DYNAMICAL EFFECTS IN SOLAR PHOTOSPHERIC FLUX TUBES

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Abstract.
The interaction of an intense flux tube, extending vertically through the photosphere, with p-modes in the ambient medium is modelled by solving the time dependent MHD equations in the thin flux tube approximation. It is found that a resonant interaction can occur, which leads to the excitation of flux tube oscillations with large amplitudes. The resonance is not as sharp as in the case of an unstratified atmosphere, but is broadened by a factor proportional to H^{-2}, where H is the local pressure scale height. In addition, the inclusion of radiative transport leads to a decrease in the amplitude of the oscillations, but does not qualitatively change the nature of the interaction.

Key words: SUN: atmosphere – SUN: magnetic fields – MHD

1. Introduction

This paper examines the effect of vertical magnetic flux tubes, in the solar photosphere, being buffeted by external p-modes. Similar problems have been investigated extensively within the framework of linear theory (e.g., Ryutov & Ryutova, 1976; Bogdan, 1989; Bogdan & Cattaneo, 1989; Bogdan & Fox, 1991 ; Ryutova & Priest, 1993; Cally, Bogdan & Zweibel, 1994).

These studies have demonstrated that the above interaction exhibits resonances, which occur when the impinging acoustic waves have a vertical phase speed that matches with that of the internal wave modes of the tube. This results in energy being extracted from the incident waves and being pumped into flux tube oscillations. The accumulation of energy into tube oscillations will not continue indefinitely, but will be eventually limited by nonlinear processes and also by damping mechanisms. The purpose of the present investigation is to examine the nonlinear response of a flux tube to external pressure perturbations using a model which realistically simulates conditions on the Sun.

A previous investigation into this problem was undertaken by Venkatakrishnan (1986). The present analysis is different in the following respects: firstly, model atmospheres are constructed for the tube and the external medium by solving the equilibrium equations, allowing for radiative and convective energy transport; secondly, radiative effects are taken into account by solving the multistream radiative transfer equation in cylindrical geometry; and thirdly, the form of the driving pressure perturbation is not specified

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ad hoc, but is determined by calculating the p-modes in the external atmosphere.

2. Model and Mathematical Technique

Let us consider a flux tube with circular cross-section extending vertically through the photosphere and convection zone. We shall let the tube be acted upon by pressure fluctuations in the external atmosphere and examine the effects of these on the tube. The form of the external pressure fluctuation is determined using linear theory. Furthermore, to keep the analysis tractable, the equations are solved within the framework of the thin flux tube approximation. In cylindrical geometry the relevant equations to leading order (in the above approximation) are the same as those given by Hasan (1985) and Hasan (1991).

2.1. Form of the external pressure fluctuation

We determine the form of the external pressure pertubation, by choosing one of the normal p-modes in the ambient medium. These are calculated by solving the linear wave equation for a plane parallel atmosphere, without a magnetic field. The applicability of this analysis is restricted to modes confined to a cavity with a vertical extension comparable to the depth of the flux tube and to p-modes with degree $l > 600$.

2.2. Initial state of the flux tube

We assume that the flux tube at the initial instant t=0 is in hydrostatic and energy equilibrium. The model atmosphere in the tube was constructed using the method of Hasan & Kalkofen (1994) and is parameterized by β_0 and R_0 (where the subscript refers to the level z=0). In the present calculations, we choose β_0=1 and R_0=100 km.

Let us now consider the effect on the tube of an external pressure perturbation, which is chosen to simulate a single p-mode, whose spatial dependence is detemined self-consistently from its eigenfunction. We assume a time dependence of the form $\sin(\omega t)$, where ω is the frequency of the mode. We take the amplitude of the pressure perturbation at z=0 to be $6 \times 10^{-4} p_0$, where p_0 is the pressure at z=0.

2.3. Method of solution and Boundary Conditions

The equations were solved numerically using a modified version of the flux corrected transport algorithm. A finite vertical extension of the tube with upper and lower boundaries at 500 km and 4000 km above and below the

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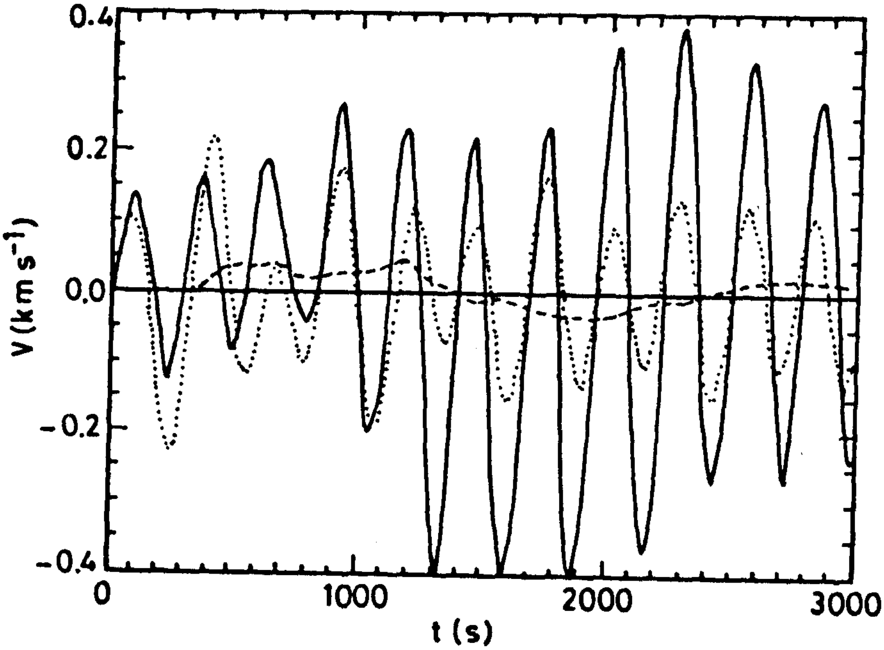

Fig. 1. Variation with time t of the vertical velocity v on the tube axis at z=0. Solid and dashed lines correspond, for the adiabatic case, to external forcing by the p_1 mode with period 268 s and by the p_2 mode with period 210 s respectively. The dotted line depicts the non-adiabatic case with external forcing due to the p_1 mode.

photosphere respectively was considered. Outflow boundary conditions were used at both boundaries, but no inflow was permitted. The method of characteristics was used to implement the boundary conditions.

3. Results and Discussion

Figure 1 shows the time variation of the vertical velocity v (positive values denoting downflow) on the flux tube axis at z=0 in the adiabatic case (i.e., when radiative and convective energy transport are neglected) due to forcing by the lowest order (p_1) mode with period 268 s (solid line) and the next order mode (p_2) with period 210 s (dashed line). The horizontal wave number of these modes is 2 Mm^{-1}. It is obvious that the response of the flux tube is very different to the two forcing frequencies. For the p_1 mode, the flux tube responds with an oscillatory flow with increasing amplitude, whereas for the p_2 mode there is a marginal flow with a very small amplitude. Clearly, the main difference between the two cases is related to the fact that the interaction of the p_1 mode is resonant compared to the other mode.

We now consider differences in the results between the adiabatic and non-adiabatic cases. In the photospheric layers, energy transport is dominated

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by radiative effects, whereas in the deeper regions convective transport is more important. The dotted line shows the velocity variation with time for the non-adiabatic case when the tube is buffeted by the p_1 mode. In this case too, we find that there is a resonant response, though the amplitude does not exhibit such large amplitudes as the previous case. However, the qualitative nature of the interaction is similar in both cases.

The calculations show that oscillations can be excited in a flux tube due to the resonant interaction with external p-modes. We have also seen that a resonance does not occur for all modes. The question then naturally arises is: Under what conditions does the resonance take place? Earlier work for an unstratified atmosphere showed that a resonance occurs when $\omega/\kappa = c_T$, where κ is the vertical wave number for an acoustic wave in the external medium and c_T is the tube speed in the flux tube. If K_z denotes the vertical wave number in the tube, then the above condition translates to $K_z = \kappa$. For a stratified tube, a WKB analysis shows the resonance is not as sharp as it is for an unstratified one. The resonance is broadened by a factor proportional to H^{-2} where H is the scale height of the atmosphere.

In the analysis, we have tacitly considered only a single mode. Actually, the observed 5-min oscillations consist of a superposition of a large number of modes. Since we do not know the phases of the different modes, it is not possible to model the interaction with a wave packet accurately. However, since the resonance at a particular frequency is sufficiently sharp with respect to the horizontal wave number, one expects that in a pressure fluctuation, the dominant contribution will come from the component for which the resonance condition is satisfied.

Finally, as to the question whether sufficient energy can be built up by this process for heating the solar atmosphere, preliminary results seem to indicate that the energy flux in the oscillations is still too low to have an appreciable effect on chromospheric heating. However, more exhaustive calculations are needed to confirm this.

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