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Dynamical Processes in Flux Tubes and their Role in Chromospheric Heating

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Abstract. We model the dynamical interaction between magnetic flux tubes and granules in the solar photosphere which leads to the excitation of transverse (kink) and longitudinal (sausage) tube waves. The investigation is motivated by the interpretation of network oscillations in terms of flux tube waves. The calculations show that for magnetic field strengths typical of the network, the energy flux in transverse waves is higher than in longitudinal waves by an order of magnitude. But for weaker fields, such as those that might be found in internetwork regions, the energy fluxes in the two modes are comparable. Using observations of footpoint motions, the energy flux in transverse waves is calculated and the implications for chromospheric heating are pointed out.

Key words. MHD — Sun: magnetic fields, oscillations.

1. Introduction

It is now generally accepted that the solar photosphere is threaded with 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., Frazier & Stenflo 1972). These flux tubes occur preferentially in the magnetic network, which essentially outlines the boundaries of supergranules (convection cells typically 30 Mm) that are clearly visible as bright points in G-band and Ca II images. High resolution observations suggest that these network bright points, located in intergranular lanes, are in a highly dynamical state, due to the buffeting effect of random convective motions (e.g., Müller 1983; Muller *et al.* 1994; Berger & Title 1996; van Ballegooijen *et al.* 1998). It is likely that the interaction of the motions with the magnetic elements can excite MHD oscillations in the flux tubes, which can contribute to chromospheric and coronal heating.

The dynamical behaviour of bright points has been examined in great detail extensively (e.g., Muller *et al.* 1994, Berger *et al.* 1998; van Ballegooijen *et al.* 1998). Many observations have confirmed that the chromosphere in the magnetic network of the quiet Sun oscillates with periods of around 7 min. (e.g., Dame 1983; Lites, Rutten & Kalkofen 1993; Curdt & Henzel 1998).

Many numerical simulations of dynamical effects associated with the interaction of magnetic fields and convection have been carried out (e.g., Nordlund & Stein 1989; Nordlund *et al.* 1992; Steiner *et al.* 1998). The simulations of Steiner *et al.* clearly show the bending of a 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, Zähringer & Musielak 1991.) The excitation of transverse (kink) waves by the footpoint motions of magnetic elements has been modelled by Choudhuri, Auffret & Priest (1993). They suggest that rapid motions (with a time constant less than 300 s) with velocities larger than 2 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, Bromm & Ulmschneider 1995); the latter can easily dissipate through shock formations and contribute to the heating of the atmosphere. Chromospheric oscillations with a period of 7 min. have been interpreted as transverse waves in a magnetic flux tube oscillating at their cutoff period (Kalkofen 1997).

The main aim of the present contribution is to quantitatively study the interaction of a magnetic flux tube that is buffeted by a granule from the ambient medium and examine the excitation of wave flux tubes modes (transverse and longitudinal) for the *same* external impulse, with a view to determine the partitioning of vertical energy flux in the two modes. Using observations of footpoint motions, the energy flux of transverse waves is calculated and the implications for chromospheric heating are pointed out.

2. Model

Consider a vertical magnetic flux tube extending through the photosphere, which we assume to be "thin" and isothermal. It is convenient to use the "reduced" displacement, $Q(z,t)$, which is related to the physical Lagrangian displacement, $\xi(z, t)$, by $Q(z, t) = \xi\pm(z, t)e^{-Z/4H}$, where H denotes the scale height of the atmosphere.

It can be shown that Q_α ($\alpha = \kappa$ for transverse waves and $\alpha = \lambda$ for longitudinal waves) satisfies the Klein-Gordon equation (Hasan & Kalkofen 1999, henceforth Paper I). Once Q_α is determined, the vertical energy flux in the two modes can easily be calculated (Paper **I**).

3. Results

We use the following default parameters: temperature $T = 6650$ K, scale height $H = 155.4$ km, sound speed $C_s = 8.4$ km s^{-1}, $\beta = 0.3$ ($B \approx 1600$ G at $z = 0$), where $\beta = 8\pi B^2/p$, B and P are respectively the magnetic field and pressure at the tube axis. The wave speed and cutoff period are 7.3 km s^{-1} and 534 s for kink waves and 7.5 km s^{-1} and 227 s for longitudinal waves. Note that the latter period is almost the same as the acoustic cutoff period. We assume that the flux tube is buffeted by a single granule with a speed of 1 km s^{-1} in a single impact with an interaction time of 50 s.

Fig. 1 shows the time variation of F_{wave}/fo (where f_0 denotes the filling factor of magnetic flux tubes at z — 0), the wave energy flux in the vertical direction, in transverse (solid lines) and longitudinal (dotted lines) modes at two different heights, using the default parameters. Note that the energy flux in longitudinal waves is measured by the scale on the right. The impulse delivered to the tube at $z = 0$ creates an oscillation that transports energy to the higher layers. The first maximum

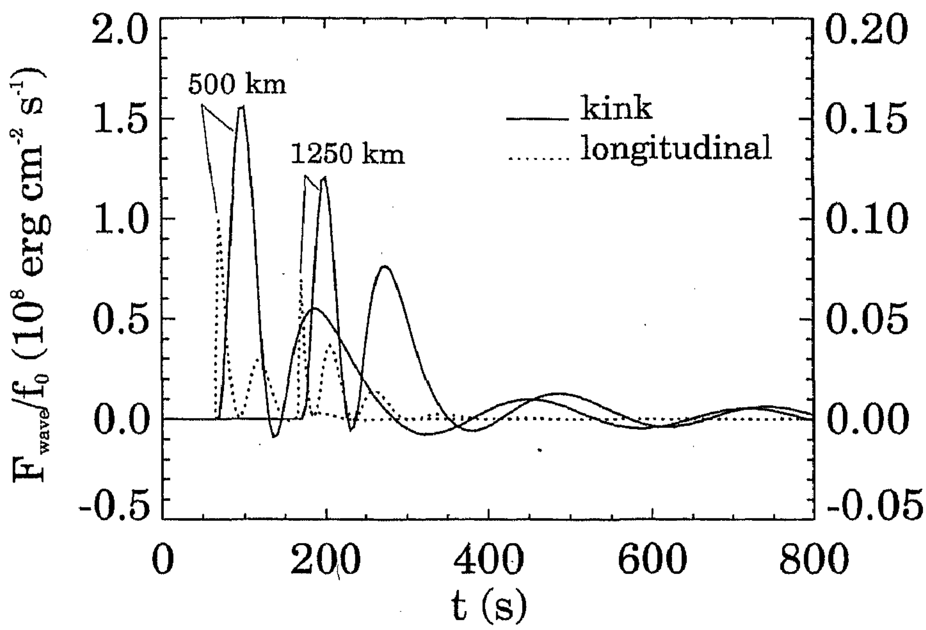

Figure 1. Time variation of F_{wave}/f_0 (where f_0 denotes the filling factor of magnetic flux tubes at $z = 0$), the vertical energy flux in transverse waves (solid lines) and longitudinal (dotted lines) at two heights for $\beta = 0.3$.

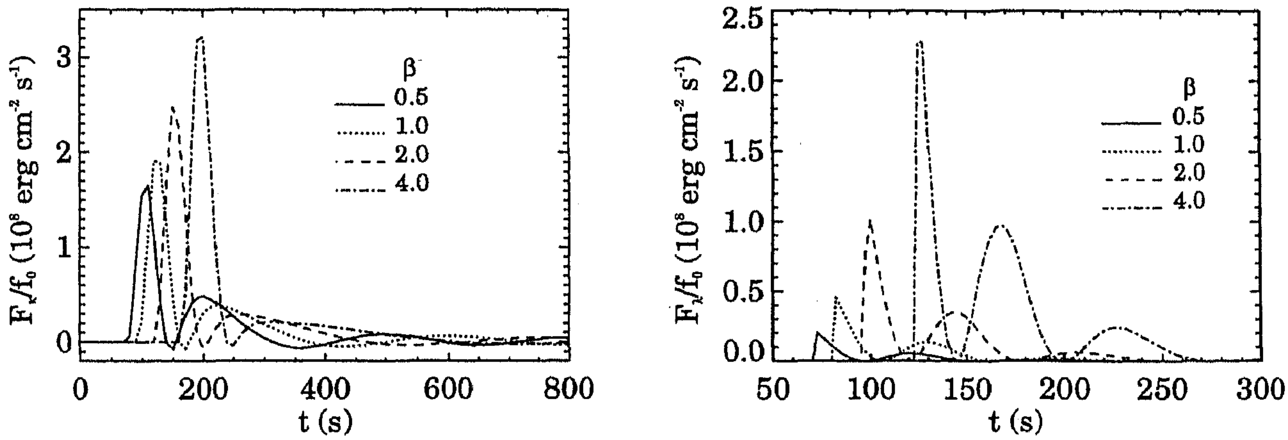

Figure 2. Time variation of the vertical energy flux in transverse waves (left panel) and longitudinal waves (right panel) at $z = 500$ km for different β.

corresponds to the initial impulse associated with the buffeting action of the external granule. It should be noted that the vertical energy flux in transverse waves is about 15 times larger than the energy flux in longitudinal waves.

Fig. 2 depicts the time variation of the vertical energy flux in transverse (left panel) and longitudinal waves (right panel) at $z = 500$ km for various values of β. We find that, whereas the maximum value of the flux associated with the primary pulse increases gradually with β (i.e. with decreasing magnetic field strength) for transverse waves, the variation is much sharper for longitudinal waves. As β increases, the energy flux in the two modes becomes comparable (typically for $\beta \geq 2$).

4. Discussion

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. We find that 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).

For strong magnetic fields, most of the energy goes into transverse waves, and only a much smaller fraction into longitudinal waves. Observationally this model is consistent with the interpretation of network bright points in terms of transverse waves, where the power spectrum observed in H_3 by Lites *et al.* (1993) shows a high peak at 2.5 mHz (the cutoff frequency of transverse waves) and a much smaller peak at 3 mHz, perhaps a contribution made by longitudinal flux tube waves. These calculations therefore support the hypothesis that mainly transverse flux tube waves are dominantly excited and the observed velocity signal measures the cutoff period of the transverse waves in the photosphere.

For weaker magnetic fields the energy fluxes in the two modes are comparable. From the absence of a strong peak at low frequencies in the power spectrum of the cell interior (CI) we conclude that both transverse and longitudinal waves must make a negligible contribution to K_{2V} bright point oscillations. The absence of the magnetic modes then implies that the waves in the CI are probably acoustic waves, and the observed 3 minute period is therefore the acoustic cutoff period — and not the cutoff period of longitudinal flux tube waves. This implies that the magnetic field structure in the CI is likely to be different from that of flux tubes in the magnetic network.

4.1 *Chromospheric heating*

Since the energy flux in transverse waves is significantly higher for magnetic elements in the network, we examine their role in chromospheric heating. We calculate the vertical energy flux in transverse waves excited due to the footpoint motion of magnetic elements using observations of G band bright points (obtained at the Swedish Solar Observatory at La Palma during 1995). The motion of the bright points was followed using a tracking technique with "corks" as tracers of bright points (van Ballegooijen *et al.* 1998). Let us assume that the motion of the G band bright points can be taken as a proxy for the footpoint motion of flux tubes at the base ($z = 0$) of the photosphere. Then by specifying the horizontal displacement of the tube at $z = 0$, the displacement at any height and hence the vertical energy flux can be determined (for details see Hasan, Kalkofen & van Ballegooijen 2000).

Fig. 3 shows the vertical energy flux in transverse waves versus time at a height $z = 750$ km for a typical magnetic element in the network. We find that the injection of energy into the chromosphere takes place in brief and intermittent bursts, lasting typically 30 s, separated by longer periods (longer than the time scale for radiative losses in the chromosphere) with lower energy flux. The peak energy flux into the chromosphere is as high as 10^9 erg cm^{-2} s^{-1} in a single flux tube, although the time-averaged flux is $\sim 10^8$ erg cm^{-2} s^{-1}.

In summary, we find that transverse waves are more efficiently excited than longitudinal waves in the magnetic network. For magnetic field strengths of the order of

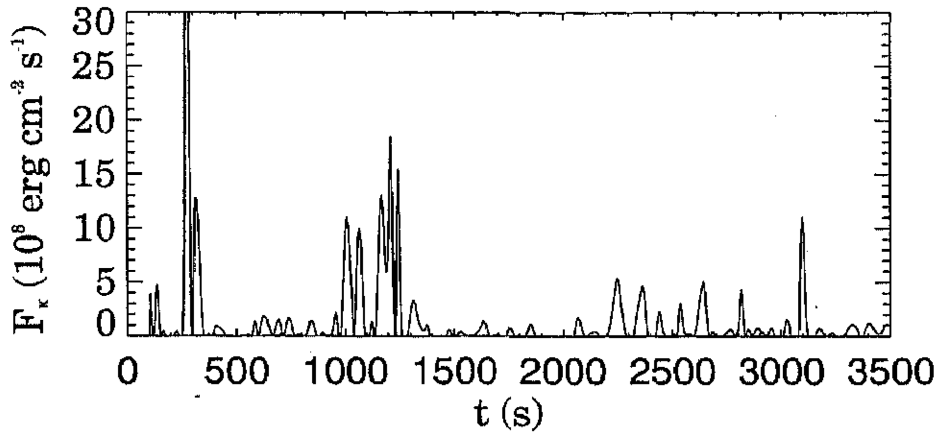

Figure 3. Time variation of the vertical energy flux in transverse waves in a single flux tube at z = 750 km due to footpoint motions taken from observations.

1500 G, the energy flux in transverse waves is an order of magnitude larger than in longitudinal waves. However, for weaker magnetic fields, the fluxes in the two modes become comparable.

The energy flux in upward propagating transverse waves has been calculated for a representative magnetic element in the network. We find that these waves supply energy to the chromosphere in short-duration sporadic bursts (lasting typically 30-60 s), separated by longer periods with low energy flux. From an observational point of view, such a scenario for heating the magnetic network would suggest a high variability in Ca II emission. A possible remedy to this difficulty would be to consider the effect of high frequency motions (Hasan, Kalkofen & van Ballegooijen 2000).

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