

## Seismology of solar spicules based on Hinode/SOT observations

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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. We determined the period of transverse displacement as  $\sim 40 - 150 \pm 8$  s and the mean amplitude as  $\sim 0.1 - 0.5$  arc sec. For the oscillation wavelength of  $\lambda \sim 1/0.06$  arc sec  $\sim 11500$  km, the estimated kink speed is  $\sim 13-83$  km  $s^{-1}$ . We obtained the magnetic field strength in spicules as  $B_0 = 2 - 12.5 \pm 1$  G and the energy flux as  $7 - 227$  J  $m^{-2} s^{-1}$ .

*Keywords:* ISM: Sun, ISM: spicules, ISM: Dynamic parameters

## 1 Introduction

Spicules can be seen almost everywhere at the solar limb. They are highly-dynamic, thin, jet-like features in the solar chromosphere. Spicules have been observed for a very long time and have been the subject of numerous reviews [1, 2, 3, 4]. Perhaps the most interesting aspect about spicules is their potential to mediate the transfer of energy and mass from the photosphere to the corona. This potential has been recognized early [1, 5, 6], but the lack of high-quality observations prevented a better understanding of spicules and their link to the corona [7]. The advent of the Hinode Solar Optical Telescope (*SOT*) [8, 9, 10] provided a quantum leap in the understanding of spicules and their properties. With its seeing free high spatial and temporal resolution observations of the chromosphere, Hinode showed much more dynamic spicules than previously thought and re-ignited the discussion on their potential to heat the corona [11, 12, 13]. While there are several recent studies of the properties of spicules using Hinode/SOT [11, 14, 15], they are either preliminary results papers or cover only one or two data sets.

It is encouraging that the results from the various groups agree quite well, despite the difficulties in obtaining reliable magnetic field measurements at the limb. Lopez-Ariste & Casini [16] used full Stokes polarimetry and Hanle effect modelling of He I D3 spectra and find that the magnetic field strength is mostly 10 G at 3500 km height, with some spicules possibly showing fields up to 40 G. Trujillo et al. [17] used both the Hanle and Zeeman effects and full Stokes polarimetry of the He I 10830 line and find 10 G at 2000 km and again, some spicules with field strengths up to 40 G. Doppler velocities of solar limb spicules show oscillations with periods of 20 – 55 and 75 – 110 s. There is also clear evidence of 3-min oscillations at the observed heights. The observed upwards steady flows are 20 – 25 km  $s^{-1}$  with short periods (20 – 55 s) in type I spicules. Type I spicules have typical lifetimes of 150 – 400 s and maximum ascending velocities of 15 – 40 km  $s^{-1}$ . Type II Spicules in the quiet sun have lifetimes between 50 – 150 s, and slightly less in coronal holes. They have a maximum velocity between 40 – 100 km  $s^{-1}$ , with a very small amount with velocities greater than 150 km  $s^{-1}$  [1].

All spicule oscillations events are summarized in a recent review by Zaqrashvili & Erdélyi [18]. 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 ( $\geq 2$  min) [18]. The most frequently observed oscillations lie in the period ranges of 3 – 7 min and 50 – 110 s. These spiky dynamic jets are propelled upwards at speeds of about 20 – 25 km s<sup>-1</sup> from photosphere into the magnetized low atmosphere of the sun. Their diameter varies from spicule to spicule having the values from 400 km to 1500 km. The mean length of classical spicules varies from 5000 km to 9000 km, and their typical life time is 5 – 15 min.

The typical electron density at heights where the spicules are observed is  $3.5 \times 10^{-10} - 2 \times 10^{-11}$  kg m<sup>-3</sup>, and their temperatures are estimated 5000 – 8000K [1]. Their periods are estimated 20 – 55 and 75 – 110 s. De Pontieu et al. [11], based on Hinode observations concluded that the most expected periods of transverse oscillations lay between 100 – 500 s, which interpreted as signatures of Alfvén waves. Phase speed begins from  $\sim 40$  km s<sup>-1</sup> at lower heights and reaches to the maximum value of  $\sim 90$  km s<sup>-1</sup> at  $\sim 2500 - 3000$  km. Then, it decreases to the minimum value of  $\sim 20 - 25$  km s<sup>-1</sup> at  $\sim 3500 - 4500$  km [19]. Therefore, the observed quasi-periodic displacement of spicule axis can be caused due to fundamental standing mode of kink waves. The energy flux storied in the oscillation is estimated as 150 J m<sup>-2</sup> s<sup>-1</sup>, which is of the order of coronal energy losses in quiet Sun regions [19]. Spicule seismology, which means the determination of spicule properties from observed oscillations and was originally suggested by [18], has been significantly developed during last years [19, 20, 21].

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 for determining period, amplitude, phase speed, magnetic field, Alfvén speed and energy flux of the studied spicules. Observed waves can be used as a tool for spicule seismology. A description of the observations and image processing is made in Section 2 and in Section 3 we discuss spicules properties. Finally, our conclusions are summarized in Section 4.

## 2 Observations and data processing

We used a time series of Ca II H-line (396.86 nm) obtained on 22 January, 2007, during 23:26 to 23:42 UT by the Solar Optical Telescope onboard [9]. The spatial resolution reaches 0.2 arcsec ( $\sim 150$  km) and the pixel size is 0.109 arcsec ( $\sim 80$  km) in the Ca II H-line. The time series has a cadence of 20 seconds with an exposure time of 0.5 seconds. The position of *X-center* and *Y-center* of slot are 945 arcsec and 0 arcsec, while X-FOV and Y-FOV are 223 arcsec and 112 arcsec, respectively.

The “fgprep”, “fgrigidalign” (available in solarsoft, <http://www.lmsal.com/solarsoft>) and “madmax” IDL algorithms are used to reduce the images spikes and jitter effect, to align time series, and to enhance the finest structures, respectively [22, 23].

## 3 Results and Discussions

In Figure 1, we presented the full view Ca II H-line image of the equator which contains the studied spicules. The processed spicules are indicated by red arrows on this image. This image was taken by Hinode/SOT telescope on 22 Jan, 2007, 23:26:04 UT. We used the time series images of this region and determined period, amplitude, phase speed, magnetic field, Alfvén speed and energy flux of the studied spicules. To this end, we selected 14 random spicules and used time-slice diagrams to illustrate their transversal oscillations.

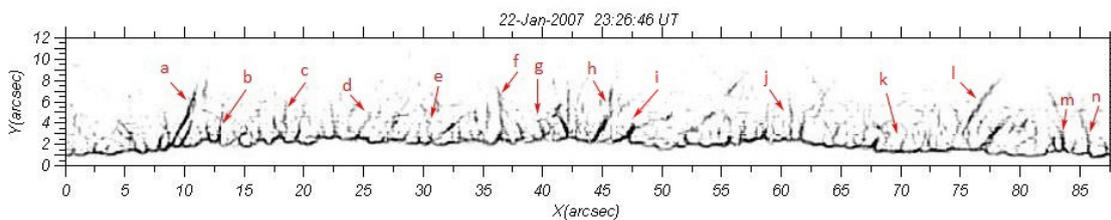


Figure 1: The full view Ca II H-line image of the solar equator which contains the processed spicules. The red arrows show the studied spicules. We used the “madmax” algorithm to enhance the finest structures.

Table 1: The amplitude ( $\xi$ ), oscillation period( $T_{obs}$ ), phase speed( $v_k$ ), magnetic field( $B_0$ ) and energy flux( $F$ ) for the spicule oscillations.

$No$	$T_{obs}$ (s)	$\xi(arcsec)$	$v_k(kms^{-1})$	$B_0$ (G)	$F(Jm^{-2}s^{-1})$
a	70	0.3	57	8.9	123
b	70	0.2	38	5.9	36
c	40	0.1	33	5	8
d	50	0.1	26	4	7
e	55	0.2	48	7.5	46
f	90	0.4	59	9.2	227
g	40	0.25	83	13	125
h	100	0.35	47	7.2	138
i	50	0.3	80	12.5	172
j	40	0.15	50	7.7	27
k	60	0.25	56	8.7	83
l	150	0.15	13	2	7
m	100	0.2	27	4.2	26
n	80	0.15	25	5.4	14

In Figure 2, we presented the time slice diagrams of the time series which consists of 30 consecutive images. The bright regions show the transversal oscillations of spicules axis. The clear quasi-periodic transverse motion of the spicules axis is seen on the figure. It should be noted that these diagrams are performed at the same height from the limb. In Figure 3, we presented the time slice diagrams and fitted polynomials for three spicules. As it is clear, the fitted functions are the best ones for our observed results. We estimated the oscillation period and amplitude at each diagram and presented them in Table 1. The density is almost homogeneous along the spicule length [1]; therefore, the density scale height should be much longer than the spicule length. The variation of oscillation amplitude with height cannot be due to the decreased density. So, we may assume 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  $\sim kz$ . Hence, the oscillation wavelength is  $\lambda \sim 1/0.06 \text{ arc sec} \sim 11500 \text{ km}$  [24]. This allows the estimation of the kink speed as  $v_k \sim 13\text{--}83 \text{ km s}^{-1}$ .

It is possible to estimate the Alfvén speed and consequently magnetic field strength through them. Kink waves are transverse oscillations of magnetic tubes and the phase

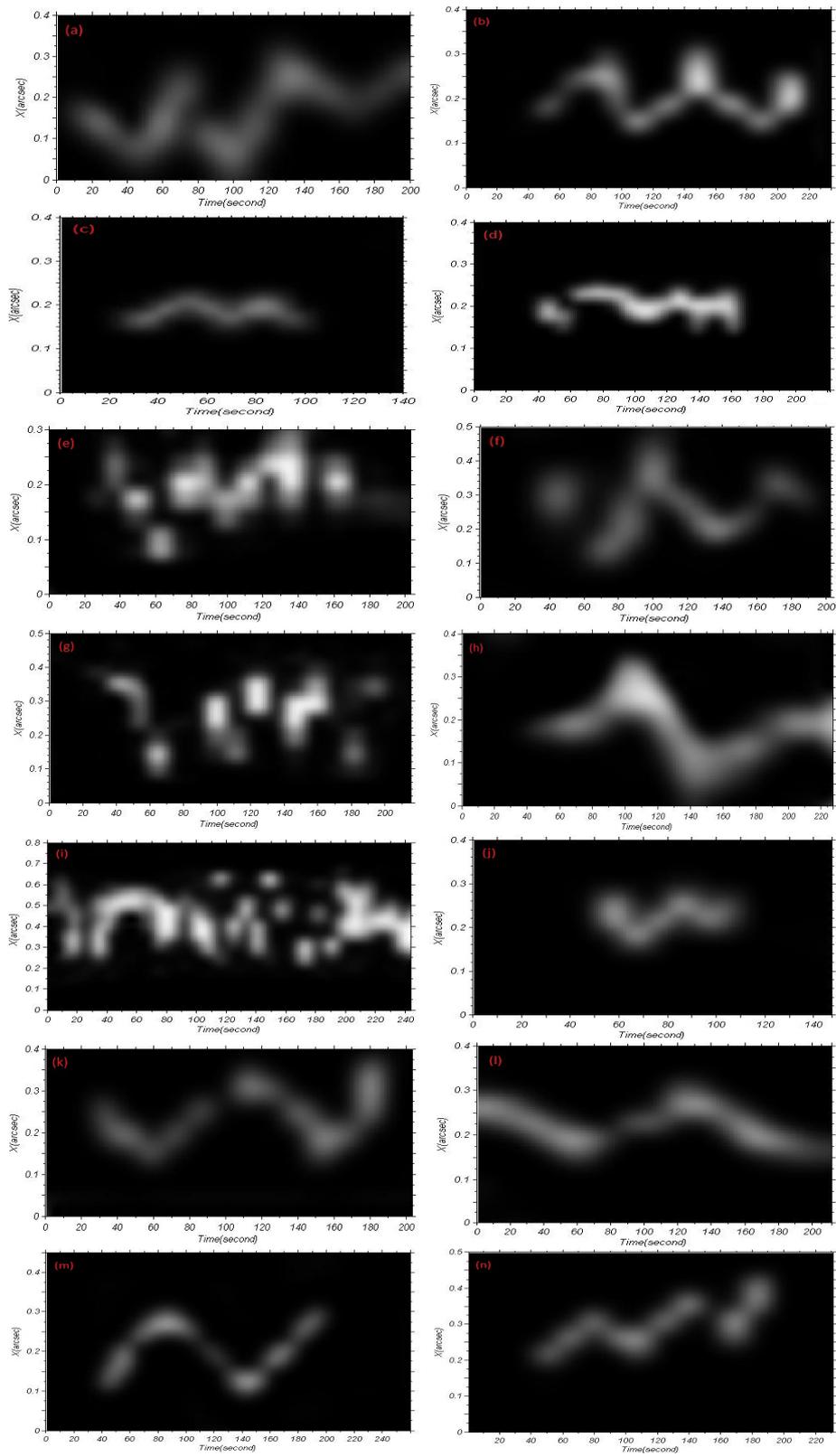


Figure 2: Time slice diagrams of the spicules in Ca II H-line. Axes are in heliocentric coordinates, where  $1'' \approx 725\text{km}$ .

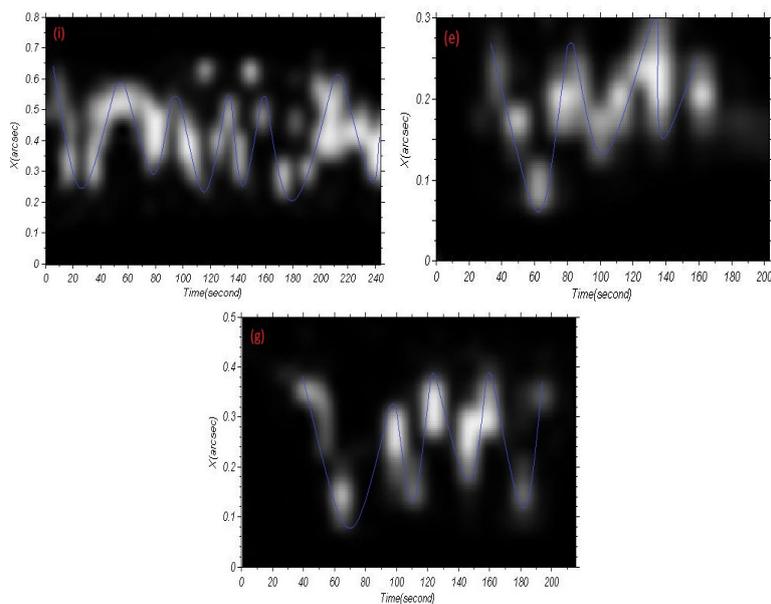


Figure 3: Time slice diagrams of spicule in Ca II H-line. The blue line is a fit to the oscillation of the spicule.

speed for a straight homogenous tube can be written as:

$$v_k = \frac{\lambda}{T_{obs}} = v_A \sqrt{\frac{\rho_0}{\rho_0 + \rho_e}}, \quad (1)$$

where  $v_A \equiv B_0/\sqrt{\mu_0\rho_0}$  is the Alfvén speed inside the tube,  $\lambda$  is the wavelength and  $T_{obs}$  is the observed oscillation period.  $\rho_e$  and  $\rho_0$  are the plasma density outside and inside of tube, respectively. The density in spicules is  $3 \times 10^{-10} \text{ kg m}^{-3}$  and  $\rho_e/\rho_0 \simeq 0.02$  [18, 24]. The oscillation amplitude and phase speed allows to estimate the energy flux,  $F$ , storied in the oscillations:

$$F = \frac{1}{2}\rho v^2 v_k \quad (2)$$

where  $\rho$ ,  $v$  and  $v_k$  are density, wave amplitude and phase speed, respectively [25]. The wave velocity can be determined as  $v = \xi/T_{obs}$ , where  $\xi$  is the axis displacement estimated as  $\sim 0.1 - 0.5 \text{ arcsec}$  and  $T_{obs}$  is the oscillation period estimated as  $\sim 40 - 150 \pm 8 \text{ s}$ . With these parameters, the energy flux is estimated as  $F = 7 - 227 \text{ J m}^{-2} \text{ s}^{-1}$ .

Using the kink speed, the magnetic field strength in spicules is estimated as  $B_0 = 2 - 12.5 \pm 1 \text{ G}$ . This is in good agreement with recently estimated magnetic field strengths in quiet-Sun spicules ( $\sim 10\text{G}$ ), which was obtained by spectropolarimetric observations of solar chromosphere in He I  $\lambda 10830$  [17, 26, 24].

## 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 studied 14 random

spicules and found that their axis undergo quasi-periodic transverse displacements. The period of the transverse displacements are  $\sim 40 - 150 \pm 8$  s and the amplitude are  $\sim 0.1 - 0.5$  arc sec. The same periodicity was found in Doppler shift oscillation by Zaqarashvili & Erdélyi [18] and De Pontieu et al. [11], so the periodicity is probably common for spicules. The magnetic field strength in spicules is estimated as  $B_0 = 2 - 12.5 \pm 1$  G. These magnetic field strengths are smaller than the values calculated by Zaqarashvili & Erdélyi [18]. We think that the observed quasi-periodic displacement of spicule axis can be caused due to standing kink waves. The energy flux storied in the oscillations is estimated as  $7 - 227 \text{ J m}^{-2} \text{ s}^{-1}$ , which is of the order of coronal energy losses in quiet Sun regions.

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## References

- [1] Beckers, J.M., 1968, *solphys*, 3, 367
- [2] Beckers, J.M., 1972, *aap*, 10, 73
- [3] Suematsu, Y., Wang, H., Zirin, H., 1995, *apj*, 450, 411
- [4] Sterling, A.C., 2000, *solphys*, 196, 79
- [5] Pneuman, G. W., Kopp, R.A., 1997, *solphys*, 57, 49
- [6] Athay, R.G., Holzer, T.E., 2005, *apj*, 255, 743
- [7] Withbroe, G. L., 1983, *apj*, 267, 825
- [8] Kosugi, T., Matsuzaki, K., Sakao, T., et al., 2007, *solphys*, 243, 3
- [9] Tsuneta, S., Ichimoto, K., Katsukawa, Y., et al., 2008, *solphys*, 249, 167
- [10] Suematsu, Y., Tsuneta, S., Ichimoto, K., et al., 2008, *solphys*, 249, 197
- [11] De Pontieu, B., McIntosh, S.W., Carlsson, M., et al., 2007, *Science*, 318, 1574
- [12] De Pontieu, B., McIntosh, S.W., Hansteen, V.H., Schrijver, C.J., 2009, *apj*, 701, L1
- [13] De Pontieu, B., McIntosh, S.W., Carlsson, M., et al., 2011, *Science*, 331, 55
- [14] Anan, T., Kitai, R., Kawate, T., et al., 2010, *PASJ*, 62, 871
- [15] Zhang, Y.Z., Shibata, K., Wang, J.X., et al., 2012, *apj*, 750, 16
- [16] Lopez-Ariste, A., Casini, R., 2005, *aap*, 436, 325
- [17] Trujillo Bueno, J., Merenda, L., Centeno, R., Collados, M., Landi DeglInnocenti, E., 2005, *apj*, 619, L191
- [18] Zaqarashvili, T.V., Erdélyi, R., 2009, *ssr*, 149, 335

- [19] Ebadi, H., Khoshrang, M., 2014, *apss*, 352, 2
- [20] Verth, G., Goossens, M., He, J.-S., 2011, *apjl*, 733, 15
- [21] Ebadi, H., Ghiassi, M., 2014, *apss*, 353, 1
- [22] Shimizu, T., Nagata, S., Tsuneta, S., et al., 2008, *solphys*, 249, 221
- [23] Koutchmy, O., Koutchmy, S., In: O. von der Lühe (ed.): *High Spatial Resolution Solar Observations: Proceedings of the Tenth Sacramento Peak Summer Workshop* (Sunspot, NM, August 22–26, 1988), p. 217, National Solar Observatory/Sacramento Peak, Sunspot, NM 88349 (1989)
- [24] Ebadi, H., Zaqarashvili, T.V., Zhelyazkov, I., 2012, *apss*, 337, 33
- [25] Vranjes, J., Poedts, S., Pandey, B.P., De Pontieu, B., 2008, *aap*, 478, 553
- [26] Singh, K.A.P., Dwivedi, B.N., 2007, *New Astron.*, 12, 479