Observation of kink waves and their reconnection-like origin 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. We follow three cases of upwardly propagating kink waves along a spicule and inverted Y-shaped structures at the cusp of it. 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 $\sim 175$ s and the mean amplitude is 1 arc sec. The oscillation periods are increasing linearly with height which may be counted as the signature that the spicule is working as a low pass filter and allows only the low frequencies to propagate towards higher heights. The oscillations amplitude is increasing with height due to decrease in density. The phase speeds are increasing until some heights and then decreasing which may be related to the small scale reconnection at the spicule basis. We conclude that transversal displacement of spicules axis can be related to the propagation of kink waves along them. Moreover, we observe signatures of small-scale magnetic reconnection at the cusp of spicules which may excite kink waves.

Keywords Sun: spicules · Kink waves · magnetic reconnection

1 Introduction

Spicules are observable in H$_\alpha$, D$_3$ and Ca II H chromospheric lines. The general properties of them can be found in some reviews [Beckers 1968, Sterling 2000]. 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. 2000, Zaqarashvili et al. 2007]. But Doppler shift oscillations with period of $\sim 5$ 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, Ebadi et al. 2012].

There are two different types of drivers in the highly dynamic photosphere: oscillatory (e.g. p-modes) and impulsive (e.g. granulation and/or explosive events due to magnetic reconnection). Both types of drivers may be responsible for the observed dynamical phenomena in upper atmosphere regions [Zaqarashvili et al. 2011]. De Pontieu et al. (2004) reported a synthesis of modeling and high-spatial-resolution observations of individual spicules. In the upper chromosphere, p-modes are evanescent and cannot propagate upwards through the temperature minimum. However, evanescence does not preclude significant tunneling of non-propagating wave energy into the hot chromosphere. More importantly, they showed that the non-verticality of flux tubes dramatically increases tunneling, and can even lead to propagation of p-modes. The leaked photosphere velocity signals steepen into shocks and the oscillatory wake behind them can led to spicule formation. It should be noted that because of the presence of cut-off periods, only frequencies above the cut-off are propagating; the frequencies below cut-off are evanescent. However, radiative relaxation of temperature perturbations
is known to be important and leads to the conclusion that all frequencies propagate (Roberts 1983). Zagharashvili et al. (2007) analyzed the consecutive height series of Hα spectra in solar limb spicules and traced wave propagations through the chromosphere. They used discrete Fourier transform analysis and detected Doppler-shifted oscillations. They concluded that the oscillations can be caused by wave propagation in thin magnetic flux tubes. They suggested the granulation as a possible source of the wave excitation. Ebadi (2013) analyzed the time series of Hα line obtained from Hinode/SOT on the solar limb. They used Wavelet analysis to show the transversal oscillations of spicules axis. They found that the strong pulses may lead to the quasi periodic rising of chromospheric plasma into the lower corona in the form of spicules. The periodicity may result from the nonlinear wake behind the pulse in the stratified atmosphere. Morton et al. (2012) based on SDO/AIA observations detected a variety of periodic phenomena in conjunction with large solar jets. Among other mechanisms that can be deduced from observations, they concluded that only one reconnection event has occurred and we are seeing the response of the transition region to a single velocity pulse. The rebound-shock model suggests that a velocity pulse can cause the transition region to generate a damped, (quasi-)periodic response. It has been demonstrated that the waves in the lower solar atmosphere can drive reconnection to produce small scale jet events with the same periodicity as the exciting wave. On the other hand, waves generated by reconnection could also display these timescales. Murawski & Zagharashvili (2010); Murawski et al. (2011) performed numerical simulations of solar spicules and macro-spicules. They studied the upward propagation of a localized velocity pulse that is initially launched below the transition region. They showed that the strong initial pulse may lead to the quasi periodic rising of chromospheric material into the lower corona in the form of spicules. The periodicity results from the nonlinear wake that is formed behind the pulse in the stratified atmosphere. The superposition of rising and falling off plasma portions resembles the time sequence of single and double (sometimes even triple) spicules, which is consistent with observational findings. They concluded that the two-dimensional rebound shock model may explain the observed speed, width, and heights of type I spicules, as well as observed multi-structural and bi-directional flows. The model also predicts the appearance of spicules with 35 min period due to the consecutive shocks. Kudoh & Shibata (1999) used the random nonlinear Alfvénic pulses and concluded that the transition region lifted up to more than ∼ 5000 km (i.e. the spicule produced). They studied the case of random perturbation in the photosphere as a source of Alfvén waves in the context of spicule formation and associated coronal heating. He et al. (2009) based on Hinode/SOT observations reported for the first time the excitation of kink waves in spicules due to magnetic reconnection. They observed transversal displacement of spicule axis which originated from the cusp of an inverted Y-shaped structure. They interpreted such structures as evidences to the magnetic reconnection at the basis of spicules. In the present work, we study the observed oscillations in the solar spicules through the data obtained from Hinode. We trace the spicule axis oscillations via time slice diagrams and deduce proportional periods at different heights. The generation of kink waves in solar spicules due to small-scale magnetic reconnection will be discussed.

2 Observations and image processing

We used a time series of Ca II H-line (396.86 nm) obtained on 18 October 2008 during 21:59 to 22:04 UT by the Solar Optical Telescope onboard Hinode (Tsuneta et al. 2008). The spatial resolution reaches 0.2 arc sec (150 km) and the pixel size is 0.109 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 960 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 (Shimizu et al. 2008; Koutchmy & Koutchmy 1983) to reduce the images spikes and jitter effect and to align time series and to enhance the finest structures, respectively.

3 Results and discussions

In Figure 1 we presented the full view Ca II H-line image of the solar north pole which contains the studied spicule. The processed spicule is indicated by a black arrow on this image. This image was taken by Hinode/SOT telescope on 10 Oct 2008, 22 : 01 : 20 UT. We used the time series images of this region and determined the average length, width, and lifetime of the studied spicule as ∼ 3000 km, ∼ 200 km, and ∼ 4 min, respectively. Figure 2 shows 5 selected images of the time series which trace spicule dynamics. In this figure we follow three different signatures of transversal oscillations of a unique spicule during its lifetime. As is clear
from this figure, the followed spicule is the same, but the sequence of time is different from top to bottom. In other words, we found three cases of upwardly propagating kink wave along a spicule in different times during its lifetime. These oscillations are showed by black arrows on the figure. The inverted Y-shaped structures are seen at the spicule base which may correspond to the magnetic reconnection origin of it (He et al. 2009). The oscillation amplitude is nearly 1 arc sec, but slightly changes with height. Oscillation amplitude grows with height due to significant decrease in density, which acts as inertia against oscillations. It should be emphasized that the density scale height in spicules is \( \sim 700 \text{ km} \) (Verth et al. 2011). In bottom panel of Figure 4, we estimated the transversal displacement velocity of spicule axis with respect to time. The mean transverse velocity is estimated from this figure \( \sim 18 \text{ km/s} \).

We presented the phase travel times and phase speed profiles for three cases of the studied spicule in Figure 4 from top to bottom, respectively. The phase speed is calculated from the first-order derivative of phase travel time. It begins from \( \sim 40 \text{ km/s} \) at lower heights and reaches to the maximum value of \( \sim 90 \text{ km/s} \) at \( \sim 2500 - 3000 \text{ km} \). Then it decreases to the minimum value of \( \sim 20 - 25 \text{ km/s} \) at \( \sim 3500 - 4500 \text{ km} \). An increase in phase speed at lower heights may be related to amplification of magnetic field away from reconnection site. On the other hand, the decreasing behavior at higher heights related to the decrease in mass density and magnetic field strength in these heights. The mass density and magnetic field variations are studied observationally.

The observed quasi-periodic displacement of spicule axis may be caused due to propagation of kink waves along spicules (He et al. 2009; Ebadi et al. 2012). Transverse oscillation of kink wave may be generated by impact of plasmoid as released from reconnecting current sheet, or be generated due to reconnection and release of shearing magnetic field.
Fig. 2 Upwardly propagation of kink waves along a spicule in different times during its lifetime are presented. The cusp of the inverted Y-shaped structures is showed by rectangular.
Fig. 4 The height variations of period, amplitude, and transverse velocity of the spicule axis oscillations are presented from top to bottom, respectively.

Fig. 5 The phase travel times and phase speed profiles for three cases of the studied spicule are showed from top to bottom, respectively. Red plots corresponded to phase travel times and the blue ones are related to phase speeds profiles.
4 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 $\sim 175$ s and the mean amplitude is $\sim 1$ arcsec. The same periodicity was found in Doppler shift oscillation by Ebadi (2013); Zaqarashvili et al. (2007); De Pontieu et al. (2007), so the periodicity is probably common for spicules.

The inverted Y-shaped structures are seen at the spicule base which may correspond to the magnetic reconnection origin of it. We observed period shift towards the higher period with height within the observed spicule, which is the signature that the spicule is working as a low pass filter and allows only the low frequencies to propagate towards higher heights. We determined the phase travel times and phase speed profiles for three cases of the studied spicule. Phase speed begins from $\sim 40$ km/s at lower heights and reaches to the maximum value of $\sim 90$ km/s at $\sim 2500 - 3000$ km. Then it decreases to the minimum value of $\sim 20 - 25$ km/s at $\sim 3500 - 4500$ km. An increase in phase speed at lower heights may be related to amplification of magnetic field away from reconnection site. On the other hand, the decreasing behavior at higher heights related to the decrease in mass density and magnetic field strength in these heights.

Therefore, the observed quasi-periodic displacement of spicule axis can be caused due to propagation 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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Fig. 3 Time slice images of the time series in different heights are shown.