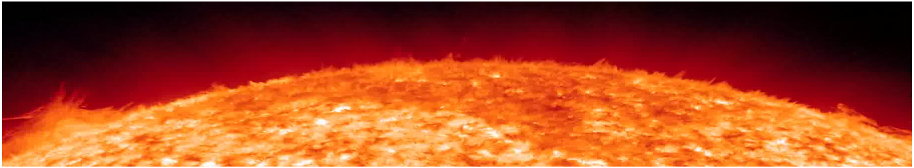
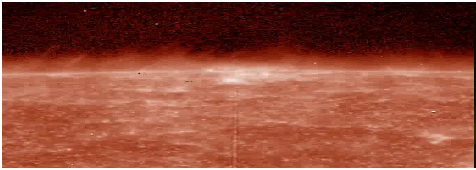
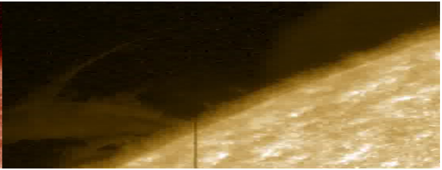


Modeling the Solar Spicule Forest

Sahel Dey[1,2], Piyali Chatterjee[1], Robert Erdelyi [3]

[1]Indian Institute of Astrophysics,[2]Joint Astronomy Programme, Indian Institute of Science, [3]University of Sheffield





Motivation

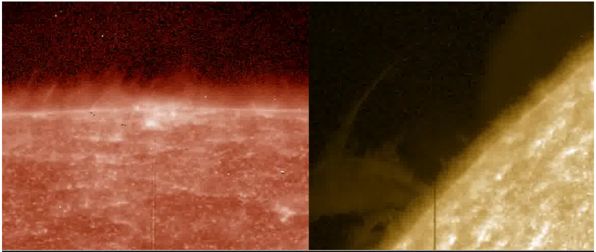
What are Spicules ?

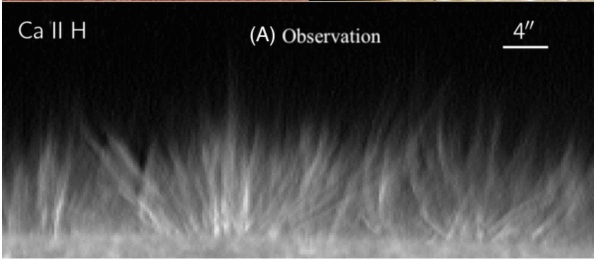
- Thin elongated spurting structures comprising of cold and dense chromospheric plasma

Why are they important ?

Positive feature !

Solar Spicule forest in different filters of IRIS:top left in Si IV and top right in Mg II k filter





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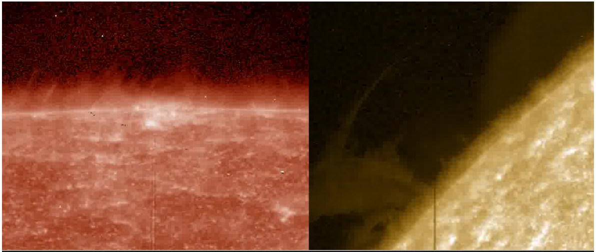
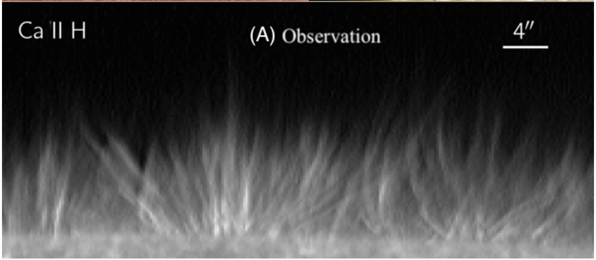




Motivation

What are Spicules ?

- Thin elongated spurting structures comprising of cold and dense chromospheric plasma

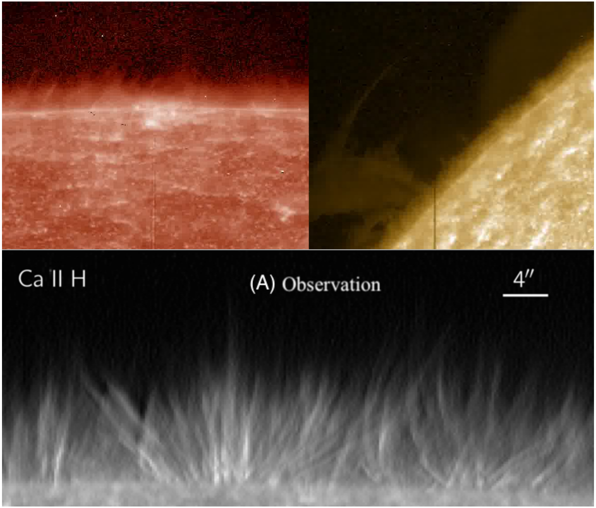
Why are they important ?

- Potential candidate for channeling mass and energy flux to Solar corona

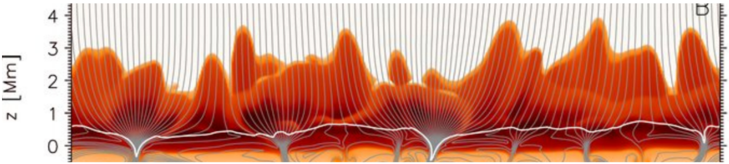
Positive feature !

- Presence in a large no over the entire Solar surface like forest

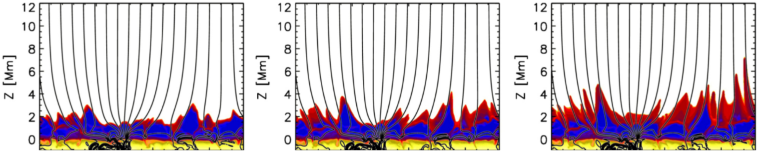
Solar Spicule forest in different filters of IRIS:top left in Si IV and top right in Mg II k filter



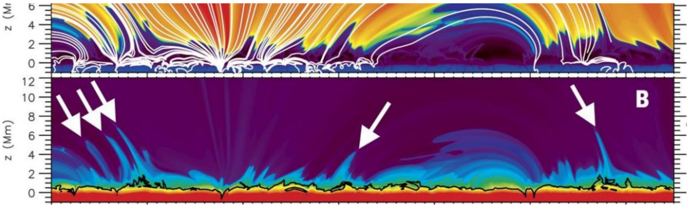
Previous significant numerical works on Spicules : including convection



Heggland et al., 2011



Iijima & Yokoyama 2015



Martínez-Sykora et al., 2017

Simulation setup using Pencil Code

- Initial setup
  1. Domain size
     (I) 2d Run :
     -18 Mm $< x <$ 18 Mm
     & -5 Mm $< z <$ 44 Mm
     (II) 3d Run :
     -3 Mm $< x <$ 3 Mm,
     -9 Mm $< y <$ 9 Mm &
     -5 Mm $< z <$ 32 Mm

Simulation setup using Pencil Code

- Initial setup
  1. Domain size
     (I) 2d Run :
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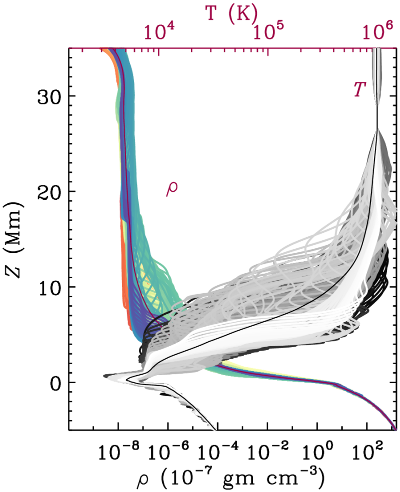
     (II) 3d Run :
     -3 Mm $< x <$ 3 Mm,
     -9 Mm $< y <$ 9 Mm &
     -5 Mm $< z <$ 32 Mm
  2. Spatial resolution
     (I) 2d coarse grid: 48 km
     (II) 2d fine grid : 16 km
     (III) 3d coarse grid : 48 km

Simulation setup using Pencil Code

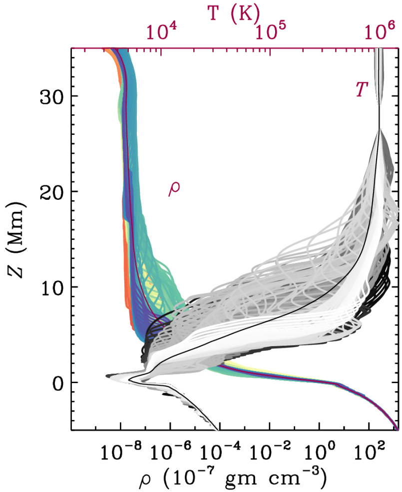
- Included approximations[a]
  1. Magnetohydrodynamics
  2. Local thermodynamic equilibrium
  3. Rosseland mean opacity for radiative transfer
  4. Anisotropic Spitzer's heat conductivity



[a] **Chatterjee 2019**.

Simulation setup using Pencil Code

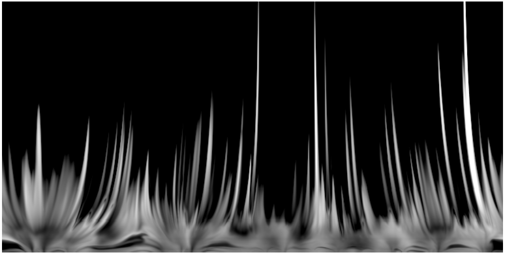
- Included approximations[a]
  1. Magnetohydrodynamics
  2. Local thermodynamic equilibrium
  3. Rosseland mean opacity for radiative transfer
  4. Anisotropic Spitzer's heat conductivity
- Boundary Condition :Periodic horizontal extent, closed bottom & open top boundary
- Background imposed $\vec{B}$ field
  1. 2D domain : Oblique and vertical orientation with strength of 25 and 74 G
  2. 3D domain : Vertical field with strength of 5 G



[a] **Chatterjee 2019**.

Differential Emission Measure of synthetic spicule forest

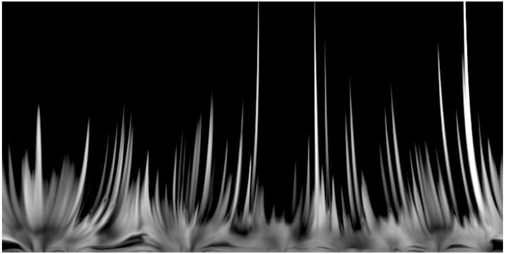
- $\mathcal{DEM}$: $\int \left(\frac{\rho}{\overline{\rho}}\right)^2 \exp\left[-\left(\frac{\log(T/T_0)}{w}\right)^2\right] ds$ [a]
- $\overline{\rho}$: horizontal averaged plasma density, $T_0 = 10^4$k & w =0.78



[a] **Iijima & Yokoyama 2017**.

Differential Emission Measure of synthetic spicule forest

- $\mathcal{DEM}$:
  $\int \left(\frac{\rho}{\bar{\rho}}\right)^2 \exp\left[-\left(\frac{\log(T/T_0)}{w}\right)^2\right] ds$ [a]
- $\overline{\rho}$: horizontal averaged plasma density, $T_0 = 10^4$k & w =0.78
- Focus on chrosmospheric plasma within temperature range of $6.4 \times 10^3 - 1.5 \times 10^4$K : similar feature like Ca II H filter
- s : line-of-sight distance (LOS)
- 2D setup : no LOS integration ! only single point



[a] **Iijima & Yokoyama 2017**.

Spicules are following magnetic fields !!

- Photospheric magnetic field : $|B_z| \approx 250$ - 400 G after stabilization
- Overall spicules are tracing magnetic field lines

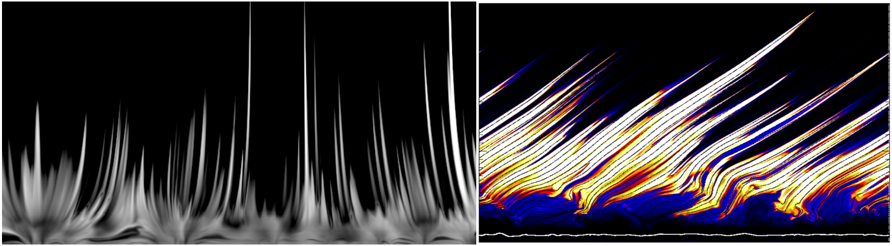
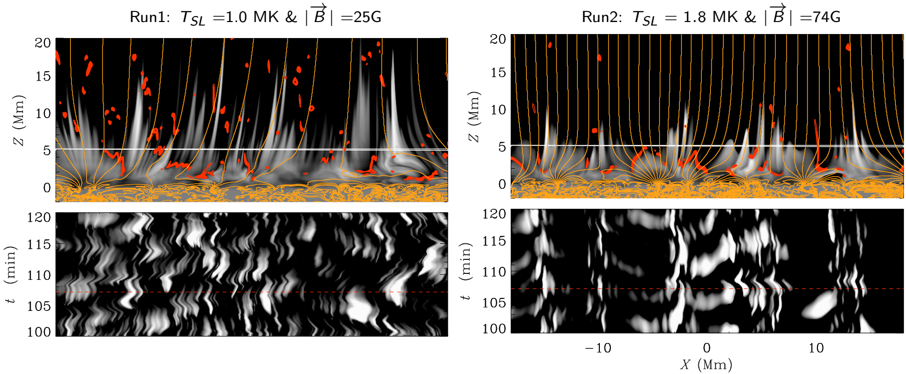


Figure: Differential emission measure of simulated spicules for T$= 10^4$ K

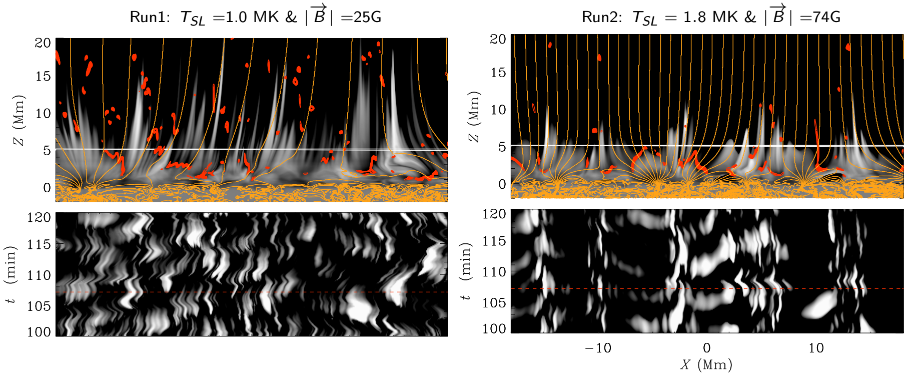
Effect of temperature and imposed fileds on sythetic spicules

- Analysis of 2 setups :



Effect of temperature and imposed fileds on sythetic spicules

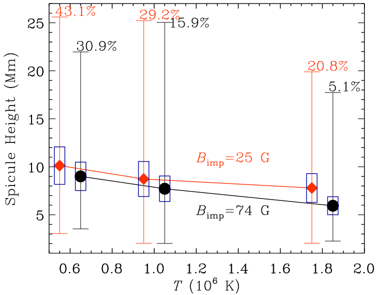
- Analysis of 2 setups :
- Shock heating at outer envelope of spicules
- A horizontal slit is placed at $z = 5$Mm to track transverse motions
- Major differences in terms of spicule's properties : Oscillation amplitude, height and location of the spicules



How much spicules can ascend in upper amosphere ? A statistical overview

- Favourable condition for reaching maximum height of the atmosphere

Sl.	Run	T_{SL} (MK)	B_{imp} (G)	N_{sp}
1	2DC0.6MK25G	0.6	25.0	3384
2	2DC0.6MK74G	0.6	74.0	2038
3	2DC1.0MK25G	1.0	25.0	4620
4	2DC1.0MK74G	1.0	74.0	2167
5	2DC1.8MK25G	1.8	25.0	2662
6	2DC1.8MK74G	1.8	74.0	2907



[1] **Heggland et al., 2011**.

How much spicules can ascend in upper amosphere ? A statistical overview

- Favourable condition for reaching maximum height of the atmosphere
  1. $|\vec{B}_{imp}|$: smaller strength
  2. T_{SL} : cooler atmosphere like Quiet sun phase[1]
- Effect of temperature in mean height of spicules : almost linearly decreasing with temperature enhancement

Sl.	Run	$T_{\rm SL}$ (MK)	$B_{\rm imp}$ (G)	$N_{\rm sp}$
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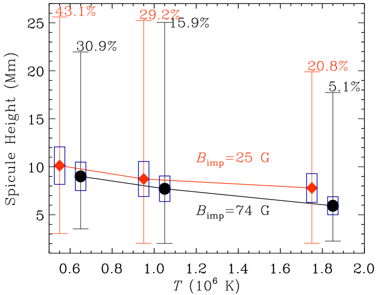
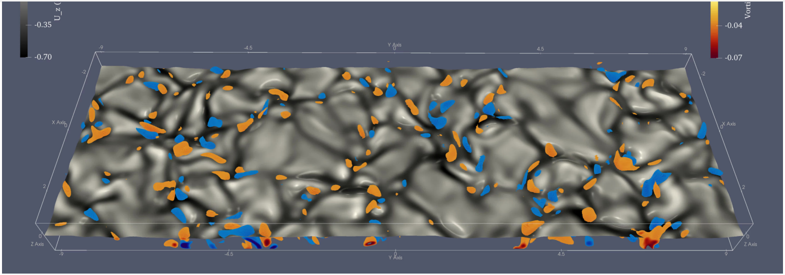
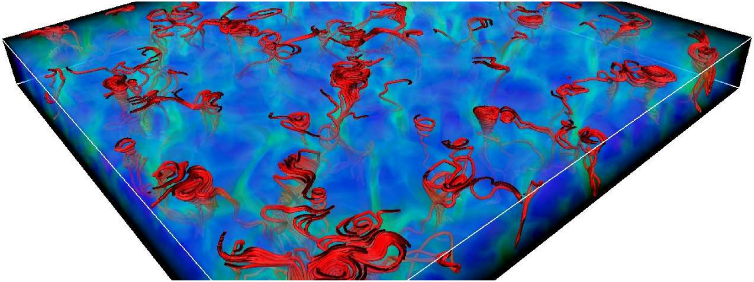


[1] **Heggland et al., 2011**.

Photosphere in 3D setup

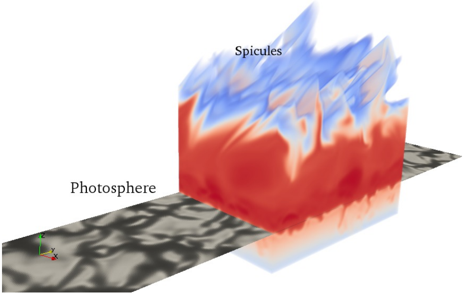


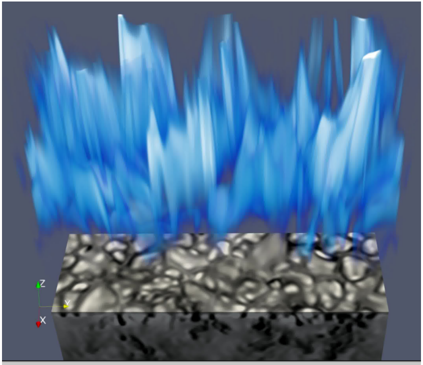


2

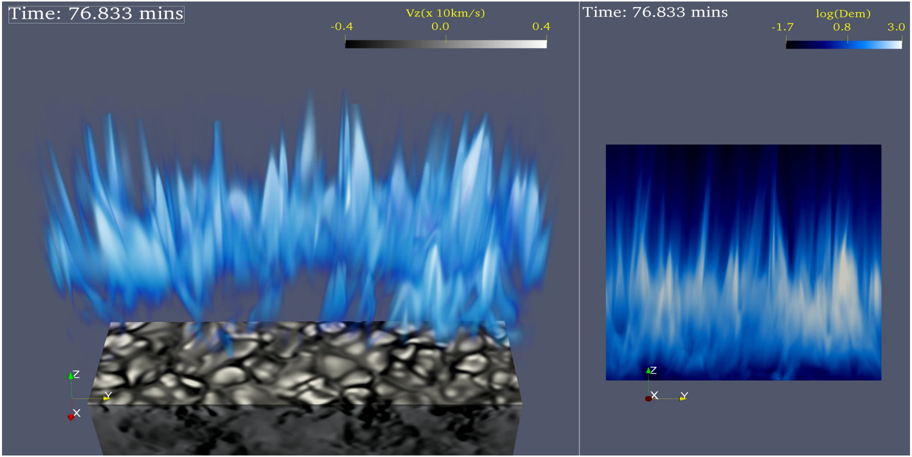
[2]shelyag et al., 2011.

No exception in 3D framework: Spicules are tracers of field lines





Dynamics of spicules & Differential Emission Measure



Oscillation modes of Chromospheric jets

- **Complex motion of simulated spicules**
  1. Tranverse undulation Kink mode → quite prominent

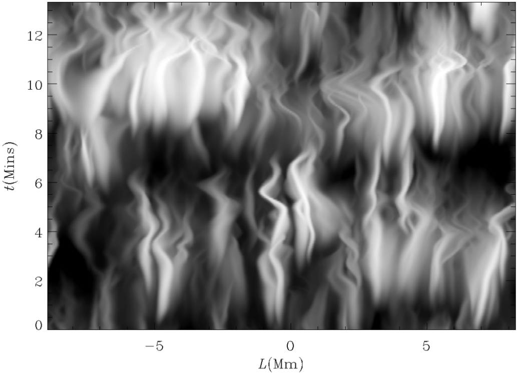


Figure: Time distance plot of Differential Emission Measure of synthetic spicules

Oscillation modes of Chromospheric jets

- **Complex motion of simulated spicules**

  1. Tranverse undulation Kink mode → quite prominent
  2. Apparent twisting motion between vertical strand structures or line of sight integration effect

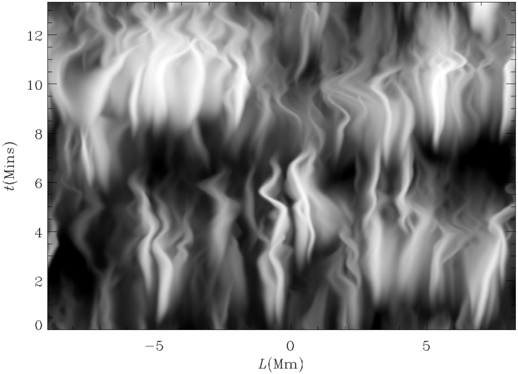
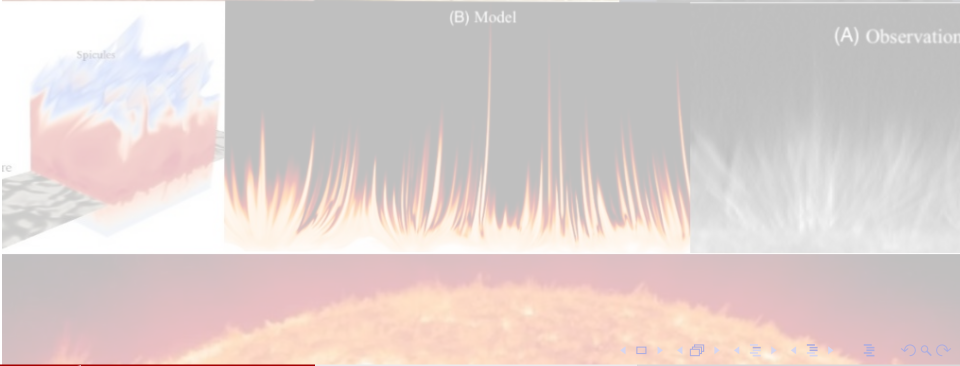


Figure: Time distance plot of Differential Emission Measure of synthetic spicules

Conclusions

- No. density of spicules is quite large, which mimics Solar Spicule forest structure
- A large fraction$(0.20 - 0.43)$ of total spicules can reach more than 10 Mm height in upper atmosphere



Conclusions

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- Magnetic field determines overall motion of Spicules
- In strong magnetic field and high atmosphere temperature, spicule's height reduces
- In presence of large magnetic field, Spicules appear assembling near internetwork region

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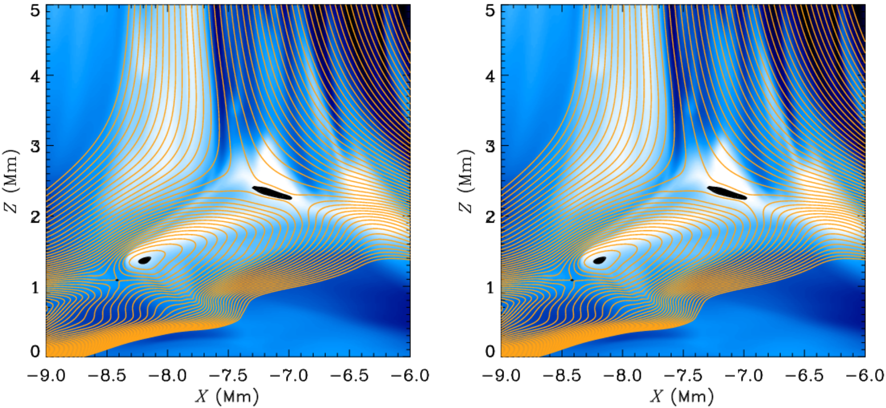
- Magnetic field determines overall motion of Spicules
- In strong magnetic field and high atmosphere temperature, spicule's height reduces
- In presence of large magnetic field, Spicules appear assembling near internetwork region
- Realistic Solar like convection zone with mean freqency 2.16-3.51 mHz(time period of 4.5-7.5 mins) and average convective cell size of 1.4 Mm
- Transverse undulations(Kink modes) are dominating in Spicule dynamics
- Further analysis are required to determine the presence of Sausage,Torsional modes and their energy contribution.

Supplementary materials



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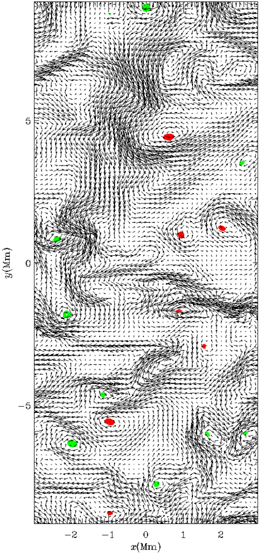

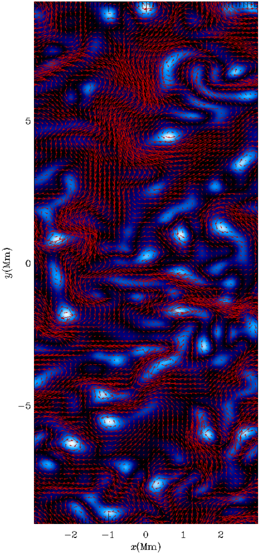

Supplementary materials

- Viscosity(ν) $= 1.0 \times 10^7 cm^2 s^{-1}$
- Hyper viscosity$= 1.0 \times 10^4 cm^6 s^{-1}$. Source is completely numerical(dissipate maximum energy in the smallest scale)
- Shock viscosity$= 5 \times 10^{15} cm^2 s^{-1}$. Only acts where shocks are generated
- Magnetic diffusion (η)$=1 \times 10^7 cm^2 s^{-1}$
- Hyper Diffusion$= 1.0 \times 10^1 cm^6 s^{-1}$. Source is completely numerical(dissipate maximum energy in the smallest scale)
- Shock diffusion$= 5 \times 10^{14} cm^2 s^{-1}$. Only acts where shocks are generated
- Density diffusion$= 4 \times 10^7 cm^2 s^{-1}$
- Thermal Diffusion$= 1 \times 10^7 cm^2 s^{-1}$

Supplementary materials

- **Initial conditions:**
  1. **Temperature and density stratification :** From Model[S Christensen-Dalsgaard et al. 1996 for convection zone and Vernazza et al. 1981] and solution of hydrostatic balance equation with Saha-ionization equation respectively.
  2. **Velocity field :** Gaussian Noise
  3. **Background magnetic field :** $[0.0, 0.0, 5.0]G$
- Grid Reynolds no $(R) = 4.54 \times 10^{1}$(lower part of corona),1.31×10^{4}(convection zone)
- Grid Magnetic Reynolds no $(R_m) =$ Same as Grid Reynolds no
- Grid Magnetic Prandtl no $(P_m) = 1.0$