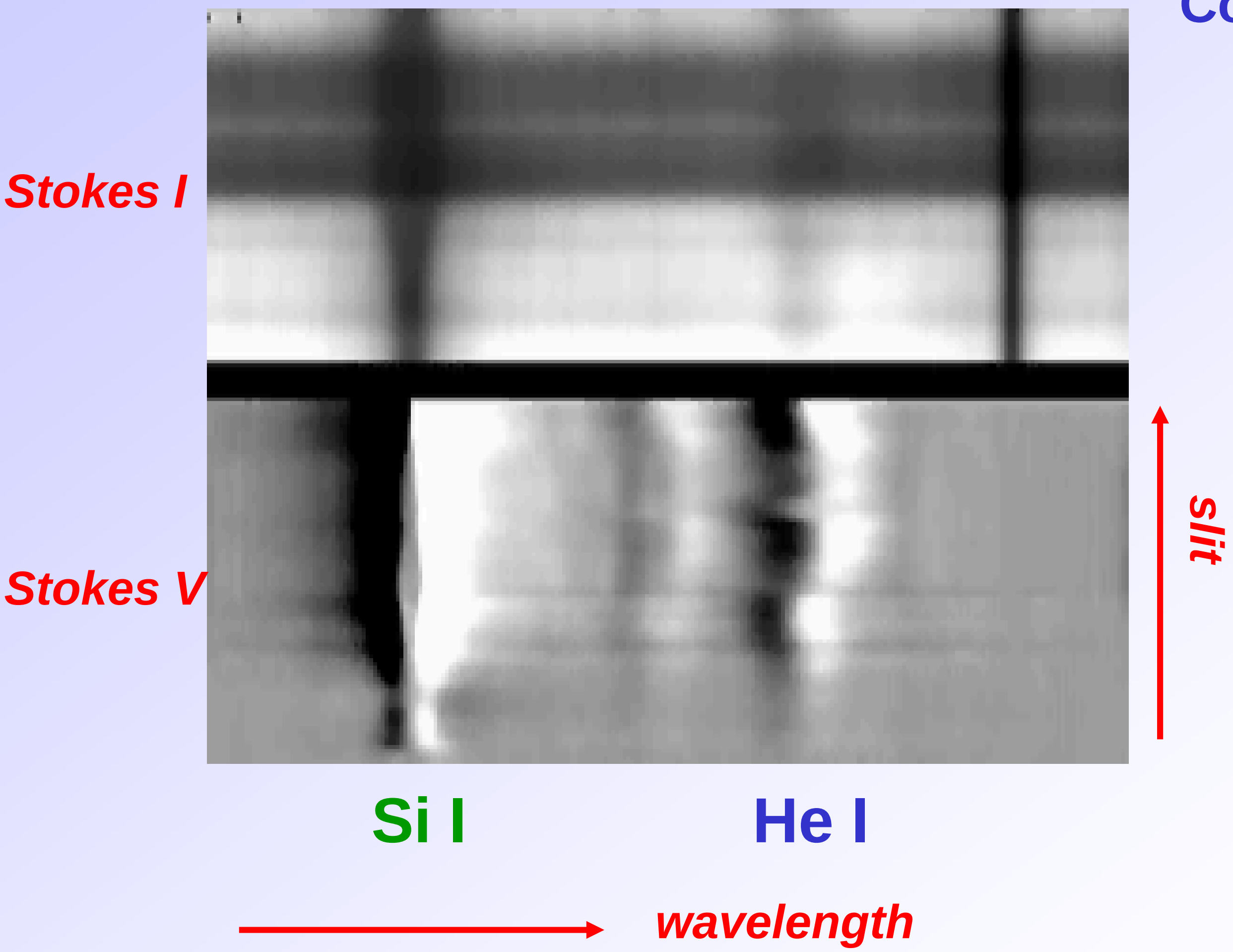
opacity variations →

magnetic field variations

Motivation

Oscillations in sunspot's photosphere and chromosphere

TIP/VTT infrared observations at 10830 A



Centeno et al. (2005, in preparation)

Collados et al. (2001)

Periods: 5 min (phot)

3 min (chrom)

Shock wave in the chromosphere

Propagation along the field lines

Delay of 6-7 min or

V_{phas} of 4-5 km/s

Photospheric pulse!

MHD equations

$$\frac{\partial \rho}{\partial t} + \vec{\nabla}(\rho \vec{V}) = 0$$

Reynolds stress   Pressure   Maxwell stress

$$\frac{\partial \rho \vec{V}}{\partial t} + \vec{\nabla}\left(\rho \vec{V}\vec{V} + (P + \frac{B^2}{8\pi})\mathrm{I} - \frac{\vec{B}\vec{B}}{4\pi} \right) = \rho\, \vec{g}$$

$$\frac{\partial}{\partial t}\left(\frac{1}{2}\rho V^2 + \frac{B^2}{8\pi} + \frac{P}{\gamma - 1} \right) +$$

Poynting vector

$$\vec{\nabla}\left(\frac{1}{2}\rho V^2 \vec{V} + \frac{\gamma}{\gamma - 1} P\vec{V} + \frac{1}{4\pi}\vec{B} \times (\vec{V} \times \vec{B}) \right) = \vec{V}\rho\,\vec{g} + \rho Q$$

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times (\vec{V} \times \vec{B})$$

See eg., Lifschitz (1988)

MHD equations: linearization

$$\vec{B} = \vec{B}_0 + \vec{B}_1$$

$$P = P_0 + P_1$$

$$\rho = \rho_0 + \rho_1$$

$$\vec{V} = \vec{V}_1$$

Need for MHS equilibrium!

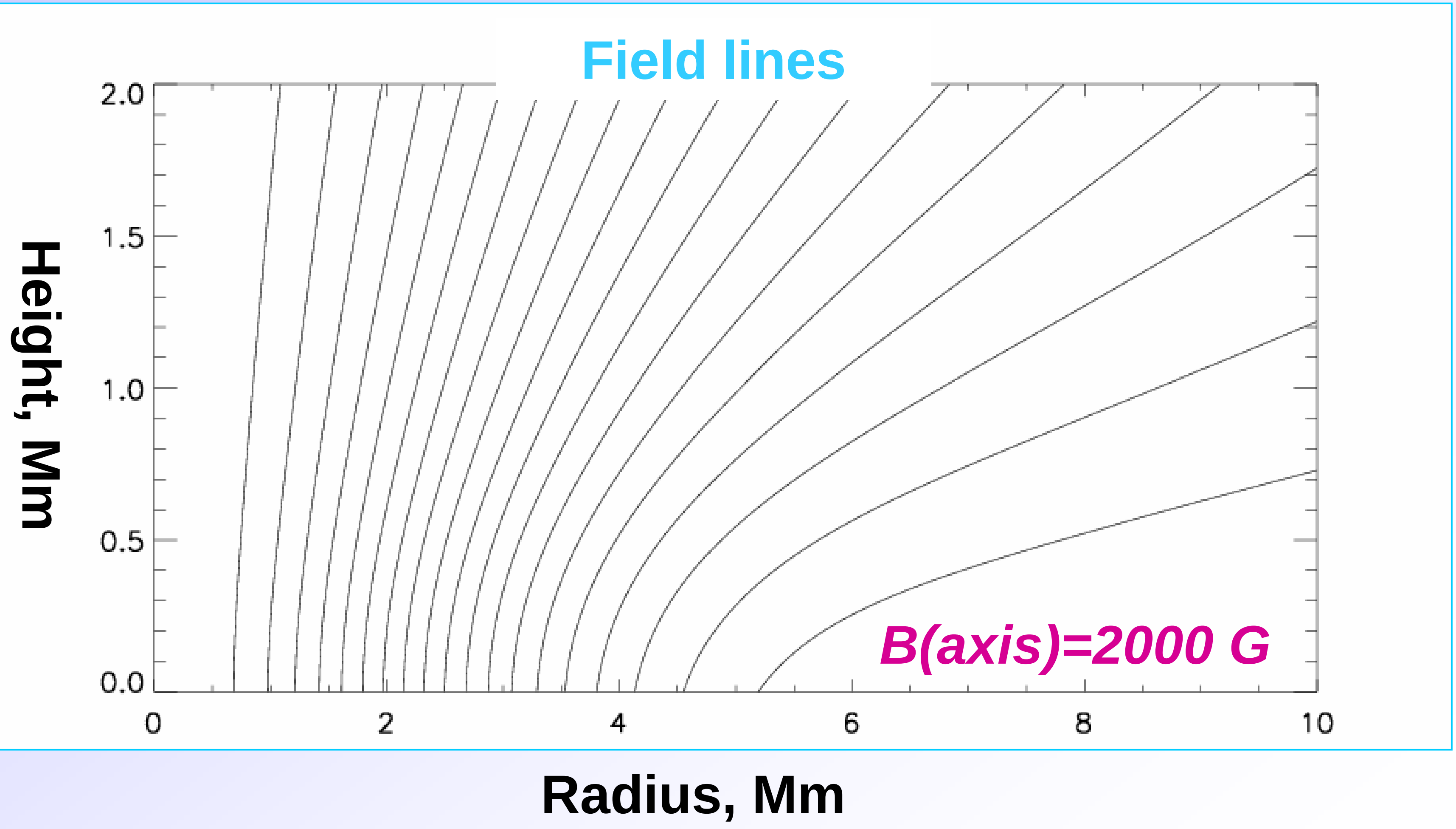
$$-\vec{\nabla} P_0 + \rho_0 \vec{g} + \frac{1}{4\pi}(\vec{\nabla} \times \vec{B}_0) \times \vec{B}_0 = 0$$

$$\vec{\nabla}\vec{B}_0 = 0$$

MHS field configuration

Pizzo (1986)

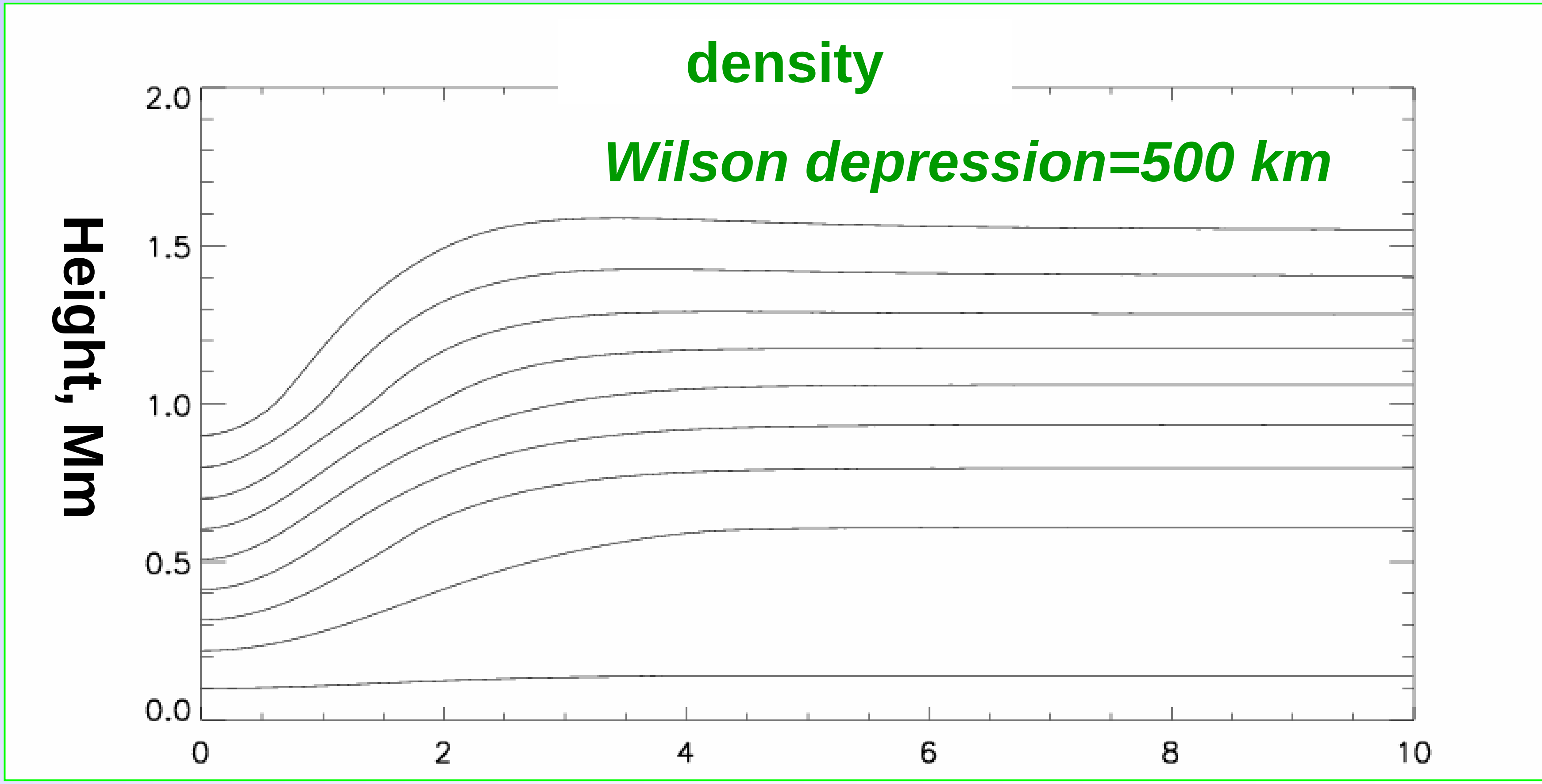
azimuthally symmetric sunspot, no twist



MHS field configuration

Semi-empirical model atmosphere on the axis

(VALC, Spruit (1977) - QS, Avrett (1981) - spot axis.



Equation of state

$$P = \frac{\rho k T}{\mu m_H}$$

Perfect gas

Energy losses

For the moment, no energy losses are taken into account: adiabatic waves

Numerical diffusivity

To reduce the high-frequency numerical noise

See Vogler et al (2005)

$$\left(\frac{\partial \rho}{\partial t}\right)_{diff} = \sum_l \frac{\partial}{\partial x_l}\left(\nu_l(\rho)\frac{\partial \rho}{\partial x_l}\right)$$

etc..

Boundary conditions

Top and side boundaries have an absorbing layer

Initial conditions

A pulse located at the lower boundary.

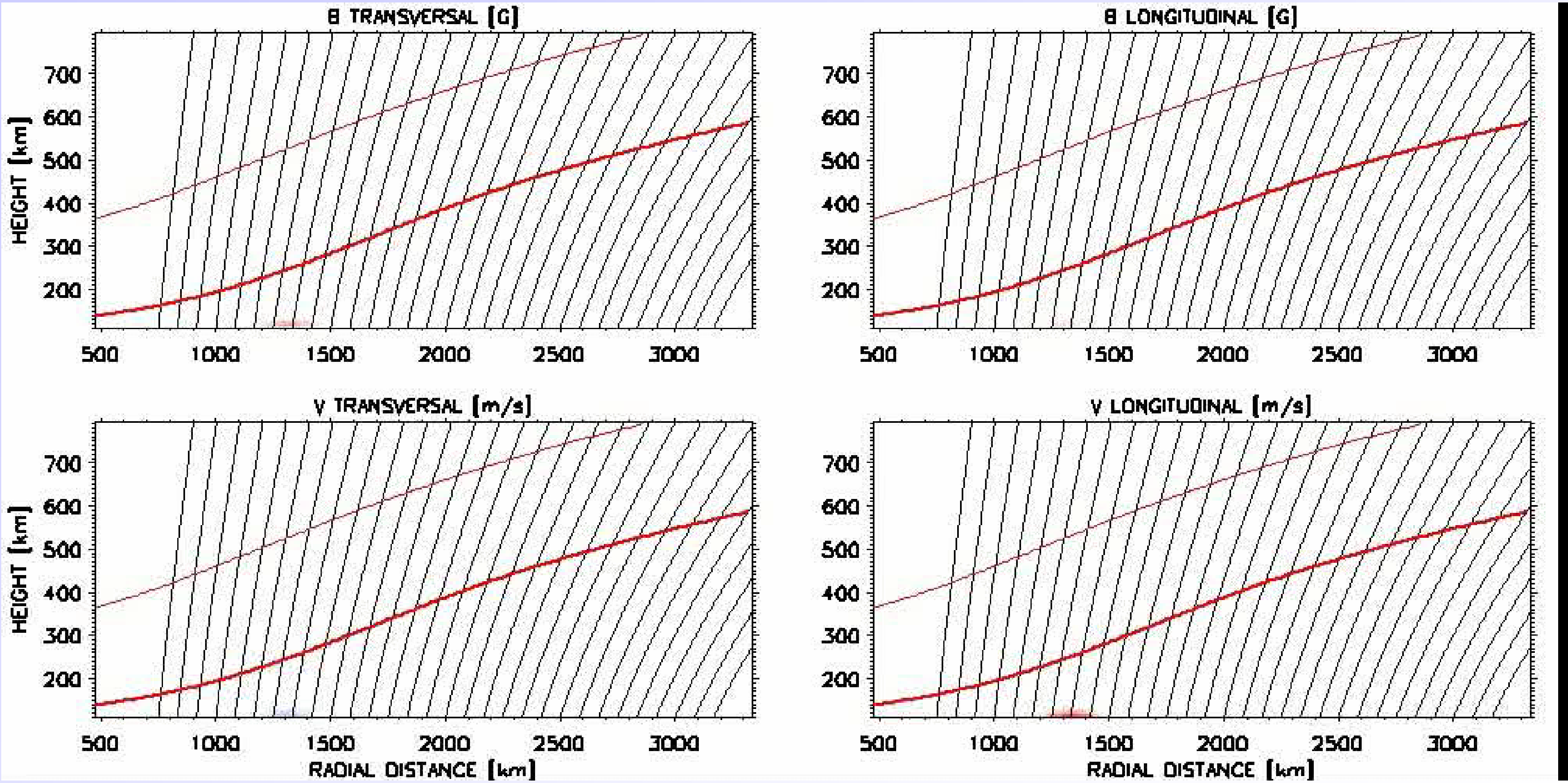
Specify horizonal $V_{1x} = V_0 \exp(i\omega t)$

OR vertical $V_{1z} = V_0 \exp(i\omega t)$ *velocity*

Pulse has a Gaussian shape.

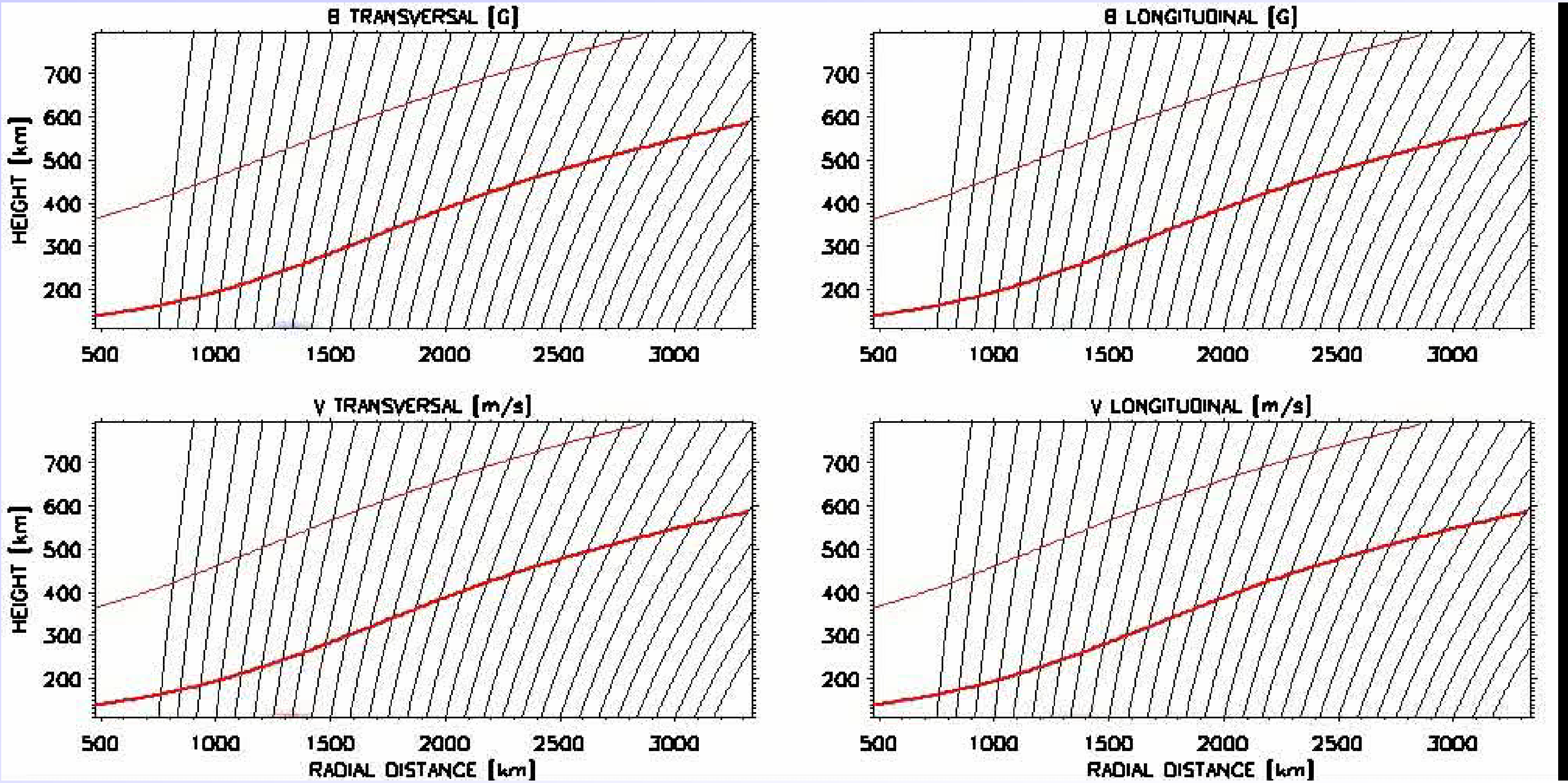
Radial driving in $\beta > 1$, T=10 sec, duration=100sec

transversal & longitudinal components



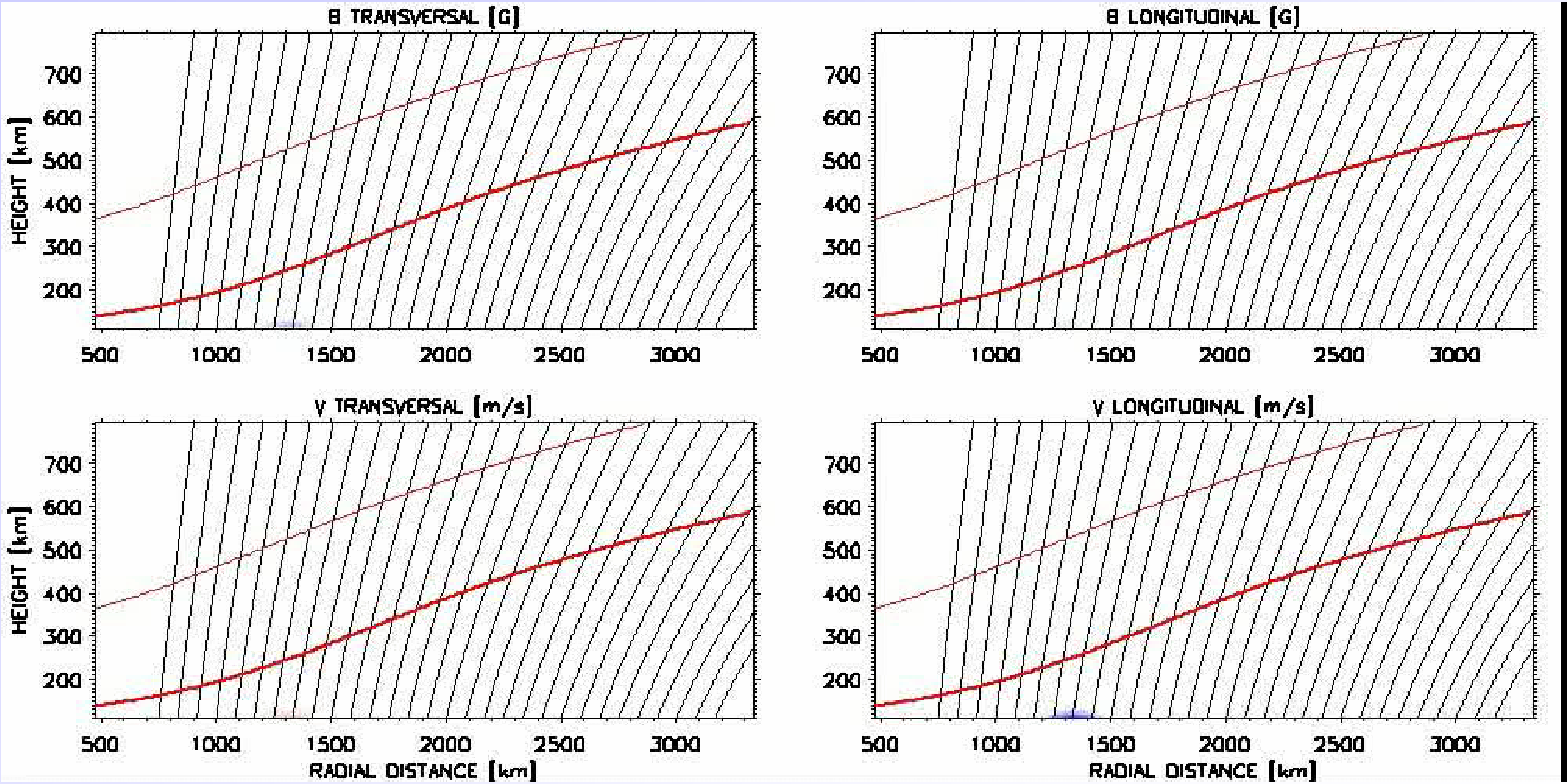
Transverse driving in β >1, T=10 sec, duration=100sec

transversal & longitudinal components



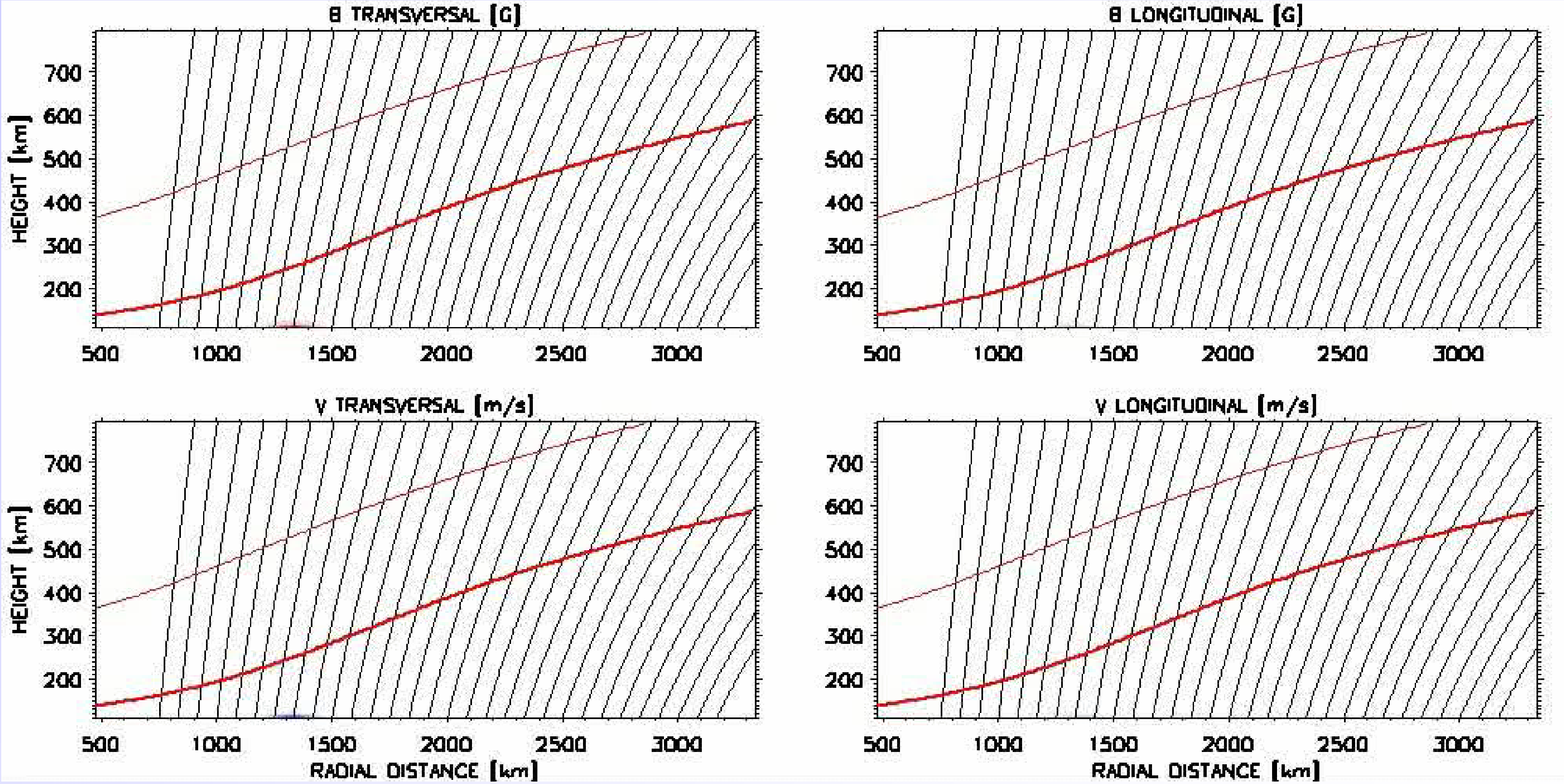
Radial driving in $\beta > 1$, T=50 sec, duration=100sec

transversal & longitudinal components



Transverse driving in $\beta > 1$, T=50 sec, duration=100sec

transversal & longitudinal components



Conclusions

- ***Fast mode refracts back to the photosphere.***
- ***Slow (acoustic) mode continues up to the chromosphere.***
- ***Larger period pulse produces more acoustic power.***