*Waves & Oscillations in the Solar Atmosphere: Heating and Magneto-Seismology*
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# Inferring the chromospheric magnetic topology through waves

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**Abstract.** The aim of this work is to examine the hypothesis that the wave propagation time in the solar atmosphere can be used to infer the magnetic topography in the chromosphere as suggested by Finsterle *et al.* (2004). We do this by using an extension of our earlier 2-D MHD work on the interaction of acoustic waves with a flux sheet. It is well known that these waves undergo mode transformation due to the presence of a magnetic field which is particularly effective at the surface of equipartition between the magnetic and thermal energy density, the $\beta = 1$ surface. This transformation depends sensitively on the angle between the wave vector and the local field direction. At the $\beta = 1$ interface, the wave that enters the flux sheet, (essentially the fast mode) has a higher phase speed than the incident acoustic wave. A time correlation between wave motions in the non-magnetic and magnetic regions could therefore provide a powerful diagnostic for mapping the magnetic field in the chromospheric network.

**Keywords.** waves, MHD, Sun: atmosphere, Sun: photosphere, Sun: chromosphere, Sun: oscillations

## 1. Introduction

Waves with frequencies above the acoustic cutoff, which can freely propagate in the solar atmosphere can potentially serve as a helioseismic tool for probing its structure. When these waves encounter a change in the dispersive characteristics of the medium, they are refracted and reflected. This was demonstrated using 2-D MHD numerical calculations by Rosenthal *et al.* (2002) and Bogdan *et al.* (2003). Since changes in dispersion can be caused by the presence of magnetic fields, high-frequency waves should also carry information on the magnetic field (see e.g. De Pontieu *et al.* 2004 and a recent review of this topic by De Pontieu and Erdélyi 2006). This effect has been employed by Finsterle *et al.* (2004) in order to obtain the three-dimensional topography of the 'magnetic canopy' in and around active regions by determining the propagation behaviour of high-frequency acoustic waves in the solar chromosphere. The idea was also explored, using the features of resonant absoprtion, by Pintér et al (2007) where the method of ring analysis was proposed to construct the chromospheric magnetic field lines. In order to test the reliability of this approach and to further explore and assess the effectiveness of this method, Steiner *et al.* (2007) have tracked plane-parallel waves in a gravitationally stratified atmosphere containing a magnetic flux sheet. In the present work we relate the travel-time difference of waves between two given height levels in the atmosphere, to the location of the $\beta = 1$ surface, where there is equipartition between magnetic and thermal energy. Waves entering this magnetically dominated layers of the chromosphere are consequently refracted and reflected. Here we consider an idealized model of a hydrostatic, gravitationally stratified atmosphere that contains a symmetric magnetic flux sheet in magnetohydrostatic equilibrium.

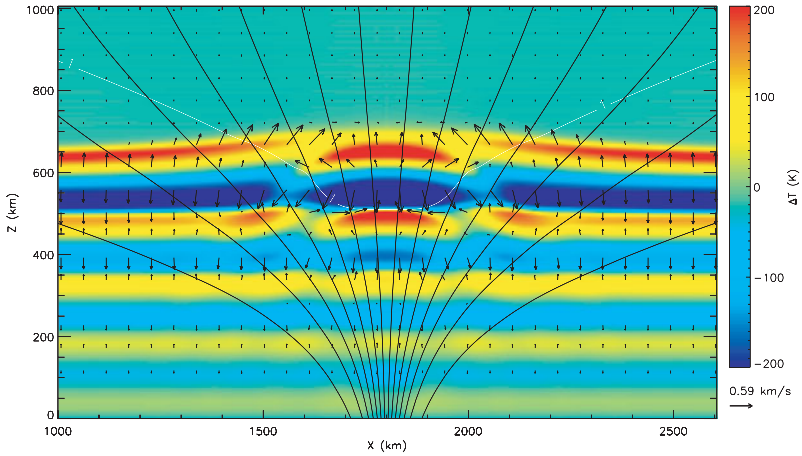


**Figure 1.** Temperature perturbation and velocity vectors (arrows) at 92 s in a network region consisting of a vertical flux sheet of thickness 150 km at the base and a field strength on the axis of 1000 G ($\beta = 2$). Waves are excited in the atmosphere due to a periodic vertical motion at the lower boundary with an amplitude of 50 m s$^{-1}$ and frequency of 50 mHz (period 20 s). Black curves denote magnetic field lines and the white curve denotes the $\beta = 1$ surface.

## 2. Model and Governing Equations

We model a network element as a non-potential magnetic flux sheet with a width of 150 km at the base of the photosphere where $\beta = 2$ on the symmetry axis (corresponding to a field strength of 1000 G), which decreases with height. The $\beta = 1$ level on the axis occurs at a height of around 500 km. Table 1 gives the model parameters on the axis.

Within the flux sheet, the pressure and density are lower than the corresponding values in the ambient medium, but the temperature is constant on horizontal planes. The magnetic field, density and pressure vary smoothly with distance from the axis. Details of the model are given in Hasan *et al.* (2005).

**Table 1.** Parameters on the Sheet Axis

| Variable | Base | Top |
|---|---|---|
| Temperature | 4700 K | 8200 K |
| Sound speed | 7.1 km s$^{-1}$ | 13 km s$^{-1}$ |
| Alfvén speed | 5.5 km s$^{-1}$ | 85 km s$^{-1}$ |
| Magnetic field | 1000 G | 44 G |
| $\beta$ | 2.0 | 0.03 |

Plane parallel waves are excited in the medium by perturbing the lower boundary with a vertical periodic motion of the form: $Vz(x, 0, t) = V_0 \sin(2\pi\nu t)$ where $V_0$ is the amplitude of the motion, which we take to be 50 m s$^{-1}$, and $\nu$ is the wave frequency. For easy visualization we choose a frequency of 50 mHz to conveniently track the wave train. The simulation was carried out using the 2-D MHD code of Steiner *et al.* (1994) on a uniform grid of spacing 5 km (in both directions), with an upper boundary at 1500 km and a horizontal extension of 3600 km. No flow boundary conditions were imposed on the lower and upper boundaries whereas periodic boundary conditions were used in the horizontal direction. More details can be found in Hasan *et al.* (2005).

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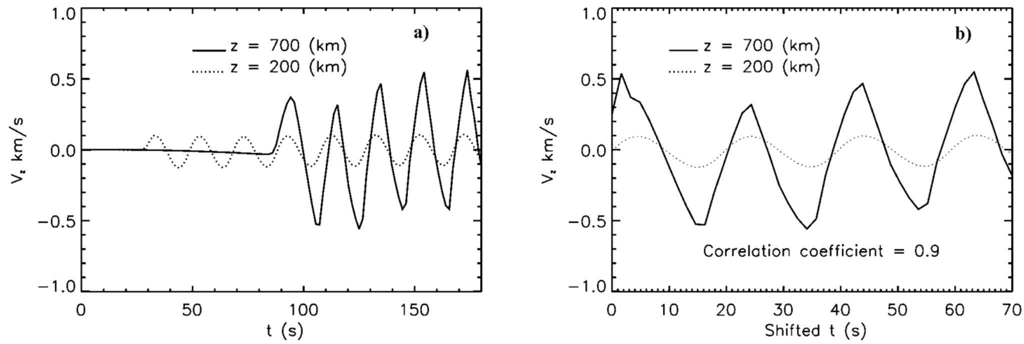


**Figure 2.** (a) Vertical component of the velocity as a function of time at $x = 1500$ km and two heights 200 km and 700 km. The wave is driven by a vertical periodic motion applied uniformly on the $z = 0$ plane. (b) Same as a) except that the two wave trains are shifted by the time delay that it takes for the waves to reach the higher level.

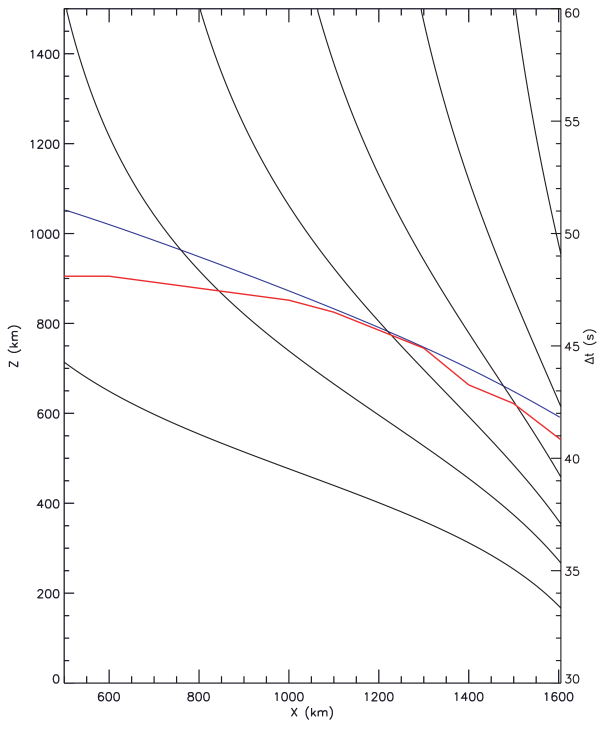


**Figure 3.** Time delay $\Delta t$ in seconds (red curve) as a function of $x$ (horizontal distance from the left boundary) in a a network element. The black curves denote the magnetic field lines and the blue curve corresponds to the $\beta = 1$ contour (blue curve). The time delay is measured by maximizing the correlation (at different $x$) in the wave trains for the vertical component of the velocity between the heights 200 km and 700 .

## 3. Results and Discussion

Vertical periodic motions along the lower boundary excite plane acoustic waves that propagate upwards through the network atmosphere. Figure 1 shows the temperature perturbation (with respect to the initial value at each height) at 92 s. The black curves denote field lines and the white curve depicts the $\beta = 1$ surface. Below this surface the

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acoustic waves do not feel the influence of the magnetic field. In these regions and also close to the sheet axis, the motions are essentially vertical. However, near the $\beta = 1$ level, where the field lines are inclined, the acoustic wave acquires a magnetic character (through transformation into a fast mode) with a higher propagation speed than the acoustic mode. Such regions can be identified by the horizontal gaps in the temperature perturbations. At these locations the velocity vectors are no longer vertical.

Figure 2(a) shows the vertical component of the velocity as a function of time at $z = 200$ km (dotted line) and $z = 700$ km (solid line) for $x = 1500$ km. The two wave trains are shifted with respect to each other in view of the time it takes for the motions to reach the higher layers. We now displace the wave trains horizontally in time to compensate for the time delay. This is carried out by finding the maximum two point correlation. Figure 2(b) shows the two wave trains superposed on each other after accounting for the time delay between the two heights. This procedure is repeated at various horizontal positions.

Figure 3 depicts the variation of the time delay (red curve) as a function of $x$. The blue curve shows the location of the $\beta = 1$ surface and the black curves denote the magnetic field lines. We find that, as expected, the time delay decreases in regions where the $z = 700$ km lies above the $\beta = 1$ surface. This happens due to a speeding up of the wave as it it enters the flux sheet.

## 4. Summary

(*a*) We have examined the hypothesis that the time delay between waves at different height levels can provide information on the magnetic field in the solar atmosphere;

(*b*) Our calculations indeed show that this delay decreases in the magnetized regions of the network by about 7 s;

(*c*) The time delay is a minimum above the $\beta = 1$ layer where the magnetic fields are inclined;

(*d*) We have demonstrated a potentially powerful technique for inferring the magnetic topology in regions of the atmosphere where direct measurements of the magnetic field are difficult.

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