Observation of standing kink waves in solar spicules

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Abstract We analyze the time series of Ca II H-line obtained from Hinode/SOT on the solar limb. The time-distance analysis shows that the axis of spicule undergoes quasi-periodic transverse displacement at different heights from the photosphere. The mean period of transverse displacement is ∼180 s and the mean amplitude is 1 arc sec. Then, we solve the dispersion relation of magnetic tube waves and plot the dispersion curves with upward steady flows. The theoretical analysis shows that the observed oscillation may correspond to the fundamental harmonic of standing kink waves.

Keywords Sun: spicules • MHD waves: dispersion relation • kink modes

1 Introduction

Observation of oscillations in solar spicules may be used as an indirect evidence of energy transport from the photosphere towards the corona. Transverse motion of spicule axis can be observed by both, spectroscopic and imaging observations. The periodic Doppler shift of spectral lines have been observed from ground based coronagraphs (Nikolsky & Sazanov 1987; Kukhianidze et al. 2006; Zaqarashvili et al. 2007). But Doppler shift oscillations with period of ∼5 min also have been observed on the SOlar and Heliospheric Observatory (SOHO) by Xia et al. (2005). Direct periodic displacement of spicule axes have been found by imaging observations on Optical Solar Telescope (SOT) on Hinode (De Pontieu et al. 2007; Kim et al. 2008; He et al. 2009). The torsional Alfvén waves were reported recently in the context of a flux tube connecting the photosphere and the chromosphere as periodic variation of spectral line width (Jess et al. 2009).

The observed transverse oscillations of spicule axes were interpreted by kink (Nikolsky & Sazanov 1987; Kukhianidze et al. 2006; Zaqarashvili et al. 2007; Kim et al. 2008) and Alfvén (De Pontieu et al. 2007) waves. All spicule oscillations events are summarized in a recent review by Zaqarashvili & Erdélyi (2009). They suggested that the observed oscillation periods can be formally divided in two groups: those with shorter periods (<2 min) and those with longer periods (≥2 min) (Zaqarashvili & Erdélyi 2009). The most frequently observed oscillations lie in the period ranges of 3–7 min and 50–110 s.

Spicule seismology, which means the determination of spicule properties from observed oscillations and was originally suggested by Zaqarashvili et al. (2007), has been significantly developed during last years (Ajabshirizadeh et al. 2009; Verth et al. 2011; Tavabi et al. 2011).

Spicules are almost 100 times denser than surrounding coronal plasma (Beckers 1968), therefore they can be considered as cool magnetic tubes embedded in hot coronal plasma. Wave propagation in a static magnetic cylinder was studied by Edwin and Roberts (Edwin & Roberts 1983). They derived general dispersion relation of all possible wave modes in magnetic tubes. Then the linear and non-linear
MHD waves propagation in a cylindrical magnetic flux tube with axial steady flows have been also studied (Terra-Homem et al. 2003). They show that steady flows change the treatments of propagating waves because of induced Doppler shifts.

In the present work, we study the observed oscillations in the solar spicules through the data obtained from Hinode. Then we model the oscillations as magnetohydrodynamic (MHD) waves in magnetic flux tubes.

2 Observations and image processing

We used a time series of Ca II H-line (396.86 nm) obtained on 25 October 2008 during 03:20 to 03:25 UT by the Solar Optical Telescope onboard Hinode (Tsuneta et al. 2008). Note, that the Ca II H-line observations of the same day have been used recently to study multi-component spicules by Tavabi et al. (2011), but they used another time interval of these data. The spatial resolution reaches 0.2 arc sec (150 km) and the pixel size is 0.1082 arc sec (~80 km) in the Ca II H-line. The time series has a cadence of 10 seconds with an exposure time of 0.5 seconds. The position of X-center and Y-center of slot are, respectively, 0 arc sec and 948 arc sec, while, X-FOV and Y-FOV are 112 arc sec and 56 arc sec respectively.

We used the “fgprep,” “fgrigidalign” and “madmax” algorithms (Koutchmy & Koutchmy 1989) to reduce the images spikes and jitter effect and to align time series and to enhance the finest structures, respectively.

Figure 1 shows 9 selected images of the time series, which consists of 27 consecutive images. We study the transverse motion of selected spicule (black narrow line) in respect with the hypothetic line (white line on the images), which is drown on the same place during whole time series. The clear quasi-periodic transverse motion of the spicule axis is seen on the figure.

We use the time slice diagrams in order to study the quasi-periodic motion of the spicule axis in detailed. Figure 2 shows the time slice diagrams performed at 6 different heights from the limb. Each cut is obtained

Fig. 1 9 images of time sequence in Ca II H-line (left to right and top to bottom). White diamonds indicate the spicule locations in time series.

by averaging over 9 pixels along the spicule axis, which corresponds to 1 arc sec around each height.

The dark regions represent the spicule at particular height. We clearly see that the spicule axis undergoes the transverse oscillation at each height with nearly same periodicity. The oscillation period at each heights is estimated as ~180 s. The oscillation amplitude is nearly 1 arcsec, but slightly changes with height. Figure 3 shows the height variation of the oscillation amplitude. The amplitude increases almost linearly with height and its slope is 0.06. The oscillations of spicules axis are closed to the standing pattern as we do not see any upward or downward propagation.

The density is almost homogeneous along the spicule axis (Beckers 1968), therefore the density scale height should be much longer that the spicule length. Then the variation of oscillation amplitude with height can not be due to the decreased density. Therefore, we assume that the height dependence of amplitude is due to the standing oscillations. Then we may have that the oscillation amplitude is proportional to sin(kz), where k is
the oscillation wave number. This expression can be approximated in the long wavelength limit as \( \approx k_0 \). Then, the oscillation wavelength is \( \lambda \sim 1/0.06 \text{arc sec} \sim 11500 \text{ km} \). This allows the estimation of the kink speed as \( v_k = \lambda/T \sim 11500/180 \text{ km s}^{-1} \sim 65 \text{ km s}^{-1} \). The estimated period and kink wave speed are in good agreement with the period and speed of fundamental harmonic of kink waves.

The oscillation amplitude and phase speed allows to estimate the energy flux, \( F \), stored in the oscillations

\[
F = \frac{1}{2} \rho v^2 k_z, 
\]

where \( \rho \), \( v \) and \( v_k \) are density, wave amplitude and phase speed respectively. The density in spicules is \( 3 \times 10^{-10} \text{ kg m}^{-3} \) (Beckers 1968). The wave velocity can be determined as \( v = \xi_0/T_0 \), where \( \xi_0 \) is the axis displacement estimated as 1 arc sec and \( T_0 \) is the oscillation period estimated as \( \sim 180 \text{ s} \). We take the estimated phase speed as \( v_k = 65 \text{ km s}^{-1} \). With these parameters the energy flux is estimated as \( F = 1500 \text{ J m}^{-2} \text{s}^{-1} \). Total coronal energy losses in the quiet Sun is 30000 \( \text{ J m}^{-2} \text{s}^{-1} \), therefore the energy flux stored in the oscillation is of the same order as the energy losses, but probably is not enough to fully compensate them.

3 Theoretical modeling

We use ideal MHD equations to model the propagation of waves in spicules. The density seems almost uniform along almost whole length of spicules (Beckers 1968), therefore we ignore the effects of stratification due to gravity. The density inside spicules is almost 100 times larger than outside, therefore we model them as magnetic flux tubes embedded in coronal magnetized plasma. We consider a uniform vertical magnetic tube of radius \( a \) with uniform magnetic field \( B_0 \hat{z} \) (\( B_c \hat{z} \)) inside (outside) the tube. The kinetic gas pressure and density inside (outside) of the tube are \( p_0 \) (\( \rho_0 \)) and \( \rho_0 \) (\( \rho_e \)), respectively. We also consider uniform steady flows inside (outside) the tube with velocity \( U_0 \hat{z} \) (\( U_c \hat{z} \)). The pressure balance condition at the tube boundary implies that

\[
p_0 + \frac{B^2_0}{2\mu} = \rho_e + \frac{B^2_c}{2\mu}. 
\]

The densities inside and outside the tube are related as

\[
\frac{\rho_0}{\rho_e} = \frac{2c^2_a + \gamma v^2_{Ae}}{2c^2_e + \gamma v^2_{A0}}, 
\]

where \( c_0 = \sqrt{\gamma p_0/\rho_0} \) (\( c_e = \sqrt{\gamma p_e/\rho_e} \)) and \( v_{A0} = B_0/\sqrt{\mu \rho_0} \) (\( v_{Ae} = B_e/\sqrt{\mu \rho_e} \)) are the sound and Alfvén speeds inside (outside) the tube, respectively. Here \( \gamma \) is the ratio of specific heats and \( \mu \) is the magnetic permeability.

Fourier transform of linearized MHD equations with the assumption that all the perturbed quantities are \( \exp[i(-\omega t + n\theta + k_0 z)] \) and the continuity of the perturbed interface (Chandrasekhar 1961) and the total pressure across the cylinder boundary \( r = a \) yield the dispersion relation (Terra-Homen et al. 2003)

\[
\rho_e (\Omega^2_e - k^2 v^2_{Ae}) m_a I'_n(m_0 a) / I_n(m_0 a) = \rho_0 (\Omega^2_0 - k^2 v^2_{A0}) m_e K'_n(m_0 a) / K_n(m_0 a), 
\]

where \( I_n \) and \( K_n \) are modified Bessel functions of order \( n \). Here \( m_\alpha \) and \( \Omega_\alpha \) (\( \alpha = 0, e \)) are given by the expressions

\[
m^2_\alpha = \frac{(k^2 c^2_\alpha - \Omega^2_\alpha)(k^2 v^2_{A\alpha} - \Omega^2_\alpha)}{(c^2_\alpha + v^2_{A\alpha})(k^2 c^2_\alpha - \Omega^2_\alpha)} 
\]

and

\[
\Omega_\alpha = \omega - k U_\alpha, 
\]

where

\[
c_{Ta} = \frac{c_\alpha v_{A\alpha}}{\sqrt{c^2_\alpha + v^2_{A\alpha}}} 
\]

is the tube speed. This dispersion relation describes both, surface \( (m_\alpha^2 > 0) \) and body waves \( (m_\alpha^2 < 0) \).

We solved the dispersion relation for the values of \( c_{\alpha 0} = 10 \text{ km s}^{-1} \), \( c_{\alpha e} = 262 \text{ km s}^{-1} \), \( v_{A0} = 40 \text{ km s}^{-1} \),
$v_{\text{Ae}} = 210$ km s$^{-1}$ and $\rho_0/\rho_e = 0.02$. With these data we have $c_k = 42.5$ km s$^{-1}$, $c_{T0} = 9.7$ km s$^{-1}$ and $c_{Te} = 100.6$ km s$^{-1}$. Figure 4 shows the dispersion diagram of kink waves under above conditions in the absence of steady flows. All speeds in the plots are normalized to $v_{A0}$. As $v_{\text{Ae}} > v_{A0}$ then the surface waves are absent (Edwin & Roberts 1983). Figure 5 shows the same dispersion diagram but in the case of steady flow $U_0 = 25$ km s$^{-1}$. It is seen that phase speeds and consequently wave frequencies are shifted due to the steady flows.

Let us assume that the full length of spicule is $L$. Then the wavelength of the fundamental standing mode is $\lambda = 4L$ and thus the wave number of the fundamental mode is $k = 2\pi/\lambda = \pi/2L$. The second and the third harmonics have the wave numbers $\pi/L$ and $2\pi/L$, respectively. The mean length of classical spicules varies from 5000 to 9000 km in H$\alpha$ (Zaqarashvili & Erdély 2009). Then the periods of standing kink modes can be estimated from the dispersion diagram. For the the spicule length of 3500–9000 km we obtain the period of fundamental, second and third harmonics in the ranges of 170–320 s, 85–160 s and 40–80 s, respectively. The observed oscillation period of $\sim 180$ s may correspond to the fundamental harmonic of standing kink waves.

4 Discussion and conclusion

We performed the analysis of Ca II H-line time series at the solar limb obtained from Hinode/SOT in order to uncover the oscillations in the solar spicules. We concentrate on particular spicule and found that its axis undergoes quasi-periodic transverse displacement about a hypothetic line. The period of the transverse displacement is $\sim 180$ s and the mean amplitude is $\sim 1$ arcsec. The same periodicity was found in Doppler shift oscillation by Zaqarashvili et al. (2007) and De Pontieu et al. (2007), so the periodicity is probably common for spicules.

We model spicules as dense plasma jets along magnetic flux tube being injected from the chromosphere upwards into the hot corona. Solving the wave dispersion relation in the presence of steady flows we conclude that the steady flows change the characteristics of wave propagation in a cylindrical magnetic flux tube. The calculated periods of fundamental, second and third harmonics of standing kink modes with an upward flow of 25 km s$^{-1}$ are in the ranges of 170–320 s, 85–160 s and 40–80 s, respectively, for the spicule length of 3500–9000 km.

Therefore, the observed quasi-periodic displacement of spicule axis can be caused due to fundamental standing mode of kink waves. The energy flux stored in the oscillation is estimated as $150$ J m$^{-2}$ s$^{-1}$, which is of the order of coronal energy losses in quiet Sun regions.

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