Analysis of 3D plasma motions in a chromospheric jet formed due to magnetic reconnection

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ABSTRACT

- Within the framework of 3D resistive MHD, we simulate the formation of a plasma jet with the morphology, upward velocity and timescale formation similar to those expected for Type II spicules as described in **González-Avilés et al. (2018a)**.
- In this paper we analyze the transverse displacements and rotational type motion of the jet.
- We calculate time series of the velocity components in different points near to the jet for various heights and find transverse oscillations in agreement with spicule observations.
- By analyzing temperature isosurfaces, we find that the line-of-sight (LOS) is approximately perpendicular to the jet axis.
- The jet shows a red-blue shift pattern caused by rotational motion.

RESISTIVE MHD EQUATIONS

We consider the EGLM resistive MHD equations that include gravity:

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho \mathbf{v}) = 0,$$

$$\frac{\partial(\rho \mathbf{v})}{\partial t} + \nabla\cdot\left(\left(p+\frac{1}{2}\mathbf{B}^2\right)\mathbf{I} + \rho\mathbf{v}\mathbf{v} - \mathbf{B}\mathbf{B}\right) = -(\nabla\cdot\mathbf{B})\mathbf{B} + \rho\mathbf{g},$$

$$\frac{\partial E}{\partial t} + \nabla\cdot\left(\mathbf{v}\left(E+\frac{1}{2}\mathbf{B}^2+p\right) - \mathbf{B}(\mathbf{B}\cdot\mathbf{v})\right) = -\mathbf{B}\cdot(\nabla\psi) - \nabla\cdot((\eta\mathbf{J})\times\mathbf{B}) + \rho\mathbf{g}\cdot\mathbf{v},$$

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla\cdot(\mathbf{B}\mathbf{v} - \mathbf{v}\mathbf{B} + \psi\mathbf{I}) = -\nabla\times(\eta\mathbf{J}),$$

$$\frac{\partial \psi}{\partial t} + c_h^2\nabla\cdot\mathbf{B} = -\frac{c_h^2}{c_p^2}\psi.$$

NUMERICAL CODE

- Newtonian CAFE solves the resistive MHD equations in three dimensions using finite volume discretization.
- It is based on high-resolution shock-capturing methods, uses the HLLE, HLLC, HLLD and Roe flux formulas combined with MINMOD, MC and WENO5 reconstructors.
- The divergence free magnetic field constraint is controlled using the Extended Generalized Lagrange Multiplier (EGLM).
- It uses the method of lines to evolve in time and it is mounted in the driver of Cactus code to use MPI and HDF5.

MODEL OF SOLAR ATMOSPHERE

We assume a gravitationally stratified solar atmosphere in hydrostatic equilibrium obeying the C7 model.

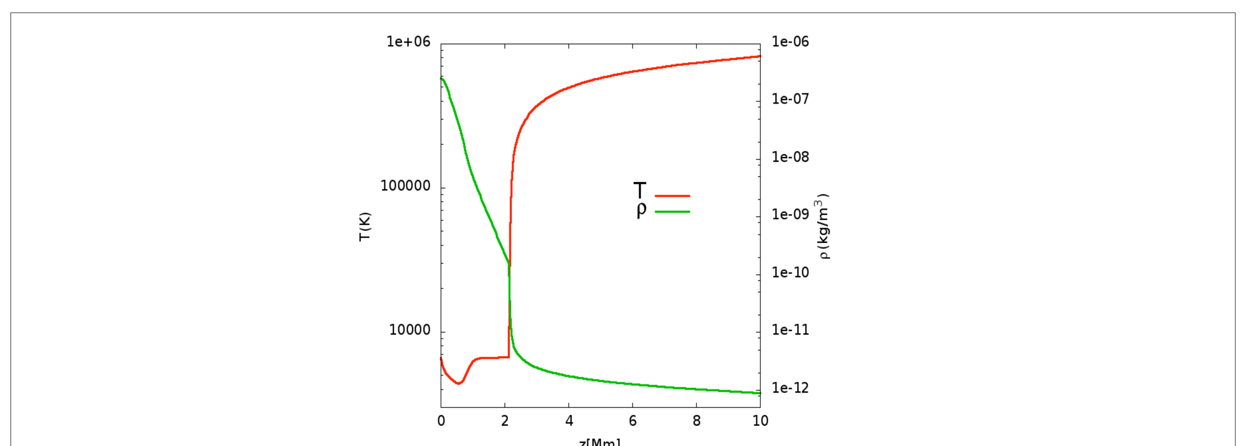

Figure 1. Temperature and mass density as a function of height for the C7 equilibrium solar atmosphere model.

MAGNETIC CONFIGURATION IN 3D

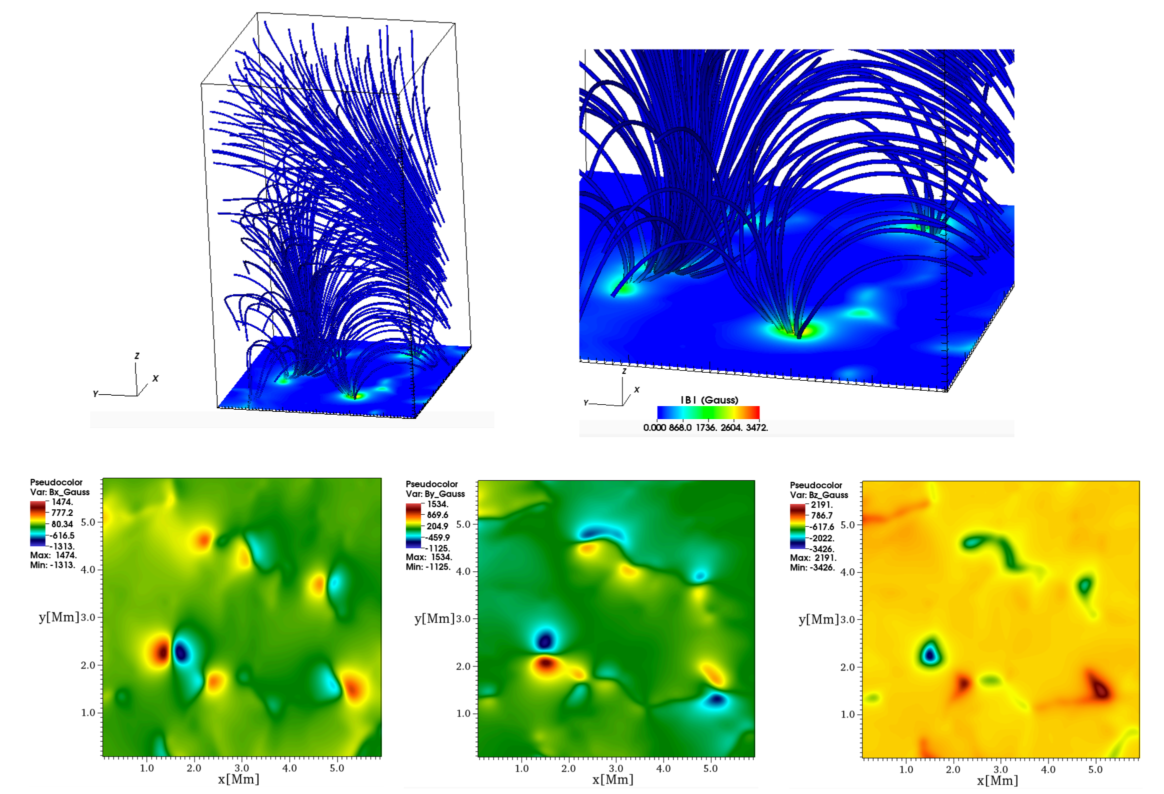

Figure 2. (Top) Magnetic field lines and zoom of the strong bipolar regions in the 3D domain at initial time. **(Bottom)** Three components of the magnetic field B_x, B_y and B_z at the plane z=0.1 Mm.

TRANSVERSE MOTIONS

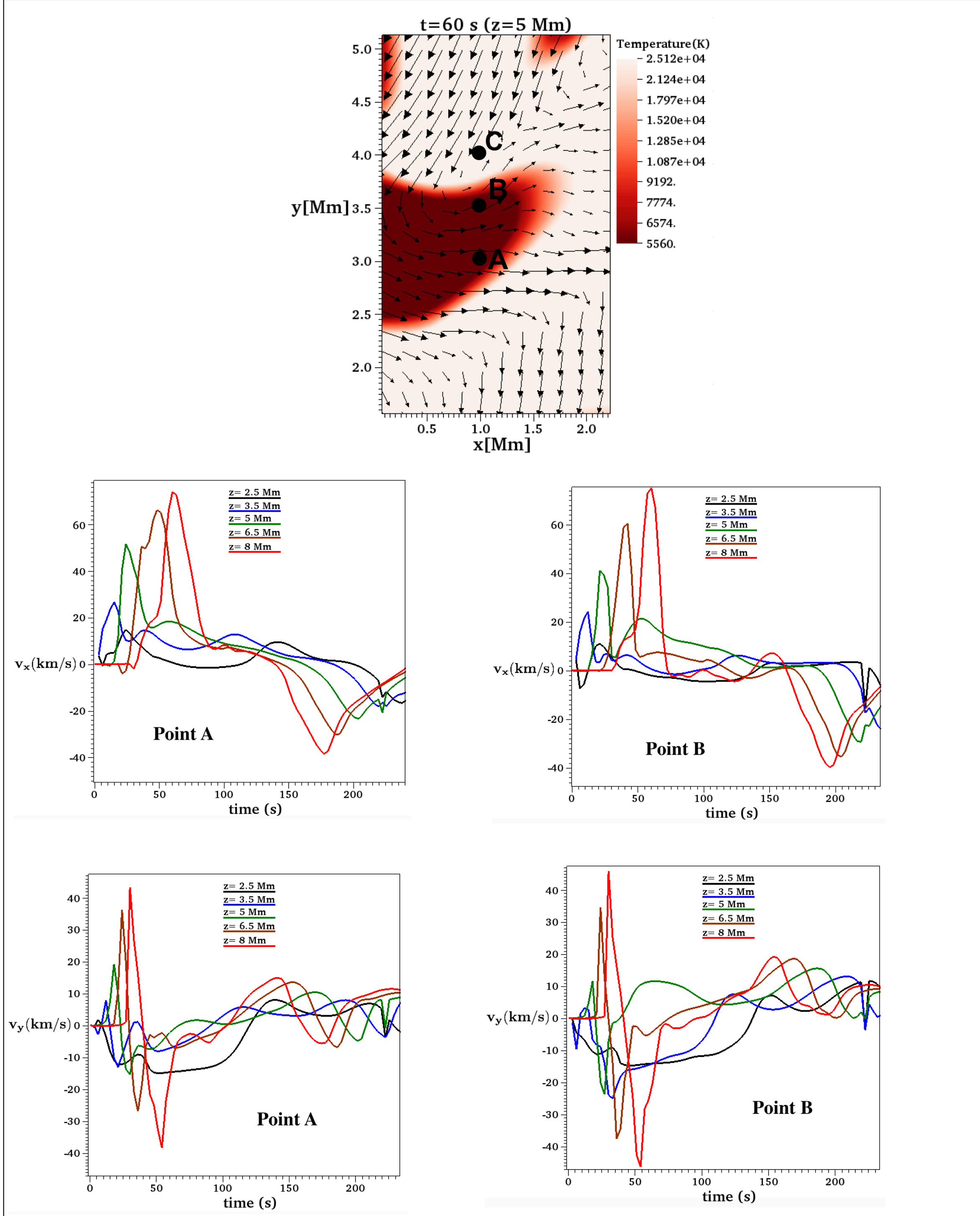

Figure 3. (Top) Region where v_x and v_y are measured. In the middle and bottom panel we show the time series of v_x and v_y in km/s of the volume elements at the points A and B measured at various planes of constant height.

ROTATIONAL MOTIONS

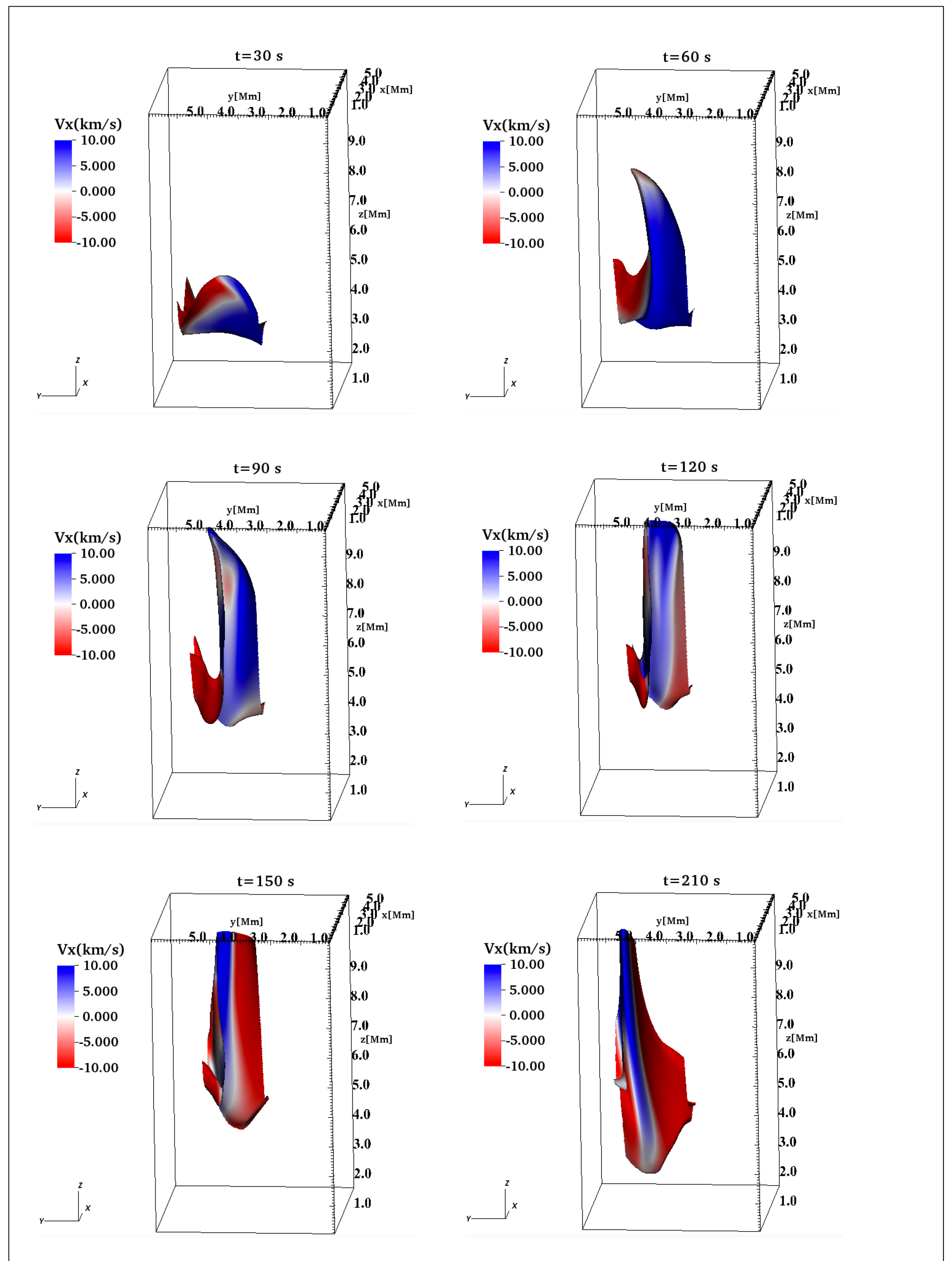

Figure 4. Snapshots of a temperature contour at various times. The jet is represented by an isosurface of the plasma temperature equal to 10^4 K. The color code label the value of v_x. In this perspective blue indicates motion toward the reader and red toward inside the page.

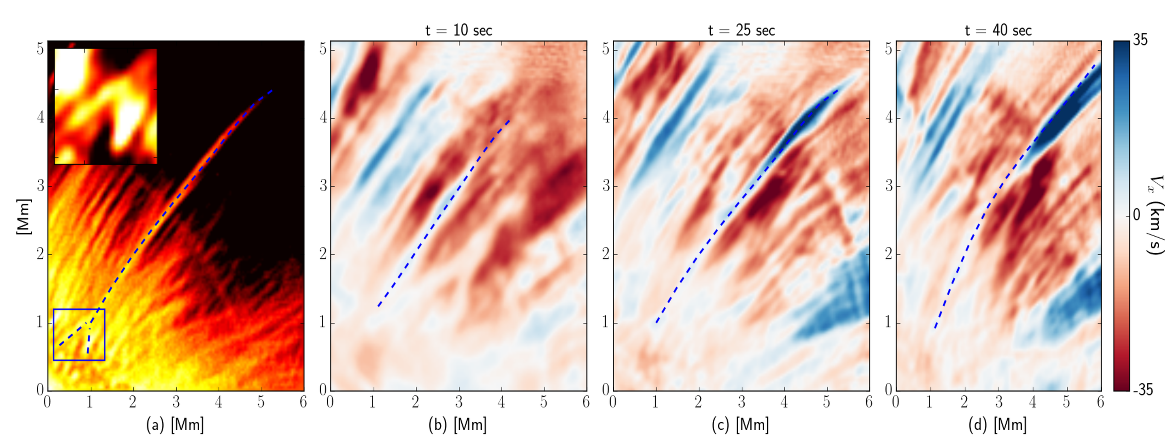

Figure 5. Left to right: Panel show a spicule (traced as dashed-line) off-limb, observed in Hα wavelength (a), with temporal evolution of the line-of-sight (LOS) Doppler velocity estimates (b-d). The unsharp-masked intensity image (a) show inverted Y-shaped structure (zoomed in inset) at the spicule footpoint (highlighted in box) suggestive of a magnetic reconnection process. Doppler estimates reveal the longitudinal rise of the spicule with its dominant motion towards the observer (b-c). The development of rotational motion is indicated by the enhanced red-blue asymmetric profile at the apex of spicule (d).

VERTICAL MOTIONS

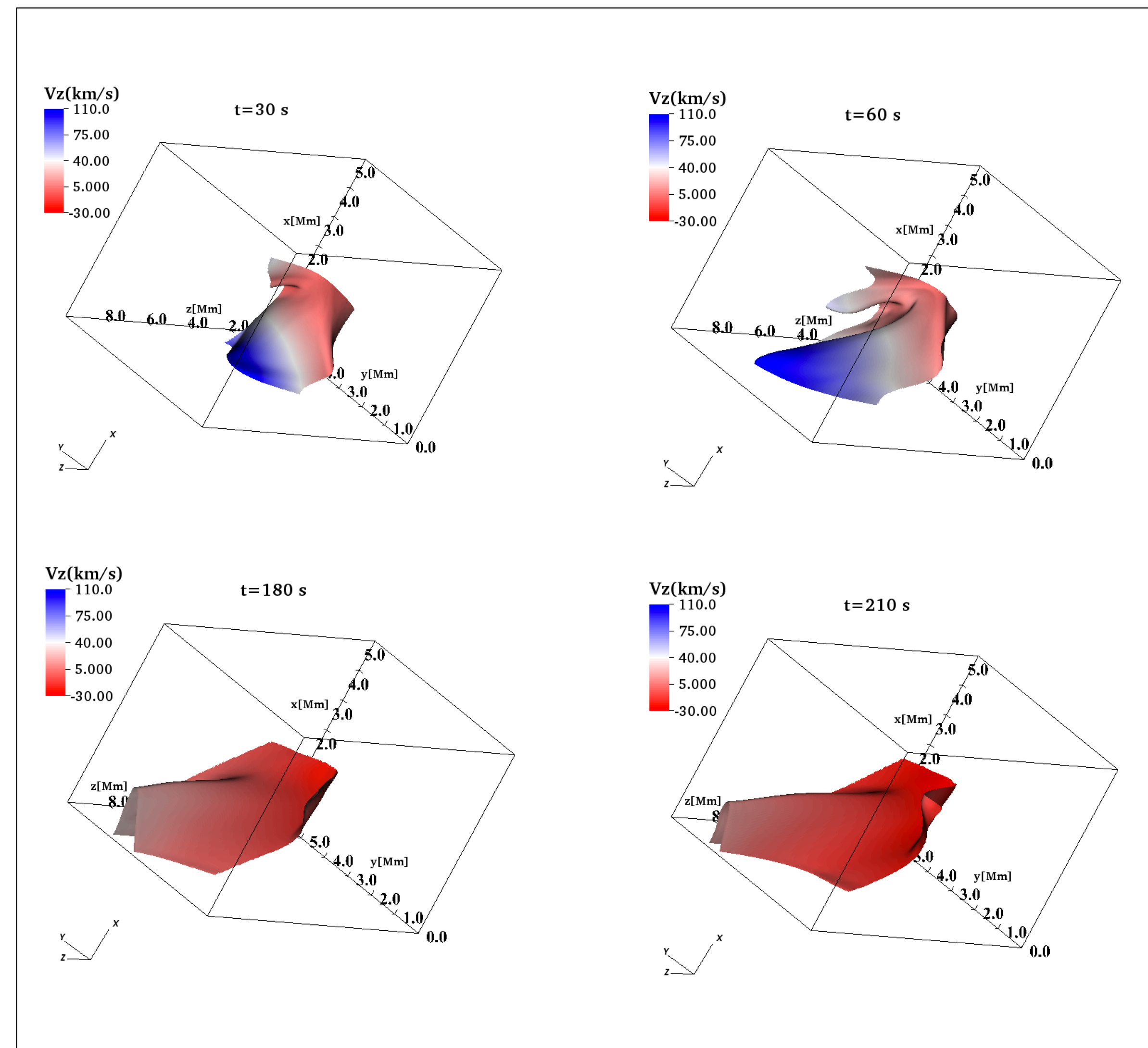

Figure 6. Snapshots of a temperature contour at various times. The jet is represented by an isosurface of the plasma temperature equal to 10^4 K. The color-code labels the value of v_z.

SUMMARY

- In this work we found that the development of a red-blue asymmetry across the jet is due to rotational motion. This rotational is initially clockwise and then begins to move in an anti-clockwise direction, indicating the presence of torsional motion.
- We have presented observational support of rotational motion in an off-limb spicule appearing in the corona.
- We can also see the simulated jet has a dual behavior (i) transverse motion at the foot (0-3 Mm) and (ii) twisted motion at the middle and top parts (3-10 Mm).
- The rotational type motion can be interpreted as torsional starting at the top of the jet, when it reached a region where the magnetic field and the Lorentz force dominate. This shows that **torsional waves can be generated directly in the corona** and therefore the whole wave energy (i.e without any losses due to propagation from the photosphere and dynamic chromosphere to the corona can be dissipated in the corona).

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