HEXICAL MOTION OF MAGNETIC FLUX TUBES IN THE SOLAR ATMOSPHERE

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ABSTRACT

Photospheric granulation may excite transverse kink pulses in anchored vertical magnetic flux tubes. The pulses propagate upward along the tubes with the kink speed, while oscillating waves are formed behind the wave front in a stratified atmosphere. The wakes oscillate at the kink cutoff frequency of stratified medium and gradually decay in time. When two or more consecutive kink pulses with different polarizations propagate in the same thin tube, then the wakes corresponding to different pulses may be superimposed. The superposition sets up helical motions of magnetic flux tubes in the photosphere/chromosphere as seen in recent Hinode movies. The energy carried by the pulses is enough to heat the solar chromosphere/corona and accelerate the solar wind.

Subject headings: Sun: oscillations — Sun: photosphere

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1. INTRODUCTION

Recent high-resolution movies obtained by the Hinode spacecraft clearly show continuous helical motions of spicule axes (De Pontieu et al. 2007). This phenomenon has been known for a long time (Beckers 1972), but no satisfactory explanation has been given yet. De Pontieu et al. (2007) suggested that these motions are caused by Alfven waves excited in the photosphere by granular motions or acoustic oscillations. Photospheric magnetic field is concentrated in thin flux tubes and therefore may support the propagation of kink and torsional Alfven waves (the tubes also support the propagation of sausage waves, but here we consider only transverse waves). The kink wave is a tube wave, i.e., the whole tube oscillates with one frequency even if the Alfven speed changes across the tube, while the frequency of torsional waves is different at different surfaces (Van Doorsselaere et al. 2008). Therefore, the excitation of torsional waves in photospheric magnetic tubes is complicated. The oscillations of spicule axis have also been explained in terms of kink waves (Kukhianidze et al. 2006; Zaqarashvili et al. 2007), but the chromospheric magnetic field has a rather expanded structure. Therefore, De Pontieu et al. (2007) suggested through Monte Carlo simulation that spicules are not wave guides for kink waves. The problem is currently under debate and more observations are needed to understand the real process.

On the other hand, granular buffeting on an anchored magnetic tube may easily excite a transverse kink pulse. The pulse propagates through the stratified photosphere with the kink speed, but the oscillating wake is formed behind the wave front. The wake oscillates at the cutoff frequency of kink waves and decays as time progresses (Roberts 1981; Rae & Roberts 1982; Spruit & Roberts 1983; Hasan & Kalkofen 1999; Muiselak & Ulmschneider 2001). However, the magnetic tube undergoes continuous buffeting of granular cells from different sides. Therefore, another pulse polarized in a different plane may quickly follow. The second pulse again propagates with the kink speed and forms another wake oscillating with the same cutoff frequency. Therefore, the superposition of the two oscillations may set up the helical motion of the tube axis in the photosphere. The helical motion will have the photospheric kink cutoff period ~7–8 minutes.

However, when the pulse penetrates into the chromosphere, then two possible scenarios can occur. If the chromospheric magnetic field has a tube structure, then the pulse continues to propagate as the kink one. But if the magnetic field is not concentrated in tubes, then it will be transformed into the Alfvenic pulse. Yet the pulse will have the same main properties in both cases: it will propagate at either the kink or Alfven speed and the wake oscillating at the chromospheric cutoff frequency will be formed behind the pulse. The superposition of the wakes corresponding to different pulses may set up helical motions of magnetic field lines just as in the photospheric case. These helical motions may be responsible for the oscillations of spicule axes as seen in Hinode movies.

Here we study the phenomenon using the Klein-Gordon equation for wave propagation in the stratified atmosphere.

2. HELICAL KINK WAVES IN THE PHOTOSPHERE

Kink wave propagation along vertical thin magnetic flux tubes embedded in the stratified field-free atmosphere is governed by the Klein-Gordon equation (Rae & Roberts 1982; Spruit & Roberts 1983; Roberts 2004)

\[
\frac{\partial^2 Q}{\partial z^2} - \frac{1}{c_s^2} \frac{\partial^2 Q}{\partial t^2} - \frac{\Omega^2}{c_s^2} Q = 0, \tag{1}
\]

where \( Q = \xi(z, t) \exp(-z/4\Lambda), \) \( c_s = B_0/[4\pi(\rho_o + \rho)]^{1/2} \) is the kink speed, \( \Lambda \) is the density scale height, and \( \Omega = c_s/4\Lambda \) is the gravitational cutoff frequency for isothermal atmosphere (temperature inside and outside the tube is assumed to be the same and homogeneous). Here \( \xi(z, t) \) is the transversal displacement of the tube, \( B_0(z) \) is the tube magnetic field, and \( \rho_0(z) \) and \( \rho(z) \) are the plasma densities inside and outside the tube, respectively (the magnetic field and densities are functions of \( z \), while the kink speed \( c_s \) is constant in the isothermal atmosphere).

Equation (1) yields simple harmonic solutions \( \exp[i(\omega t \pm k_z z)] \) with the dispersion relation

\[
\omega^2 - \Omega_c^2 = c_s^2 k_z^2, \tag{2}
\]

where \( \omega \) is the wave frequency and \( k_z \) is the wavenumber. The dispersion relation shows that the waves with higher frequency
tubes. Here we plot the tube transverse displacement \( y \) with circular polarization if \( \omega \). As a result, the tube kink waves with the same frequency but polarized in elliptical polarization. Consider, for example, two harmonic waves with the same amplitudes lead to the circular polarization of two-plane electromagnetic waves, where the complex motion of the tube. The process is similar to the superposition of two or more wave is polarized arbitrarily and the polarization plane depends on the excitation source. Then the superposition of two or more kink waves polarized in different planes may give rise to the complex motion of the tube. The process is similar to the superposition of kink waves polarized in different planes may give rise to the elliptical polarization. Consider, for example, two harmonic kink waves with the same frequency but polarized in \( x-z \) and \( y-z \) planes: \( A_x = A_{x0} \cos(\omega t + k_x z) \) and \( A_y = A_{y0} \sin(\omega t + k_y z) \). The superposition of these waves sets up the helical wave with circular polarization if \( A_{x0} = A_{y0} \). As a result, the tube axis rotates around the vertical, while the displacement remains constant (Fig. 1). If \( A_{x0} \neq A_{y0} \) then the resulting wave is elliptically polarized. The superposition of a few harmonics with different frequencies and polarizations may lead to more complex motion of the tube axis.

However, simple harmonic kink waves are hardly excited in the photosphere. The more realistic process is the impulsive buffeting of granules on an anchored magnetic flux tube. For the sake of simplicity, we consider the simplest impulsive forcing in both time and coordinates. Then equation (1) appears as

\[
\frac{\partial^2 Q}{\partial z^2} - \frac{1}{c^2_p} \frac{\partial^2 Q}{\partial t^2} = \frac{\Omega^2}{c^2_k} Q = -A_{x0} \delta(t) \delta(z), \tag{3}
\]

where \( z > -\infty, \ t > 0, \ A_{x0} \) is constant, and the pulse is set at \( t = 0, \ z = 0 \).

The solution of this equation is the Green’s function for the Klein-Gordon equation, which can be written as (Lamb 1909, 1932; Duffy 2001)

\[
Q = \frac{c_p A_{x0}}{2} J_0 \left[ \Omega_x \sqrt{1 - z^2/c^2_k} \right] H \left[ \Omega_p \left( t - \frac{z}{c_p} \right) \right], \tag{4}
\]

where \( J_0 \) and \( H \) are Bessel and Heaviside functions, respectively. Equation (4) shows that the wave front propagates with the kink speed \( c_p \), while the wake oscillating at the cutoff frequency \( \Omega_p \) is formed behind the wave front and decays as time progresses (Rae & Roberts 1982; Spruit & Roberts 1983; Hasan & Kalkofen 1999; Roberts 2004). Figure 2 shows the plot of transverse displacement \( Q(z, t) = Q(z, t) \exp(\gamma z/B) \), where \( Q \) is expressed by equation (4). The rapid propagation of the pulse is seen, which is followed by the oscillating wake (the time is normalized by the cutoff period \( T_p = 2\pi/\Omega_p \)). Just after the propagation of the pulse, the tube begins to oscillate with the cutoff period at each height. The amplitudes of pulse and wake increase upward due to the density reduction, but the oscillations at each height decay in time.

Hence, the transverse impulsive action on the magnetic tube at the \( t = 0 \) moment near the base of the photosphere (set at \( z = 0 \)) excites the upward propagating kink pulse, while the tube in the photosphere oscillates at the photospheric kink cutoff frequency \( \Omega_b \), which depends on the plasma \( \beta \) parameter \((= 8\pi p_x/B^2) \) inside the tube. In the case of temperature balance inside and outside the tube, the kink speed can be expressed as \( c_p = c_s \gamma(1 + 2\beta/\gamma)^{-1/2} \), where \( c_s \) is the sound speed and \( \gamma \) is the ratio of specific heats \((\gamma = 5/3 \) for adiabatic process). Then the photospheric sound speed of \( 7.5 \) km s\(^{-1} \) and \( \beta = 0.3 \) gives 6.5 km s\(^{-1} \) for the kink speed. Consequently, we may estimate the kink cutoff period as \( \approx 8 \) minutes using the photospheric scale height of 125 km. Hence the magnetic tube will oscillate with \( \approx 8 \) minute period in the photosphere. If the external pulse is directed along, say, the \( x \)-axis, then the tube will oscillate in the \( x-z \) plane.

However, the anchored magnetic tube undergoes the granular buffeting from different sides. Therefore, suppose that after
$t_0$ time another granular cell acts on the same tube along the $y$-axis. The solution governing the pulse propagation is

$$
\xi_y = \frac{c_s A_0}{2} J_0 \left[ \frac{\Omega_c}{c_s} \sqrt{(t - t_0)^2 - \frac{z^2}{c_s^2}} \right]
$$

$$
\times H \left[ \frac{\Omega_c}{c_s} \left( t - t_0 - \frac{z}{c_s} \right) \right] \exp \left( \frac{z}{4A} \right).
$$

Thus the rapidly propagating pulse is again excited with the oscillating wake behind the front. The wake oscillates with the same cutoff frequency, but the oscillation is polarized in the $y$-$z$ plane. Hence there are two transverse oscillations with the same frequency, but polarized in perpendicular planes. The time interval between consecutive buffeting $t_0$ (say, the granular lifetime) is comparable to the photospheric kink cutoff period. Therefore, these oscillations will be superimposed, because the oscillation excited by the previous pulse still exists in the same tube. The superposition will set up the helical motion of the tube axis with photospheric cutoff period $\sim 8$ minutes. Figure 3 shows the superposition of solutions (4) and (5) at the height of 250 km above the photosphere. The first pulse is imposed along the $x$-direction, which is followed by another pulse in the $y$-direction. The top panel corresponds to the same amplitudes of both pulses, but the bottom panel corresponds to the case when the first pulse is twice as strong as the second. We see that the tube rotates along nearly circular spiral in the first case and along elliptical spiral in the second case. The displacement gradually decreases with time. Therefore, the granular buffeting with the same amplitudes excites the nearly circular motion of the tube, while the buffeting with different amplitudes excites the elliptical motion.

The wavelength of oscillations $\lambda = c_s T_\perp \sim 3000$ km is quite long compared to the width of the photosphere. Therefore, the photospheric magnetic tube will just rotate around the vertical without additional wave nodes. The tube displacement increases with height due to the decreasing density (Fig. 2). Thus the observations should show that the upper part of the tube rotates with larger amplitude than the lower part. We believe that the high-resolution observations will reveal similar behavior of the photospheric magnetic tubes.

3. PROPAGATION OF THE TRANSVERSE PULSE THROUGH THE CHROMOSPHERE

The situation is changed when the pulse crosses the photosphere and penetrates into the chromosphere. Photospheric magnetic tubes may expand in the chromosphere giving rather different geometry than thin tubes. On the other hand, chromospheric spicules seem to behave like magnetic tubes. But recent Monte Carlo simulations (De Pontieu et al. 2007) suggest that the spicules are not wave guides for tube waves. Therefore, this question is currently under debate and more observations are needed to clarify the intrinsic process (Erdélyi & Fedun 2007). The transverse pulse retains its properties in any case. It continues to be the kink pulse in structured magnetic field, but probably is transformed into the Alfvénic one in the case of the smooth transverse profile of the magnetic field.

The photosphere and the chromosphere can be approximated as two different regions with different isothermal temperatures, densities, and other plasma parameters. Then the propagation of the pulse in the chromosphere is governed by equation (3), but with different phase speed and scale height ($z = 0$ now corresponds to the base of the chromosphere). It must be mentioned, however, that the phase speed remains constant only if the magnetic field is expanded with height. This necessarily requires the horizontal component of the magnetic field, which is neglected in the equation. Therefore, equation (3) is valid only near the tube axis, where the magnetic field is predominantly vertical.

Then the photospheric solution (4) can be directly applied here, but with chromospheric phase speed and scale height. The chromospheric scale height $L_{ch}$ can be estimated as $\sim 500$ km for $25,000$ K temperature. The value of phase speed determines the wave cutoff frequency. For example, the Alfvén wave cutoff frequency is $\Omega_{A} = v_A/4L_{ch}$ (Roberts 2004), which gives a cutoff period of $\sim 250$ s for the Alfvén speed of $50$ km s$^{-1}$. On the other hand, a cavity with higher density concentrations (for example spicules) may guide kink waves with smaller phase speed. This increases the cutoff period. For example, a kink speed of 25 km s$^{-1}$ yields a cutoff period of 500 s.
Therefore, the transverse pulse may set up an oscillating wake in the chromosphere with a period of 250–500 s. The two perpendicularly polarized transverse pulses may form the helical motion in the chromosphere as observed by Hinode (De Pontieu et al. 2007). De Pontieu et al. (2007) argued that the helical motion is caused by Alfvén waves directly excited in the photosphere. The estimated energy flux of the waves was enough to power the solar wind and to heat the quiet corona. However, if observed oscillations of spicule axes are caused by wakes formed after the transverse pulse propagation, then the energy transported into the chromosphere/corona can be much higher, as almost the entire energy of the initial perturbation is carried by the pulse, while the energy of the wake is much smaller.

The energy flux stored in the initial transverse pulse at the photospheric level is \( F \sim n_e c_s v_p^2 \), where \( v_p \) is the granular velocity, being 1–2 km s\(^{-1}\). Then for photospheric values of electron density and kink speed, the estimated energy flux is \( 5 \times 10^8 \) erg cm\(^{-2}\) s\(^{-1}\). Almost all of the energy is carried by the pulse; therefore even if the filling factor of the magnetic tubes is 10%, the energy flux is more than enough to heat the solar chromosphere/corona.

4. CONCLUSIONS

We suggest that the propagation of consecutive transverse pulses in the stratified atmosphere, which are excited by photospheric granular buffeting, may set up the helical motions of magnetic flux tubes through the superposition of oscillating wakes formed behind the wave fronts. This scenario may explain the continuous motions of spicule axes seen in recent Hinode movies. The pulses carry almost all of the energy of initial perturbations, while the energy in wake oscillations is much smaller. Therefore, the energy carried into the corona by transverse pulses can be much higher than is estimated by observed oscillations. More observations and numerical/analytical works are needed to look further into this problem.

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