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EXCITATION OF OSCILLATIONS IN THE MAGNETIC NETWORK ON THE SUN

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ABSTRACT

We examine the excitation of oscillations in the magnetic network of the Sun through the footpoint motion of photospheric magnetic flux tubes located in intergranular lanes. The motion is derived from a time series of high-resolution *G*-band and continuum filtergrams using an object-tracking technique. We model the response of the flux tube to the footpoint motion in terms of the Klein-Gordon equation, which is solved analytically as an initial value problem for transverse (kink) waves. We compute the wave energy flux in upward-propagating transverse waves. In general we find that the injection of energy into the chromosphere occurs in short-duration pulses, which would lead to a time variability in chromospheric emission that is incompatible with observations. Therefore, we consider the effects of turbulent convective flows on flux tubes in intergranular lanes. The turbulent flows are simulated by adding high-frequency motions (periods 5–50 s) with an amplitude of 1 km s^{-1}. The latter are simulated by adding random velocity fluctuations to the observationally determined velocities. In this case, we find that the energy flux is much less intermittent and can in principle carry adequate energy for chromospheric heating.

Subject headings: MHD — Sun: magnetic fields — Sun: oscillations

1. INTRODUCTION

It is now well established that the solar photosphere is threaded with strong (kilogauss) magnetic fields in the form of vertical flux tubes located in the network, where they are observed as bright points. Observations have revealed that these network bright points are in a highly dynamical state due to the buffeting action of granules (e.g., Muller 1983; Muller et al. 1994; Berger & Title 1996; Berger et al. 1998; van Ballegooijen et al. 1998).

The jostling of magnetic elements by granules can excite oscillations in flux tubes, which can in principle be an important mechanism for chromospheric and coronal heating, provided that the motions are rapid enough (Choudhuri, Auffret, & Priest 1993; Steiner et al. 1998; Hasan & Kalkofen 1999, hereafter Paper I). As transverse waves excited in the photosphere travel upwards, their velocity amplitude increases. In chromospheric layers, the velocity amplitude becomes comparable to the tube speed for kink waves, leading to an efficient coupling with longitudinal waves (Kalkofen 1997). The latter can dissipate by forming shocks (e.g., Zhugzhda, Bromm, & Ulmschneider 1995).

In Paper I it was argued that network oscillations can be efficiently excited through the buffeting action on flux tubes by external granules with intermittent motions (of about 2 km s^{-1}) occurring on a timescale of less than about half the cutoff period of kink waves. Typically, a period of 1 minute is consistent with the general result. We assumed an analytic form for the external motions. In the present work, we use observational data obtained at the Swedish Solar Observatory at La Palma during 1995 (Berger et al. 1998) to infer the horizontal footpoint motions of magnetic elements in the photosphere. We model the response of flux tubes to these motions and calculate the energy flux in upward-propagating transverse (kink) waves. We also simulate the effect of hypothetical motions on timescales of a few seconds, which could significantly enhance the energy flux in kink waves. Finally, we examine some implications of our results.

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2. MEASUREMENT OF BRIGHT-POINT MOTION

The data were collected on 1995 October 5 between 10:57 and 12:08 UT, simultaneously in the *G* band (4305 Å) and the nearby continuum (4686 Å), using the phase-diversity method (see Löfdahl et al. 1998; Berger et al. 1998). After filtering out *p*-mode oscillations, a time series of 180 images was obtained, with high spatial resolution and with an interval between frames of 23.5 s. Following Berger et al. (1998), we subtract the images in the *G* band and 4686 Å, which clearly highlights the network bright points.

The motion of the bright points was followed using a tracking technique with "corks" as tracers of bright points (van Ballegooijen et al. 1998). The corks, each with a radius of 60 km (the pixel size of the current data set), were advected by an artificial flow field that is proportional to the gradient of the intensity in the magnetic image, and their positions were followed in time (for details, see van Ballegooijen et al. 1998). In Figure 1 we show the cork positions superposed on a typical frame of a magnetic difference image, where *x* and *y* denote the horizontal coordinates on the Sun. Figure 2 shows the *x*- and *y*-components of the velocity as a function of time for two representative corks, whose initial locations are indicated by arrows in Figure 1.

3. KINK WAVE EXCITATION DUE TO FOOTPOINT MOTION

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 of the photosphere ($z = 0$). Furthermore, for simplicity, we assume that flux tubes are isothermal and "thin" compared to the pressure scale height *H*. It is convenient to work in terms of the "reduced" transverse displacement $Q_\perp(z, t) = \xi_\perp e^{-z/4H}$, where $\xi_\perp$ is the Lagrangian displacement. Once the footpoint motion is specified, the velocity ($\dot{Q}_\perp$) at any height *z* and time *t* can be determined by the following ex-

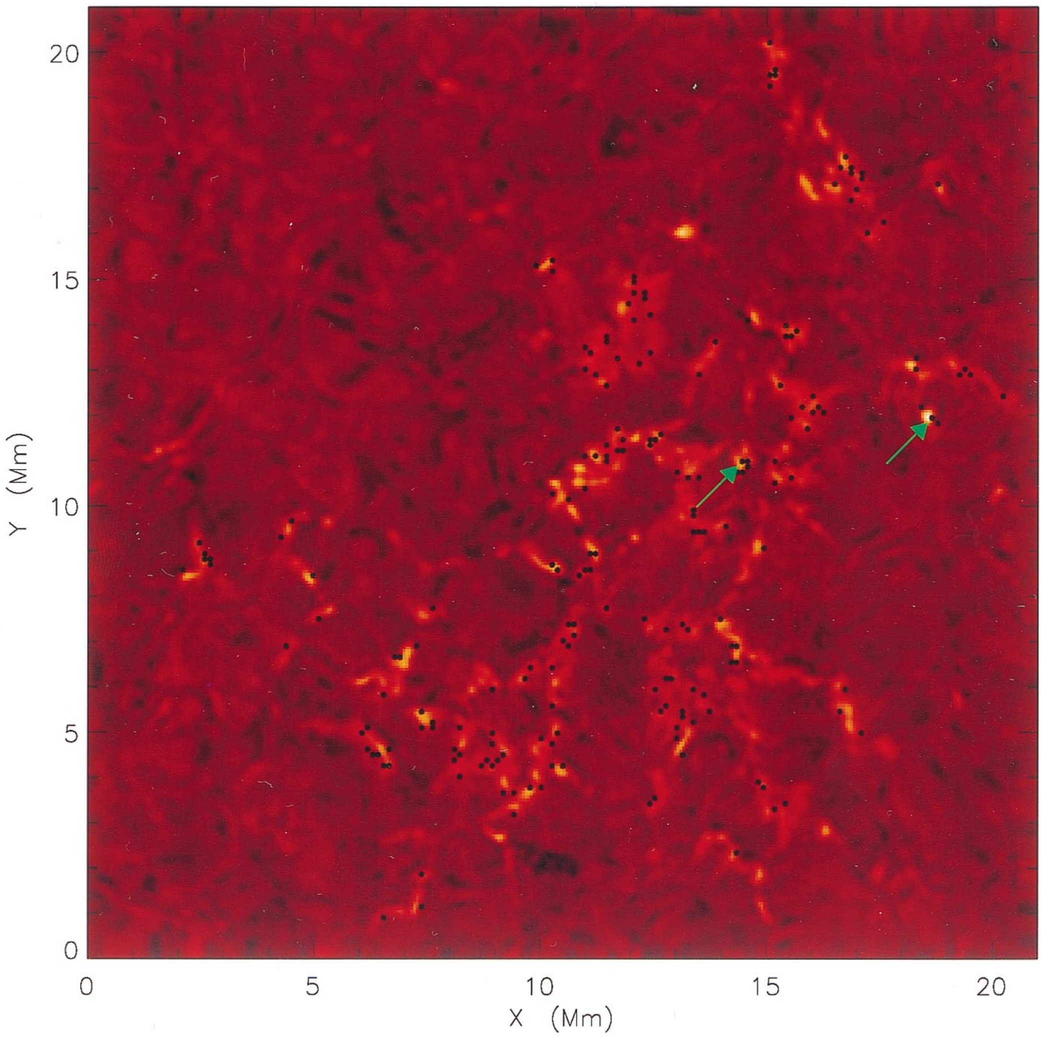

FIG. 1.—Difference between *G*-band and continuum images in the initial frame. The black dots depict the corks, used for tracking the bright points. The arrows denote the locations of two representative corks.

pression (Paper I):

$$\dot{Q}_\perp(z, t) = \dot{Q}_\perp(0, t - z/c_\kappa) - k_\kappa z \int_0^{t-z/c_\kappa} \dot{Q}_\perp(0, t_0) \frac{J_1(\omega_\kappa \zeta_\kappa)}{\zeta_\kappa} dt_0, \quad (1)$$

where J_1 is a Bessel function, $\zeta_\kappa = [(t - t_0)^2 - (z/c_\kappa)^2]^{1/2}$, c_κ and ω_κ are, respectively, the propagation speed and cutoff frequency for kink waves, given by

$$c_\kappa^2 = \frac{2}{\gamma} \frac{c_s^2}{1 + 2\beta} \quad \text{and} \quad \omega_\kappa^2 = \frac{g}{8H} \frac{1}{1 + 2\beta},$$

c_s is the sound speed, $k_\kappa = \omega_\kappa / c_\kappa$, $\gamma = 5/3$, $\beta = 8\pi p/B^2$, $p(z)$ is the gas pressure inside the tube, and $B(z)$ is the magnitude of the vertical component of the magnetic field on the tube axis. The energy flux (F_κ) in a single flux tube is given by (Paper I)

$$F_\kappa = -\frac{2p_{e,0}}{\beta + 1} \dot{Q}_\perp \left(\frac{\partial Q_\perp}{\partial z} + \frac{1}{4H} Q_\perp \right) e^{-z/2H}, \quad (2)$$

where $p_{e,0}$ denotes the external gas pressure at $z = 0$.

Figure 3 shows the vertical energy flux in transverse waves versus time at a height $z = 750$ km for two observed magnetic elements located initially at the coordinates shown above the figure. The left and right panels correspond to footpoint motions with the *x*- and *y*-components of the velocity, respectively.

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 timescale for radiative losses in the chromosphere) with lower energy flux. The peak energy flux into the chromosphere is as high as $\sim 10^9$ ergs cm^{-2} s^{-1} in a single flux tube, although the time-averaged flux is $\sim 10^8$ ergs cm^{-2} s^{-1}. This scenario for heating the magnetic network would produce strongly intermittent chromospheric emission consisting of brief intense flashes superposed on generally a very low background. However, in dense network regions the observed chromospheric emission is stably present and exhibits relatively low-amplitude, long-period variations (e.g., Damé, Gouttebroze, & Malherbe 1984; von Uexküll et al. 1989; Lites, Rutten, & Kalkofen 1993). Therefore, the above scenario cannot readily explain the observed persistence of emission from dense network regions. A possible remedy is to consider the effect of high-frequency motions.

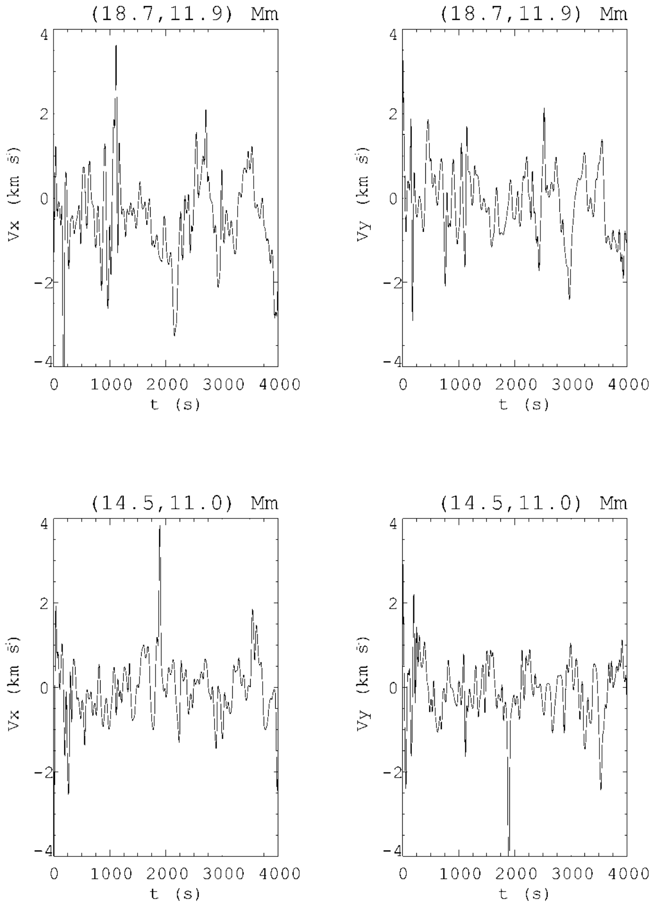

FIG. 2.—Variation with time of the *x*- and *y*-components of the horizontal velocity of *G*-band bright points. The coordinates (in Mm) of the corks at the initial instant (shown in Fig. 1) are given above each panel.

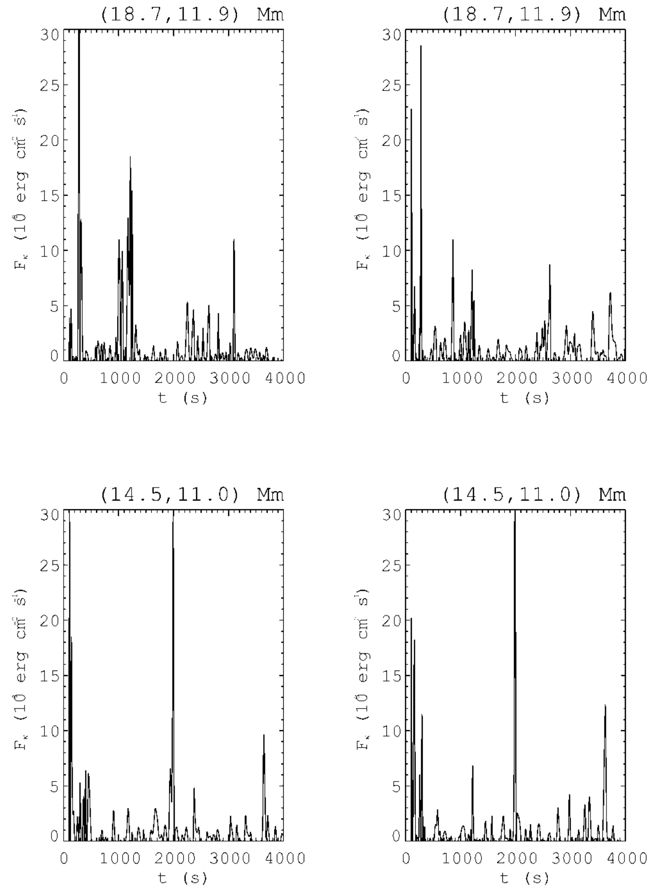

FIG. 3.—Variation with time of the vertical energy flux in transverse waves at $z = 750$ km due to footpoint motions corresponding to initial locations (18.7, 11.9) Mm (*top*) and (14.5, 11.0) Mm (*bottom*). The left and right panels correspond to motions associated with the *x*- and *y*-components of the velocity, respectively.

4. SIMULATING HIGH-FREQUENCY MOTIONS

The observations of *G*-band bright points were taken with a time cadence of 23.5 s. However, the possibility of random footpoint motions occurring on a shorter timescale cannot be ruled out. The solar convection has very high Reynolds number and is expected to be highly turbulent, involving a wide range of length and timescales. Indeed, spectroscopic observations of the solar granulation have shown enhanced broadening of spectral lines in intergranular lanes, indicating enhanced turbulence within these regions (e.g., Nesis et al. 1993, 1996). Magnetic flux tubes interact with these turbulent flows within the lanes. We speculate that these interactions produce transverse displacements of magnetic field lines on length scales much less than the flux tube diameter (~100 km), i.e., the magnetic field inside a flux tube has fine structure on transverse scales $l \ll 100$ km. These perturbations are likely to generate Alfvén waves which propagate upward along the field lines and dissipate their energy higher up in the chromosphere.

The velocity at small spatial scales can be estimated as follows. Assuming the turbulence has a Kolmogorov spectrum, the velocity of eddies on a length scale l is given by $v(l) \sim v_0(l/l_0)^{1/3}$, where l_0 is the outer scale of the turbulence and v_0 is the velocity of the largest eddies. We assume that l_0 is given by the width of an intergranular lane as determined from three-dimensional simulations of the solar granulation (e.g., Stein & Nordlund 1998) and that v_0 is the convective velocity predicted by such simulations: $l_0 \sim 100$ km and $v_0 \sim 2.5$ km s^{-1}. This turbulence model predicts that $v \sim 1$ km s^{-1} on a length scale $l \sim 10$ km, i.e., there is significant power in motions at this scale. The timescale of such motions is $l/v \sim 10$ s, which is significantly shorter than the timescale for granular buffeting.

In the following, we simulate the effect of such high-frequency motions on the response of the flux tube (similar to the study of longitudinal wave excitation in flux tubes by Ulmschneider & Musielak 1998). For simplicity, we ignore the small transverse scale of the motions and we describe the "turbulence" in terms of footpoint displacements of the flux tube. We do this by superposing random motions, with an rms amplitude of 1 km s^{-1} and a zero mean value, on the observationally determined velocity. The random motions vary on a timescale of 2.35 s. Such high-frequency motions (if present) would not have been detected in the present observations. Hence, it is not possible a priori to rule them out. Results from such simulations are shown in Figure 4 for the *x*-component of the velocity as a function of time for two representative corks whose initial locations are indicated above each panel and in Figure 5 for the corresponding vertical energy wave flux. We note that the energy flux in upward-propagating transverse waves is much larger and less intermittent than in the case without high-frequency footpoint motions.

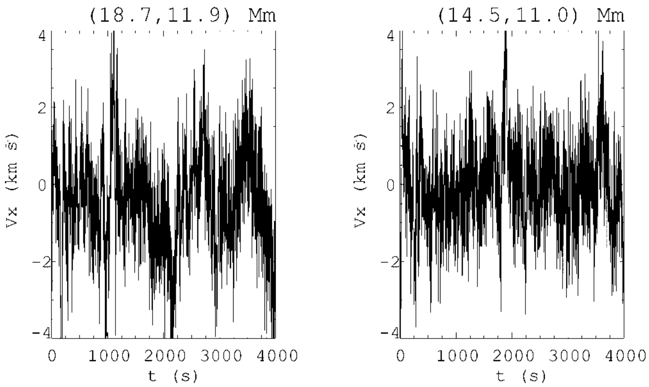

FIG. 4.—Variation with time of the horizontal velocity of *G*-band bright points with random noise added for footpoint motions associated with corks initially at (18.7, 11.9) Mm (*left*) and (14.5, 11.0) Mm (*right*).

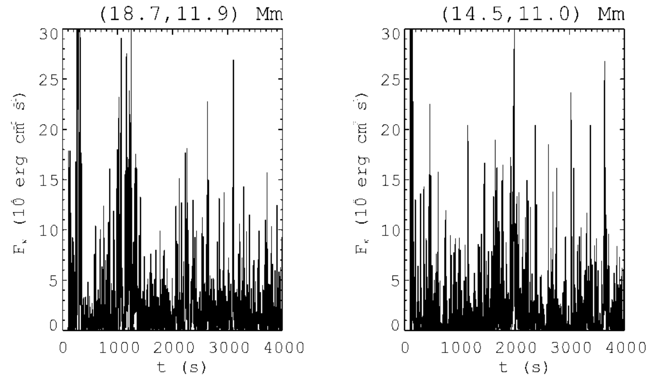

FIG. 5.—Variation with time of the vertical energy flux in transverse waves at $z = 750$ km due to footpoint motions with random noise associated with corks initially at (18.7, 11.9) Mm (*left*) and (14.5, 11.0) Mm (*right*).

The energy flux in the form of high-frequency transverse waves appears adequate to continuously heat the chromosphere. Taking a filling factor of 10% at a height $z = 750$ km above the photosphere, the predicted flux is approximately 2×10^7 ergs cm^{-2} s^{-1}, which is sufficient to balance the observed radiative loss of the chromospheric network ($\sim 10^7$ ergs cm^{-2} s^{-1}; see model F′ in Avrett 1985).

5. DISCUSSION

The energy flux in upward-propagating transverse waves has been shown for a few representative magnetic elements. We should point out that we carried out similar calculations for several corks before selecting two as being typical of the large sample that we examined.

We find that the injection of energy into the chromosphere occurs in brief and intermittent bursts (lasting typically 30–60 s), separated by longer periods (longer than the typical timescale for radiative loss) with low-energy flux. The peak energy flux into the chromosphere is typically 10^9 ergs cm^{-2} s^{-1} in a single flux tube. Observationally, such a scenario for heating of the magnetic network on a 1″ scale would lead to high variability in Ca II K emission, contrary to observations. However, the observations of *G*-band bright points used here do not have the time resolution and sensitivity necessary to detect motions on shorter timescales. We simulate such high-frequency motions by adding random velocity fluctuations with a zero mean value and an rms amplitude of 1 km s^{-1}. We conclude that for transverse waves to provide a viable mechanism for *sustained* chromospheric heating, the main contribution to the heating must come from high-frequency motions (periods 5–50 s).

The proposed high-frequency motions have a very small spatial scale (10–100 km), and the transverse displacements involved are also very small (for example, a motion with a period 50 s and velocity amplitude of 1 km s^{-1} has a displacement amplitude of only 8 km). Such length scales are well below the angular resolution of present-day solar telescopes. Therefore, it is unlikely that such high-frequency motions will ever be detected in studies of the proper motions of photospheric flux tubes. Spectroscopic methods, such as measurements of spectral line broadening by unresolved turbulent flows, offer greater promise but will still require very high angular resolution.

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