ON THE PROMINENCE FORMATION IN A CURRENT SHEET – SOME NUMERICAL EXPERIMENTS

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Abstract. Three numerical simulations of prominence formations in a current sheet are presented. The effects of chromospheric mass injection (temporary or continuous) and of gravitation are taken into account.

Key words: prominence - current sheet – numerical simulation.

1. INTRODUCTION

The solar prominences form by condensations in different magnetic coronal structures: in current sheets, in arcades or in loops. Other mechanisms may be possible too, as chromospheric evaporation. The current sheets appear naturally between two magnetic opposite polarities, everywhere in the solar atmosphere. Usually, both normal and inverse magnetic polarity types of prominences can form in a current sheet. Kuperus and Tandberg-Hanssen (1967) elaborated the first such model of prominence formation. They have shown that the neutral sheet between two active regions is thermally unstable after a flare onset and can lead to a condensation in the closed magnetic field loop to form a solar prominence. Smith and Priest (1977) have demonstrated that the necessary time for condensation depends on the rate of the sheet grows up to a critical value.

Numerical MHD simulations have been performed by Forbes and Malherbe (1986), using SHASTA method (Weber, 1978; Forbes & Priest, 1982). They have shown that the shock waves play an important role in the plasma condensation – these ones reduce the radiative time-scale and compress the plasma increasing so the density to form prominence.

Dumitrache and Suran (1997) have performed a numerical experiment taking into account the injection of plasma in the current sheet. The effect of gravitational force and Ohmic heating were considered. They have obtained a temperature of 12000 K but using an unrealistic subroutine of radiation in the SHASTA method (Wim Weber's version, 1978)

The present work focus on three 2-D MHD numerical experiments, where the initial state is a current sheet, placed in the solar hot corona. The gravitational effects and a complete energy equation are taken into account. The chromospheric mass injection (continuous or temporary) is initiated in the current to increase the prominence mass. The computations were made on an SGI – Challenge M supercomputer with the same code Alfvén (Terry Forbes' version), (Forbes and Priest, 1982), using SHASTA method (Weber, 1978). The computational grid covers a distance of one solar radius, placed in a meridional solar plane. The gravitation **g** is directed along the *Ox* axis. We have modified the numerical grid at 100 x 100.

2. EQUATIONS, INITIAL AND BOUNDARY CONDITIONS

The MHD equations for our two-dimensional numerical models are, in the usual notation:

$$\frac{\partial \rho}{\partial t} + \mathbf{div}(\rho \mathbf{v}) = 0 \tag{1}$$

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

$$\frac{\partial \mathrm{B}}{\partial t} = \nabla\times(\mathrm{v}\times\mathrm{B}) + \eta\nabla^2\mathrm{B} \tag{3}$$

$$\frac{\rho^4}{\gamma-1}\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{p}{\rho^\gamma}\right) = -\nabla(k\nabla\cdot T) - \rho^2 Q(T) + \frac{j^2}{\sigma} + h\rho \tag{4}$$

$$p = \rho T, \tag{5}$$

Where $Q(T)$ is the Cox-Tucker function and $\mathbf{B}, \mathbf{v}, \rho, p, T$ are dimensionless variables defined by

$$
\begin{aligned}
\rho &= \rho' / \rho_0 \\
T &= T' / T_0 \\
\mathbf{v} &= \mathbf{v}'/v_{sc} \\
\mathbf{B} &= \mathbf{B}' / \left|\mathbf{B}'_0\right| \\
p &= 4\pi p' / (\mathbf{B}'_0 \cdot \mathbf{B}'_0)
\end{aligned} \tag{6}
$$

$\mathbf{B}', \mathbf{v}', \rho', T', p'$ are the dimensional magnetic field, flow velocity, density, temperature and pressure. The index zero denotes the initial values and v_{sc} is the sound velocity, $\gamma = 5/3$ is the ratio of the specific heats and η is the dimensionless resistivity. With η the magnetic Reynolds number, more properly, the Lundquist number (see Forbes and Priest, 1982), is

$$R_m = \eta^{-1} = v_a\, w' / \eta', \tag{7}$$

where η' is the resistivity and w' is the characteristic scale-length of the initial conditions (i.e. the width of the initial current sheet defined below). The dimensionless time, t, and spatial coordinates, x and z, are related to their dimensional counterparts, t', x', z', by

$$x = x' / R_{Sun},\ z = w / z_0,\ t = t' / t_0 \tag{8}$$

where $z'_0 = 2w'$ is the computational box, $t_a = w' / v_a$ is the Alfvén scale-time and R_{Sun} is the solar radius.

In the solar corona, we consider a current sheet given by

$$\mathrm{B}_x = \begin{cases} \sin(\pi z / 2w), |z| \le w \\ 1, |z| > w \end{cases} \tag{9}$$

$$B_z = 0 \tag{10}$$

and $v_x = 0$, $v_z = 0$, $\rho = 1$ and $p = \rho T$, $w = 27$.

The boundary conditions along the four sides of the computational box are:

- at the top $(x = 1)$

$$\frac{\partial B_x}{\partial x} = \frac{\partial B_z}{\partial x} = 0 \tag{11}$$

$$\frac{\partial B_z}{\partial x} = -\frac{\partial B_x}{\partial z} \tag{12}$$

- at the right-hand side $z = 1$

$$\frac{\partial B_x}{\partial z} = \frac{\partial B_z}{\partial z} = 0 \tag{13}$$

$$\frac{\partial B_z}{\partial z} = -\frac{\partial B_x}{\partial x} \tag{14}$$

- on the symmetry axis (z=0)

$$\frac{\partial B_x}{\partial z} = B_z = 0 \tag{15}$$

- at the bottom (x=0)

$$\frac{\partial B_z}{\partial x} = \frac{\partial B_x}{\partial x} = 0 \tag{16}$$

3. NUMERICAL RESULTS

3.1. THE FIRST NUMERICAL EXPERIMENT

In the first numerical experiment we have considered a plasma with $\beta = 0.5$. We have initiated a Reynolds stress, which leads to magnetic reconnections. At the time $t = 0.264$ the neutral magnetic line was formed on the symmetry axis and, for a long time, had no important dynamics. Tearing–modes have appeared to lead to magnetic reconnections and a coronal loop with cold plasma has formed. In the current sheet, we have injected chromospheric plasma with a density rate equal to 2 and a velocity equal to the sound velocity, starting with time $t = 0.332$.

First the temperature grew up in the current sheet and a flare has occurred $(t = 0.350)$; after the closing of the magnetic field lines, the condensation process has started, also the increase of the density in the just formed coronal loop. At $t = 1.260$, we have obtained the prominence mass – the density one hundred times greater than the coronal density.

At $t = 1.115$, gravitational instabilities have become very important and, unfortunately, numeric instabilities have appeared at $t = 2.054$.

Fig. 1 displays the magnetic field line's evolution at different moments of Alfvén time.

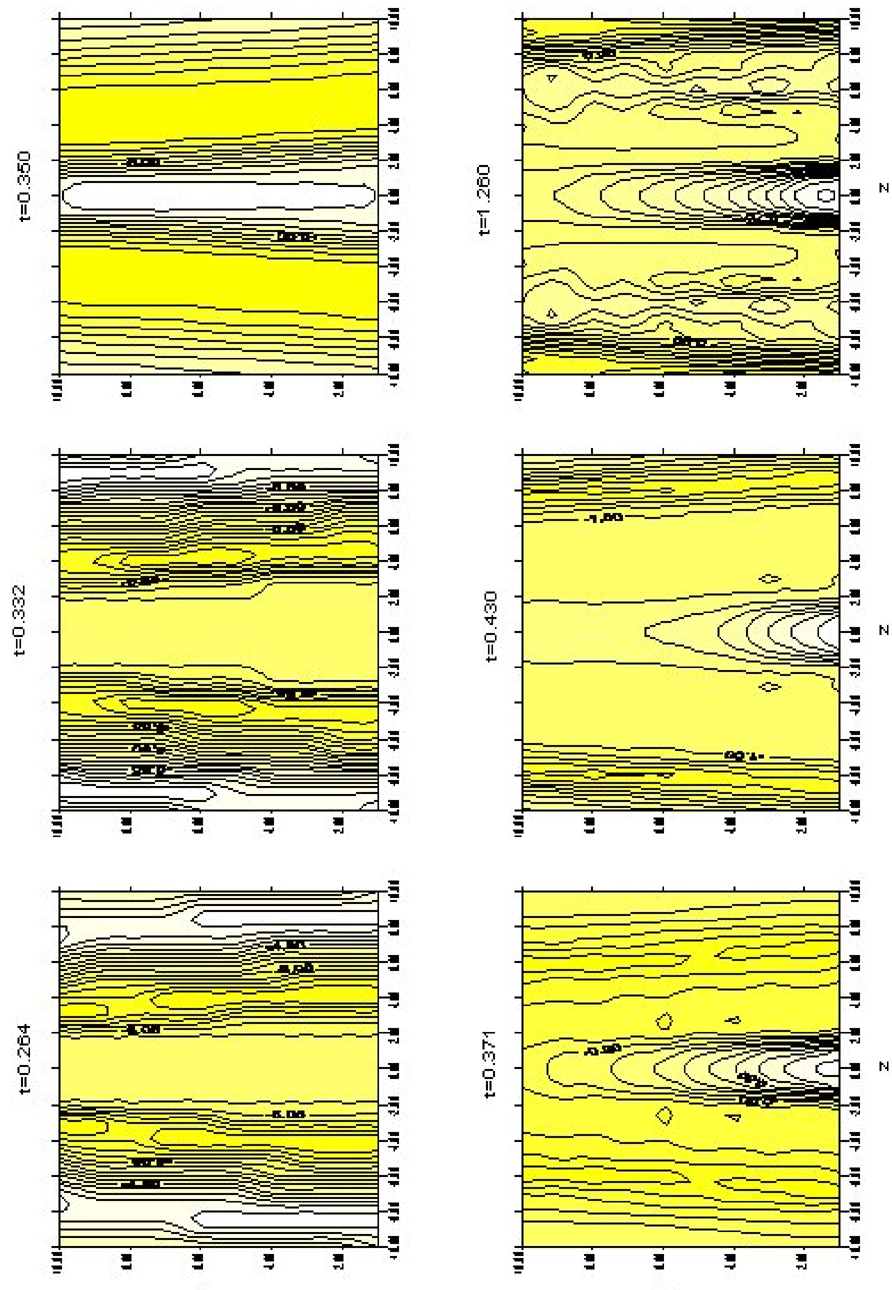

Fig. 1 – The magnetic field lines at different Alfvén times, for the first numerical experiment.

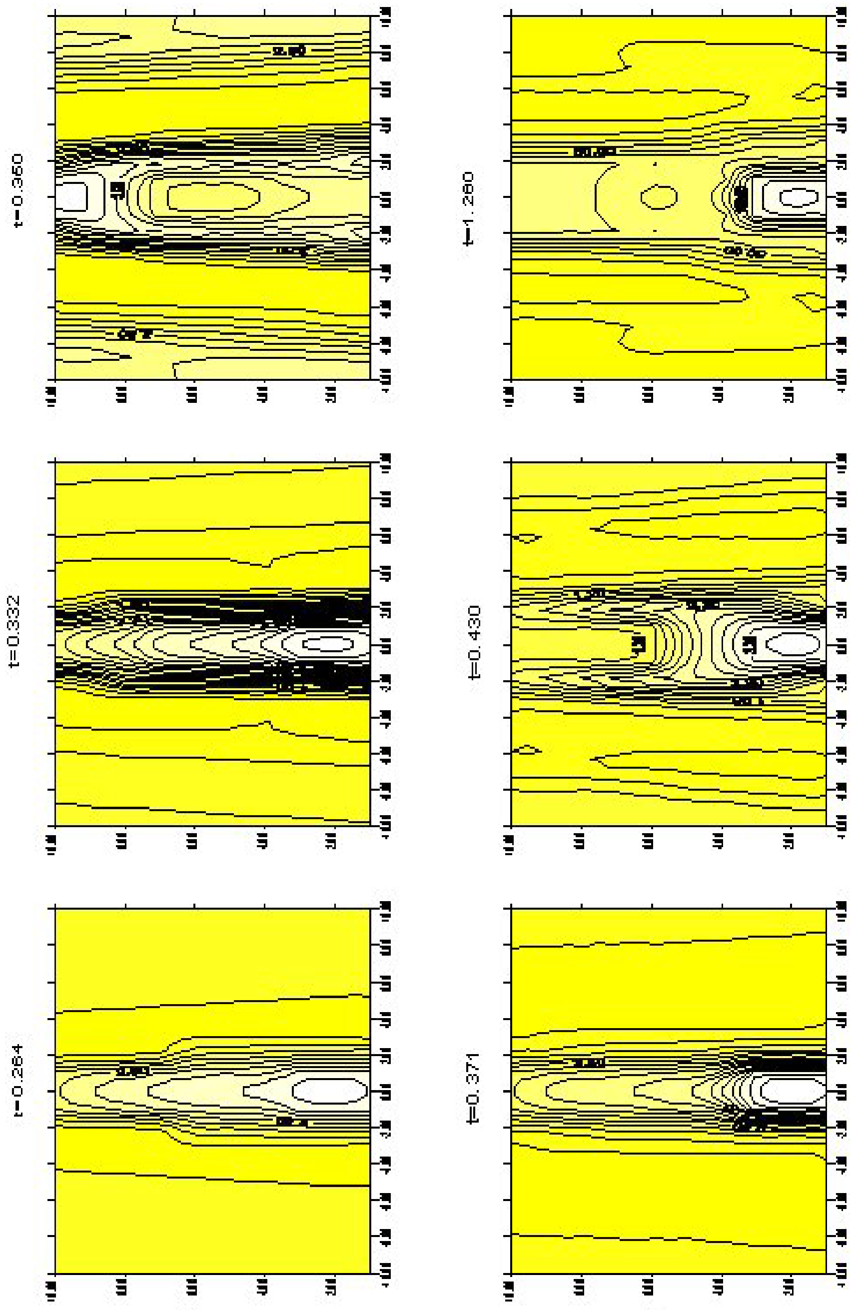

Fig. 2 – The density contours at different Alfvén times, for the first numerical experiment.

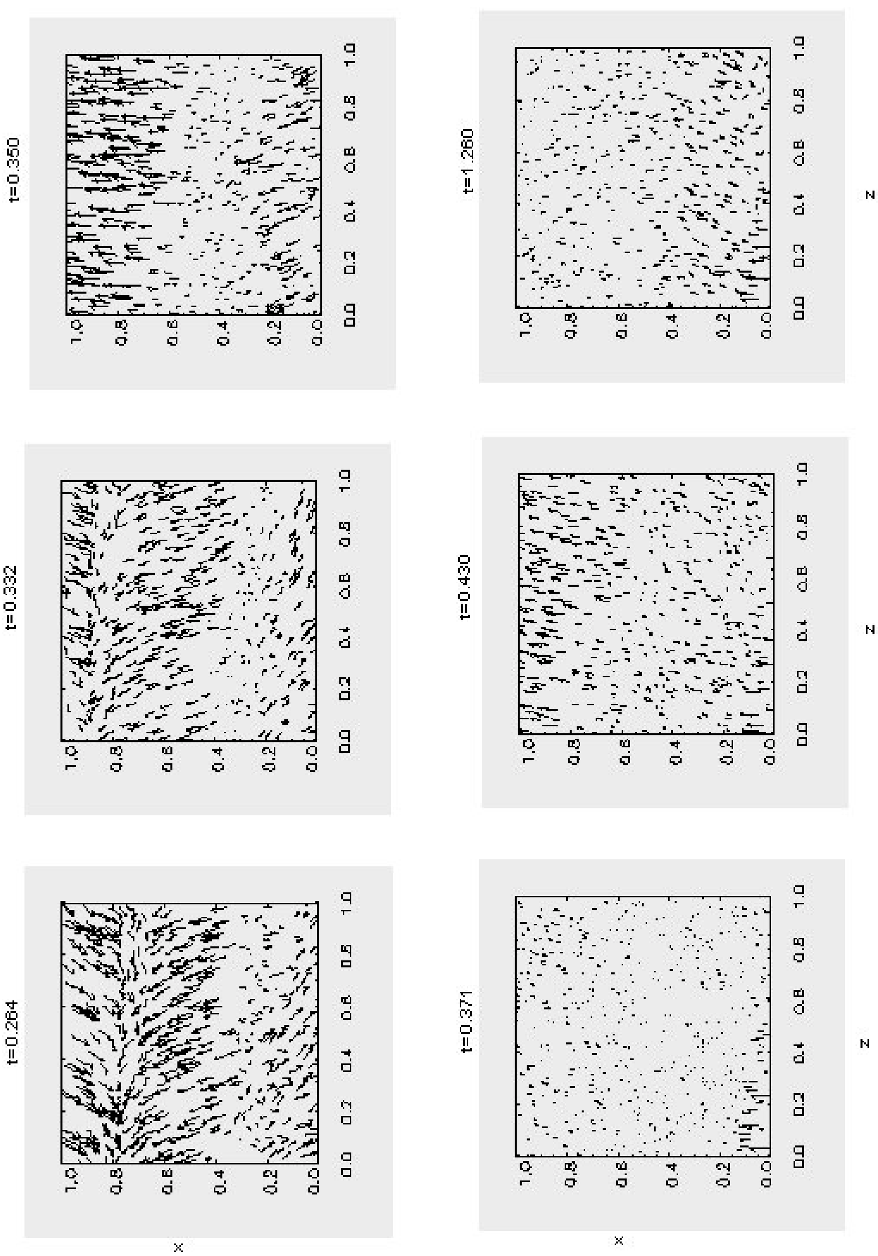

Fig. 3 – The velocity field at different Alfvén times, for the first numerical experiment.

Fig. 2 shows the density distribution. One can observe a mass ejection like a solar flare (with the density five times greater than the coronal density) at $t = 0.350$, and the concentration of the mass up to the prominence mass in the coronal loop after that.

The velocity field of the plasma flow is displayed in Fig. 3, as only a half part of the flow (the numeric box of computation) – the symmetry axis is on the left part. Upward flows could be seen after $t = 0.371$. Initially, the flow is horizontal toward the symmetry axis. A downward flow had tendency to appear, but the chromospheric mass injection helped the up-flow to support the material against the gravity force.

We have obtained an inverse polarity prominence-like object at $t = 73.367$ (Fig. 4).

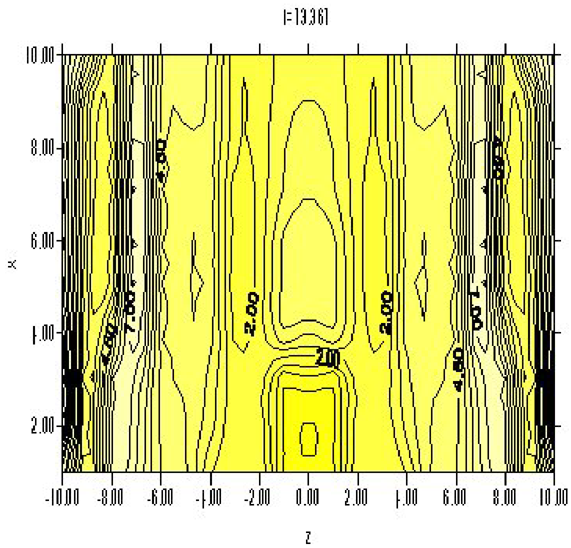

Fig. 4 – Magnetic field lines at the end of the first numerical experiment: an inverse magnetic polarity prominence – like was obtained.

3.2. THE SECOND NUMERICAL EXPERIMENT

This numerical experiment has same initial conditions with the first one, but we have added a slight Ohmic heating, with the purpose of study the evaporation effect on the prominence formation. The mass injection is initiated at $t = 0.219$ with a density rate equal to 2, but with a velocity equal to half the sound velocity. Both rates of injection (density and velocity) are increased smoothly to $\rho_{injection} = 3.5$ and $v_{injection} = 2$.

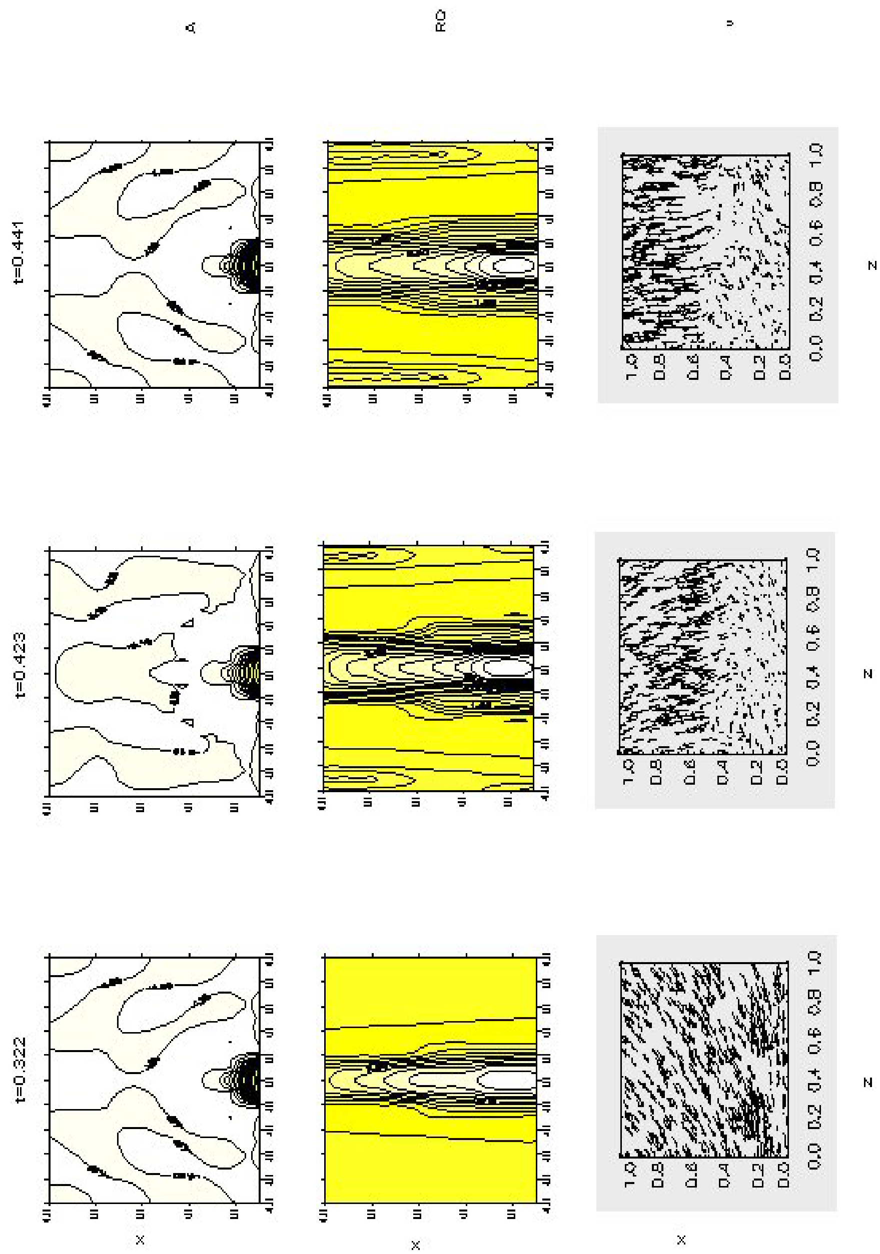

Fig. 5 – The magnetic field lines (at top), contour density (at the middle) and velocity field at different Alfvén times, for the second numerical experiment.

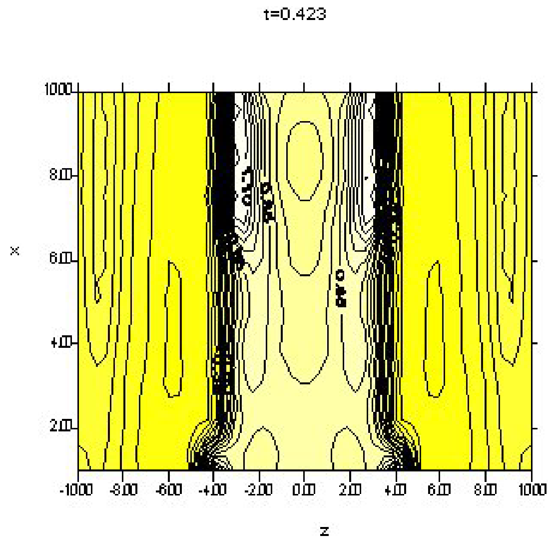

Fig. 6 – The temperature distribution at t=0.423, in the second numerical experiment: two points of heating may be observed at the prominence-corona interface.

Fig. 5 shows the magnetic field lines (at the top), the density contours (at the middle) and the velocity field (at the bottom), at different moments. The coronal loop is formed at t = 0.322, when the flow is still downward. An increase of the temperature may be observed and upward flow appeared, but also downward flows still exist. At t = 0.423 the flow became only upward and the temperature decreased in the coronal loop. At the border of the sheet one may observe two hot points where the temperature is maximum - two points where the plasma evaporates (Fig. 6).

The formed prominence-like object is of normal polarity, as prominences that usually appear in solar active regions. After t = 0.441 numerical instabilities have stopped the experiment.

3.3. THE THIRD NUMERICAL EXPERIMENT

We have added boundary conditions concerning the velocity, pressure and density. The mass injection has been initiated at $t = 2.624$ and has been finished at $t = 3.296$. The Ohmic heating was very low ($\sigma = 1$)

The magnetic reconnections have started after the mass injection has been finished at $t = 3.589$. The prominence-like object may be seen at t = 22.245; it is a normal polarity prominence (Fig. 7). The velocity field (Fig. 8) shows an ascendant flow at $t = 3.589$.

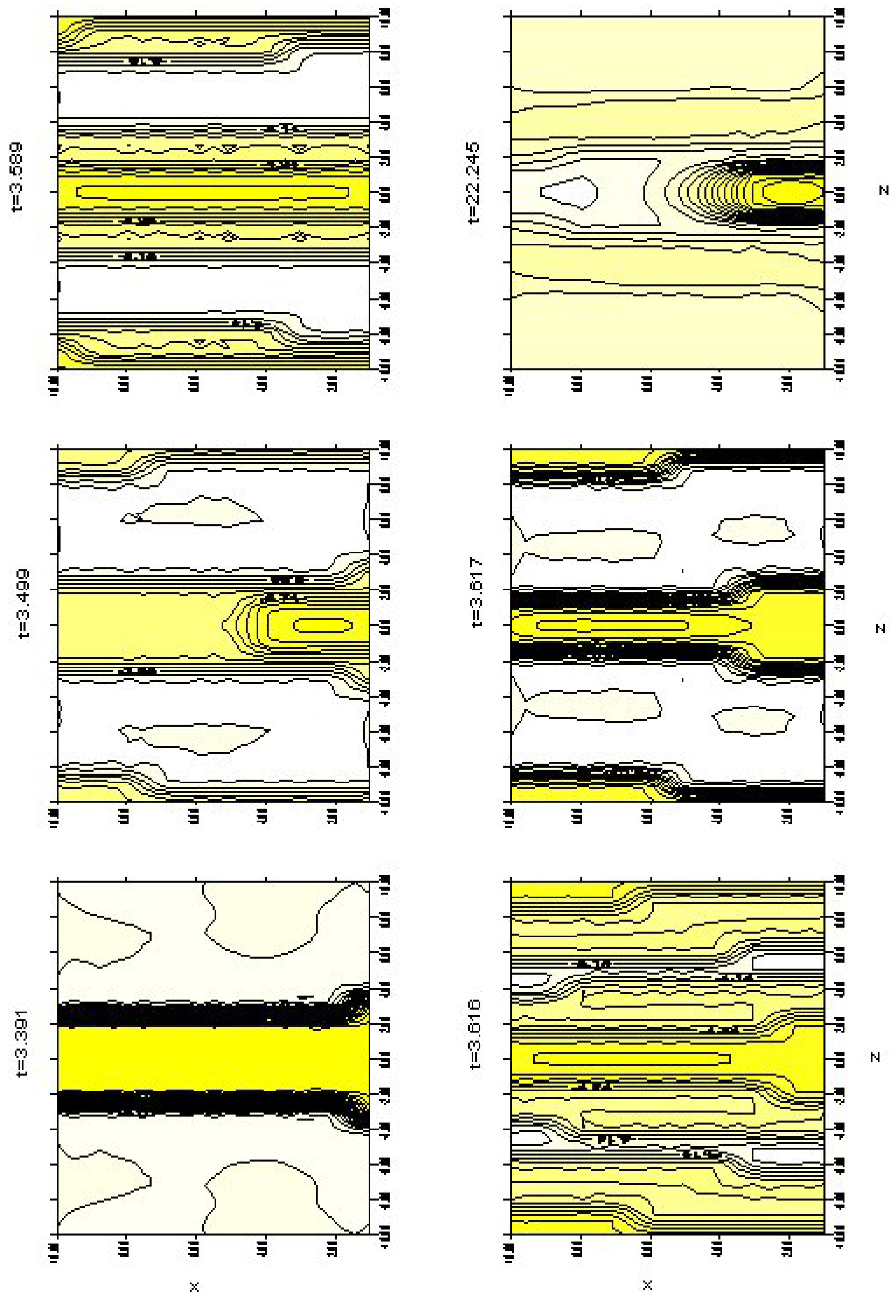

Fig. 7 - The magnetic field lines at different Alfvén times, for the third numerical experiment.

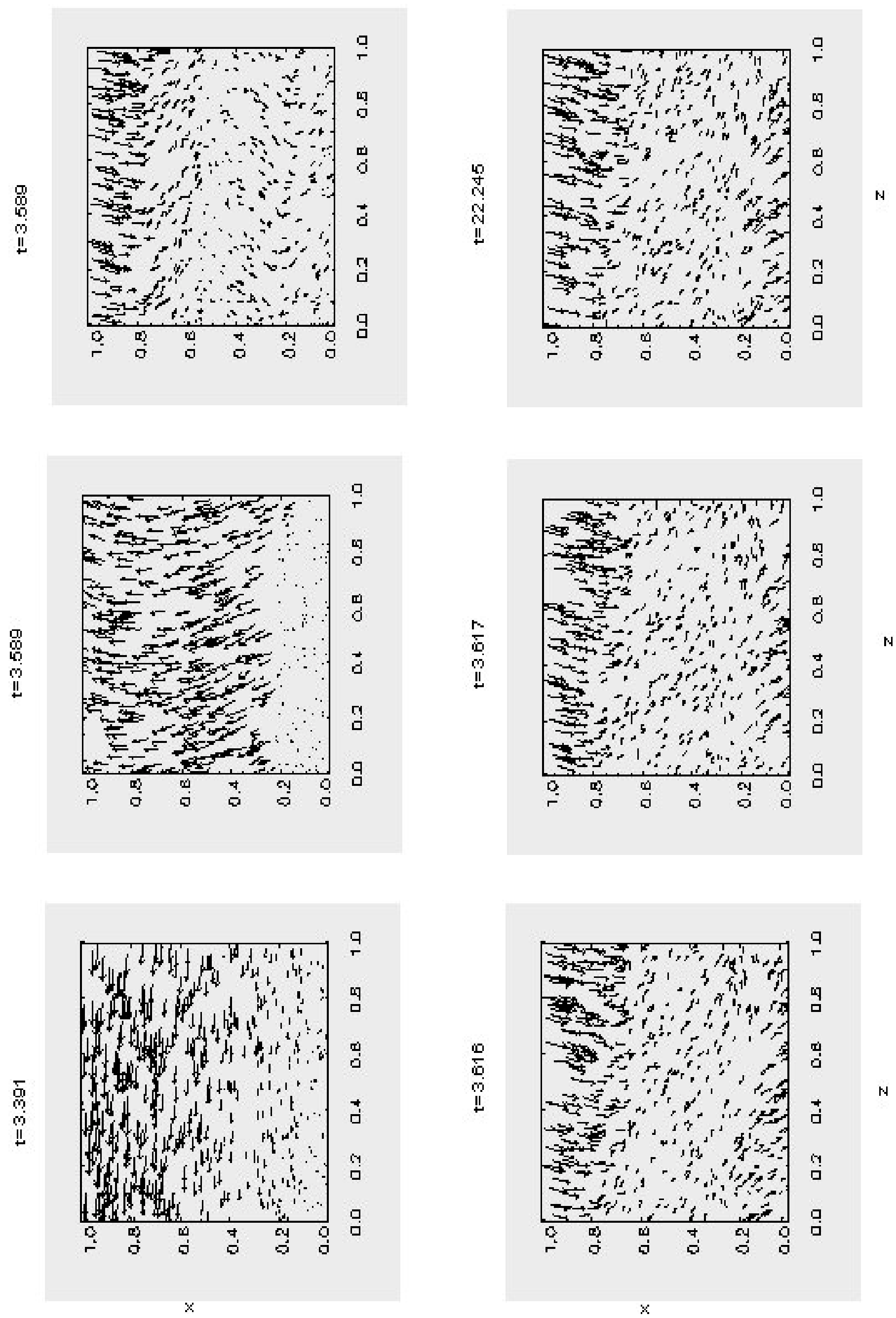

Fig. 8 - The velocity field at different Alfvén times, for the third numerical experiment.

After $t = 3.616$, the temperature stays almost constant and the magnetic field (Fig. 7) reveals very fast reconnections, when the flow becomes super-alfvenic. At t = 22.245, the flow is descending and the plasma velocity reaches the sound velocity level, while v_{fm} decreases. It is the moment when the numerical instabilities have appeared. Forbes (1982) explained the apparition of the numerical instabilities by the rapid decrease of the Kolmogoroff scale-length (associated to the resistive flow), when magnetic reconnection appears.

4. CONCLUSIONS

We have presented three numerical experiments of prominence formation in a current sheet. We have taken into account the effect of gravity, the Ohmic heating as well as a chromospheric mass injection (temporary or continuous). Magnetic reconnections and flare events accompany this process, before the condensation start, similar to Kuperus - Tandberg-Hanssen scenario. Both types of prominence can be formed in this way: normal (first case) and inverse magnetic polarity configuration (second and third cases). Numeric instabilities have appeared when the plasma flow reaches the sound speed.

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