

Multi-thermal dynamics and transverse oscillations of solar spicules revealed by coordinated SST, IRIS, and SDO observations

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ABSTRACT

Context. Solar spicules are highly dynamic chromospheric jets that play an important role in the mass and energy balance of the solar atmosphere, even though their connection to the transition region and corona remains unclear.

Aims. We investigated the dynamical and multi-thermal properties of spicules, their connection to higher atmospheric layers, and their transverse oscillations and associated energy flux.

Methods. We analyzed coordinated high-resolution observations from the Swedish 1-m Solar Telescope in H α , the Interface Region Imaging Spectrograph in Si IV 1400 Å, and the Solar Dynamics Observatory/Atmospheric Imaging Assembly coronal channels. Space-time diagrams, spectral analysis, and wavelet techniques were used to study temporal evolution, Doppler velocities, and oscillatory properties. Transverse displacements of spicules were tracked to estimate wave properties and energy flux.

Results. Space-time analysis reveals a clear correspondence between chromospheric spicules and coronal emission in AIA 171 Å, evolving coherently with spicule extension. Doppler velocities from H α and Si IV show opposite signs, indicating multi-thermal plasma flows. Wavelet analysis reveals frequently dominant ~3-minute oscillations, along with high-frequency transverse oscillations (65–270 s) with velocity amplitudes of 3.3–9.9 km s⁻¹ and a mean energy flux of $(2.14 \pm 0.78) \times 10^3$ W m⁻².

Conclusions. These results demonstrate that spicules are multi-thermal dynamic structures connected to the transition region and corona and that transverse waves carry substantial energy, highlighting their role in coronal heating.

Key words. Sun: atmosphere – Sun: chromosphere – Sun: corona – Sun: magnetic fields – Sun: photosphere

1. Introduction

The solar chromosphere is a highly dynamic and structured layer that plays a crucial role in mediating the transfer of mass and energy between the photosphere and the corona (Pereira 2019; Carlsson et al. 2019). This complex and highly structured region is shaped by the intricate interplay between magnetic fields, plasma dynamics, and radiative processes. As a result, it hosts a wide variety of dynamic phenomena, including numerous jet-like structures such as spicules (Beckers 1968; De Pontieu et al. 2004; De Pontieu et al. 2007b; Pereira et al. 2012, 2014, 2016; Chaurasiya et al. 2024, 2026a) as well as pervasive wave activity that propagates through different atmospheric layers (Zaqarashvili & Erdélyi 2009; Jess et al. 2023; Chaurasiya & Bayanna 2025; Chaurasiya et al. 2025).

Among the most prominent chromospheric features are spicules, which are ubiquitously observed at the solar limb in chromospheric spectral lines such as H α and Ca II H. Spicules exhibit rapid evolution, with typical lifetimes of a few minutes, lengths of several megametres, and upward velocities ranging from a few to tens of kilometers per second (Beckers 1968;

De Pontieu et al. 2007b; Pereira et al. 2012). Due to their ubiquity and dynamic nature, spicules have long been considered potential contributors to coronal mass supply and heating.

Recent high-resolution observations have revealed that spicules exhibit complex multi-thermal behavior, with signatures extending from chromospheric to transition region temperatures. Observations from the Interface Region Imaging Spectrograph (IRIS) have shown that spicular plasma can reach transition region temperatures, suggesting that spicules may play an important role in supplying heated plasma to higher atmospheric layers (Pereira et al. 2014; Skogsrud et al. 2015; Chaurasiya et al. 2024). Furthermore, coordinated observations with the Solar Dynamics Observatory (SDO) have revealed coronal counterparts associated with spicular activity, supporting the idea that spicules may contribute to coronal dynamics and energy balance (De Pontieu et al. 2011; Henriques et al. 2016; Samanta et al. 2019; Chaurasiya et al. 2024, 2026b). However, the exact physical relation between chromospheric spicules and coronal emission remains a subject of ongoing debate.

In addition to their thermal evolution, spicules exhibit a wide range of wave motions, including Alfvén waves, torsional motions, and transverse oscillations (De Pontieu et al. 2007a, 2012; Okamoto & De Pontieu 2011; Shetye et al. 2021; Bate et al. 2022). These waves are of particular interest because they

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can transport significant energy into the upper solar atmosphere and may contribute to atmospheric heating. Previous studies have reported oscillations with periods ranging from tens of seconds to several minutes, including the ubiquitous 3-minute chromospheric oscillations, which are thought to be associated with upward-propagating magneto-acoustic waves originating in the lower atmosphere (Jess et al. 2015, 2023). However, most studies have focused on vertical velocity oscillations rather than horizontal oscillations.

Despite significant progress, several key questions remain unresolved. In particular, the temporal and spatial relation between chromospheric spicules and coronal emission, the multi-thermal velocity structure of spicules, and the role of oscillations in driving spicule dynamics are not yet fully understood. Coordinated multiwavelength observations combining chromospheric, transition region, and coronal diagnostics provide a powerful means to address these questions.

In this study, we analyzed coordinated high-resolution observations of spicules obtained with the Swedish 1-m Solar Telescope (SST), the Interface Region Imaging Spectrograph (IRIS), and the Solar Dynamics Observatory (SDO). These observations allowed us to simultaneously investigate the chromospheric, transition region, and coronal response associated with spicule evolution. Using space-time analysis, spectroscopic diagnostics, and wavelet techniques, we examined the multi-thermal dynamics, velocity structure, and transverse oscillatory behavior of spicules, and their connection to coronal emission.

The rest of the paper is structured as follows. Section 2 describes the observations used in this study. Section 3 presents the results, including the multiwavelength evolution of the solar atmosphere and the wave analysis. The results are discussed in Sect. 4 followed by the conclusion in Sect. 5.

2. Observations

We analyzed coordinated datasets of a quiet-Sun (QS) region near the north pole of the Sun, observed on 17 June 2014 between 10:20 UT and 11:15 UT. The heliocentric coordinates of the target region were ($24''$, $939''$), giving rise to $\mu = \cos \theta = 0.207$, where θ is the heliocentric angle between the observer's line of sight and the local solar vertical. The observed region was predominantly quiet, without any major active region or plage. Further information regarding the data from various instrumentation facilities is provided below.

2.1. Swedish 1-m Solar Telescope

The SST dataset consists of imaging spectroscopic observations of the $H\alpha$ spectral line acquired with the CRisp Imaging SpectroPolarimeter (CRISP; Scharmer et al. 2008) mounted on the SST. The observations cover a duration of approximately 55 minutes, with a temporal cadence of 5.5 s. The seeing conditions were excellent during this period. The field of view is about $61'' \times 61''$, and the spatial sampling is $0''.058$ per pixel.

The $H\alpha$ line was sampled at 25 wavelength positions spanning a spectral range of $\pm 1.2 \text{ \AA}$ around the line center. The data were processed using the CRISPRED reduction pipeline (de la Cruz Rodríguez et al. 2015), which includes standard calibration procedures such as dark subtraction, flat-field correction, and image restoration. Image reconstruction was performed using the multi-object multi-frame blind deconvolution (MOMFBD)

technique (Van Noort et al. 2005) to improve the spatial resolution. Additional details about this SST observation and reduction procedures can be found in Pereira et al. (2016).

2.2. Interface Region Imaging Spectrograph (IRIS)

We used coordinated level 2 data from the Interface Region Imaging Spectrograph (IRIS; De Pontieu et al. 2014) obtained under OBSID 3820259453 as part of the SST–IRIS joint observing campaign which consisted of both slit-jaw images (SJIs) and spectroscopic observations. The IRIS observations cover the interval from 07:30 UT to 11:00 UT on 17 June 2014, overlapping with most of the SST observing period but not covering the final 15 minutes. The level 2 data were processed using the standard IRIS reduction pipeline (*iris_prep*, version 2.65), which includes dark current subtraction, flat-field correction, geometrical correction, and wavelength calibration.

The SJIs were acquired in the Si IV 1400 Å and Mg II k 2796 Å channels, both with a spatial sampling of $0''.166$ per pixel. The average temporal cadence of the SJIs was 18.82 s. These channels sample plasma formed in the transition region and upper chromosphere, respectively. In addition to the imaging observations, IRIS performed spectroscopic measurements in a large sit-and-stare mode with an effective cadence of 9.2 s. The spectral windows include chromospheric and transition region lines such as C II 1336 Å, Si IV 1394 Å and 1403 Å, and Mg II k 2796 Å. In the present study, we focus on the Si IV 1394 Å line, which has a spectral sampling of approximately 25.44 mÅ. The absolute wavelength calibration provided by the level 2 pipeline is based on neutral reference lines formed in the lower solar atmosphere, where intrinsic velocities are typically small (De Pontieu et al. 2014).

For co-alignment purposes, the IRIS SJI images were resampled to match the spatial sampling of the SST observations using bilinear interpolation. The alignment was refined by cross-correlating nearly simultaneous IRIS SJI 2796 Å images with the corresponding SST wideband images.

2.3. Solar Dynamics Observatory (SDO)

Context observations from the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) onboard the Solar Dynamics Observatory (SDO; Pesnell et al. 2012) were obtained using the cutout service. We used extreme ultraviolet images from the AIA 171 and 193 Å channels, as well as ultraviolet images from the 1600 and 1700 Å channels. The AIA images have a spatial sampling of $0''.6$ per pixel. The EUV channels have a temporal cadence of 12 s, while the UV channels have a cadence of 24 s. To ensure accurate co-alignment, the AIA images from different channels were first aligned with each other. The aligned images were then resampled to match the SST spatial sampling. The final alignment between SDO and SST observations was achieved by cross-correlating nearly simultaneous AIA 1700 Å images with SST $H\alpha$ wing images, which sample similar atmospheric heights. Figure 1 presents an overview of the coordinated observations, showing the chromospheric structures observed in the $H\alpha$ line wing and line center, together with the co-aligned IRIS SJI 1400 and AIA 171 Å images, which sample the transition region and the lower corona, respectively.

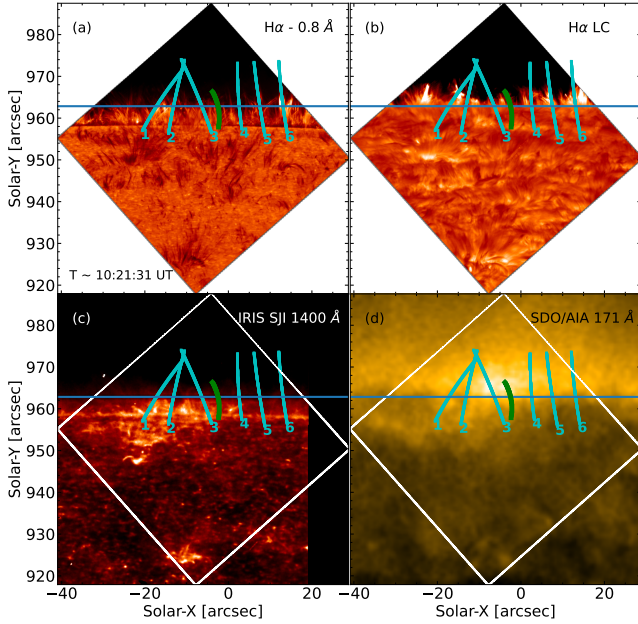


Fig. 1. Overview of coordinated multiwavelength observations sampling the chromosphere, transition region, and corona. Panels a and b: SST $H\alpha$ $-0.8 \text{ \AA}$ wing and $H\alpha$ line core images, respectively, representing the lower and middle chromosphere. Panel c: IRIS SJI $1400 \text{ \AA}$ image, sampling the transition region. Panel d: SDO/AIA $171 \text{ \AA}$ image, representing the million-degree corona. The horizontal blue line indicates the location of the IRIS spectrograph slit. The green line marks the positions of the virtual slit used to construct the space-time diagrams, as shown in Fig. 2. The six cyan lines mark the positions of the selected virtual slits, which are used to construct multi-thermal space-time diagrams for investigating the temporal and spatial evolution of structures across different atmospheric layers. The white diamond outlines the common field of view of the SST observations, overplotted on the IRIS and AIA panels for reference.

3. Results

3.1. Dynamical properties of the observed spicules

We first examined whether the dynamical properties of these spicules are broadly consistent with those reported for spicules in previous studies. In particular, earlier observations have shown that spicules frequently exhibit rapid upward motions, projected velocities of several tens of kilometers per second, and approximately parabolic trajectories associated with decelerating motions.

To assess these characteristics, we constructed space-time diagrams along a selected virtual slit (see Fig. 1; green slit) and examined shorter temporal windows to better isolate the evolution of individual spicules. Representative examples are shown in Fig. 2. The temporal evolution of the spicule apex was approximated using a parabolic fit, while the initial upward phase was fitted with a linear function to estimate the projected upward velocity.

The inferred projected velocities are on the order of $30\text{--}40 \text{ km s}^{-1}$, which is broadly consistent with velocity ranges previously reported for limb spicules (De Pontieu et al. 2007b; Pereira et al. 2012). Having established that the analyzed structures exhibit characteristic spicular dynamics, we next investigated their multi-thermal evolution across chromospheric, transition-region, and coronal diagnostics.

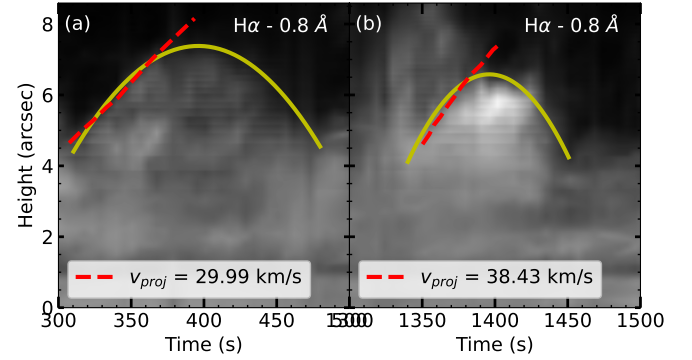


Fig. 2. Representative examples of limb spicules exhibiting parabolic trajectories in the $H\alpha - 0.8 \text{ \AA}$ space-time diagrams for the green slit shown in Fig. 1. The yellow curves indicate parabolic fits tracing the temporal evolution of the spicule apex, while the dashed red lines represent linear fits to the initial upward phase used to estimate the projected upward velocity (v_{proj}).

3.2. Multi-thermal evolution of spicules

To investigate the multi-thermal evolution of spicules across different layers of the solar atmosphere, we constructed space-time diagrams using virtual slits placed along selected spicular structures. The slit positions were chosen to sample different regions within the field of view and follow the orientation of clearly identifiable, elongated spicules. A total of six representative events were analyzed. The locations of these virtual slits are marked by cyan lines in Fig. 1. Each slit has a width of seven SST pixels, corresponding to a projected width of approximately 0.29 Mm on the plane of sky. The resulting space-time diagrams are shown in Fig. 3 for slits 1–4 and in Fig. 4 for slits 5 and 6. These diagrams sample the temporal evolution of spicular structures from the chromosphere, as observed in SST $H\alpha$, from the transition region and corona, as observed in IRIS and AIA channels.

3.3. Spectral signatures and Doppler velocities

To quantify the velocity variations associated with the spicules at different atmospheric heights, we analyzed the spectral profiles obtained from SST $H\alpha$ and IRIS Si IV $1394 \text{ \AA}$ observations at selected locations. These locations are indicated by colored circles in Fig. 5. Since the observations were performed near the solar limb, the derived line-of-sight velocities primarily correspond to transverse plasma motions.

The Doppler velocities were estimated by determining the wavelength shift of the spectral line-centers relative to the averaged profile, which served as a reference profile. For the $H\alpha$ line, the line-center position was obtained by fitting a second-order polynomial (parabola) around the line core, whereas for the Si IV $1394 \text{ \AA}$ line, a Gaussian function was fitted to the observed spectral profile. The derived wavelength shifts were subsequently converted into Doppler velocities.

The reference profile for $H\alpha$ was constructed by averaging all spectral profiles over the on-disk field of view for ten consecutive line scans. To assess the robustness of this choice, we also tested alternative averaging procedures, including averaging profiles within a 100×70 pixel QS region (devoid of obvious spicular structures) over ten consecutive line scans. The resulting reference line-center positions differed by only $\sim 0.02 \text{ km s}^{-1}$, indicating negligible sensitivity to the adopted averaging procedure. For the Si IV $1394 \text{ \AA}$ line, the reference profile was obtained

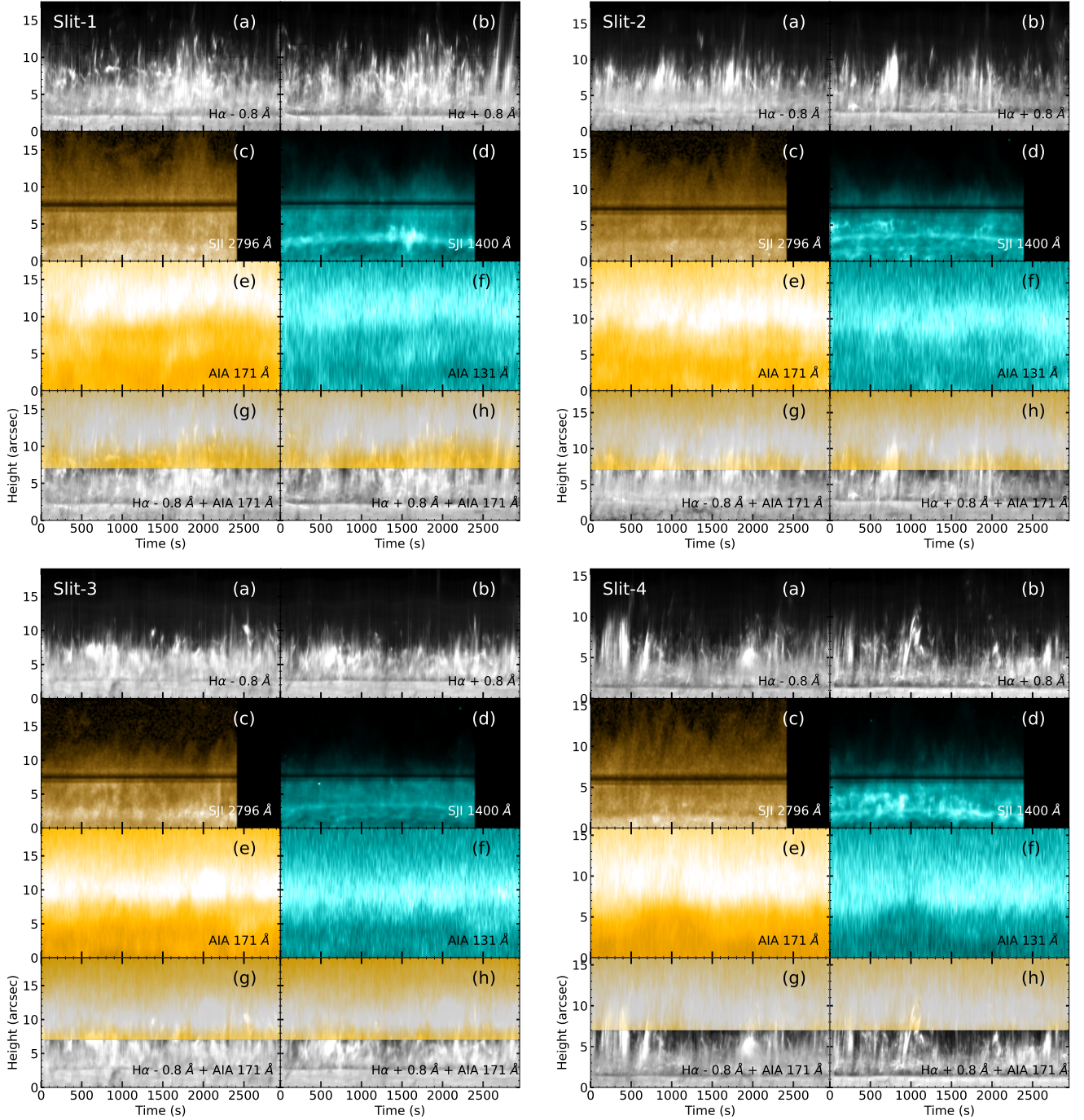


Fig. 3. Multi-thermal space-time maps constructed along four different slits (see Fig. 1) using coordinated SST, IRIS, and SDO observations, illustrating the temporal and spatial evolution of plasma across different layers of the solar atmosphere. Top row (each example): SST $H\alpha$ -0.8 Å (left) and $H\alpha$ $+0.8$ Å (right) wing maps, sampling the lower chromosphere and revealing numerous upward-propagating jet-like structures. Second row: IRIS SJI 2796 Å (left) and SJI 1400 Å (right) maps, representing the upper chromosphere and transition region, respectively. Third row: corresponding coronal emission observed in the SDO/AIA 171 Å (left) and 131 Å (right) channels. Bottom row: composite maps formed by overlaying $H\alpha$ -0.8 Å with AIA 171 Å (left) and $H\alpha$ $+0.8$ Å with AIA 171 Å (right), highlighting the temporal and spatial correspondence between chromospheric jets and their coronal counterparts. The horizontal axis represents time, while the vertical axis shows the projected height along the slit.

by averaging spectra over approximately 100 temporal frames and 500 spatial pixels along the slit. The resulting spectra and derived Doppler velocities for both $H\alpha$ and Si IV 1394 Å are presented in Fig. 6.

3.4. Wavelet analysis of chromospheric velocity oscillations

To investigate the temporal behavior of velocity oscillations, we performed a wavelet analysis (Torrence & Compo 1998) of the $H\alpha$ line-center velocity time series at the same selected locations where the Doppler velocities from $H\alpha$ and Si IV 1394 Å

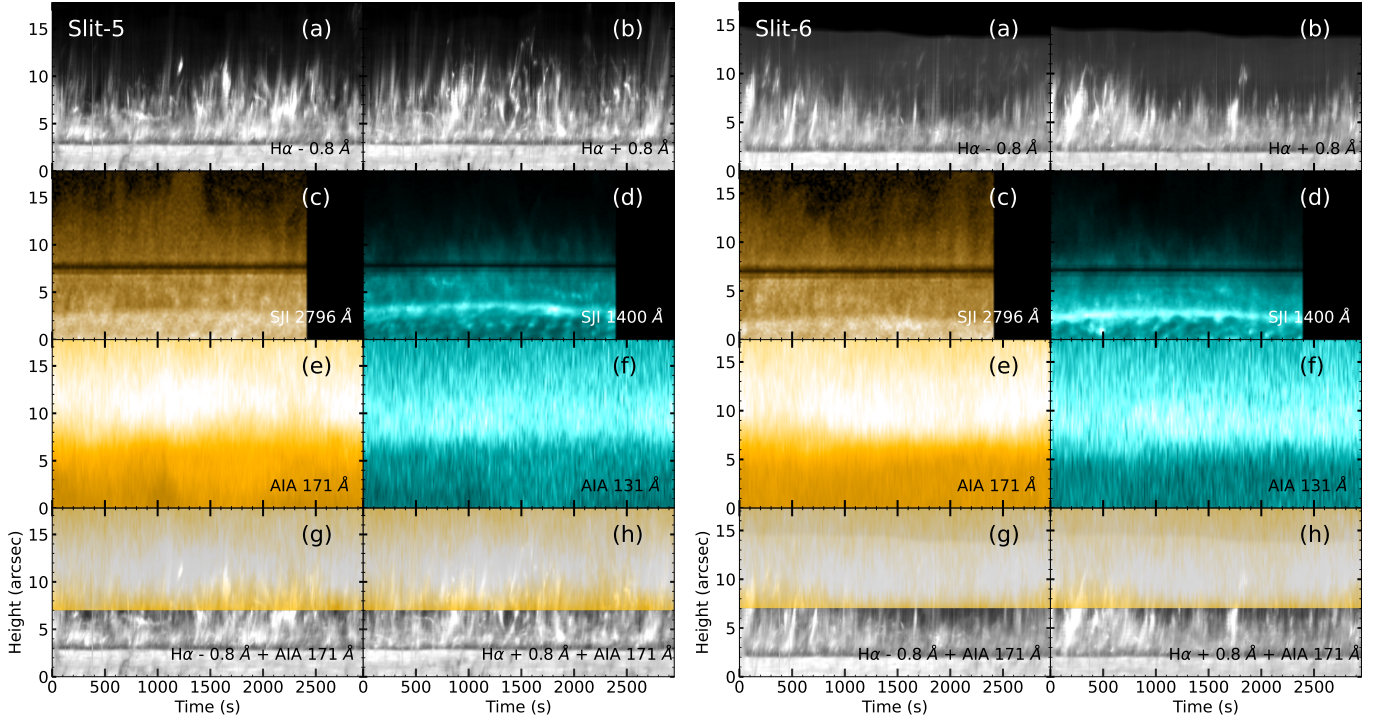


Fig. 4. Same as Fig. 3 but for slit-5 and slit-6. These examples confirm the consistent multi-thermal evolution of the observed jet-like structures.

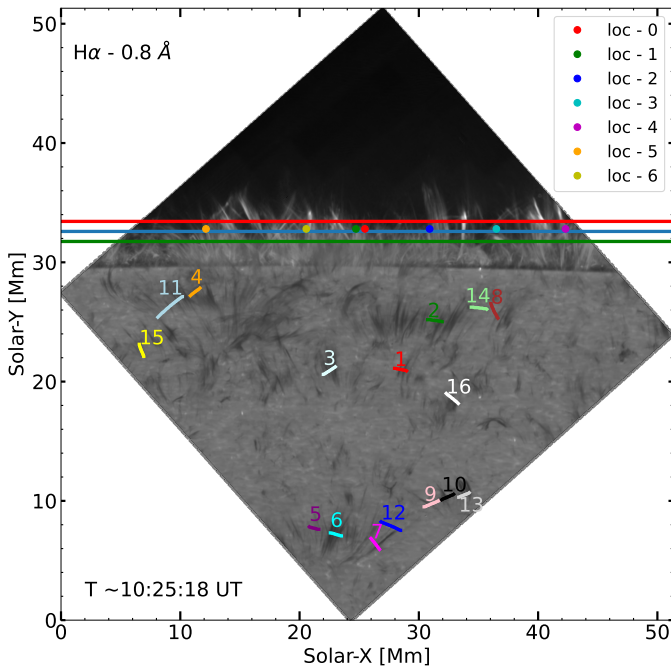


Fig. 5. Context image showing the locations of the 16 virtual slits used to investigate transverse waves in spicules (numbered and marked by colored segments), whose space-time diagrams are presented in Fig. 8. The horizontal blue line indicates the position of the IRIS spectrograph slit. The seven colored circles mark the selected locations along the IRIS slit where the IRIS spectra are compared with the SST H α spectra (see Fig. 6) and used for the wavelet analysis (see Fig. 7). The horizontal green and red lines indicate positions approximately 0.84 Mm below and above the IRIS slit, respectively. The background image is an SST H α -0.8 Å map at the reference time indicated in the lower-left corner.

were compared (See Fig. 5). In addition to the reference positions, the analysis was also carried out at locations approximately 0.84 Mm above and below each reference point, while keeping the horizontal position fixed. This approach allowed us to examine the variation of oscillatory behavior with height in the chromosphere.

The results of the wavelet analysis are shown in Fig. 7, which displays the temporal evolution of the oscillatory power and the corresponding dominant periods. It should be noted that wavelet analysis was not applied to the Si IV velocity measurements due to the presence of pointing jitter in the IRIS observations.

3.5. Estimation of transverse wave parameters: period, amplitude, velocity, and energy flux

To quantify the transverse oscillatory motions of individual spicules on disk, we tracked the displacement of the spicule axis as a function of time using the space-time diagrams shown in Fig. 8. The central ridge of each oscillating structure was identified, and a polynomial function was fitted to trace its temporal evolution. This procedure provides the transverse displacement, $y(t)$, of the spicule axis.

The oscillation period was determined by measuring the time interval between successive intensity maxima in the displacement curves. In cases where only one maximum was clearly identifiable, the period was estimated from the time difference between a complete crest and the adjacent trough.

$$A = \frac{y_{\max} - y_{\min}}{2}, \quad (1)$$

$$v(t) = \frac{dy}{dt}. \quad (2)$$

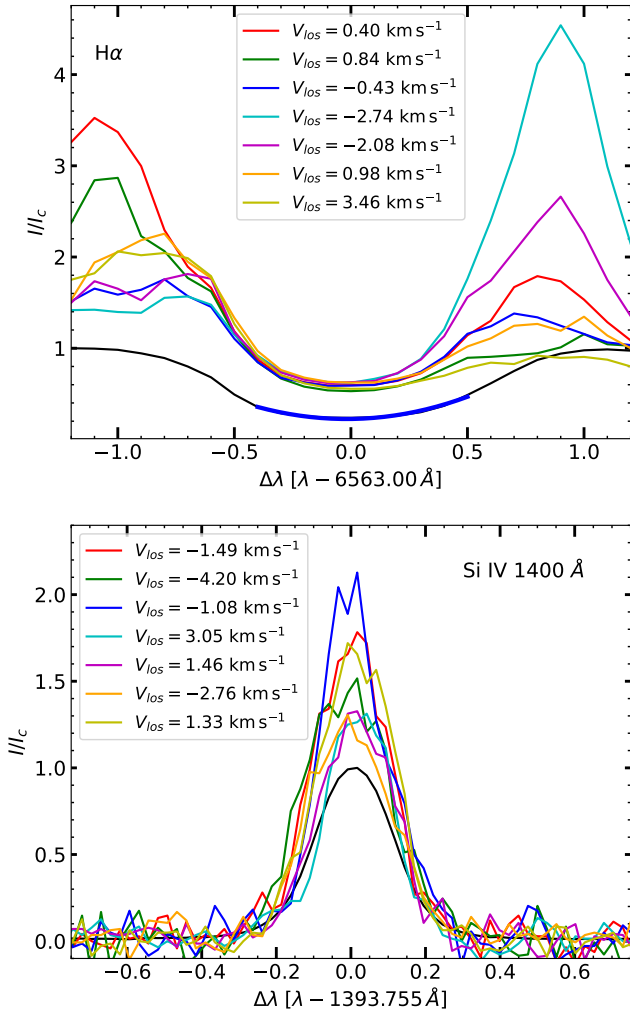


Fig. 6. Observed spectral profiles at the seven selected locations marked in Fig. 5. Top: SST $H\alpha$ line profiles. Bottom: corresponding IRIS Si IV 1400 Å line profiles. The black curve in each panel represents the reference average profile used for estimating the relative Doppler shifts. In the upper panel, the thick blue curve overplotted on the average $H\alpha$ profile indicates the quadratic (parabolic) fit used to determine the line-center position, where the minimum of the fitted parabola is taken to estimate the Doppler shift of the $H\alpha$ line. The different colored curves represent the spectra at the seven selected spatial locations, with the corresponding line-of-sight Doppler velocities indicated in the legends.

The displacement amplitude, A , was calculated using Eq. (1) as half of the peak-to-peak variation, where $y_{\max}$ and $y_{\min}$ represent the maximum and minimum transverse displacements, respectively. The transverse velocity, $v(t)$, was then obtained from the temporal derivative of the displacement using Eq. (2).

$$v_{\text{rms}} = \sqrt{\left\langle \left(\frac{dy}{dt} \right)^2 \right\rangle}. \quad (3)$$

Since the observed oscillations are not strictly sinusoidal, we estimated the characteristic velocity amplitude using the root-mean-square (RMS) velocity defined by Eq. (3). The energy flux carried by the transverse waves was then estimated as

$$F = \frac{1}{2} \rho v_{\text{rms}}^2 V_A, \quad (4)$$

where ρ is the plasma density and V_A is the Alfvén speed. The energy flux was calculated using Eq. (4), adopting typical chromospheric spicule values of $\rho = 5 \times 10^{-10} \text{ kg m}^{-3}$ and $V_A = 200 \text{ km s}^{-1}$ (De Pontieu et al. 2007c).

The measured transverse oscillation parameters and the corresponding energy flux values are summarized in Table 1. The uncertainties in the transverse wave parameters were estimated using standard error propagation. The uncertainty in the displacement amplitude was taken as one SST pixel ($\delta A = 42 \text{ km}$), while the uncertainty in the period was taken as the temporal cadence of the observations ($\delta P = 5.5 \text{ s}$). Since the velocity depends on both the displacement amplitude and the oscillation period, its uncertainty was estimated as

$$\delta v = v \sqrt{\left(\frac{\delta A}{A} \right)^2 + \left(\frac{\delta P}{P} \right)^2}, \quad (5)$$

where Eq. (5) follows from standard propagation of independent uncertainties. The uncertainty in the energy flux was then obtained by propagating the velocity uncertainty into the energy flux expression, yielding Eq. (6).

$$\delta F = F \left(2 \frac{\delta v}{v} \right). \quad (6)$$

4. Discussion

We used a unique coordinated dataset between SST, IRIS, and SDO, which allowed us to trace the evolution of spicules across the chromosphere, transition region, and corona. Our multi-wavelength space-time analysis reveals a clear correspondence between chromospheric spicules observed in the $H\alpha$ wings and enhanced emission signatures detected in transition region and coronal passbands. The associated coronal brightening is predominantly concentrated near the tip of the spicules and evolves coherently with their motion. This behavior is clearly illustrated in the composite space-time maps constructed using $H\alpha \pm 0.8$ and AIA 171 Å observations (bottom panels g and h of Figs. 3 and 4). The coronal brightening follows the extension of spicules: when spicules are shorter, it appears lower, and when spicules are taller it appears higher. This strongly suggests that the enhanced coronal emission is connected to the tops of spicules. This occurs not only for a few spicules, but also consistently over the entire field of view. To our knowledge, this is the first and most clear detection of spicule coronal signatures seen at the limb.

This observational behavior is consistent with the on-disk findings reported by Chaurasiya et al. (2024), who showed that coronal emission enhancements are co-spatially associated with the tip of spicular structures. If the on-disk scenario described in their study is extended to the limb geometry, the expected observational signature would naturally appear as enhanced emission concentrated near the apparent tip of the spicule, as observed in the present study. In this interpretation, the apparent localization of coronal brightening near the tip reflects the same physical process viewed from a different line-of-sight perspective, thereby reinforcing the interpretation that spicules are directly associated with coronal plasma heating and emission.

In addition to this geometrical interpretation, another possible physical scenario may also contribute to the observed emission distribution. Spicules are known to exhibit multi-thermal plasma properties (e.g., Skogsrud et al. 2015; Chaurasiya et al.

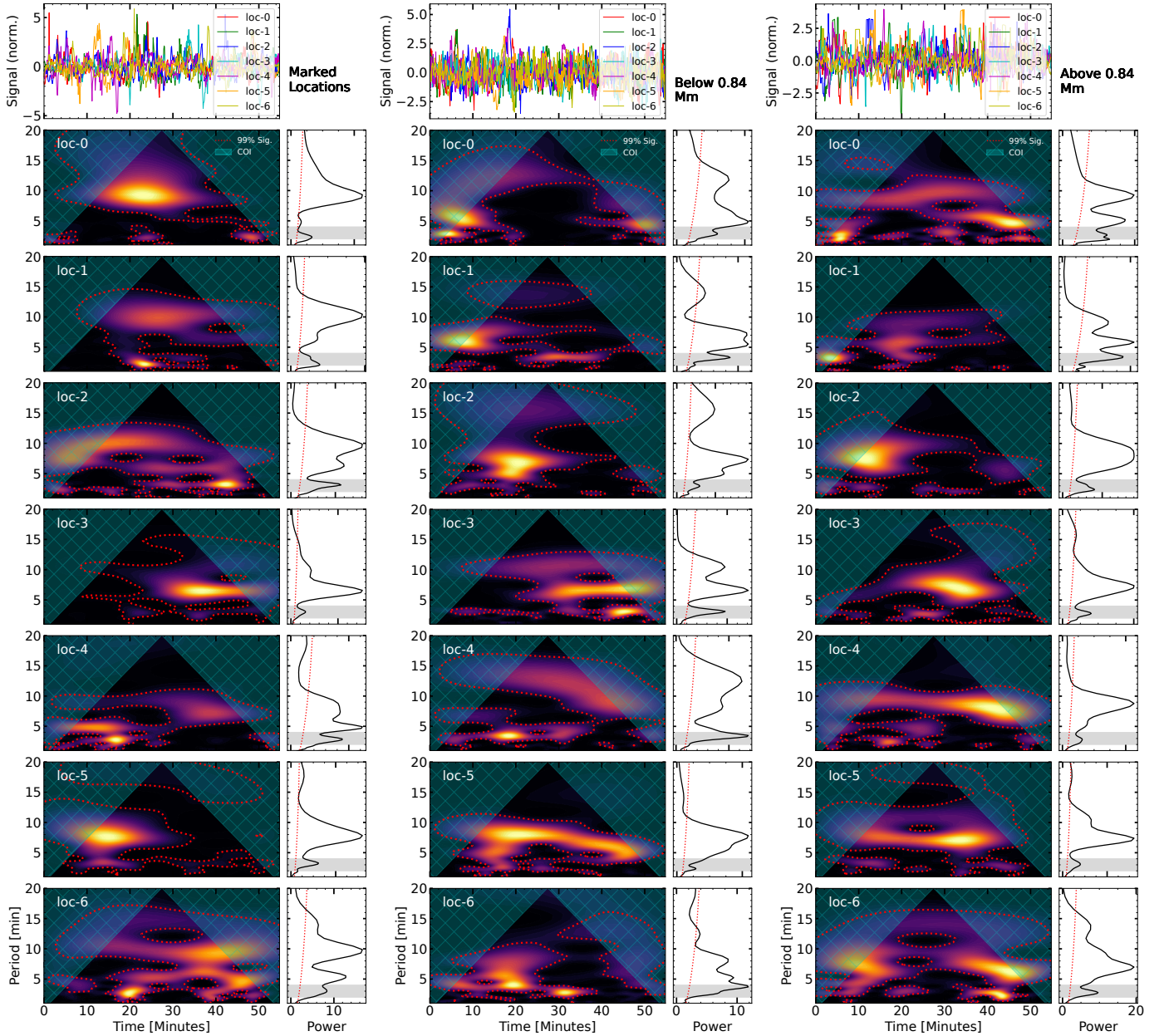


Fig. 7. Wavelet analysis of the $H\alpha$ line-center velocity fluctuations at the seven selected locations shown in Fig. 5. Left: results at the reference locations along the IRIS slit. Middle and right: corresponding wavelet power spectra at positions approximately 0.84 Mm below and 0.84 Mm above the reference locations, respectively. Top subpanel (in each panel): normalized velocity time series. The color map represents the wavelet power as a function of time and period, with the dotted red contours indicating the 99% confidence level. The cross-hatched regions mark the cone of influence. Rightmost subpanels: corresponding global wavelet power spectra, with the dotted red line indicating the 99% significance level. The gray-shaded region represents the period range between 2 and 4 minutes.

2024), which are also evident in our space-time maps showing significant simultaneous enhancement in chromospheric and transition-region diagnostics. The presence of cooler and partially ionized plasma within spicules may, in principle, lead to the attenuation of background coronal radiation along the line of sight. However, simple estimates indicate that the extinction at $171\text{ \AA}$ is small. For a typical spicule mass density of $\rho \sim 5 \times 10^{-10} \text{ kg m}^{-3}$, corresponding to an electron density of $n_e \sim 3 \times 10^{17} \text{ m}^{-3}$, and assuming a characteristic spicule width of $L \sim 300 \text{ km}$, the Thomson scattering optical depth is only $\tau \sim 6 \times 10^{-6}$, indicating that continuum attenuation due to Thomson scattering is negligible.

In addition, bound-free (photoionization) absorption at $171\text{ \AA}$ can arise from H I, He I, and He II. Estimates of the total extinction coefficient show that the dominant contribution arises from He I bound-free opacity at lower temperatures; however, even under conditions representative of dense spicular plasma, the resulting extinction remains small. Moreover, the opacity decreases rapidly above $\sim 2 \times 10^4 \text{ K}$ as He I becomes ionized. For typical values of the extinction coefficient ($\alpha \sim 10^{-7} \text{ m}^{-1}$) and path lengths of $L \sim 300 \text{ km}$, the corresponding optical depth is $\tau \sim 0.03$, which remains modest. Therefore, even when considering multiple spicules along the line of sight in limb

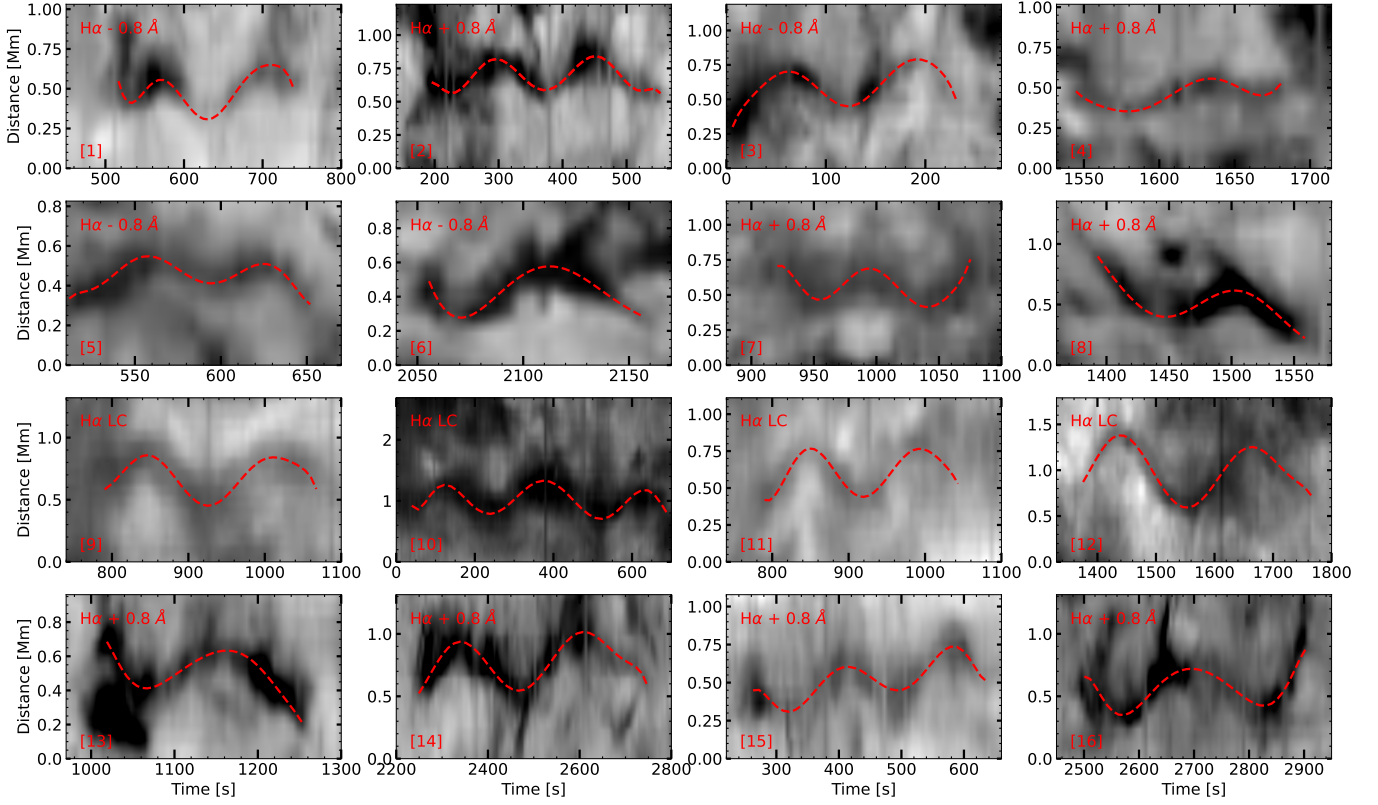


Fig. 8. Space-time diagrams for the 16 locations marked in Fig. 5, illustrating the transverse oscillations of the spicules. The panels show SST $H\alpha$ -0.8 Å, $H\alpha$ line-center, and $H\alpha$ $+0.8$ Å observations, as indicated. The horizontal axis represents time, and the vertical axis shows the transverse displacement (distance) in megameters. The dashed red curves represent polynomial fits to the transverse motion of the spicule axis. The numbers in the lower-left corner of each panel correspond to the slit identification numbers shown in Fig. 5. The derived wave parameters are listed in Table 1.

Table 1. Transverse oscillation parameters and estimated wave energy flux.

Slit	Period (s)	Amplitude (km)	Velocity (km s^{-1})	Energy flux (W m^{-2})
1	142	236.08	7.88	3105.16
2	156	191.56	4.79	1149.44
3	126	338.37	9.85	4846.86
4	87	140.11	6.20	1923.69
5	65	121.11	5.37	1441.42
6	83	150.22	9.91	4910.81
7	83	170.12	8.49	3604.97
8	122	338.01	7.83	3062.51
9	163	203.41	5.56	1547.39
10	251	312.32	5.04	1268.90
11	142	175.32	5.50	1510.36
12	230	393.86	7.10	2519.21
13	191	239.21	4.75	1128.26
14	269	246.23	3.94	774.73
15	172	213.77	3.32	551.06
16	257	262.40	4.25	902.08
Mean	159	233 ± 43	6.23 ± 1.14	$(2.14 \pm 0.78) \times 10^3$

Notes. The energy flux is calculated as $F = \frac{1}{2} \rho v^2 V_A$, assuming an Alfvén speed of $V_A = 200 \text{ km s}^{-1}$ and a spicule density of $\rho = 5 \times 10^{-10} \text{ kg m}^{-3}$ (De Pontieu et al. 2007c). Uncertainties in the mean values are estimated through standard error propagation using the SST pixel scale and temporal cadence.

observations, it is difficult to achieve sufficiently large optical depths to significantly attenuate the background 171 Å emission.

The coordinated spectroscopic analysis of SST H α and IRIS Si IV 1394 Å observations reveals complex plasma dynamics within the multi-thermal spicular structures. The line-of-sight velocity measurements show that chromospheric and transition-region plasma components do not always evolve coherently and may exhibit opposite Doppler signatures at the same projected location and nearly the same time. Since the observations were obtained close to the solar limb, the measured velocities are expected to predominantly reflect transverse plasma motions rather than purely field-aligned flows.

The physical origin of these temperature-dependent Doppler signatures remains uncertain. One possible explanation is that unresolved multistranded structures along the line of sight contribute differently to the H α and Si IV 1394 Å signals, particularly because H α is optically thick while Si IV 1394 Å is optically thin. Alternatively, torsional or rotational motions within multi-thermal spicular structures may cause different temperature diagnostics to preferentially sample different regions of the same structure. We also cannot exclude the possibility that thermally distinct plasma components evolve differently within the same projected magnetic structure. Therefore, while the observations clearly indicate dynamically complex multi-thermal behavior, the precise physical mechanism responsible for the observed opposite Doppler signatures cannot be uniquely determined from the present data.

To investigate the oscillatory behavior associated with spicules, we performed wavelet analysis of horizontal velocity signals at different heights. Our results show that oscillations with periods around ~3 minutes are commonly present at multiple locations and heights, exhibiting significant power above the 99% confidence level. These oscillations are consistent with chromospheric oscillations frequently observed in the solar atmosphere (with the vertical velocity fluctuations) and are likely associated with magneto-acoustic wave propagation along magnetic structures (Jess et al. 2015, 2023). Furthermore, the wavelet power distribution shows that oscillatory power is not uniformly distributed but is often concentrated at specific times. The intermittent nature of the wave power observed in our wavelet analysis suggests that wave excitation may be episodic rather than continuous. This behavior may be related to impulsive energy release events, magnetic reconnection, or buffeting of magnetic flux tubes by convective motions in the photosphere. The presence of these oscillations across different heights indicates efficient wave propagation within spicules.

In addition to the longer-period oscillations discussed above, we detect clear signatures of high-frequency transverse waves within individual spicules. The space-time analysis of the transverse displacement reveals oscillation periods ranging from 65 to 269 s, with a mean period of 159 s. The corresponding displacement amplitudes vary between 121 and 394 km, with a mean value of 233 ± 43 km, while the transverse velocity amplitudes range from 3.3 to 9.9 km s⁻¹, with a mean value of 6.23 ± 1.14 km s⁻¹. Using these velocity measurements, we estimate the associated energy flux to lie between 5.5×10^2 and 4.9×10^3 W m⁻², with a mean value of $(2.14 \pm 0.78) \times 10^3$ W m⁻². The detection of these transverse waves is enabled by the high spatial and temporal resolution of the SST observations, which enable precise tracking of the spicule axis. These oscillations manifest as periodic lateral displacements of the spicule structure and are consistent with magnetohydrodynamic (MHD) kink-mode waves

propagating along magnetic flux tubes (Zaqarashvili & Erdélyi 2009).

Transverse oscillations of this nature have been reported in numerous previous studies. Using Hinode observations, De Pontieu et al. (2007c) first identified transverse waves in spicules and suggested that they may carry sufficient energy to contribute to coronal heating. Similarly, Okamoto & De Pontieu (2011) detected transverse motions in chromospheric structures and interpreted them as Alfvénic waves. Such waves are expected to arise naturally in thin magnetic flux tubes embedded within a magnetized plasma and can efficiently transport energy upward along magnetic field lines.

Our measured wave properties are broadly consistent with these earlier observational results, although some important differences are present. For example, De Pontieu et al. (2007c) reported periods between 100 and 500 s, velocity amplitudes of 10–30 km s⁻¹, and displacement amplitudes of 200–500 km. While our displacement amplitudes are comparable, the measured velocity amplitudes are somewhat lower. However, our observations reveal significantly shorter periods, extending down to 65 s, indicating the presence of higher-frequency wave components that were not as clearly resolved in earlier studies. These differences likely reflect the improved spatial and temporal resolution of the SST, intrinsic variability among individual spicules, and differences in observing conditions.

The estimated energy flux in our study (derived primarily from spicule-dominated strands structures), with a mean value of $(2.14 \pm 0.78) \times 10^3$ W m⁻², substantially exceeds the typical energy requirement for heating the QS corona (~100–200 W m⁻²; Withbroe & Noyes 1977). However, this comparison does not include the dissipation height, damping efficiency, and conversion of wave energy into thermal energy. Additionally, we did not explicitly quantify losses due to reflection and mode conversion. Nevertheless, the estimated wave energy flux suggests that these oscillations may contribute significantly to the energy transport into the upper atmosphere. However, the role of spicules in coronal heating remains debated. Several observational and numerical studies have argued that spicules provide only a limited contribution to sustaining the hot corona, as direct plasma injection by spicules cannot account for the majority of coronal emission (Klimchuk 2012; Tripathi & Klimchuk 2013; Patsourakos et al. 2014; Klimchuk & Bradshaw 2014; Bradshaw & Klimchuk 2015; Sow Mondal et al. 2022). Collectively, these studies suggest that while spicules may not be the primary source of coronal plasma or heating, they may still contribute indirectly through waves, shocks, or magnetic energy transport. Importantly, many of these studies focus on direct plasma supply or chromospheric heating scenarios, whereas our estimates concern energy transported by transverse wave motions. Therefore, our estimated wave energy flux should be interpreted as evidence that transverse oscillations in spicules may represent a potentially important channel for energy transport into the upper atmosphere, while their exact contribution to coronal heating remains uncertain.

5. Conclusion

In this work, we investigated the multi-thermal and dynamical behavior of solar spicules using coordinated SST/H α , IRIS Si IV, and SDO/AIA observations. Our analysis reveals a clear temporal and spatial correspondence between chromospheric spicules and coronal emission at the limb, indicating a direct connection between plasma at different atmospheric layers. The

Doppler velocity measurements can show opposite flow signatures in $H\alpha$ and Si IV , providing evidence for the coexistence of distinct multi-thermal plasma components within individual spicules. We also find that high-frequency transverse oscillations in spicules (periods of 65–270 s) can provide more than sufficient energy flux to contribute to coronal heating. In addition, we identify frequently dominant ~ 3 -minute oscillations across multiple heights, highlighting the coherent chromospheric oscillatory processes within these structures.

Our findings demonstrate that spicules are not only multi-thermal and highly dynamic but also can be efficient channels for both mass and wave energy transport into the upper solar atmosphere. The combined evidence of multi-thermal plasma flows and energetically significant transverse waves highlights their important role in coupling the chromosphere to the transition region and corona, and in contributing to the overall energy balance of the solar atmosphere.

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