PADEU
PADEU **15**, 45 (2005)
ISBN 963 463 557

MHD Simulation of Solar Coronal Mass Ejection

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Abstract
Time dependent magnetohydrodynamic computations on three solar radii, starting with a current sheet initial configuration, is presented. A prominence formation and eruption, trigger CMEs in 'raffales', with a coronal streamer formation as last result.
Keywords: *Sun, CME, MHD, numerical simulation*

1 Introduction

One of the amazing feature of the solar activity are the explosive phenomena, especially that which affect directly our planet life. Thecoronal mass ejections (CMEs) are huge magnetized bubbles of gas ejected from the Sun into the planetary space, which add to the solar wind. Large spatial scales are involved during a such process (average width of 47deg). The timescales of CMEs events range between several minutes to several hours. The CMEs are impressive phenomena: their velocities could rich from 10 to 2100 km/s, their masses range between $2 \times 10^{14} - 4 \times 10^{16}$ g, developing kinetic energies between 10^{29} to 10^{31} ergs.

Observationally, the CMEs are related to prominences eruptions or to coronal streamers disruptions, but also to big solar flares. CMEs are driven by the magnetic field. A CME appears in the active zones with closed magnetic field configurations stretched above the polarity inversion line. The material is coronal: once the CME produces, it observes a exhaustion of the mater back the bubble. Before the disruption of the material, strong movements are observed in zone. The ejection rate varies from a phenomenon to another, depending on the causes.

Many models and reviews were given within the past years and this topic is still on the top of the actuality.

Wu et al. (2000) distinct three CME initiation processes: streamer destabilization due to increase of currents via increase of axial fields, photospheric shears and plasma flow induced at the boundary region of a streamer and coronal hole.

Klimchuk (cited by Poedts et al., 2002) reviewed the theoretical model for CME initialization as follow:

(1) Directly driven models

(a) Thermal blast - characterized by a sudden release of thermal energy (Dryer, 1982; Wu, 1982) - CME associated with flares

(b) Dynamo models - real-time stressing of the magnetic field involves the rapid generation of coronal magnetic flux (Chen, 1989)

(2) Storage and release models - three classes in which a slow buildup of magnetic stress precedes the eruption

(a) Mass loading models - the field is loaded with mass (Low, 1999)

(b) Tether release models - the strain increase on a decreasing number of tethers (Forbes & Isenberg, 1991)

(c) Tether straining models - total stress increases (Antiochos et al., 1999)

A 3-D numerical simulation of CMEs by coupled coronal and heliospheric model was performed by Odstrcil et al. (2002). The coronal model is based on the 3-D resistive MHD equations solved by a semi-implicit finite-difference scheme.. The output of this model consists of a temporal sequence of the MHD flow parameters, which are used as boundary conditions for the heliospheric solutions.

Forbes (2002) conclude that a CME is triggered by the disappearance of a stable equilibrium as a result of the slow evolution of the photospheric magnetic field. This disappearance may be due to a loss of ideal-MHD equilibrium or stability such as occurs in the kink mode, or to a loss of resistive-MHD equilibrium as a result of magnetic reconnection.

Our simulation is based on a prominence formation in a current sheet and its evolution. The current sheets naturally appear in the solar atmosphere. They are linked to the lines of magnetic polarity inversion line. They are places where prominences form and seldom their are at the base of a coronal streamer.

2 2-D numerical simulation

The MHD equations are solved with SHASTA method used by Alfven code, developed by Weber (1978). This code was described by Forbes & Priest (1982) and also by Dumitrache (1999).

$$\frac{\partial \rho}{\partial t} + \overrightarrow{\nabla}(\rho \cdot \overrightarrow{v}) = 0 \quad (1)$$

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

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

$$\frac{\rho^\gamma}{\gamma-1}\frac{d}{dt}(\frac{p}{\rho^\gamma}) = -\vec{\nabla}(k\vec{\nabla}T) - \rho^2 Q(T) + j^2/\sigma + h\rho \tag{4}$$

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

The initial configuration is:

$$B_x = \begin{cases} \sin(\frac{\pi z}{2w}), \text{ for } |z| \leq w \\ 1, \text{ for } |z| > w \end{cases} \quad B_z = 0 \tag{6}$$

with $v_x = 0$, $v_z = 0$, where $w(= 0,25$ from the computation grid) is the thickness of the sheet , $\rho = 1$ and $p = \rho T$.

The boundary conditions imposed on 49x97 mesh:

-at top (x=1)

$$\frac{\partial B_z}{\partial x} = \frac{\partial B_z}{\partial x} = 0 \tag{7}$$

$$\frac{\partial B_z}{\partial x} = -\frac{\partial B_x}{\partial z} \tag{8}$$

- at right (z=1)

$$\frac{\partial B_x}{\partial z} = \frac{\partial B_z}{\partial z} = 0 \tag{9}$$

$$\frac{\partial B_z}{\partial z} = -\frac{\partial B_x}{\partial x} \tag{10}$$

- at left - the symmetry axis (z=0)

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

- at bottom (x=0)

$$\frac{\partial B_x}{\partial x} = \frac{\partial B_z}{\partial x} = 0 \tag{12}$$

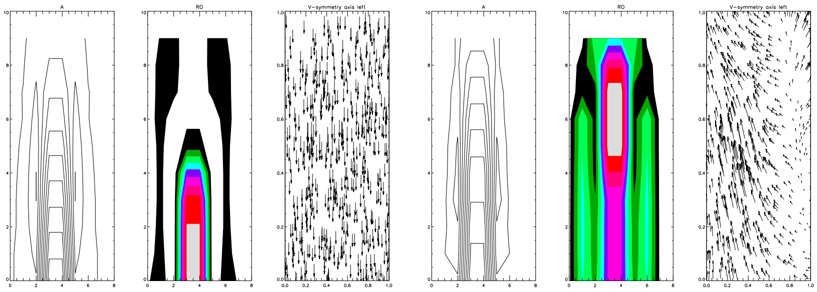

Figure 1: *Left: t=0.026; Right:t=0.031*

3 CMEs "en raffales"

Starting with a current sheet initial configuration and with $\beta = 0.5$ and $Rm = 10^3$, we performed this numerical experiment on 3 solar radii.

We obtain a prominences configuration, after a cooling process in the sheet, at the Alfven time $t = 0.026$. The temperature in the sheet is about 5000 K. The Figure 1 (left panel) displays the magnetic field lines at left, the density at middle and a half of grid for the velocity vector field at the right. The symmetry axis of the vector field is at left. At this stage, downward motions are registered.

The first CME starts at $t = 0.031$ (Fig.1, right), very impulsively with a $v = 1245$ km/s.

At $t = 0.036$ (Fig.2, left), the material is pushed to the lateral side of the current sheet and upward. Its velocity does dot exceed 507 km/s. The exhaustion of the matter is observed below the bubble, while the magnetic field picture displays plasma insulation. Lateral legs of the old loop could be seen steel at the bottom of the figure 2 (left), while at $t = 0.040$ (Fig.2, right) the magnetic loop is reformed, but plasma push strongly at the lateral side of the sheet. The legs of the old loop are ejected with about 566 km/s and this could be considered the second CME.

At $t = 0.042$ (Fig.3, left) gravitational instabilities appear again. On the feet of the old prominences, the matter is upward moved: as result a new CME consisting from the leg's material, appears again, but more impulsively. The velocity attain 715 km/s this time. From now, and continuing with the legs' elongation at $t = 0.043$ (Fig.3, right), to $t = 0.053$ (Fig.4) the matter is expulsed en raffales. This could be considered as the third CME.

The process of loop reforming replies at $t = 0.077$ (Fig.5, left). During this time, after each CME, the temperature in the sheet increased very much and attains now 10^6K, so we have a hot coronal loop. At $t = 0.081$ (Fig.5, right) we assist at a new magnetic reconnection, when the field lines open and a neutral O point from below

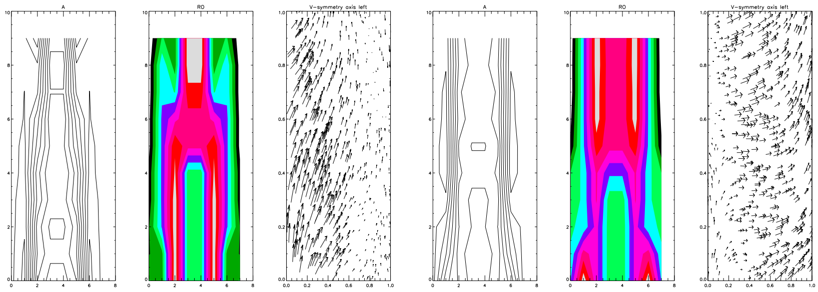

Figure 2: *Left: t=0.036; Right:t=0.040*

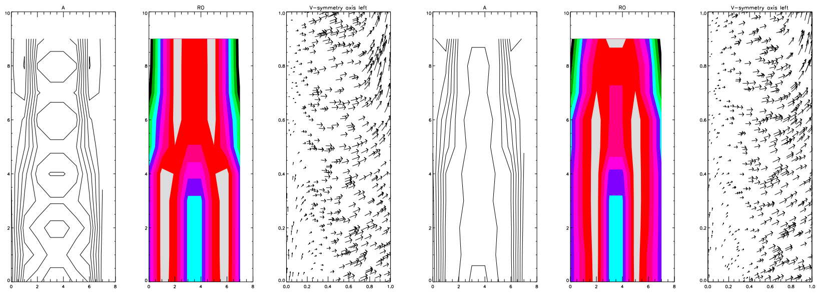

Figure 3: *Left: t=0.042; Right:t=0.043*

the bubble of plasma which elongated to start in a new CME. This new CME produce at $t = 0.085$ (Fig.6, left), but with low velocity (243 km/s). The temperature of the ejected bubble reaches 2×10^6 K. After this CME, a coronal helmet streamer installed, at $t = 0.096$ (Fig.6,right), with a temperature of 9×10^5 K at base and 1×10^6 K at top.

The first CME produced after 17.9 h after start of the simulated process, where the prominence formed in about 15 h. The second CME appeared after 23.2 h. New mass collected in the sheet and a hot loop reformed. The lateral material pushing has determined gravitational instabilities and new CMEs produced, at 24.36 h and 49.3 h. After 6.3 h from the last CME, the structure evolved in a helmet streamer configuration, which had its proper dynamics that our simulation follow till the streamer dissolution.

The regime of the velocities is displayed in Figure 7. The dot curve shows the modules of the velocities on the bottom of the computational grid, the doted curve represents the velocities at the middle of the grid and the solid one represents the top

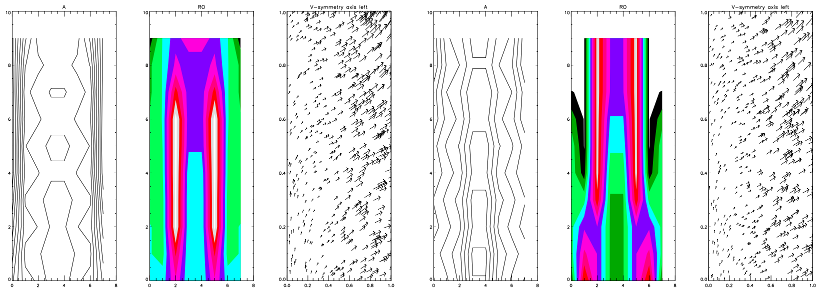

Figure 4: *Left: t=0.047; Right:t=0.053*

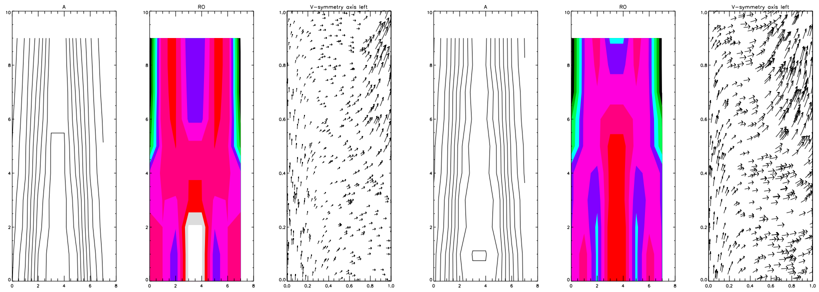

Figure 5: *Left: t=0.077; Right:t=0.081*

velocities, all of them considered on the symmetry axis.

The top-left side windows displays the modules of the velocities on all the computational grid. The axis with values from 0 to 15 represents moments of time (sixteen values). The top of the histograms are shaded at the CMEs start moments; also the correspondant points on the curves are shaded too. The solid curve with circle (corresponding to the top of the computational grid) is the most relevant for the velocity evolution during the "raffales". It seems the firsts two CMEs are impulsive ones, but the lasts are only a remanent process with slow movements of the matter.

4 Conclusions

Our simulation reveals a phenomenon reminding that observed by SOHO on 27 March 2001, the so-called "cannibal coronal mass ejections". In our simulation, a prominence structure, formed in a current sheet, evolved in CME disruptions "en raffales".

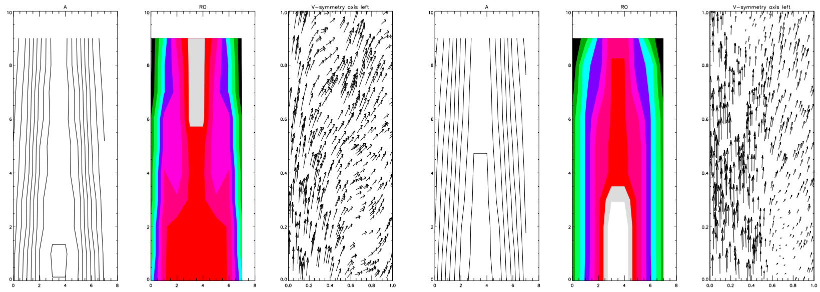

Figure 6: *Left: t=0.085; Right:t=0.096*

These transient phenomena ”en rafalle” are expression of the small-scale reconnections in the current sheet. The reconnections produced between two open field lines from both sides of a streamer current sheet and created a new closed field line (which becomes part of the helmet with a prominence at the base) and a disconnected field line, which moves outward. The CMEs are formed by plasma collected in the sheet that is swept up in the trough of the outward-moving field line.

In this numerical experiment the first CMEs are impulsive, but the last ones moves slow, proving that the energy storage was exhausted and the sheet will accomplish a new equilibrium state. This new equilibrium permits that a new solar feature forms on this site: a new stage of evolution concerning in a coronal streamer. We account that the new feature is possible to form in our simulated case, with two shoks ”raffales” and two slow CMEs later, and not in the ”cannibal” case, where all the matter and energy is probable exhausted. On the other hand, the slowness is probable do to the second and third CMEs which consist in the legs of a loop or in the matter from lateral side of the sheet.

The streamer evolution will be treat in another paper.

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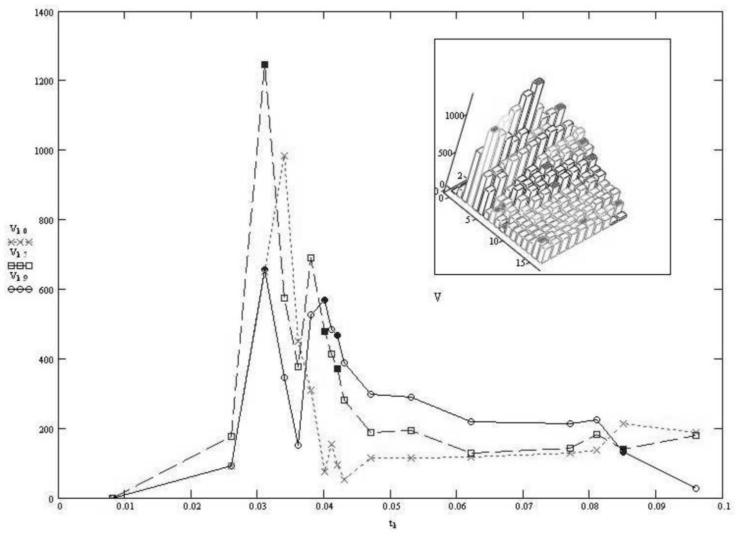

Figure 7: *Velocity evolution during all process (see text exolanations).*

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