



Solar Spicule Rotation Driven by Plasma Curtain–Vortex Interactions

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Abstract

Rotational and transverse motions are frequently observed in solar spicules, yet the physical origin of these motions remains debated. We investigate how apparent spicule rotation arises in a stratified, magnetized solar atmosphere using three-dimensional radiative magnetohydrodynamic (rMHD) simulations. We show that the observed spinning signatures can arise without intrinsic rotation of individual jets. Instead, spicules organize into fluted, curtain-like plasma structures. The evolving emission from these three-dimensional curtains, when projected onto the plane of the sky through line-of-sight integration, produces clustered spicule-like features with lifetimes, heights, and apparent speeds comparable to observed ranges. The synthetic spicules develop strong density gradients at their periphery that generate (i) baroclinic vorticity and also interact with (ii) vortical flows driven by magnetic tension in the surrounding plasma. The associated vortical flows in our simulation are organized as vertically extended rotating plasma columns that reach coronal heights—in some cases, the spicules directly feeding the swirling columns. As a result, recurrent spinning signatures emerge in projected jet clusters, consistent with commonly observed solar limb dynamics, including high-cadence observations from Hinode and IRIS as also shown here for comparison. These results link spicule rotation to jet–vortex coupling and show that rotating spicule clusters may trace vortical plasma structures that transport energy and momentum into the solar corona.

Unified Astronomy Thesaurus concepts: [Solar spicules \(1525\)](#); [Solar chromosphere \(1479\)](#); [Shocks \(2086\)](#); [Radiative magnetohydrodynamics \(2009\)](#); [Solar corona \(1483\)](#)

Materials only available in the [online version of record](#): animations

1. Introduction

Solar spicules exhibit a wide range of dynamical behavior, including transverse motions and apparent rotation, as revealed by high-resolution observations of the solar limb (Y. Suematsu et al. 2008a; B. De Pontieu et al. 2012; D. Kuridze et al. 2016; W. Bate et al. 2022). While transverse displacements are often interpreted in terms of magnetohydrodynamic (MHD) wave motions, the physical origin of spicule rotation and its relationship to the surrounding chromospheric plasma remain open questions, with reasons ranging from torsional Alfvén waves (D. H. Sekse et al. 2013; P. Antolin et al. 2018; J. Liu et al. 2019; W. Oxley et al. 2020) and minifilament eruption (A. C. Sterling et al. 2010) to emerging new magnetic flux reconnecting over a solar plage region (S. Danilovic 2023). Vortical flows have been observed across photospheric and chromospheric layers, from photospheric whirlpools associated with granular flows to chromospheric “swirls.” They have been proposed as a source of rotational signatures in jets; notable observational studies include S. Wedemeyer-Böhm & L. Ruppe van der Voort (2009), J. A. Bonet et al. (2010), T. V. Zaqarashvili & R. Erdélyi (2009), and B. De Pontieu et al. (2012). Previous reported numerical simulations with the

top boundary extending only until the upper chromosphere (I. N. Kitiashvili et al. 2011; S. Shelyag et al. 2011, 2013; S. Wedemeyer-Böhm et al. 2012; A. F. Battaglia et al. 2021; N. Yadav et al. 2021) have studied the properties of vortices, including their drivers, lifetimes, and sizes in photospheric and chromospheric layers, as well as their contribution to Poynting fluxes. A few other modeling studies with the top boundary extending until the corona (A. J. Finley et al. 2022; H. Kuniyoshi et al. 2023; S. S. A. Silva et al. 2025) have also reported vortices with twisted magnetic field lines and contribution of vortices to plasma heating, although the interaction of vortices with spicules remains unclear. Previous numerical (H. Iijima & T. Yokoyama 2017) and analytical (W. Oxley et al. 2020; J. Scalisi et al. 2021a, 2021b, 2023) works have also explored how Lorentz force can lead to spicule matter being lifted upward by a single swirl. In summary, previous studies have provided useful insights into vortical flows and spicules, but have often examined them separately or focused on localized rotational motions of individual jets.

Here we investigate spicule dynamics in a stratified solar atmosphere using three-dimensional radiative MHD simulations that naturally produce spicule-like jets through the interaction of waves, shocks, and magnetic forces. We focus on how these jets organize into extended plasma structures whose interaction with vortical flows leads to apparent rotational signatures consistent with those reported in high-cadence observations of the solar limb.



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2. Numerical Model

We analyze a three-dimensional radiative magnetohydrodynamic simulation of a stratified solar atmosphere that extends from the upper convection zone into the low corona. The simulation is based on the MHD solver PENCIL CODE (A. Brandenburg & W. Dobler 2002; Pencil Code Collaboration et al. 2021), which solves the MHD equations for a compressible plasma medium and includes radiative energy exchange and thermal conduction; a description of the numerical setup, boundary conditions, and radiative treatment is provided in the Appendix. The simulation is initialized with a convectively unstable stratification and maintained by an imposed energy flux at the lower boundary, leading to the self-consistent development of magnetoconvective flows and chromospheric jets. The computational domain spans $6 \text{ Mm} \times 9 \text{ Mm}$ horizontally and 37 Mm vertically, out of which the lower 5 Mm is the subsurface convection zone. A grid spacing of 24 km resolves granular-scale motions and spicule-like jet dynamics. We impose a vertical magnetic field of magnitude $B_{\text{imp}} = 7.5 \text{ G}$ in the entire domain to mimic the open magnetic field of a solar coronal hole region. During the evolution, no additional magnetic flux emergence process is employed at the bottom boundary. This is by design so that the effect of magnetic reconnection is negligible in the atmosphere except near the photosphere where the convection will stretch, twist, and fold the imposed magnetic field lines. Our goal here is to study the basic model of the forest of spicules excited by the convection and leakage of acoustic modes.

For the detection of spicules in the numerical model, we choose to compute the synthetic Si IV plasma emission corresponding a plasma temperature of $\sim 80,000 \text{ K}$. Being an optically thin transition region line, this is easy to synthesize from MHD variables. Two different methods, namely, the FoMo code (T. Van Doorsselaere et al. 2016) for Si IV and a simpler analytical contribution for plasma at $80,000 \text{ K}$, are used. The details are provided in Appendix B, where we further show that both methods lead to very similar results. In this paper, unless otherwise stated, we use the analytical contribution function to calculate the synthetic emission, since it is computationally less expensive.

3. Observational Data

To place the simulated dynamical characteristics within an observational context, we analyze Ca II H intensity maps from the Hinode/Solar Optical Telescope (SOT) Broadband Filter Imager or BFI (T. Kosugi et al. 2007) of a region near the northern polar coronal hole obtained on 2007 November 7 (Y. Suematsu et al. 2008b; P. G. Judge & M. Carlsson 2010). The dataset consists of $111'' \times 111''$ images acquired while the instrument was pointing at the solar limb, spanning a continuous duration of ~ 56 minutes.

We also investigate IRIS slit-jaw Si IV filter images of the solar spicules from the IRIS (B. De Pontieu et al. 2014) observatory. A region of $82 \text{ Mm} \times 36 \text{ Mm}$ inside a coronal hole near the solar north pole is analyzed from 2016 October 19 at 19:04:09 UT for 39 minutes. With further filtering/processing (as discussed in Appendix D and E), we find that the Hinode/SOT (Y. Suematsu et al. 2008b) Ca II H data have a stronger signal-to-noise ratio compared to Si IV IRIS observations for a comparable time cadence. The Hinode Ca II H observations enable a clearer visual comparison of the spicule dynamics with simulations due to higher spatial

resolution and cadence. On the other hand it is difficult to forward-model the Ca II H emission due to optically thick non-LTE effects, etc., but synthesis of the optically thin Si IV line is comparatively easier. Therefore, we opt for the Ca II H channel as a probe from observations and for the Si IV channel to analyze plasma emission from the numerical model.

4. Results

4.1. Spicules as Warped Plasma Curtains

In our three-dimensional simulation, the spicule material is launched by upward-propagating slow MHD waves driven by convective motions in the photosphere. The photosphere acts as a vibrating boundary with a dominant periodicity of order ~ 5 minutes, which excites compressive disturbances in the overlying chromosphere, similar to earlier two-dimensional simulations (L. Heggland et al. 2011; H. Iijima & T. Yokoyama 2015; S. Dey et al. 2022). Because of strong density stratification, these slow MHD waves steepen into large-amplitude nonlinear waves as they propagate along magnetic field lines, producing localized regions of strong compression, heating, and upward plasma acceleration. The chromospheric plasma is propelled by these successively passing compression fronts, leading to the formation of extended, rising plasma structures that constitute the curtain-like features shown in Figure 1(a). In Figure 1(b), we show how a representative compression front (blue contours) lifts a spicule in its wake as it propagates upward. The compressive fronts are identified by regions where $-\hat{b} \cdot \nabla(\hat{b} \cdot \mathbf{v}) > 0.15 \text{ s}^{-1}$ (E. Khomenko et al. 2018), with $\hat{b}$ representing a unit vector parallel to the magnetic field. The same sequence of processes in energizing the spicular plasma has also been identified using the Lagrangian tracking technique of the material forming the spicules in a two-dimensional model (S. Dey et al. 2022). There, it was found that compression fronts are regions of strong vertical acceleration. Therefore, strong shocks are more likely to produce longer spicules (S. Srivastava et al. 2025). The reason the shock front is always ahead of the spicule tip is that the shock front travels at a higher speed than the plasma at the spicule tip, as evident from simultaneous time–distance plots of shock and spicule plasma in the above paper. Recently, two-dimensional MHD simulations by L. Ni et al. (2026) have also reported compressive structures above spicule tips and interpreted them as shocks driven by spicule upflows. However, the temporal evolution required to distinguish between upward-propagating slow-mode shocks and in situ generation is not demonstrated there.

Next, we analyze a single compression front (shown in Figure 1(c)) to determine if it is indeed a shock by checking for the validity of Rankine–Hugoniot conditions for adiabatic shocks. Here, the temperature and density jumps associated with the front are plotted in Figure 1(d). The density compression ratio, r , ranges from 1.86 to 2.19 within $3.5 < z < 4.5 \text{ Mm}$. Using the Rankine–Hugoniot jump condition, we estimate the corresponding upstream Mach number, $\mathcal{M} = \sqrt{2r/[\gamma + 1 - r(\gamma - 1)]} \sim 1.61\text{--}1.90$ with respect to the stationary frame of the front. Here, γ is the ratio of specific heats. We also find that the temperature is enhanced in the downstream direction of the front by a factor of 2.01–2.64 compared to the upstream region. The Mach numbers inferred from the Rankine–Hugoniot relation give an approximate diagnostic of shock strength because the chromospheric plasma is not a strictly ideal gas with fixed ionization. In

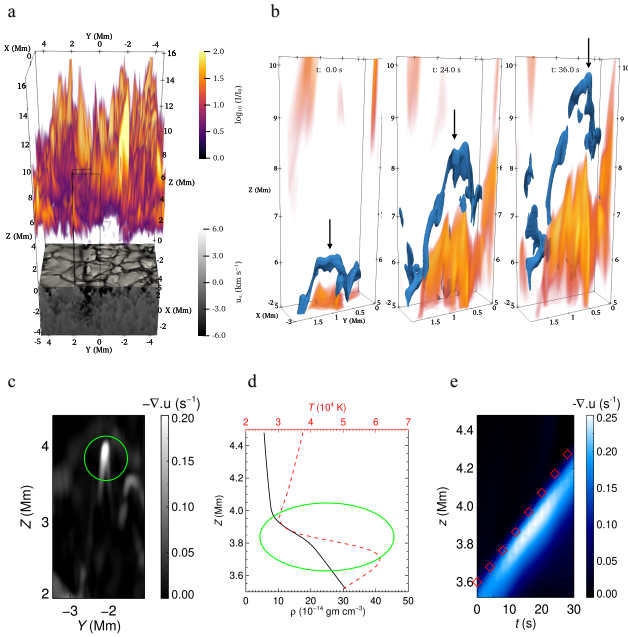


Figure 1. The role of slow MHD shocks in driving spicules: (a) Volume rendering of synthetic plasma emission at 80,000 K, $\log_{10}(I/I_0)$ (similar to Si IV channel) with orange isocontours. The turbulent convection zone is shown as a rectangular box, shaded in gray by the vertical velocity. A rectangular subvolume with $5 < z < 10$ Mm is indicated by black outlines for further analysis. (b) The driving mechanism for the spicule inside the rectangular subvolume is demonstrated by tracking a slow MHD shock front for 36 s. The blue shaded regions are the isocontours of the strong flow convergence along the magnetic field (where $-\hat{b} \cdot \nabla(\hat{b} \cdot \mathbf{v}) > 0.15 \text{ s}^{-1}$). (c) A typical example of part of a compression front lying in the y - z plane is highlighted by the green circle. (d) Jump in density and temperature profile perpendicular to the front shown in panel (c). (e) Time-distance plot of the flow convergence, associated with the same shock front. Red diamonds represent the shock front characteristic curve, independently computed using the Rankine-Hugoniot jump condition.

panel (e) of Figure 1, we track the compression profile of the associated shock front with time-distance (t - z) diagrams. The slope of the compression regions in the t - z diagram represents the front speed in the simulation frame. In order to test consistency, we also parallelly determine the front speed, u_{shock} , using the Mach number estimated using the Rankine-Hugoniot condition, by using the following relation: ($u_{\text{shock}} = c_s \mathcal{M} + u_{\text{upstream}}$). The characteristic curve obtained by integrating u_{shock} over time is represented by red squares. The slope of this curve matches quite well with the slope of the compression regions in the t - z diagram. This consistency shows that the compression front propagates at the same speed expected for slow MHD shocks.

The synthesized Si IV (80,000 K) emission used to describe Figures 1(a)–(b) reveals pleated curtain morphology with strongly nonuniform brightness and enhanced emission in regions containing multiple folds. To make this clear, we represent a subdomain within $5 < z < 10$ Mm in Figure 2(a), where the spicule cross sections clearly show the folds of the denser plasma curtain. The curtain-like plasma structures rise under the effect of quasiperiodic kicks received from the passage of shocks and later fall under gravity. When the three-dimensional emission is integrated along a line of sight (LOS), this dynamic plasma drapery appears as localized, spikelike features (Figure 2(b)). The brightest spikes correspond to LOS paths intersecting multiple folds of the curtain (indicated by ellipses), demonstrating that the apparent jets are a projection

of the underlying sheetlike plasma rather than being isolated one-dimensional structures.

The LOS integration effect of the strongly emitting plasma curtains manifests as spikelike jet features, resembling observed solar spicules. The simulated jets also demonstrate similar characteristics to observation, including lifetimes of ~ 5 – 10 minutes, apparent upward speeds of ~ 20 – 70 km s^{-1} , heights of ~ 6 – 16 Mm, widths of ~ 200 – 1500 km , and parabolic trajectories of their tips (T. M. D. Pereira et al. 2014; H. Skogsrud et al. 2015). The above range broadly agrees with synthetic H α signatures of spicules from a MURaM-ChE simulation (S. Chandra et al. 2025). In our model, the LOS-projected jetlike features frequently exhibit apparent rotational motions during their evolution (see the animation for Figure 2). Further, LOS integrations from different viewing angles show that multiple bright apparent strands correspond to different regions of the inhomogeneous plasma curtain, naturally giving rise to apparent splitting and merging of spicules (Figure 2(c)), similar to features reported in observations (Y. Suematsu et al. 2008a). Viewing the structure from different angles is effectively equivalent to observing a rotating curtain from a fixed vantage point, so that the evolving three-dimensional geometry and time-dependent bulk motion of the plasma enhance these projection effects. A synthetic emission measure sampled at a cadence of 2 s is used to create the animation for Figure 2(b) which shows transverse motions within clusters of LOS-integrated spicule-like features. To quantify these motions, we construct a time-distance map along the horizontal slit indicated in the same panel. The resulting pattern of interbraiding spicules in the time-distance domain (Figure 2(d)) indicates multiple spicular threads crossing in projection during the lifetime of the event. Such interbraiding could arise either from neighboring threads undergoing independent transverse (kink-like) oscillations or from rotation produced by evolving three-dimensional structure.

To distinguish between these possibilities, we jointly examine the three-dimensional volume rendering of the plasma and the LOS-integrated emission (animations corresponding to Figures 2(a) and (b)), and we find that the transverse signatures result from sheetlike plasma structures that stretch, curl, and overlap along the LOS, producing spinning and braiding in projection. In contrast to the commonly assumed conical jet geometry, the curtain-like morphology highlighted here provides a different geometrical interpretation of spicular plasma in the simulation. Alternative interpretations based on Doppler effects in reduced-dimensionality models (T. M. D. Pereira et al. 2016) cannot be ruled out observationally; however, the simulation demonstrates that such signatures can arise purely from the three-dimensional evolution of sheetlike plasma. The plane-of-the-sky projected dynamical features of the underlying curtain-like plasma structures shown above can now be compared with observational diagnostics. The observed Hinode/SOT field of view (FOV) after the image filtering is illustrated in Figure 3(a). Within the sequence of images taken at a cadence of 5 s, multiple instances of apparent bulk spinning and transverse motion in clustered spicules are observed; five particularly clear examples from the entire observation period are highlighted in the animation accompanying Figure 3(a), in which similar behavior is frequently detected. One such case, shown in Figure 3(b) as a time-distance diagram (and the other four examples in panel (a) of Figure B2), can be compared with bunches of simulated spicules on equal footing (Figure 2(d) and panel (b) of Figure B2). Independently, data from Si IV emission line images

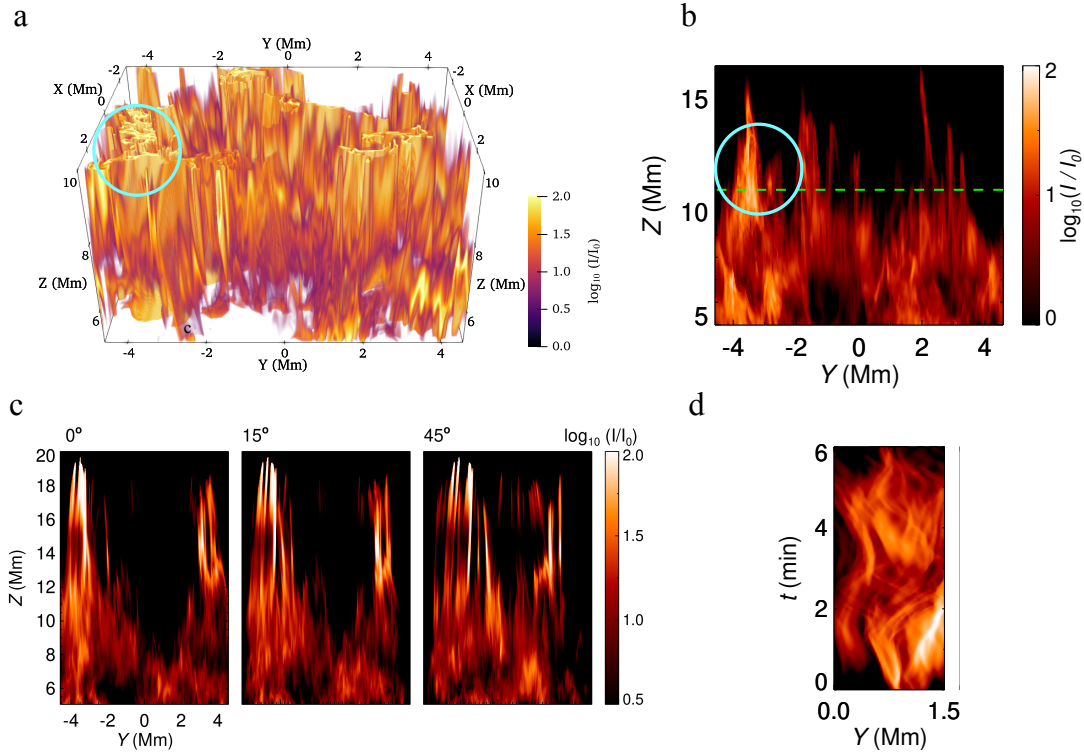


Figure 2. Plasma curtain structures and LOS effects: The subdomain within $5 \text{ Mm} < z < 10 \text{ Mm}$ clearly reveals the pleated curtain-like morphology of spicules. The synthetic intensity is obtained using the FoMo code. The ratio of the brightest region of the plasma curtain and the averaged horizontal intensity is greater than a factor of 10. (b) LOS integration profile of the same set of spicules shown in panel (a). The bright region encircled with the cyan circle has been obtained by an LOS integration over the densely pleated region of the three-dimensional structure (indicated by a cyan circle in panel (a)). (c) Simulated forest of spicules as seen from different LOS angles with respect to the x -axis of the domain. (d) Time-distance diagram of synthetic spicules at $z = 11 \text{ Mm}$, a horizontal slit (green dashed line of panel (b)). Panel (b) is available as an animation with different smaller fields of view (FOVs) for better visual clarity of apparent spicule cluster rotation. The horizontal coordinates corresponding to FOV 1–5 are mentioned in Mm, in the order in which they appear in the animation: $(-1.5 \leq x \leq 3.0, 2.3 \leq y \leq 4.5)$, $(1.6 \leq x \leq 2.8, -4.5 \leq y \leq 2.3)$, $(-2.4 \leq x \leq 0.0, -0.2 \leq y \leq 2.3)$, $(-3.0 \leq x \leq 0.0, -0.1 \leq y \leq 2.0)$, and $(-2.4 \leq x \leq 0.0, -0.2 \leq y \leq 2.3)$. (An animation of this figure is available in the [online article](#).)

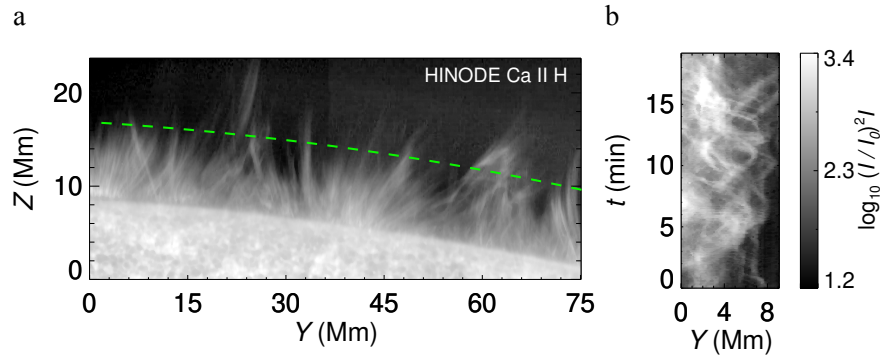


Figure 3. Observation of clusters of spicules at the solar limb position: (a) SOT Ca II H filtered image of spicules, observed at 19:11:37 UT on 2007 November 7. (b) Time-distance diagram of observed spinning spicules at 8 Mm height in the solar atmosphere, using a slit parallel to the limb (green dashed line of panel (a)). Panel (a) is available as an animation. The second part of the animation is similar but for a 39 minute long IRIS Si IV observation, which is sensitive to plasma temperature of 80,000 K.

(An animation of this figure is available in the [online article](#).)

from IRIS taken on 2016 October 19 at 9.3 s cadence also shows clusters of spicules rotating in the second part of the animation. However, because the spatial resolution and signal-to-noise ratio are higher for Hinode Ca II H than for the IRIS data with 5 s cadence, the rotational motion is more discernible. Time-distance maps constructed across a horizontal slit indicate quantitative differences between observations and simulation (Figure B2),

while exhibiting similar intertwined features. Observed spicule bundles exhibit more extensive thread braiding and longer intervals between successive crossings (1–4 minutes) than those in the simulation (0.5–2 minutes), indicating longer-lived rotational episodes on the Sun. This may reflect longer lifetimes or higher rotational energies of coronal swirling conduits compared to the simulation.

4.2. Three-dimensional Vortical Structures and Coronal Swirling Conduits

To identify the physical origin of the apparent rotational signatures described above, we examine the vorticity field associated with the evolving curtain-like plasma. The generation and evolution of vorticity can be understood from the vorticity equation for a compressible magnetized plasma. Taking the curl of the Navier–Stokes equation and dotted with $\omega_z \hat{\mathbf{z}}$ yields the equation for enstrophy, namely, $\omega_z^2/2$:

$$\begin{aligned} \frac{\partial}{\partial t} \left(\frac{\omega_z^2}{2} \right) = \omega_z \hat{\mathbf{z}} \cdot & \left[\underbrace{-\mathbf{v} \cdot \nabla \omega}_{\text{advection}} - \underbrace{\omega (\nabla \cdot \mathbf{v}) + (\omega \cdot \nabla) \mathbf{v}}_{\text{stretch+tilt}} \right. \\ & + \underbrace{\frac{1}{\rho^2} \nabla \rho \times \nabla (p_g + p_m)}_{\text{baro-pressure}} - \underbrace{\frac{1}{\rho^2} \nabla \rho \times \left(\frac{\mathbf{B} \cdot \nabla \mathbf{B}}{\mu_0} \right)}_{\text{baro-tension}} \\ & \left. + \underbrace{\frac{1}{\rho} \nabla \times \left(\frac{\mathbf{B} \cdot \nabla \mathbf{B}}{\mu_0} \right)}_{\text{tension}} \right] \end{aligned} \quad (1)$$

where $\omega = \nabla \times \mathbf{v}$ is the vorticity, ρ is the mass density, p is the gas pressure, and $\mathbf{J} = \nabla \times \mathbf{B}/\mu_0$ is the current density. We ignore the viscous stress tensor term here. In the simulation, evaluation of the individual terms shows that baroclinic vorticity generation dominates at the boundaries of the dense spicular plasma, while magnetic tension-driven vorticity is prevalent in the surrounding atmosphere. To characterize the three-dimensional structure of the vortical flows associated with spicules, we apply the Automated Swirl Detection Algorithm (L. Graftieaux et al. 2001; ASDA; see Appendix) to the simulated velocity fields. ASDA identifies coherent vortex columns extending over multiple height layers from three-dimensional velocity datasets sampled at a very high cadence of 2 s, allowing us to track highly dynamical individual vortical structures throughout the chromosphere and into the lower corona (see Figure 4(a)). These detected vortices correspond to the vertically extended rotating plasma columns reaching coronal heights, which we refer to as coronal swirling conduits (CoSCos). The widths of CoSCos reported here are comparable (factor of 0.5) to spicule widths in the range 300–600 km, and they have rotational speeds of 2–20 km s^{−1} and an average lifetime of 20–120 s. Along its entire length, the swirling plasma rotates either clockwise or counterclockwise. For a few exemplary swirls, the winding number, $v_h/2\pi r v_z$, of the streamline is in the range 0.19–0.95 Mm^{−1}. Figures 4(b) and (c) show the horizontal velocity streamlines and horizontal magnetic field lines, respectively, on the $z = 9$ Mm plane in relation to the spicule plasma. Observed chromospheric swirls and associated Doppler measurement (J. Liu et al. 2019; J. Shetye et al. 2019) indicate winding numbers in a similar range. Line integral convolution (LIC) maps of the horizontal flow shaded by synthetic emission, at a horizontal plane taken at $z = 9$ Mm, reveal coherent swirling structures that develop all over the domain (see Figure 4(b)). The associated horizontal magnetic field structure is presented in panel (c) of the same figure. The

CoSCos identified in our simulation are aligned along the local magnetic field and can be classified into two categories based on their dominant vorticity source. The first category, CoSCo-I, consists of magnetic tension-driven swirls whose origin may not be directly linked with spicule formation. An example is shown in Figures 5(a)–(b), where helical velocity streamlines remain cospatial with twisted magnetic field lines over heights of ~ 4 –8 Mm during interaction with a spicule. The present example does not show a unique correspondence between CoSCo and photospheric vortex structures. While some vortical features can be traced across multiple atmospheric layers, others appear to be generated locally in the chromosphere and transition region, indicating that multiple formation pathways may operate. Enstrophy analysis confirms that magnetic tension dominates vorticity generation in CoSCo-I (Figure 5(c)). In these structures, velocity and magnetic field perturbations exhibit oppositely directed horizontal components, resulting in cospatial velocity and magnetic swirls with π phase difference (Figures 5(d)–(e)). The second category, CoSCo-II, forms in close proximity to spicules, persists throughout spicule lifetimes, and is driven primarily by baroclinic vorticity generation associated with sharp density gradients at spicule boundaries. As spicules rise and fall, the density inside the jet is significantly higher than that of the surrounding plasma, leading to baroclinic vorticity generation along the flanks of the curtains during the spicule lifetime. This process continues even after the passage of the driving shocks and can persist during the descending phase of the spicules, indicating that vortex formation may not be confined to the launch phase alone. An example is shown in Figures 6(a)–(b), where a pronounced velocity swirl develops without a corresponding magnetic swirl along its height. Enstrophy diagnostics show that baroclinic terms, i.e., a combination of baro-pressure and baro-tension terms, dominate vorticity generation at the spicule periphery (Figure 6(c)), indicating that CoSCo-II are triggered in situ by spicule evolution rather than originating from lower atmospheric layers. In contrast to CoSCo-I, the horizontal velocity and magnetic field vectors in CoSCo-II do not exhibit a π phase difference (Figures 6(d)–(e)) over the entire swirling region, reflecting the plasma-driven nature of the rotation. Although Figure 6(e) appears visually dominated by regions with $\cos \theta \approx -1$, the horizontal magnetic field remains approximately unidirectional across the CoSCo-II cross section while the velocity field circulates around the vortex center (inside the black rectangular region). Consequently, $\cos \theta$ changes signs across the vortex, with one side characterized by $\cos \theta \approx -1$ and the opposite side by $\cos \theta \approx +1$. Averaging over the full vortex cross section therefore yields $\langle \cos \theta \rangle \approx 0$. Despite their different origins, both CoSCo-I and CoSCo-II exhibit upward-propagating vortex pulses with phase speeds comparable to the local Alfvén speed (Figures 5(f) and 6(f)) for $7 < z < 11$ Mm.

In both cases, CoSCos may reside within spicular plasma and impart rotational and lateral motions to spicules as they evolve. Additional examples of both categories (summarized in Table 1) are shown in Figure C1.

Having established the physical properties and vorticity sources of CoSCos, we now examine how spicule plasma

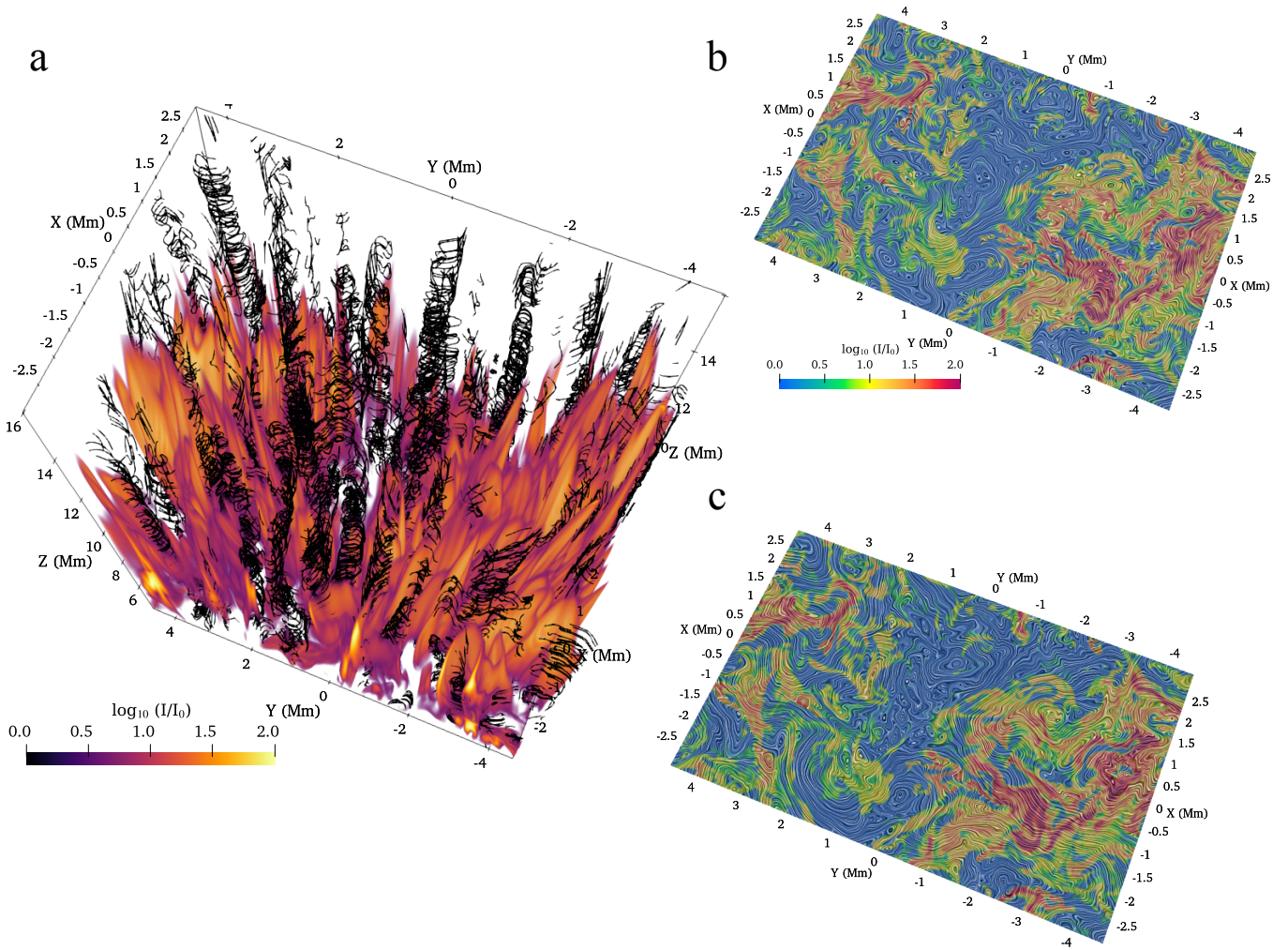


Figure 4. Forest of spicules and embedded CoSCOs from the simulation: (a) Spicules are represented by the strong plasma emission regions ($\log_{10}(I/I_0) > 0.75$) at 80,000 K, shown in purple–yellow patches. CoSCOs are detected horizontally, layer by layer, using the ASDA method and then visualized in three dimensions by streamlines (spiraling black lines). (b) The horizontal velocity field shown at a cut with $z = 9$ Mm using the LIC technique. The color map shows the synthetic scaled plasma emission in panel (a) at the horizontal plane. (c) Same as panel (b), but now the LIC represents the horizontal magnetic field. This figure is available as a 15 s animation. The first 0–4 s of the animation shows the plasma curtain embedded in vortical flow in panel (a) and corresponds to 148 s of solar time. The next 4–9 s (120 s solar time) and last 9–15 s (182 s solar time) of the animation show the evolution of the LIC representation of flow for two smaller FOVs of panel (b) for visual clarity. (An animation of this figure is available in the [online article](#).)

interacts with these vortical structures. In the simulation, CoSCOs are observed to form both along the edges of spicules and in their immediate surroundings. As a result, spicules evolve within a flow field that contains vertically extended vorticity, which modifies the surrounding plasma motion and can impart rotational signatures to the spicules (see animation of Figure 4(b)). Spicule rotation is most pronounced during the late stages of their evolution, particularly during the falling phase when a significant fraction of the spicular mass has drained back toward the photosphere. During this phase, the reduced inertia of the spicule facilitates lateral and rotational motion, as evident from the three-dimensional renderings of the plasma evolution (see animation to Figure 4(a)). In contrast, during the rising phase, the upward mass flux inhibits sustained rotation. For a fraction of their lifetime, CoSCOs spatially overlap with spicules, and in some cases penetrate into the spicular plasma. In such instances, the CoSCo and the spicule become cospatial, and their plasma properties cannot be clearly distinguished (e.g., the third segment of animation to Figure 4(b)). These swirl structures arise

naturally in the simulation without any prior assumptions regarding spicule morphology or oscillation modes.

Vortex-like signatures associated with spicules have also been reported in high-resolution observations (D. Kuridze et al. 2016), and shear-driven vortex formation around cylindrical flux tubes has been demonstrated in previous analytical and numerical studies (J. Terradas et al. 2008; P. Antolin et al. 2018; M. Barbulescu et al. 2019). The phenomena reported in this paper are distinct, as they involve folded, sheetlike structures of stratified and highly compressible plasma rather than isolated tubelike geometries.

5. Discussion

The results presented here provide a unified interpretation of the rotational and transverse motions frequently observed in spicule clusters. Rather than invoking isolated, one-dimensional jet dynamics, our simulation demonstrates that spicules may be organized into extended, curtain-like plasma structures whose three-dimensional evolution naturally produces

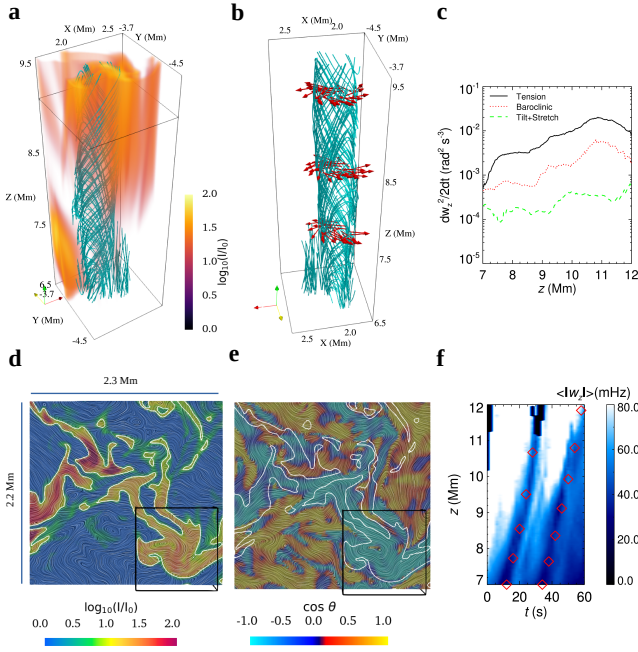


Figure 5. Formation mechanism of CoSCo-I dominated by magnetic tension term in Equation (1) (see Table 1) and their contribution to the bulk spinning motion of spicules. (a) Synthetic intensity of a spicule is shown in orange along with the cospatial CoSCo-I (velocity streamlines in cyan). (b) Horizontal component of twisted magnetic fields (red arrows) and velocity streamlines (cyan). (c) Rate of change of enstrophy due to different source components. (d) LIC visualization of horizontal magnetic field lines shaded by synthetic spicule intensity at $z = 9$ Mm. (e) Horizontal velocity streamlines shaded by the cosine of the angle between horizontal magnetic and velocity vectors. (f) Time-distance diagram of vorticity component, $\langle \omega_z \rangle$, for the same CoSCo-I from panel (a) obtained using a three-dimensional vertical slit of extent $600 \text{ km} \times 600 \text{ km} \times 4 \text{ Mm}$. The Alfvén speed varies between 125.3 and 302.8 km s^{-1} in the range $6.6 < z < 12 \text{ Mm}$.

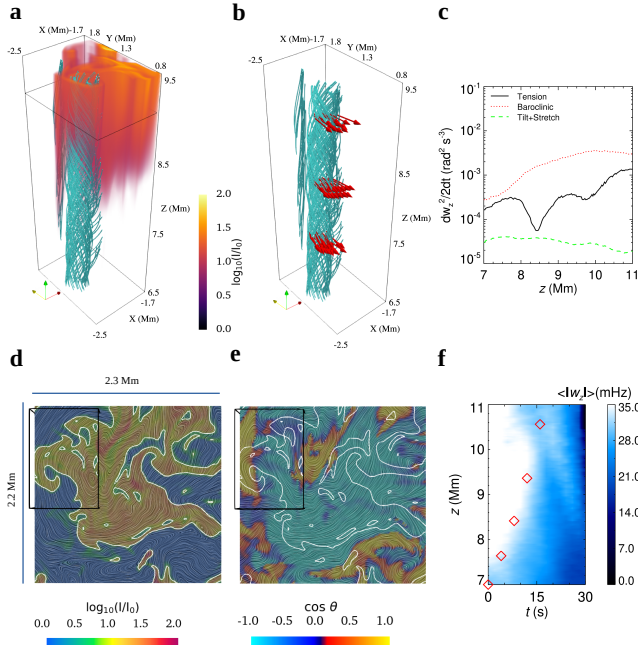


Figure 6. Generation of CoSCo-II due to baroclinic term of Equation (1), also summarized in Table 1. Same as Figures 5(a)–(f) but for a different spicule at a different location and time. The extent of the three-dimensional vertical slit used for the time-distance analysis is $600 \text{ km} \times 600 \text{ km} \times 4 \text{ Mm}$. The Alfvén wave speed varies in the range 217.2 and 489.5 km s^{-1} within $8 < z < 12 \text{ Mm}$.

Table 1
Distinction between CoSCo Regimes

Feature	CoSCo-I	CoSCo-II
Primary Driver	Magnetic tension	Baroclinic term
Average Phase	$\langle \cos \theta \rangle \sim -1$	$\langle \cos \theta \rangle \sim 0$
Magnetic Signature	Both $\mathbf{v}_h$ and $\mathbf{B}_h$ swirls	Only $\mathbf{v}_h$ swirl
Spatial Origin	Any region	Spicule periphery
Propagation Speed	Alfvén speed	Alfvén speed

Notes. The angular brackets refer to the spatial average of $\cos \theta = \mathbf{v}_h \cdot \mathbf{B}_h / (|\mathbf{v}_h| |\mathbf{B}_h|)$ over the horizontal cross section of the detected CoSCo. Here, $\mathbf{v}_h$ and $\mathbf{B}_h$ represent the horizontal velocity and magnetic field vectors.

apparent spinning, braiding, and splitting when viewed in projection. This geometrical reinterpretation provides a framework for understanding several long-standing ambiguities in the interpretation of spicule rotation signatures derived from limb observations, such as the difficulty in distinguishing between apparent rotation, transverse motions, and multi-threaded structure in projected views. More generally, we should be mindful that the structures inferred from two-dimensional plane-of-the-sky images need not necessarily correspond to what actually exists on the Sun. Sheetlike or fluted geometries for spicular plasma have previously been conjectured, often in connection with current-sheet interpretations, but have never been dynamically established as the primary organizing structure of spicule clusters (P. G. Judge et al. 2011, 2012; I. Lipartito et al. 2014; A. C. Sterling et al. 2020). Similarly, a coronal veil hypothesis has also been put forward for overlying bright coronal loops above a simulated emerging active region (A. Malanushenko et al. 2022). Recent laboratory fluid experiments of Faraday excitation also point to such morphology (S. Dey et al. 2022) in the context of jet formation. Similarly, and as Earth’s upper atmospheric analog and counterpart, high-resolution images of auroras observed above the Earth’s atmosphere also have a curtain-like appearance (G. Baranowski et al. 2000).

Further, this morphological information for spicules would be crucial for estimating the mass and energy fluxes to the solar corona by considering the correct filling factor for solar spicules and not just the contribution from the brightest regions of the plasma drapery. The temporally averaged mass flux, over the entire domain and not just in the brightest regions of the plasma drapery (identified as spicules), over the five cycles spanning a 28 minute duration is always positive for our simulation and of the order of $4.4 \times 10^{-9} \text{ kg m}^{-2} \text{ s}^{-1}$ at $z = 25 \text{ Mm}$. Note that in solar coronal holes, the mass loss due to fast solar wind is estimated to be $2 \times 10^{-9} \text{ kg m}^{-2} \text{ s}^{-1}$ in the solar corona from observations made near the Earth (G. L. Withbroe & R. W. Noyes 1977). In contrast to spicules that fall back to the solar chromosphere, CoSCos and the associated shearing flow form by drawing energy from the thermal and magnetic energy reservoir of the chromospheric plasma. For example, the horizontally averaged Poynting flux in the domain, $\langle S_z \rangle(t) = \langle v_z B_h^2 - B_z (\mathbf{v}_h \cdot \mathbf{B}_h) \rangle / \mu_0$, can be positive in the same region where the spicule drapery is falling ($\langle v_z \rangle < 0$). For this to happen, the second term in the expression of the Poynting flux must be negative, namely, $\langle \mathbf{v}_h \cdot \mathbf{B}_h \rangle < 0$ when $B_z > 0$. Therefore, CoSCos have the potential to carry the rotational energy further upward than the typical length of spicules seen in the Si IV emission lines even when the spicules are falling sunward. A comprehensive

statistical study of this relation between mass flux and Poynting flux due to spicules and swirls is a topic worthy of future study. The detection of the rotating bunches of spicules, both in observations and in simulation, presented here affirms that rotating spicules on the Sun mark regions where CoSCos exist. Rotating spicule clusters may exchange energy with vortical conduits that extend into the corona, linking chromospheric jets with the transport of energy and momentum into the solar wind. Therefore, a complete picture of momentum and energy transport to the fast solar wind must take into account this coupling between spicules and CoSCos. By analyzing the vorticity equation and identifying resultant three-dimensional vortex columns (CoSCos), we show that spicule rotation can arise from the motion of dense spicular plasma in a vortical flow environment. Two limiting regimes for vorticity generation are identified: vortical structures driven predominantly by magnetic tension in the ambient atmosphere, and vortical flows generated in situ by baroclinic effects, induced by the sharp density gradients along spicule boundaries. However, the relative occurrence rate, energy content, and flux transport associated with the two classes have not yet been quantified. A statistical assessment of their relative importance throughout the computational domain will be reported in a future study. While previous studies have reported vortex formation due to the magnetic tension, vortical columns driven by the baroclinic terms due to misaligned density and pressure gradients at the spicule boundary have not been explored previously. In summary, we provide a complementary framework for interpreting spicule rotation and highlighting the role of collective plasma behavior in chromospheric dynamics.

The Hinode observations considered here serve to illustrate that the similar classes of transverse and rotational signatures (produced by the simulation) exist in real spicule populations too. This suggests that projection effects and three-dimensional flow organization should be considered carefully when inferring spicule dynamics from two-dimensional observables. Stereoscopic observations of the same region on the Sun performed simultaneously, with a pair of telescopes for chromospheric or transition region lines, may be required to establish whether spicules are morphologically two-dimensional fluted curtains embedded in three-dimensional plasma (P. G. Judge et al. 2011; M. P. Rast et al. 2021) or simply one-dimensional straws. Finally, we emphasize that our results focus on the dynamical organization of spicules and the origin of their rotational signatures, rather than on detailed thermodynamic balance or energy dissipation. While the quantitative properties of spicules and CoSCos may depend on the specific radiative treatment and numerical setup, the identification of curtain-like morphology and vortex-mediated spicule rotation points to a physically consistent mechanism operating in the solar chromosphere. Future observations with improved spatial and temporal resolution, combined with simulations exploring a wider range of thermodynamic prescriptions, will be essential for further testing and extending this picture.

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Data and Code Availability

The simulation data used to produce Figure 1 will be made available upon request. The Hinode SOT datasets used in this paper can be downloaded from the DARTS⁷ archive. The analyzed IRIS Si IV slit-jaw images are available at the Heliophysics Events Knowledgebase.⁸ The configuration and

⁷ darts.isas.jaxa.jp/solar/hinode/query.php?coA=basic&fgA=advanced&spA=basic&xrA=basic&eiA=basic&coB=&coC=&coD=0&coE=&coF=0&coG=1&coH=0&coI=0&coJ=0&coK=0&coL=0&coM=0&coN=0&coO=0&coP=0&coQ=0&spB%5B%5D=0&spC=&spD=1&spE=&spF=&spG=&spH=&spI=&spJ=&spK=&spL=&spM=&spN=&spO=&spP=&spQ=&spR=&spS=&spT=&spU=&spV=&xrB%5B%5D=0&xrC=&xrD=&xrE=&xrF=&xrG=&xrH=&xrI=&xrJ=&xrK=&xrL=&xrM=&xrN=&xrO=&xrP=&xrQ=&xrR=&eiB%5B%5D=0&eiC=&eiD=&eiE=&eiF=&eiG=&eiH=&eiI=&eiJ=&eiK=&eiL=&eiM=&eiN=&eiO=&eiP=&eiQ=&eiR=&eiS=&A19=Search&inst%5B%5D=fg&plot=no&tmSY=2007&tmSM=11&tmSD=07&tmSh=18&tmSm=30&tmEY=2007&tmEM=11&tmED=07&tmEh=19&tmEm=30&posX=97&posY=939&posrX=111&posrY=111&fgB%5B%5D=0&fgD=&fgE=0&fgG=&fgH=&fgI=&fgJ=&fgL=&fgM=1&fgN=0&fgO=0&fgP=0&fgQ=0&fgR=&fgS=&fgT=0

⁸ www.lmsal.com/hek/hcr?cmd=view-event&event-id=ivo://sot.lmsal.com/VOEvent%23VOEvent_IRIS_20161019_190409_3620109603_2016-10-19T19:04:092016-10-19T19:04:09.xml

source files for the three-dimensional radiative MHD setup are available at doi:[10.5281/zenodo.20740008](https://doi.org/10.5281/zenodo.20740008).

Appendix A Numerical Model

The two-dimensional version of our setup including the equations solved, the local thermodynamic equilibrium (LTE) based equation of state, the initial and boundary conditions, the Rosseland mean opacity functions for optically thick atmospheres, and the cooling function for optically thin atmospheres is provided in P. Chatterjee (2020), S. Dey et al. (2022), K. Kesri et al. (2024), and S. Srivastava et al. (2025). We include a temperature-dependent hydrogen-ionization fraction via the Saha ionization equation, while helium is treated with a fixed ionization fraction. Here, we extend our setup to three dimensions using the same PENCIL CODE framework. The code includes a sixth-order finite-difference scheme for spatial derivatives and a three-step Runge–Kutta–Williamson time-stepping scheme out of several other available modules. Further, the MHD solver includes several nonideal MHD parameters, e.g., explicit viscosity and ohmic resistivity, anisotropic Spitzer conductivity, shock viscosity, and hyperdissipation (P. Chatterjee 2020). We consider the same explicit kinematic viscosity and magnetic diffusivity value, which is $1.02 \times 10^6 \text{ m}^2 \text{ s}^{-1}$ in the solar corona. In the setup, in addition to explicit diffusion, we use a sixth-order hyperdissipation scheme that conserves both the linear and the angular momentum (W. Lyra et al. 2017) for compressible plasma. The bottom of the domain lies at $z = -5 \text{ Mm}$ (in the convection region) and the top extends to 32 Mm height (the lower corona), above the photosphere located at $z = 0$. The bottom boundary is closed to mass fluxes and open to conductive and radiative fluxes. To minimize the reflection of outgoing waves at the top boundary, we place a 6 Mm thick sponge layer at $z = 26 \text{ Mm}$ to absorb any outgoing fluxes by adding damping terms to the velocity equation. Further, in the absence of any self-sustained heating process, the temperature in the sponge layer is maintained at 10^6 K (H. Iijima & T. Yokoyama 2017; M. Rempel & D. Przybylski 2021; H. Kuniyoshi et al. 2023).

We impose a vertical magnetic field in the simulation box and gradually increase its strength from 0.25 G to the final

value of $B_0 = 7.5 \text{ G}$ in 25 minutes of solar time. This strength is reminiscent of the large-scale polar field of the Sun. The magnetic field in the domain is therefore $\mathbf{B}_{\text{imp}} = B_0 \hat{z}$ in addition to $\mathbf{b}$ which is generated due to the flows acting on $\mathbf{B}_{\text{imp}}$. Thus, the total field is given by $\mathbf{B} = \mathbf{B}_{\text{imp}} + \mathbf{b}$. In PENCIL CODE, we use a vector potential such that $\mathbf{b} = \nabla \times \mathbf{A}$. We use a perfect conductor boundary condition for $\mathbf{A}$ at the bottom and at the top we copy the electromotive force at the last boundary to outer ghost zones. After evolving for ~ 50 minutes, we observe several turbulent granulation cells on the photosphere. Then, we continue for a further 30 minutes and analyze this data. At this time the convection spans the entire depth of the convection zone and the root mean square value of velocity in the convection zone has saturated with time. The average temperature at the optical depth, $\tau = 1$, surface is 5774 K. Initial shocks due to lack of numerical equilibrium are not found after the relaxation period. In the presence of turbulent convective flows, the magnetic field strength reaches $\sim 300\text{--}500 \text{ G}$ in some regions at the photosphere. The horizontally averaged unsigned magnetic field at the photosphere is about 11 G, which is similar to the observed photospheric magnetic field at coronal hole regions (K. L. Harvey et al. 1982). In the absence of flux emergence at the photosphere, the coronal temperatures are reported to cool to $< 200,000 \text{ K}$ (A. J. Finley et al. 2022). Therefore, a constant temperature in the sponge layer below the top boundary has been included as a precautionary measure so as not to allow the atmosphere to collapse during the time the convection is building up. In any case, the sponge layer cannot heat the atmosphere to temperatures beyond a million kelvin. The resultant temperature stratification after convective relaxation is shown in the left panel of Figure A1. In addition to the simulation with a uniform grid resolution of 24 km and an imposed field of 7.5 G, we also perform additional runs with a coarser grid resolution of 48 km and an imposed field of 3 and 25 G. In all cases, key features, e.g., forest of spicules, ubiquitous swirls, and spinning clusters of spicules, remain robust. In our simulation, the plasma- $\beta = 1$ surface is distorted in the presence of spicules and it is located between 1.5 and 4.5 Mm from the photosphere (see right panel of Figure A1). The horizontally averaged plasma- β value remains ~ 0.05 for $z > 6 \text{ Mm}$.

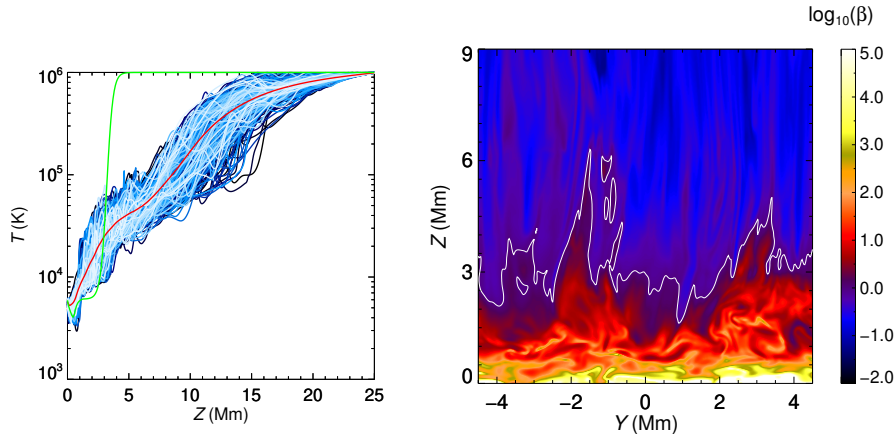


Figure A1. Left panel: temperature profile of the simulated solar atmosphere as a function of height. The initial temperature stratification is shown by the green line. The curves with different shades of blue color correspond to the temperature profiles of 250 randomly chosen horizontal points at $t = 74.1$ minutes in the presence of synthetic spicules and CoSCos. The red curve represents the averaged temperature profile for the entire horizontal extent of the domain ($6 \times 9 \text{ Mm}^2$) at $t = 74.1$ minutes. Right panel: variation of the plasma- β at the $X = -0.05 \text{ Mm}$ plane. The white contour corresponds to the plasma- $\beta = 1$ value.

Appendix B Synthetic Plasma Emission

We have compared both the volume rendering and the LOS integration of Si IV emission from Equation (B1) with FoMo (T. Van Doorselaere et al. 2016), which uses the CHIANTI package for generalized contribution functions of optically thin lines. Spicules consist of multithermal plasma emitting at several wavelengths. Therefore, if the spicule structure undergoes certain dynamics, e.g., swaying or rotation, we would expect the corresponding emission to also reflect the same dynamics. The agreement between the images using an analytical contribution function and those from FoMo (Figure B1) shows that even if the calculation of the emission is not accurate, the time variation of the original feature will still be reflected in the forward-modeled emission. Therefore, when analyzing a sequence of simulation snapshots at 2 s cadence we have used the simpler analytical function for lower processing times. The scaled synthetic plasma emission (I_λ/I_0)

for λ wavelength is defined by

$$I_\lambda/I_0 = \int Q_\lambda(\rho, T)(\rho/\rho_0)^2 ds, \quad (\text{B1})$$

where ρ_0 is the horizontally averaged plasma density and the definition holds for temperatures between 10^4 and 10^8 K (E. Landi & F. Chiuderi Drago 2008). The contribution function is

$$Q_\lambda(\rho, T) = \exp \left[-(\log(T/T_\lambda)/w)^2 \right],$$

with $T_\lambda = 80,000$ K (compare with the optically thin line Si IV) and $w = \log 2.0$. The integration is performed along the LOS with the infinitesimal path length denoted by ds . The chromospheric line (Ca II H at $T_\lambda \approx 9000$ – $20,000$ K) is difficult to forward-model due to partial redistribution effects and strong departures from local thermodynamic equilibrium. Figure B2 shows the time-distance images generated along a horizontal slit at $z=11$ Mm for a sequence of LOS-integrated images of four different instances of spinning spicules as compared to Hinode observations.

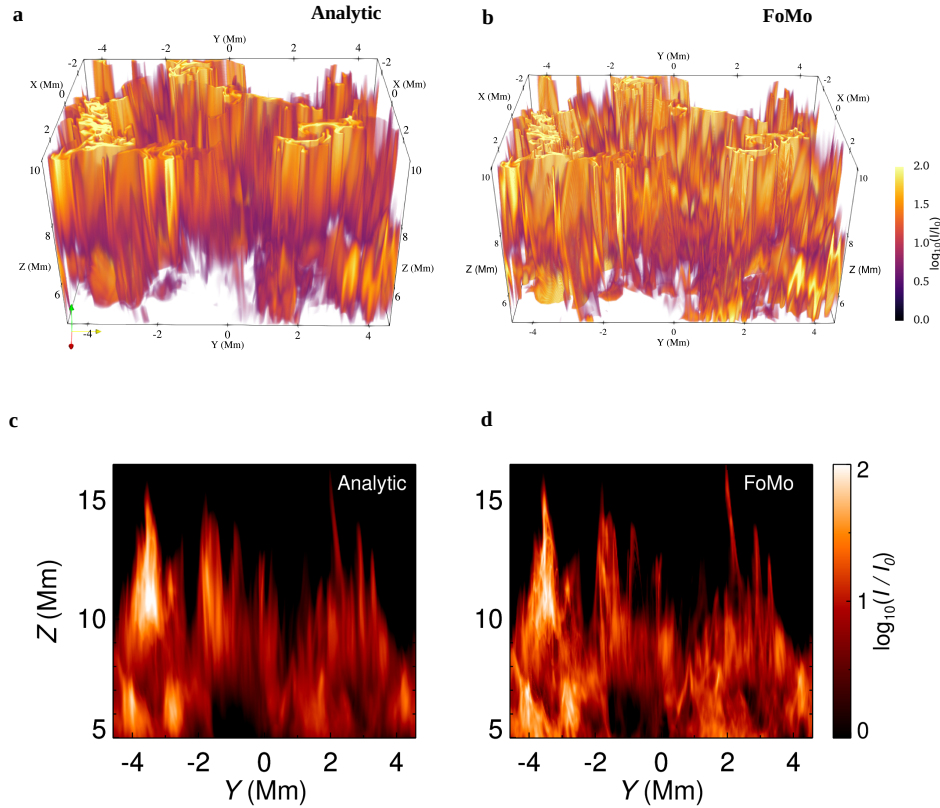


Figure B1. (a) Volume rendering of plasma emission at 80,000 K, calculated by forward modeling of our simulation, using the simple Gaussian contribution function; (b) using FoMo code for Si IV emission with the CHIANTI database; (c)–(d) LOS-integrated emission using the analytical expression for the contribution function and the CHIANTI database, respectively.

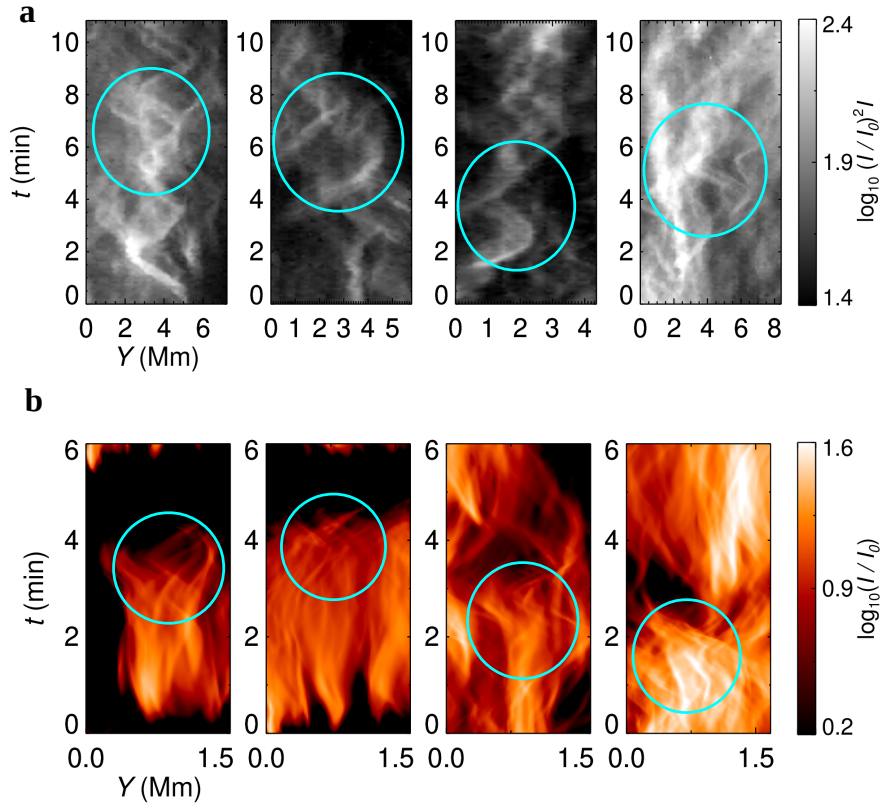


Figure B2. Identification of spinning spicules in observations and numerical model using the time–distance diagrams. (a) Scaled Ca II H/SOT intensity as seen through four different horizontal slits placed $z = 8$ Mm above and parallel to the observed solar limb similar to Figure 2(d) to capture several examples of spinning clusters. Encircled regions (cyan) show crossing of spicule strands, a feature of spinning clusters of spicules. (b) Similar to panel (a), but for synthetic spicules seen through a slit at $z = 11$ Mm at four different times.

Appendix C

Vortex Detection and Visualization with ASDA and LIC

The detection of vortices over multidimensional data is an active field of research and its usage can be found across different disciplines. There are several methods—namely, the Automatic Swirl Detection Algorithm (L. Graftieaux et al. 2001) (ASDA), the swirling strength criterion (J. Zhou et al. 1999), and the Lagrangian averaged vorticity deviation (LAVD) (G. Haller et al. 2016)—to detect vortices over different time frames. Here, we use the ASDA method to track swirls distributed between the solar photosphere and the lower corona. In this method, there exists a free parameter known as window size, which acts as a local filter to smooth out small-scale fluctuations in the velocity field. We have selected a window of 480×480 km, which is a typical diameter of existing vortices. Over the window in each horizontal plane, two crucial quantities γ_1 and γ_2 are computed to locate the

center and circumference of the vortex tube. Incompressible fluid models provide a range of threshold values of axisymmetric vortices to demarcate the core rotating region. In our compressible turbulent convection model, we have noticed that $|\gamma_1| \geq 0.55$ regions distinguish clockwise- and counterclockwise-rotating vortices with nonaxisymmetric cross sections even in the presence of strong shear flows. We have also confirmed these regions independently by comparison with a two-dimensional flow visualization method known as line integral convolution applicable to streamlines in the horizontal plane. We apply this method at every horizontal layer in the height range 0–20 Mm and track the vortex tubes over the time duration of 30 minutes. We have also confirmed these regions independently by comparison with a two-dimensional flow visualization method known as Line Integral Convolution (LIC) applicable to streamlines in the horizontal plane, as shown in Figure C1.

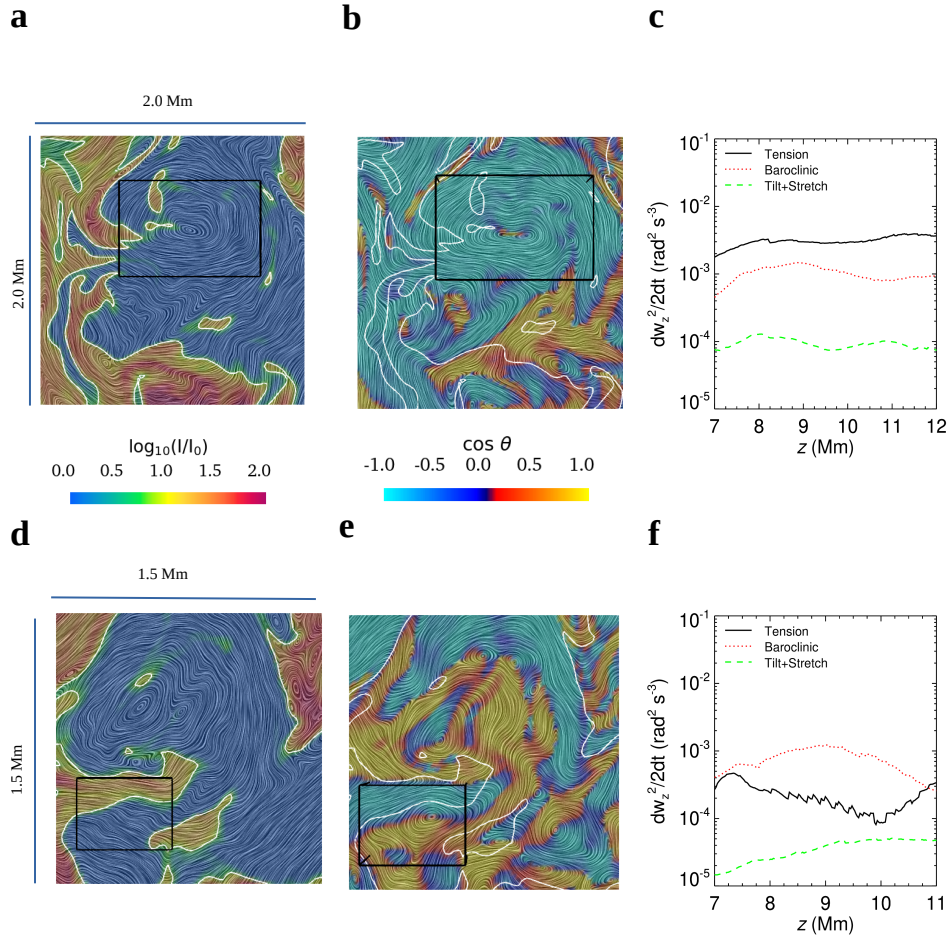


Figure C1. Examples of different types of CoSCos and associated entrophy sources. (a) The horizontal magnetic field lines colored by the synthetic intensity of the spicules in the $z = 9$ Mm plane. (b) The velocity streamlines shaded by the cosine of the angle between the horizontal magnetic and velocity field vectors. Overplotted white contours represent the boundaries of spicules and the black rectangular box locates the region of CoSCo-I. (c) Rate of change of entrophy due to different source components, averaged over the region of the corresponding CoSCo-I. Panels (d)–(f) provide an example of CoSCo-II also at $z = 9.0$ Mm, similar to panels (a)–(c).

Appendix D Filtering of Hinode SOT Images

To enhance the intensity of spicules over the background, we employ the radial filtering technique on the Level 1 Hinode SOT datasets, obtained after `fg_prep.pro` (available under the SolarSoftWare suite written in IDL) operation on the raw images as part of the calibration. We first compute the nondimensional weight factor as the ratio of intensity at each pixel to the average intensity over all pixels lying on the arc parallel to the solar limb. After applying the same operation to all radii, we multiply intensity with the square of the weight factor at every pixel. This makes relatively bright (dim) pixels even brighter (dimmer) than before and enhances the visibility of the spicule forest compared to the surroundings. A similar method (B. De Pontieu et al. 2007) was used earlier as well for off-limb spicules in Hinode data.

Appendix E Processing IRIS Slit-jaw Images

We have selected an $82 \text{ Mm} \times 36 \text{ Mm}$ region inside a coronal hole near the solar north pole with IRIS slit-jaw Si IV filter images, starting from 2016 October 19 at 19:04:09 UT. The analyzed observation sequence is 39 minutes long. The

Level 2 calibrated images are first cleaned up by removing cosmic rays and dust spots by using `array_despike.pro` and `iris_dustbuster.pro` (available under the SolarSoftWare platform), respectively. The Level 2 corrections on IRIS data can move values outside the range of 14 bit pixel values. Hence, it should be scaled appropriately using an algorithm that also applies a normalization based on exposure time to the image sequence. This kind of scaling allows maximizing the information content of the processed animation. Therefore, we scale the intensity from 14 bit to 8 bit pixel values with `iris_intscale.pro` as suggested in the manual to enable us to clearly show the fine-scale structure of spicules.

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