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Observation of kink waves in solar spicules

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ABSTRACT

Height series of Hα spectra in solar limb spicules obtained with the 53 cm coronagraph of the Abastumani Astrophysical Observatory are analyzed. Each height series covered 8 different heights beginning at 3800 km above the photosphere. The spatial difference between neighboring heights was 1″, consequently ~3800−8700 km distance above the photosphere has been covered. The total time duration of each height series was 7 s. We found that nearly 20% of measured height series show a periodic spatial distribution of Doppler velocities. We suggest that this spatial periodicity in Doppler velocity is caused by propagating kink waves in spicules. The wave length is found to be ~3500 km. However the wave length tends to be ~1000 km at the photosphere due to the height variation of the kink speed. This probably indicates to a granular origin for the waves. The period of waves is estimated to be in the range of 35−70 s. These waves may carry photospheric energy into the corona, therefore can be of importance in coronal heating.

Key words. Sun: chromosphere – Sun: oscillations

1. Introduction

The heating of the upper chromosphere and corona is still an unsolved problem in solar physics. It is clear that the energy source supporting the high temperature lays in the highly dynamical and dense photosphere. There the mechanical energy of photospheric motions can be guided upwards by structured magnetic fields in the form of waves or electric currents. Therefore the energy transport by magnetohydrodynamic (MHD) waves throughout the solar atmosphere is one of the key process towards the solution of the heating problem (Roberts 2004). Observations of oscillatory phenomena in the solar atmosphere have increased dramatically in the last few years through observations from SOHO (Solar and Heliospheric Observatory) and TRACE (Transition Region and Coronal Explorer). The space missions uncovered the rich spectrum of MHD oscillations in the transition region and corona (Doyle et al. 1999; Nakariakov et al. 1999; Ofman et al. 2000; Banerjee et al. 2001; O'Shea et al. 2001; De Moortel et al. 2004). The coronal waves are either generated in situ or they penetrate from the photosphere. Hence the observation of oscillatory phenomena in chromospheric spectral lines is of vital importance.

Most of the chromospheric radiation in quiet Sun regions comes from spicules, which are jet-like chromospheric structures observed at the solar limb mainly in Hα line. Spicules often show the group behaviour and probably are concentrated between supergranule cells (see e.g. reviews of Beckers 1972 and Sterling 2000). Therefore spicules probably are formed in regions of magnetic field concentration and consequently MHD wave propagation in the solar atmosphere may be traced through their dynamics. Oscillations in spicules with ~5 min period have been detected by ground based (Kulidzanishvili & Zhugzhda 1983) and recently by space observations (De Pontieu et al. 2003; Xia et al. 2005). On the-other-hand, oscillations in spicules with shorter period have been reported more than 30 years ago by Nikolsky & Platova (1971). They found that spicules oscillate along the limb with a characteristic period of about 1 min. The oscillation, which they reported, was a periodic transversal displacement of the spicule axis at one particular height.

If spicules are formed in thin magnetic flux tubes, then the periodic transverse displacement of the axis observed by Nikolsky & Platova (1971) probably was due to the propagation of kink waves. It is well known that transverse kink waves can be generated in photospheric magnetic tubes by buffeting of granular motions (Roberts 1979; Hollweg 1981; Spruit 1981; Hasan & Kalkofen 1999). Kink waves cause the displacement of the tube axis, therefore their propagation can be traced either by direct observation of the tube displacement along the limb as in Nikolsky & Platova (1971) or spectroscopically by the Doppler shift of spectral lines. The later possibility arises when the velocity of kink waves is polarized in the plane of observation. The periodic spatial distribution of Doppler

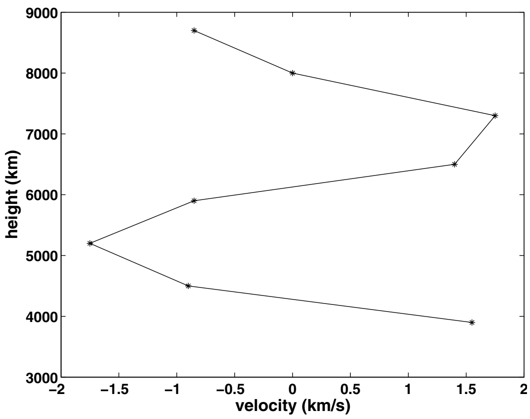

Fig. 1. The Doppler velocity spatial distributions for one of the height series is shown. Marked dots indicate the observed heights. The Doppler velocity has clear periodic spatial distribution, which indicates wave propagation.

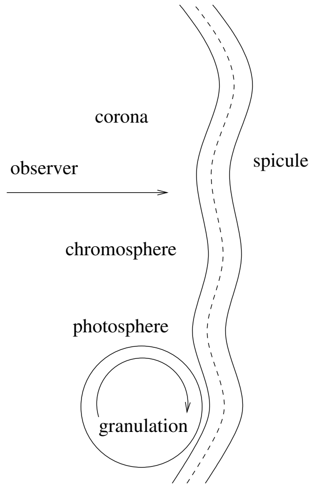

Fig. 2. Schematic picture of propagating kink waves in spicules. Due to the kink waves, the observed spectral line is Doppler shifted when the wave velocity is polarized in the plane of observation.

velocities in spicules has been detected almost 20 years ago by Khutsishvili (1986). Unfortunately, neither observers nor theorists paid attention to the phenomenon which can be simply explained in terms of kink waves. In this letter, we reanalyze the height series of Hα spectra obtained by Khutsishvili (1986) and then model the observation as propagating kink waves.

2. Observation

The big (53 cm) coronagraph and universal spectrograph of Abastumani Astrophysical Observatory has been used to obtain chromospheric Hα line spectra at different heights (8 heights) above the photosphere (Khutsishvili 1986). Instrumental spectral resolution is 0.04 Å and dispersion 1 Å/mm in Hα. Observation has been carried out at the solar limb as height series beginning at 3800 km above the photosphere with a step size of 1 arcsec. Thus the distance ~3800−8700 km above the photosphere was covered. The exposure time was 0.4 s at lower heights and 0.8 s at higher ones. The duration of each height series was 7 s, with the total duration of the observation being 44 min. More details about the observation can be found in Khutsishvili (1986).

We analyzed spatial distributions of Doppler velocities in selected Hα height series. Nearly 20% of measured height series showed a periodic spatial distributions in the Doppler velocities. The Doppler velocity spatial distributions for one of the height series is shown in Fig. 1. Periodic spatial distribution is clearly seen, which indicates a wave propagation. The wave length can be estimated as ~3500 km. The maximal time difference between the observations at the lowest and highest heights in one series is 7 s. If the wave propagates with the Alfvén speed, being say ~50 km s^{-1} in the chromosphere, then during 7 s it will pass a distance ~350 km. So during one height series the wave will propagate along the distance which is less than the distance between consequent observed heights. Therefore the spatial structure of the wave velocity in one height series can be considered as nearly simultaneous.

Thus the observations show the evidence of transversal wave propagation in spicules with typical wave length of ~3500 km. The waves can be either kink or linearly polarised Alfvén waves (torsional Alfvén waves in magnetic tubes will cause periodic broadening of spectral lines not the Doppler shift, see Zaqarashvili 2003). But as spicules are highly structured phenomena (their width are ~1″), the observed Doppler shift can be caused due to the propagation of kink waves.

Kink waves propagating along the magnetic tube lead to the oscillation of the tube's axis (see Fig. 2). Therefore if the velocity of the kink wave is polarized in the plane of observation, then it results in the Doppler shift of the observed spectral line. The Doppler shift will have a periodic behaviour in height: at the same time, the spectral line will have blue shift at antinodes where the tube moves towards the observer and red shift where the tube moves in the opposite direction; at the velocity nodes the Doppler shift tends to zero. This means that kink waves manifest itself in the same spatial behaviour of Doppler shift as revealed by our height series (Fig. 1). However if the spicule axis is inclined with respect to the local vertical direction then a steady flow inside the spicule will shift the Doppler velocity at all heights with the same value. Indeed, some spicules show this behaviour. Three consecutive height series of Doppler velocity in one spicule are shown in Fig. 3. The velocity is shifted by ~12 km s^{-1} at all heights, although the wave signature is still seen. If the spicule is inclined by approximately 35° (Trujillo Bueno et al. 2005) then the real steady flow velocity will be ~22 km s^{-1}, similar to the typical mass raising speed in spicules. Also Fig. 3 shows that the maximum of the Doppler velocity moves up in consecutive height series. This may indicate a wave phase propagation. The phase is displaced at ~1500 km in about 18 s giving the phase speed of ~80 km s^{-1}, very similar to the expected kink speed at these heights.

3. The model

The mechanism of spicule formation is still not well understood (see the recent review of Sterling 2000 and references therein). Therefore this letter does not address the spicule

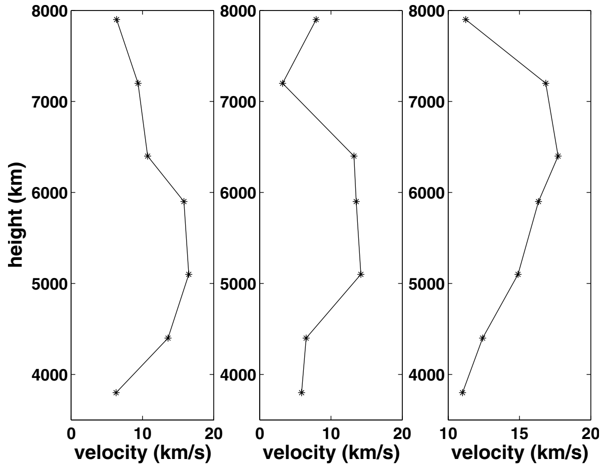

Fig. 3. Three consecutive height series of Doppler velocity in one spicule. The time difference between the consecutive plots is ∼8 s. The maximum of Doppler velocity moves up in consecutive height series, which probably indicates a wave propagation.

formation mechanism. Spicule life time is ∼10−15 min, while the period of observed waves is much shorter: 70 s for the wave with phase speed of 50 km s^{-1} and wave length of 3500 km. In 2−3 periods the wave will propagate along the whole spicule length. During this short time intervals spicules can be considered as existing stable structures. Therefore the waves may propagate independently of the spicule formation mechanism.

During short time intervals spicules can be modeled as thin magnetic flux tubes embedded in a field free environment, anchored in the photosphere and persisted towards the corona. Propagation of kink waves in vertical magnetic tube embedded in a field free environment is governed by the equation (Roberts 2004)

$$\frac{\partial^2 \xi}{\partial t^2} = c_k^2 \frac{\partial^2 \xi}{\partial z^2} + g\frac{\rho_0 - \rho_e}{\rho_0 + \rho_e}\frac{\partial \xi}{\partial z}, \quad (1)$$

where ξ is the transverse displacement, $\rho_0(z)$, $\rho_e(z)$ are the plasma densities inside and outside the tube accordingly, g is the gravitational acceleration and $c_k = c_A \sqrt{\rho_0/\rho_0 + \rho_e}$ the kink speed. Here $c_A = B_0/\sqrt{4\pi\rho_0}$ is the Alfvén speed with $B_0(z)$ as the tube magnetic field. Note that this equation does not include the flow along the tube, while spicules show continuous upward mass motion. Therefore Eq. (1) may correctly describe the waves only in the co-moving frame (with the steady flow), and thus the wave phase speed will be Doppler shifted due to the mass motion inside the spicule, which may slightly alter the theoretical results.

Spicule density and magnetic field show almost no spatial variation at observation heights (∼3800−8700 km above the photosphere) and the stratification also can be neglected in this part of the solar atmosphere, then Eq. (1) gives the approximate dispersion relation $c_k^2 k_z^2 = \omega^2$, where k_z is the vertical wave number and ω is the frequency of kink waves. From the dispersion relation we may estimate the period of kink waves using the observed wave length and typical kink speed. The observed wave length of kink waves is of order ∼3500 km. Then for the kink speed of ∼50−100 km s^{-1} at heights of 3800−8700 km above the photospheric, the period of kink waves can be estimated as ∼35−70 s.

It can be suggested that the source of observed kink waves resides in the lower part of the solar atmosphere. The cut-off period of kink waves due to stratification at the photosphere (for the pressure scale height of 125 km and plasma β of ∼1) is ∼660 s. So the expected period of kink waves is well below the cut-off value. Thus the kink waves with periods of ∼35−70 s may easily propagate upwards. As estimated frequency of the observed waves is much higher than the frequency of 5-min oscillations, then the oscillations can be ruled out to be the source of kink waves. Therefore, the only source which may excite the kink waves in the photosphere is the granulation. The photospheric granulation has been often suggested as the source of kink waves in thin magnetic tubes (Roberts 1979; Spruit 1981; Hollweg 1981; Hasan & Kalkofen 1999). Photospheric granulation is very dynamic even during the life time of one granular cell. If the magnetic tube, in which the spicule is formed, is anchored in the photosphere, then any perturbation of the granular cell probably excites the kink waves with wave length similar to the cell diameter (see Fig. 2). But the observed wave length (∼3500 km) of the kink waves in the higher atmosphere is a few times longer than the mean granular diameter, which is of order ∼800−1000 km. The discrepancy can be resolved by an increase of wave phase speed with height. Indeed, the kink speed being ∼10 km s^{-1} at the photosphere increases up to ∼50 km s^{-1} (or even more) in the higher atmosphere. Therefore it can be suggested that granular cells generate kink waves with a wave length comparable to their diameter, but the wave length increases due to increasing phase speed when waves propagate upwards.

In order to show this, one should solve the kink wave Eq. (1) along the whole solar atmosphere from the photosphere to the present observed heights. As Eq. (1) is homogeneous with time, we may perform a Fourier expansion in time in the form $\xi = \xi_1(z)\exp(i\omega t)$, where ω is the wave frequency. Then its numerical solution is straightforward; we only need to fix the spatial variations of the unperturbed parameters. Unfortunately, the height variation of the physical quantities is not well known. There are only suggested values of density and magnetic field in spicules and they are also controversial. Also the difference between plasma densities inside and outside of spicule are not well determined. At the photospheric level the thermal equilibrium inside and outside the tube i.e. $T_0(z) = T_e(z)$ (here $T_0(z)$, $T_e(z)$ are plasma temperatures inside and outside of tube) is a good approximation, which gives a higher density outside the tube than inside (in order to hold the transverse pressure balance at the tube boundaries). But in the higher atmosphere, say at heights >2000 km, the plasma temperature is much lower in spicules than in the environment. On the-other-hand, the plasma density seems to be much higher in spicules than the surroundings. Due to this uncertainty in the medium parameters, it is better to give the height dependence of the Alfvén speed and the density ratio inside and outside the spicule ρ_0/ρ_e. Therefore we take the height dependence of the Alfvén speed as 10 km s^{-1} at the photosphere and ∼100 km s^{-1} at 6000 km. For the density ratio we take 1/3 at the photosphere (being higher outside the tube), which increases up to 10^3 at a

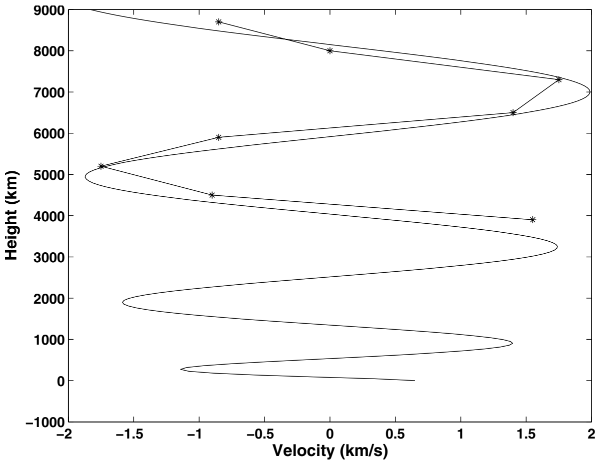

Fig. 4. Comparison of observed Doppler velocity plot (Fig. 1) and the numerical solution of the kink wave equation. Vertical axis shows the height in km and the horizontal axis shows the kink wave velocity in km s^{-1}. It is seen that the wave length of the computed kink waves at the photospheric level is ~1000 km, which is comparable to the granular diameter.

height of 6000 km. With this spatial dependence of the Alfvén speed and the density ratio we solve numerically the kink wave equation for different values of frequency ω. Then we fit the numerical solution to the observed curve of the Doppler velocity. The numerical solution is best fitted to the observation (Fig. 4) when the wave period is ~40 s. From Fig. 4 it is seen that the wave length of the kink waves at the photospheric level is ~1000 km, which is comparable to the granular diameter. It clearly indicates a granular origin for the waves.

4. Discussion

Kink oscillations of coronal loops have been frequently observed in the solar corona by TRACE as periodic loop displacement in space. However in the lower atmosphere the observation of kink waves is complicated due to their nearly incompressible character. Here we report the spectroscopic observation of kink waves in solar limb spicules. We have shown that nearly 20% of measured Hα height series at the solar limb (~3800−8700 km distance above the photosphere) show the periodic spatial distribution of Doppler velocities in spicules, which can be caused by propagating kink waves. The wave length at these heights is ~3500 km, which goes to ~1000 km at the photosphere if the height dependence of the kink speed is taken into account. The estimated wave period is ~35−70 s. The computed wave length at the photospheric level is comparable to the granular size, therefore the granulation is probably the most plausible source for the wave excitation. Then the granulation will excite kink waves in any thin magnetic flux tube anchored in the photosphere. As we already noted only ~20% of measured height series show periodic spatial distribution of Doppler velocities. Indeed spectroscopic detection of kink waves is possible only when the wave velocity is polarised in the plane of observation. But the granulation will excite the waves with any direction of polarisation; there is no preferred direction. Therefore 20% of measured height series is a good percentage for the observation of waves.

It must be noted that some spicules show a multi-component structure (i.e. several spicules are located close together) mostly at lower heights, which may give the impression of a velocity shift (Xia et al. 2005). Therefore we choose only the spicules with well defined single-component structure. We also note that the data analysis has been made only for selected height series. Now we are doing the data reduction of the whole observation, which will be analysed in the near future.

Here we do not address the mechanism of wave excitation in detail as it is beyond the scope of this letter. But we suggest that granular cells will frequently excite the kink waves with the wave length comparable to their diameter in anchored magnetic tubes. The waves may propagate upwards carrying the photospheric energy into the corona, thus may cause significant input into the coronal heating. Therefore detailed spectroscopic search of waves with period of ~40−60 s and wave length of ~3000−4000 km is desirable to be performed in the future.

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References

Banerjee, D., O'Shea, E., Doyle, J. G., & Goossens, M. 2001, A&A, 380, L39

Beckers, J. M. 1972, ARA&A, 10, 73

De Moortel, I., Hood, A. W., Gerrard, C. L., & Brooks, S. J. 2004, A&A, 425, 741

De Pontieu, B., Erdélyi, R., & de Wijn, A. G. 2003, ApJ, 595, L63

Doyle, J. G., van den Oord, G. H. J., O'Shea, E., & Banerjee, D. 1999, A&A, 347, 335

Hasan, S. S., & Kalkofen, W. 1999, ApJ, 519, 899

Khutsishvili, E. 1986, Sol. Phys., 106, 75

Kulidzanishvili, V. I., & Zhugzhda, Y. D. 1983, Sol. Phys., 88, 35

Hollweg, J. V. 1981, Sol. Phys., 70, 25

Nakariakov, V. M., Ofman, L., Deluca, E. E., Roberts, B., & Davila, J. M. 1999, Science, 285, 862

Nikolsky, G. M., & Platova, A. G. 1971, Sol. Phys., 18, 403

Ofman, L., Romoli, M., Poletto, G., Noci, G., & Kohl, J. L. 2000, ApJ, 529, 592

O'Shea, E., Banerjee, D., Doyle, J. G., Fleck, B., & Murtagh, F. 2001, A&A, 368, 1095

Roberts, B. 1979, Sol. Phys., 61, 23

Roberts, B. 1981, in The Physics of Sunspots, Sunspot, Sacramento Peak Observatory, ed. J. H. Thomas, & L. E. Cram, 369

Roberts, B. 2004, In Proc. SOHO 13 Waves, Oscillations and Small-Scale Transient Events in the Solar Atmosphere: A Joint View from SOHO and TRACE, Palma de Mallorca, Spain, (ESA SP-547), 1

Spruit, H. C. 1981, A&A, 98, 155

Sterling, A. C. 2000, Sol. Phys., 196, 79

Trujillo Bueno, J., Merenda, L., Centeno, R., Collados, M., & Landi DeglInnocenti, E. 2005, ApJ, 619, L191

Xia, L. D., Popescu, M. D., Doyle, J. G., & Giannikakis 2005, A&A, 438, 1115

Zaqarashvili, T. V. 2003, A&A, 399, L15