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Excitation of Longitudinal Modes in Solar Magnetic Flux Tubes by p-Modes

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Abstract:

This is a continuation of earlier work by Hasan (1997) on the interaction of longitudinal (sausage) waves in a slender flux tube with p-modes in the ambient medium. We use a realistic stratification for the flux tube and external atmospheres based upon the models of Hasan & Kalkofen (1994). The MHD equations for a thin flux tube are solved as an initial value problem incorporating radiative and convective energy transport. Our calculations confirm the linear prediction that the interaction is *non-resonant*. We find that the response (for a fixed order) increases with mode degree l up to a maximum and then falls off sharply as l increases. For the f-mode, $l_{\max} \approx 650$. The amplitude of the oscillations tend to become stationary implying a balance between energy input from p-modes and losses through radiative damping and leakage from boundaries. Low order p-modes with degrees of several hundred appear to be most efficient for exciting longitudinal oscillations in flux tubes. The energy flux in these oscillations appears to be insufficient for chromospheric heating, but may contribute partially to the required flux.

1. Introduction

Small-scale magnetic flux tubes in the solar atmosphere occur preferentially at the boundaries of supergranulation cells, outlined by the chromospheric Ca network, and in plage regions. They are important features of the solar atmosphere and have a significant influence on the structure and dynamics of the chromosphere and corona as well as the solar wind. Their field strength is empirically known to be in the kilogauss range and typically their diameters in the photosphere are believed to be in the range of 100–300 km (for a review see Stenflo 1989 and Solanki 1993).

In the photosphere, flux tubes are surrounded by a field-free medium which supports p-modes with periods in the 5 min. range. This paper examines the effect of these modes on flux tubes. Observationally there is evidence that magnetic regions absorb acoustic waves (e.g., Braun, Duvall, & Labonte 1987; for a review see Bogdan & Braun 1995 and references therein). Recently, the time asymptotic response of a vertical flux tube with p-modes in the ambient medium was examined for an isothermal atmosphere by Hasan (1997) and for a polytrope by Bogdan et al. (1996) using linear theory. The purpose of the present investi-

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gation is to model the above interaction as a time-dependent problem, in which the effects of radiative transfer and convection are included.

Briefly, the objective of our investigation is to firstly, analyse the response of a stratified thin flux tube when it is buffeted by p-modes from the ambient medium; secondly, to examine the conditions under which a significant transfer of energy occurs from p-modes into sausage or longitudinal mode oscillations of the flux tube; and finally, to study the buildup of energy in tube oscillations as a function of time with a view to seeing whether these oscillations last sufficiently long and carry adequate energy flux to heat the chromosphere.

2. Equations

Let us consider a magnetic flux tube extending vertically through the photosphere and convection zone of the Sun. The MHD equations in the thin flux tube approximation are (for longitudinal or sausage modes):

$$\frac{\partial}{\partial t}\left(\frac{\rho}{B}\right) + \frac{\partial}{\partial z}\left(\frac{\rho v}{B}\right) = 0, \tag{1}$$

$$\rho\left(\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial z}\right) = -\frac{\partial p}{\partial z} + \rho g, \tag{2}$$

$$p + \frac{B^2}{8\pi} = p_e + \Pi_e, \tag{3}$$

$$\frac{\partial T}{\partial t} + v\frac{\partial T}{\partial z} = -\frac{\chi_\rho}{\chi_T}(\gamma - 1)T\Delta + \frac{1}{\rho C_V}\left\{4\pi\kappa(J - S) - \frac{\partial F_c}{\partial z}\right\}, \tag{4}$$

where z is the depth (positive into the Sun), v is the vertical component of the velocity, $\Delta = (\nabla\cdot\mathbf{v})_{r=0}$, $\chi_\rho = (\partial\ln p/\partial\ln\rho)_T$, $\chi_T = (\partial\ln p/\partial\ln T)_\rho$, B is the magnitude of the magnetic field, p_e is the equilibrium external gas pressure, Π_e is the (Eulerian) perturbation in p_e, κ is the Rosseland mean opacity per unit distance, J is the mean radiation intensity on the flux tube axis, S is the source function, and F_c is the vertical component of the convective flux.

2.1. Radiative Transfer

We calculate the mean radiation intensity J by solving the radiative transfer equation in cylindrical geometry for a grey atmosphere in LTE using the combined opacity tables of Kurucz (1992, private communication) and Roger & Iglesias (1992).

2.2. Convection

The convective flux is calculated using a mixing length formalism with an additional parameter, α, that characterizes the suppression of convection by the strong magnetic field inside the tube (for details see Hasan 1988). We neglect the radial component of the convective energy flux within the tube. For simplicity we assume that α is constant.

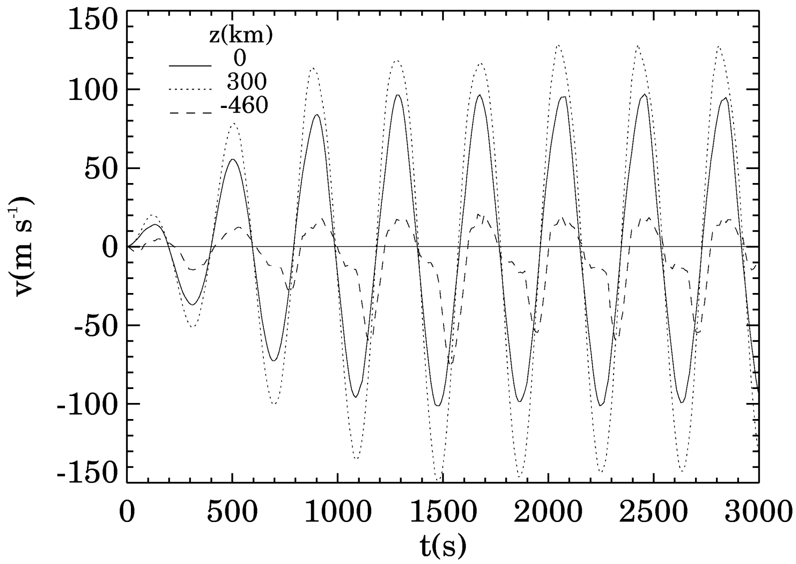

Figure 1. Variation with time of the vertical velocity v in the flux tube at different depths when the tube is buffeted by a f-mode with $k_x = 1$ Mm^{-1}, and $\omega = 0.0166$.

2.3. Form of the External Pressure Fluctuation

We assume that the flux tube is buffeted by a single p-mode from the ambient medium. We determine the mode frequency ω and the pressure perturbation Π_e for a fixed degree by solving the linear adiabatic wave equation for a plane parallel field-free atmosphere.

2.4. Initial State of the Flux Tube

At the initial instant $t = 0$, we assume that the tube is in hydrostatic and energy equilibrium. The model atmospheres in the tube and in the ambient medium are constructed using the technique of Hasan & Kalkofen (1994) for $\beta_0 = 0.5$ ($\beta = 8\pi p/B^2$) and tube radius of 100 km at $z = 0$.

2.5. Method of Solution and Boundary Conditions

We solve equations (1)–(4) numerically using a combined explicit and implicit scheme.

The calculation proceeds in two phases: in the first phase, we use a modified version of FCT (flux corrected transport algorithm), which is an explicit finite difference scheme, to advance all variables in time without the heating terms arising from radiative and convective energy transport. The latter are incorporated in the second phase of the calculation using an implicit scheme.

We consider a finite vertical extension of the flux tube, with upper and lower boundaries at $z = -500$ km and $z = 5000$ km. Flow through boundary conditions are used allowing the outflow of matter at both boundaries. No inflow of matter is, however, permitted. The boundary conditions are implemented using the method of characteristics.

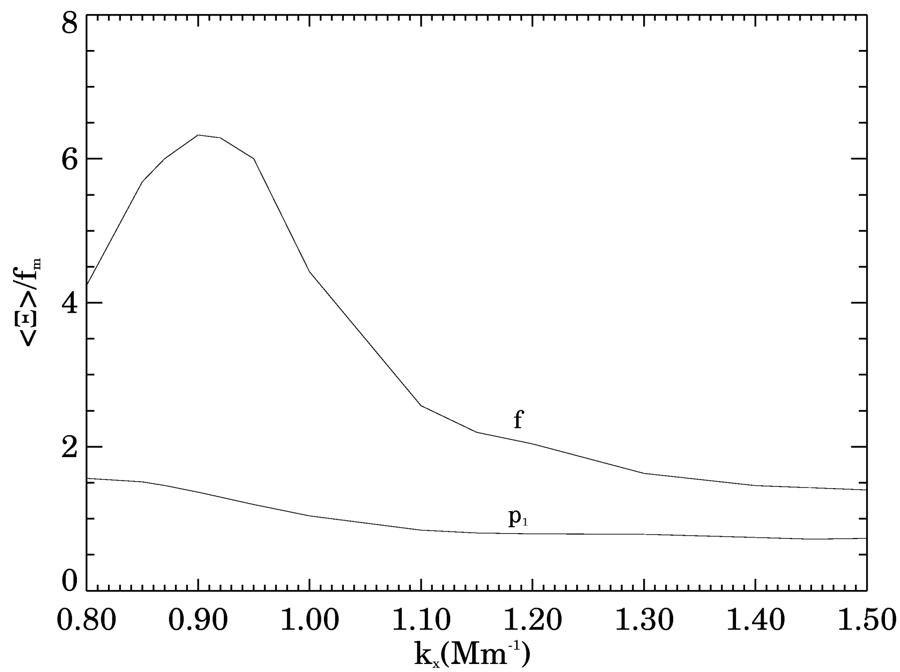

Figure 2. Variation of the time-averaged flux tube response $\langle \Xi \rangle / f_{\rm m}$ with horizontal wave number k_x of the incident p-mode.

The calculations were carried out for $\beta_0 = 0.5$ on a uniform grid with a step size of 10 km and a Courant number of 0.4 during the explicit phase of the calculation. The solution of the radiative transfer equation was carried out in the 1-angle approximation, in the interest of computational economy. A typical run with 35,000 time iterations took aound 90 min CPU on a Cray C90.

3. Results

In order to examine the efficiency of the p-mode interaction with a flux tube, let us define the response Ξ (following Hasan 1997) as follows:

$$\Xi = \frac{\int \ {\rm dz}\ (E\,A)}{\int \ {\rm dz}\ (\langle E_e\ rangle\, A_e)}, \tag{5}$$

where E is the energy density in the flux tube oscillations, $\langle E_e \rangle$ is the time-averaged energy density associated with the p-modes, A denotes the cross-section area of the tube and A_e denotes the (constant) area in the horizontal plane in the external medium.

Figure 1 shows the variation with time of the vertical velocity v in the flux tube at different depths when the tube is buffeted by a f-mode with $k_x = 1$ Mm^{-1}, and $\omega = 0.0166$ (corresponding to a period of 380 s), assuming that the amplitude of the pressure perturbation $\Pi_e/p_e = 3.2 \times\ 10^{-2}$ at $z = 0$. We find that the velocity shows an oscillatory behavior with a period of the incident p-mode. The boundary condition allows the flow to propagate through the upper boundary.

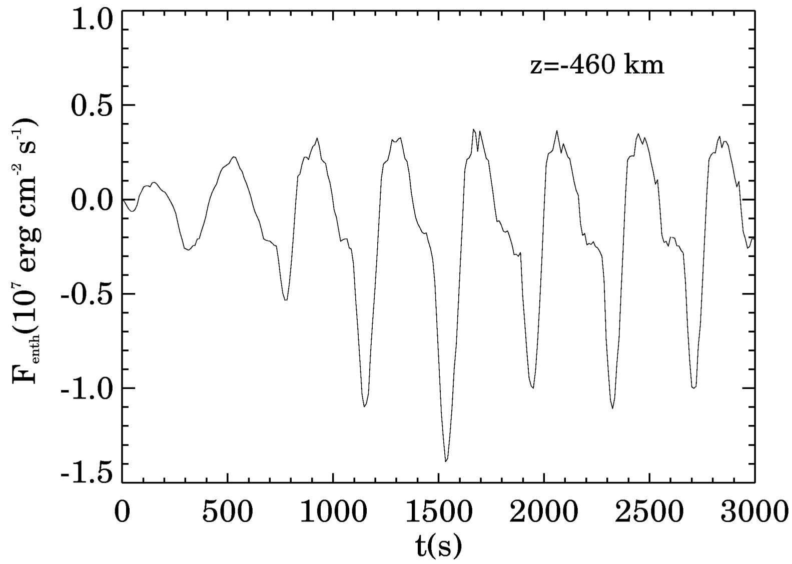

Figure 3. Variation with time of the vertical component of the enthalpy flux $F_{\rm enth}$ in the flux tube at $z = -460$ km for an incident f-mode with $k_x = 1$ Mm^{-1}.

Figure 2 shows the variation of the time-averaged flux tube response $\langle \Xi \rangle / f_{\rm m}$ with horizontal wave number k_x for the f- and p_1 modes, where $f_{\rm m} = A_0/A_e$ denotes the magnetic filling factor and A_0 is the flux tube cross-section area at $z = 0$. For the f-mode, the response increases with k_x to a maximum and thereafter it falls off sharply. For small k_x ($l \approx 650$) the response of the f-mode is much larger than for the p_1 mode.

Figure 3 shows the variation with time of the vertical component of the enthalpy flux $F_{\rm enth}$ in the flux tube at $z = -460$ km, which is close to the upper boundary of the computational domain, for an incident f-mode with $k_x = 1$ Mm^{-1}. During the upflow phase of the oscillation ($F_{\rm enth} < 0$) energy can be fed into the chromosphere.

4. Discussion and Summary

We have found that the buffeting action of a p-mode on a flux tube leads to a buildup of energy in flux tube oscillations on a time-scale typically of some 1000 s. These oscillations approach a constant amplitude, implying a balance between the input energy from p-modes and various energy losses through the boundary and through radiative damping. For a p-mode of fixed degree, the response is maximum for the f-mode. The f-mode response increases with mode degree upto a maximum at $l \approx$ 650 and thereafter it drops rapidly. For the higher order modes, the response decreases monotonically with l (for $l > 650$). We also find that the time-averaged enthalpy flux in the longitudinal oscillations is somewhat low compared to the requirement for chromospheric heating ($\sim 10^7$ erg cm^{-2} s^{-1}).

5. Conclusions

The main conclusions to emerge from our investigation are:

- The interaction of a flux tube with external p-modes does not exhibit a resonant behavior, confirming the linear results found by (Bogdan et al. 1996) and Hasan (1997) for polytropic and isothermal atmospheres respectively;
- Buffeting by p-modes leads to an accumulation of energy in flux tube oscillations — these oscillations persist for large time even in the presence of dissipative processes;
- The most efficient coupling of external p-modes with longitudinal flux tube oscillations occurs for f-modes with degrees around 650 — the higher order modes evoke a much weaker response;
- Longitudinal oscillations driven by external p-modes are probably inadequate for chromospheric heating, but may contribute partially to it.

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