I. JET FORMATION AND EVOLUTION DUE TO 3D MAGNETIC RECONNECTION

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ABSTRACT

Using simulated data-driven three-dimensional resistive MHD simulations of the solar atmosphere, we show that magnetic reconnection can be responsible of the formation of jets with characteristic of Type II spicules. For this, we numerically model the photosphere-corona region using the C7 equilibrium atmosphere model. The initial magnetic configuration is a 3D potential magnetic field, extrapolated up to the solar corona region from a dynamic realistic simulation of solar photospheric magnetohconvection model which is mimicking quiet-Sun. In this case we consider a uniform and constant value of the magnetic resistivity of 12.56 Ω m. We have found that formation of the jets depends on the Lorentz force, which helps to accelerate the plasma upwards. Analyzing various properties of the jet dynamics, we found that the jet structure shows Doppler shift near to the regions with high vorticity. The morphology, upward velocity, covering a range up to 100 km s$^{-1}$, and life-time of the structure, bigger than 100 s, are similar to those expected for Type II spicules.

Keywords: magnetic reconnection - magnetohydrodynamics (MHD)- methods: numerical - Sun: atmosphere - Sun: magnetic fields

1. INTRODUCTION

Jet-like emissions of plasma in the solar atmosphere have been extensively observed over a range of wavelengths, e.g. X-ray, EUV and Hα, that usually occur in active regions and polar coronal holes. It is believed that many plasma jets are produced directly by magnetic reconnection, when oppositely directed magnetic fields come in contact (see e.g. Shibata et al. 2007). The magnetic reconnection acts as a mechanism of conversion of the magnetic field energy into thermal and kinetic energy of the ejected plasma and can occur from the convection zone to the solar corona. In particular, the observed chromospheric dynamics at the solar limb is dominated by spicules (Beckers et al. 1968), which are ubiquitous, highly dynamic jets of plasma (Secchi 1878; Tsiropoula et al. 2012; De Pontieu et al. 2007b). The improvement in the resolution of the observations by the Hinode satellite and Swedish 1 m Solar Telescope (SST) on La Palma (Kosugi et al. 2007; Scharmer et al. 2003, 2008) has suggested the existence of two classes of spicules.

The first type of spicules are so-called Type I, which reach maximum heights of 4-8 Mm, maximum ascending velocities of 15-40 km s$^{-1}$, have a lifetime of 3-6.5 minutes (Pereira et al. 2012), and show up and downward motions (Beckers et al. 1968; Suematsu et al. 1995). These Type I spicules are probably the counterpart of the dynamic fibrils on the disk. They follow a parabolar (ballistic) path in space and time. In general the dynamics of these spicules is produced by magneto-acoustic shock wave passing or wave-driving through the chromosphere (Shibata et al. 1982; De Pontieu et al. 2004; Hansteen et al. 2006; Martínez-Sykora et al. 2009; Matsumoto & Shibata 2010; Scullion et al. 2011). The second type of spicules (Type II) reach maximum heights of 3-9 Mm (longer in coronal holes) and have shorter lifetimes of 50-150 s than Type I spicules (De Pontieu et al. 2007a; Pereira et al. 2012). These Type II spicules show apparent upward motions with speeds of order 30-110 km s$^{-1}$. At the end of their life they usually exhibit rapid fading in chromospheric lines (De Pontieu et al. 2007b). However the timescale of both types of spicules depends on the temperature, i.e., Ca II observations show short spicules, whereas Mg II or transition region lines show lifetimes of the order of ten minutes (Pereira et al. 2014; Skogsrud et al. 2015). In contrast to Type I spicules, Type II spicules are not understood well. It has been suggested from observations that Type II spicules are continuously accelerated while being heated to at least transition region temperatures (De Pontieu et al. 2009, 2011). Another observations indicate that some Type II spicules also show an increase or a more complex velocity dependence with height (Sekse et al. 2012).

Apart from the upward motion, Type II spicules show swaying or transverse motions at the limb with velocity amplitudes of the order 10-30 km s$^{-1}$ and periods of 100-500 s (De Pontieu et al. 2007b; Tomczyk et al. 2007; Zaqrashvili & Erdélyi 2009; McIntosh et al. 2011; Sharma et al. 2017), suggesting generation of upward, downwards and standing Alfvén waves (Okamoto & De Pontieu 2011; Tavabi et al. 2015), the generation of MHD kink mode waves or Alfvén waves due to magnetic reconnection (Nishizuka et al. 2008; He et al. 2009; McLaughlin et al. 2012; Kuridze et al. 2012). Also, Suematsu et al. (2008) suggest that some spicules show multi-thread structure as result of possible rotation. Another possible motions that Type II spicules show are the torsional motions as suggested in (Beckers 1972), and established using high-resolution spectroscopy at the limb (De Pontieu et al. 2012). According to the latter, Type II spicules show torsional motions with 25-30 km s$^{-1}$ speeds.

There are observational results and theoretical models for the Type II spicules, however our understanding of their physical origins remains limited. Some possibilities are that Type II spicules are due to magnetic reconnection (Isobe et al. 2008;
De Pontieu et al. 2007b; Archontis et al. 2010; González-Avilés et al. 2017a), oscillatory reconnection processes (Heggland et al. 2009; McLaughlin et al. 2012), strong Lorentz force (Martínez-Sykora et al. 2011; Goodman 2012) or propagation of $p$-modes (de Wijn et al. 2009). More recently, (Martínez-Sykora et al. 2017) showed that spicules occur when magnetic tension is amplified and transported upward through interaction between ions and neutrals or ambipolar diffusion. The tension is impulsively released to drive flows, heat plasma, and generate Alfvénic waves.

In this paper, we show that 3D magnetic reconnection can be responsible for formation of a jet with characteristics of a Type II spicule. For that (i) we assume a completely ionized solar atmosphere which is governed by the resistive MHD equations subject to a constant gravitational field, (ii) we model the solar atmosphere based on the C7 model in combination with a 3D potential magnetic field configuration extrapolated from a realistic photospheric quiet-Sun model. The magnetic reconnection takes place at the X point localized at the chromospheric level, which in turn accelerates the plasma and produces the jet structure.

The system of equations, the magnetic field configuration, the numerical methods and the model of the solar atmosphere are described in detail in Section 2. The results of the numerical simulations are presented in Section 3. Finally in the Section 4, we present the final comments and conclusions.

2. MODEL AND NUMERICAL METHODS

2.1. The system of Resistive MHD equations

We solve the dimensionless Extended Generalized Lagrange Multiplier (EGLM) resistive MHD (Jiang et al. 2012) equations that include gravity:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \quad (1)
\]

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

\[
\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot \left( \mathbf{v} \left( E + \frac{1}{2} \mathbf{B}^2 + p \right) - \mathbf{B} (\mathbf{v} \cdot \mathbf{v}) \right) = -\mathbf{B} \times (\nabla \psi) - \nabla \times (\eta \mathbf{J}) + \rho \mathbf{g} \cdot \mathbf{v}, \quad (3)
\]

\[
\frac{\partial \mathbf{J}}{\partial t} + \nabla \cdot (\mathbf{B} \mathbf{v} - \mathbf{v} \mathbf{B} + \psi \mathbf{I}) = -\nabla \times (\eta \mathbf{J}), \quad (4)
\]

\[
\frac{\partial \psi}{\partial t} + c_h^2 \nabla \cdot \mathbf{B} = -c_p^2 \psi, \quad (5)
\]

\[
\mathbf{J} = \nabla \times \mathbf{B}, \quad (6)
\]

\[
\frac{\partial E}{\partial t} + \nabla \cdot (\mathbf{S} \mathbf{v}) = (\gamma - 1) \rho \frac{\nabla \cdot \mathbf{B}}{\rho}, \quad (7)
\]

where $\rho$ is the mass density, $\mathbf{v}$ is the velocity vector field, $\mathbf{B}$ is the magnetic vector field, $E$ is the total energy density and $\gamma = 5/3$ is the adiabatic index. The plasma pressure $p$ is described by the equation of state of an ideal gas. $\mathbf{g}$ is the gravitational field, $\mathbf{J}$ is the current density, $\eta$ is the magnetic resistivity tensor and $\psi$ is a scalar potential that aims at damping out the violation of the constraint $\nabla \cdot \mathbf{B} = 0$. Here $c_h$ is the wave speed and $c_p$ is the damping rate of the wave of the characteristic mode associated with $\psi$. In this study we consider uniform and constant magnetic resistivity for simplicity. The system of Equations (1)-(7) was normalized by the quantities given in Table 1, which are typical scales in the solar atmosphere.

In the EGLM-MHD formulation, Equation (5) is the magnetic field divergence free constraint. As suggested in Dedner et al. (2002), the expressions for $c_h$ and $c_p$ are

\[
c_h = \frac{c_{f1}}{\Delta t} \min(\Delta x, \Delta y, \Delta z), \quad c_p = \sqrt{\frac{-\Delta t}{\ln c_d}} c_h^2,
\]

where $\Delta t$ is the time step, $\Delta x$, $\Delta y$ and $\Delta z$ are the spatial resolutions, $c_{f1} < 1$ is the Courant factor, $c_d$ is a problem dependent coefficient between 0 and 1, this constant determines the damping rate of divergence errors. The parameters $c_h$ and $c_p$ are not independent of the grid resolution and the numerical scheme used, for that reason one should adjust their values. In our simulations we use $c_p = \sqrt{c} c_h$, with $c_p = 0.18$ and $c_h = 0.1$. In this work we solve the 3D resistive MHD equations with resolutions $\Delta x$, $\Delta y$ and $\Delta z$.

The gas pressure is computed using the thermal energy, which is obtained by subtracting the kinetic and magnetic energy from the total energy, defined by the total energy Equation (7). In the solar corona region, the plasma-$\beta$ can become very small, and the thermal energy could be many orders of magnitude smaller than magnetic energy. Therein, small discretization errors in the total energy can produce unphysical negative pressure. We fix this problem by replacing the total energy density Equation (3) in low-beta regions ($\beta \leq 10^{-5}$) with the entropy density equation.

\[
\frac{\partial S}{\partial t} + \nabla \cdot (\mathbf{S} \mathbf{v}) = (\gamma - 1) \rho \frac{\nabla \cdot \mathbf{B}}{\rho}, \quad (8)
\]

where $S = \frac{\rho}{\rho^*}$ is the entropy density and $\mathbf{J}^* = \mathbf{J}_x^2 + \mathbf{J}_y^2 + \mathbf{J}_z^2$. In this way, we calculate the pressure directly using the entropy, which, by definition, is a positive quantity. The entropy density equation is used to maintain the positivity of gas pressure in the context of the ideal MHD simulations (Balsara & Spicer 1999; Li 2008; Derings et al. 2016), and is also used in some resistive MHD simulations of the solar corona (Takasao et al. 2015). In the ideal MHD limit, equation (8) is an advection type of equation, whereas in the case of the resistive MHD equations is added as a source term representing the Ohmic dissipation, consistent with the second law of thermodynamics in the continuum limit (Derings et al. 2016).

2.2. The magnetic field

As an initial magnetic configuration, we use a 3D potential (current-free) magnetic field extrapolated from a simulated quiet-Sun photospheric field. The latter has been obtained from a large-scale, high-resolution self-consistent simulation of solar magnetoconvection with MURaM code (Shelyag et al. 2012; Vögler et al. 2005). The original computational box had a size of $480 \times 480 \times 400$ pixels with a spatial resolution is 25 km in all directions.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Quantity</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>x,y,z</td>
<td>Length</td>
<td>$l_0$</td>
<td>$10^6$ m</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density</td>
<td>$\rho_0$</td>
<td>$10^{-12}$ kg m$^{-3}$</td>
</tr>
<tr>
<td>$\mathbf{B}$</td>
<td>Magnetic field</td>
<td>$B_0$</td>
<td>11.21 G</td>
</tr>
<tr>
<td>$\mathbf{v}$</td>
<td>Velocity</td>
<td>$v_0$</td>
<td>$10^6$ m s$^{-1}$</td>
</tr>
<tr>
<td>$t$</td>
<td>Time</td>
<td>$t_0$</td>
<td>1 s</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Resistivity</td>
<td>$\eta_0$</td>
<td>$1.256 \times 10^6$ m$^2$ s$^{-1}$ N A$^{-2}$</td>
</tr>
</tbody>
</table>

| Table 1 | Normalization units |

The expression for $c_h$ and $c_p$ are
The potential field extrapolation is based on a vector-potential Grad-Rubin-like method as described in Amari et al. (1997). The potential field extrapolation uses open boundary conditions on the side and top of the computational box: the first derivative of the magnetic field component normal to the surface of the box vanishes. We select a 3D domain of \(6 \times 6 \times 10\) Mm containing a topology of interest to perform our numerical simulations. The magnetic field lines of the 3D configuration and the components of the magnetic field \(B_x, B_y, B_z\) in the \(xy\) plane at \(z = 0.1\) Mm are shown in Figure 1, where dipolar structures can be observed. In our convention the \(xy\) plane is horizontal and \(z\) labels height. These plots show the region used for the evolution of the system, which contains intense magnetic field dipoles at around the location \((x, y, z) \sim (1.4, 2.3, 0.1)\) Mm, where the magnetic reconnection happens and triggers the jet.

2.3. Numerical methods

The implementation is the same High Resolution Shock Capturing method as used in González-Avilés et al. (2017a), based on finite volume approximation. However, in the present paper we exploit the full three-dimensional capabilities of the Newtonian CAFE code (González-Avilés et al. 2015). A summary of the specific numerical methods is as follows. We solve numerically the system of Equations (1)-(8) on a uniform cell centered grid, using the method of lines with a third order Runge-Kutta time integrator (RK3) (Shu & Osher 1989). The discretization of the resistive MHD equations above is based on finite volume approximation. We use the MINMOD and MC limiters for the flux reconstruction, and a combination of the HLLE and HLLC approximate flux formulas (Einfeldt 1988; Harten et al. 1983; Li 2005). The combinations of limiters and flux formulas is adaptive and depends on the magnitude of the discontinuities and shocks formed during the evolution, using the maximum dissipative combination MINMOD-HLLE in zones where \(\beta < 10^{-2}\) and the least dissipative combination MC-HLLC otherwise.

2.4. Model of the solar atmosphere

We choose the numerical domain to cover part of the interconnected solar photosphere, chromosphere and corona (see top left panel of Figure 1 and Figure 2). For this the atmosphere is initially assumed to be in hydrostatic equilibrium. The temperature field is considered to obey the semi-empirical C7 model of the chromosphere-transition region (Avrett & Loeser 2008) and is distributed consistently with observed line intensities and profiles from the SUMER atlas of the extreme ultraviolet spectrum (Curdt et al. 1999). The photosphere is extended to the solar corona as described by Fontela et al. (1990) and Griffiths et al. (1999). The temperature \(T(z)\) and density \(\rho(z)\) as functions of height \(z\) are shown in Figure 2, where the transition region is characterized by the
that at the initial time there is an interesting region with an $X$-point, located around $z \approx 3.5$ Mm. In this region the magnetic reconnection is initiated and consequently the further triggering of the spicule-like jet begins. At time $t = 30$ s, the jet starts to appear and the magnetic field lines near to the $X$-point reconnect with each other. At time $t = 60$ s a jet with features of a Type II spicule appears with a basis located precisely around the former $X$-point and reaches a height of about $z \approx 6.5$ Mm (see Figure 4), which is in agreement with the observed heights between 3-9 Mm (Pereira et al. 2012; Tavabi et al. 2015). The structure of the spicule obtained at time $t = 60$ s is similar to the obtained in Figure 5 in Martínez-Sykora et al. (2011). At time $t = 120$ s, the spicule reaches the corona located at $z = 10$ Mm where the magnetic field lines are open and show an uniform pattern. At time $t = 180$ s, the spicule reaches the maximum height. Between times $t = 240$ s and $t = 300$ s, the spicule start to dissipate. Finally by time $t = 390$ s the spicule-like jet fades away and the magnetic field lines are predominantly open and uniform.

In order to locate regions that may have reconnection during the appearance of the jet, we show 2D perspectives of the evolution of the ratio $|\mathbf{J}|/|\mathbf{B}|$ and temperature contours (K) in Figure 5. For instance, at time $t = 60$ s, we can see regions of intense current density at the bottom and top of the jet. At time $t = 120$ s, there are not regions with high current density concentrations, however at time $t = 180$ s, we see a region which goes from the lower half of the domain until a height of about 6 Mm, this region is related with the appearance of a new $X$-point as is shown in Figure 4 that does not produce a new spicule, but only is part of the process at late times. When the spicule is dissipating the ratio $|\mathbf{J}|/|\mathbf{B}|$ decreases, which is consistent with the open topology of the magnetic field lines.

Finally by time $t = 390$ s, the spicule disappears.

As it has been reported in a number of observational papers (De Pontieu et al. 2007a; Anan et al. 2010; Pereira et al. 2012; Zhang et al. 2012), the upward velocity of spicules is important, therefore we monitor this quantity in our simulation. For instance, we show 2D velocity perspectives of the evolution of the vertical velocity $v_z$ (km s$^{-1}$), the vector velocity field and temperature contours (K) in Figure 6. At time $t = 60$ s, according to the temperature contours and the vector field the spicule is moving upwards with a maximum vertical velocity $v_z \sim 130$ km s$^{-1}$ and temperature of the order $10^5$ K, these characteristics are similar to those of a Type II spicule. At time $t = 120$ s, the spicule continues to move upwards until it reaches the maximum height with a vertical velocity $v_z \sim 50$ km s$^{-1}$ by time $t = 180$ s, as seen from the velocity field. After that time, the spicule starts to vanish, we can see this process at times $t = 240$ s and $t = 300$ s. At time $t = 390$ s, the vertical velocity is practically negative and the spicule disappears due to the interaction with the hot plasma in the upper region. The lifetime of this spicule is larger than the observed time for Type II spicules, however is within a valid range of observational lifetimes reported in Pereira et al. (2014) and Skogsrud et al. (2015).

In order to understand the physics behind the modeled spicule formation, it is important to identify the dominant force(s) acting during the formation and development of the spicule. For this we compare the forces due to the magnetic field and hydrodynamics, thus we calculate the ratio between the magnitude of the Lorentz force and the magnitude of pressure gradient $|\mathbf{J} \times \mathbf{B}|/|\nabla p|$. The results of the evolution of the ratio $|\mathbf{J} \times \mathbf{B}|/|\nabla p|$ and temperature contours (K) are shown in Figure 7 in the cross cut at the plane $x=0.1$ Mm of the 3D do-

3. RESULTS OF NUMERICAL SIMULATIONS

We carried out a numerical simulation within a specific domain with magnetic fields constructed with the MURaM code, which contained a region with a high magnetic field strength dipoles. We define the numerical domain to be $x \in [0,6]$, $y \in [0,6]$, $z \in [0,10]$ Mm, covered with $240 \times 240 \times 400$ grid cells, i.e., the effective resolution is 25 km in each direction. In the faces of the numerical box we set fixed in time boundary conditions, which keep the value of the variables set to their initial condition value at the boundary.

Once we set the magnetic field and the atmosphere model described above, we start evolving the plasma according to the Equations (1-8). We do not apply any explicit perturbation to the system, instead, the round-off errors suffice to trigger the instability of the whole system, including the magnetic field and hydrodynamic equilibria, that later on traduces into the burst of material upwards. The reconnection happens and is accompanied by the introduction of a finite magnetic resistivity $\eta = 12.56 \, \Omega \, m$.

We analyzed the temperature evolution that helps understanding the dynamics of the system. In Figure 3 we show snapshots of temperature on the plane $x = 2.5$ Mm and the magnetic field lines in 3D at different times. For instance, at time $t = 30$ s the spicule-like structure starts to develop in the region of magnetic reconnection which accelerates the plasma. At time $t = 60$ s, we can see a structure with a height of about $z \approx 6.5$ Mm from the transition region (Tavabi et al. 2015) and vertical velocity of about $v_z \approx 100$ km s$^{-1}$ as shown in Figure 6, these characteristics are similar to those of a Type II spicule (De Pontieu et al. 2007a). At about $t = 180$ s, the structure penetrates the corona and reaches its maximum height, where the magnetic field lines are predominantly open. After that time, the structure starts to dissipate, which is clear at times $t = 300$ s and $t = 360$ s. Finally by time $t = 390$ s the spicule practically disappears, which is consistent with the evolution of the vertical velocity $v_z$ as shown in Figure 6.

We show a useful 2D perspective of the process with a cut of the 3D domain at the plane $x = 0.1$ Mm in Figure 4, where various snapshots of the evolution of the temperature (in Kelvin) and the magnetic field lines are shown. We note...
We can see at time $t = 60\,\text{s}$, which is the time when the spicules is well formed, that Lorentz force dominates. This dominance can be seen until the time $t = 240\,\text{s}$. In the last period of the evolution, the spicule is dissipating in conjunction with the Lorentz force until the time $t = 390\,\text{s}$. This analysis shows that Lorentz force is the main responsible of the jet formation.

Another important diagnostics of Type II spicules is whether they are twisted, rotate or show torsional flows. Observations on the Doppler shift of various emission lines in the limb suggest that Type II spicules are rotating (De Pontieu et al. 2012; Sekse et al. 2013; Sharma et al. 2017). Thus we calculate the vorticity $\omega = \nabla \times \mathbf{v}$ and the vector velocity field in order to look for rotational motion in the spicule region. For this we consider two planes, plane 1 at $z = 3.5\,\text{Mm}$ located around the bottom part of the spicule as can be seen in Figure 4 and plane 2 at $z = 5\,\text{Mm}$ located in an upper region.

For the plane 1 we show the magnitude of $\omega$, velocity field and temperature contours (K) in Figure 8. By $t = 15\,\text{s}$ we can see regions where the magnitude of vorticity is high, the vector velocity field starts to circulate and the temperature is low. At $t = 120\,\text{s}$ the appearance of vortex is clearer, which indicates a very dynamic process of the spicule. At late times the spicule starts to dissipate, so the vorticity magnitude decreases, however we can still see circular patterns in the vector velocity field. Finally at $t = 390\,\text{s}$ we do not see circulation in the vector field and the magnitude of the vorticity nearly vanished.

We produce similar plots for plane 2 in Figure 10. At this plane we can see clear rotational behavior. The most representative picture is at time $t = 60\,\text{s}$, where a vortex can be seen near the location of a high value of the vorticity and a low value of the temperature. This vortex is related to the motion of the spicule structure. This behavior lasts until $t = 240\,\text{s}$, which is the time when the spicule starts dissipating. By $t = 390\,\text{s}$ the vorticity reaches its minimum value and the spicule practically vanishes.

**Vorticity and Doppler.** We estimate in the two planes defined above the Doppler effect related to the dynamic of the spicule in a simple way. We specifically estimate this effect in a small region where the vorticity is high, the velocity vector field is circulating and the temperature is low. In order to estimate the Doppler effect we define a center in the region mentioned above where the velocity is $\mathbf{v}_c$. Then we chose a set of points to the left and to the right along the $x$ direction from the center (it could have been any other), with velocities $\mathbf{v}_L$, $\mathbf{v}_R$, respectively. Then we calculate the difference in the $y$ component of these velocities with respect to that of the center, specifically $\Delta v_D = v_{y_L} - v_{y_R}$, where $v_{y_L}$ and $v_{y_R}$, which is an estimate of the tangent velocity of the points around the center and therefore a measure of a red and blue shift. This method is illustrated in Figures 9 and 11 for each case. We show a zoom in of the vortex where the circulation of the vector velocity field is more evident. In these particular cases we calculate plots of $\Delta v_D$ for the $y$ component of the velocity $v_y$ as a function of the distance $d_c$ from the center to the right or left, along the blue or red line. The amplitude of the red shift is of the order of 15 km s$^{-1}$ in both cases, whereas the blue shift for the plane 1 has an amplitude of the order 25 km s$^{-1}$ and for the plane 2 the amplitude is of the order 20 km s$^{-1}$. The results of the estimation of the Doppler effect due to tangent motion $\Delta v_D$ are shown also in Figures 9 and 11.
Figure 4. Snapshots of the logarithm of temperature (K) and magnetic field lines in the cross cut at the plane $x=0.1$ Mm at times 30, 60, 120, 180, 240 and 300, 330, 360 and 390 s are shown. Note the X type of region at initial time, at a location where the spicule will be triggered later on.
Figure 5. Snapshots of the ratio $|J|/|B|$ and temperature contours (K) in the cross cut at the plane $x = 0.1\text{Mm}$ at various times.

Figure 6. Snapshots of the vertical component of velocity $v_z$ (km s$^{-1}$), temperature contours (K) and vector velocity field (black arrows) in the cross cut at the plane $x = 0.1\text{Mm}$ at various times.
Figure 7. Snapshots of the ratio $|\mathbf{J} \times \mathbf{B}|/|\nabla p|$ and temperature contours (K) in the cross cut at the plane $x = 0.1 \text{Mm}$ at various times. A comparison with Figures 3 and 4 indicates that the Lorentz force dominates in the region where the spicule is formed.

Figure 8. Snapshots of the magnitude of the vorticity $|\boldsymbol{\omega}|$ s$^{-1}$, vector velocity field and temperature contours (K) in the plane $z = 3.5 \text{Mm}$ at various times.

4. CONCLUSIONS

In this paper we have presented a 3D numerical simulation on a small region of the solar atmosphere, showing the formation of a jet structure with characteristics of a Type II spicule, specifically the morphology, upward velocity range and lifetime. This result provides a simple explanation and is in contrast with that in Martínez-Sykora et al. (2017), where out of 2D simulations the formation of spicules is explained in terms of the amplification of the magnetic tension and the interaction between ions and neutrals. In our simulation we show that even if magnetic tension might be important, the magnetic pressure, which is a part of full Lorentz force is important as well, which is consistent with the results in Kitiashvili et al. (2013) in the simulations of vortex tubes and in Iijima & Yokoyama (2017) the formation of solar chromospheric Jets.

A quantitative distinction between the components of the different forces involved, would require the development of new analysis tools for time-dependent structures.

For this, we solve the equations of the resistive MHD submitted to the solar constant gravitational field. We use a 3D magnetic field configuration extrapolated up to the solar corona region from a simulated quiet-Sun photospheric field. This magnetic field configuration contains bipolar regions with a strong magnetic field strength at the bottom, which helps the development of the magnetic reconnection process near a $X$-point.

A key result of our analysis is that the Lorentz force dominates over the pressure gradient in the region where the spicule takes place and helps accelerating the structure upwards.

We understand the magnetic reconnection triggers the ac-
celeration of plasma upwards with a jet structure. This 3D model, reveals the complexity, since a solar atmosphere containing the transition region in combination with a magnetic field with a complex topology sketch better the complexity of the solar atmosphere.

Our findings include also that the vorticity near the spicule is important. By looking at the velocity field in specific crosscuts of the spicule we can track the circular displacement of plasma that eventually can be identified with blue-red shifts. A detailed analysis on the torsional properties of the spicule, generated waves, rotational and radial displacements will be presented in a separate paper (González-Avilés et al. 2017b).

In order to contrast our simulations with other similar analyses, we mention that our simulations are limited in the sense that we do not consider thermal conductivity, radiation and partial ionization as in Martínez-Sykora et al. (2017), however our simulation uses a topologically complex magnetic field in full 3D.

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