A Model for Polar Jets

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1 Abstract

◇ Reconnection is believed to play the central role in the interaction between matter and magnetic field in solar/heliospheric physics. One of the most important ingredients for inducing reconnection is the presence of topological structures such as separatrices where electric current sheets are likely to develop. Magnetic nulls points are generally associated with such topologies.
◇ We present results of 3D numerical simulations of reconnection in coronal plasma around a null point, between open and close magnetic field, leading to the generation of a jet. The simulation are done with **ARMS (Adaptively Refined MHD solver)**, a 3D flux-corrected transport magnetohydrodynamic code using adaptive meshes.

2 Numerical model

◇ ARMS solves the standard equations of ideal MHD in a 3D Cartesian coordinate system (x,y,z):

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

$$\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v}) + \nabla \cdot P = \frac{(\nabla \times \mathbf{B}) \times \mathbf{B}}{\mu_0} \tag{2}$$

$$\frac{\partial U}{\partial t} + \nabla \cdot (U \mathbf{v}) + P \nabla \cdot \mathbf{v} = 0 \tag{3}$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) \tag{4}$$

◇ Even if the resistive terms are not solved explicitly, numerical diffusion provides an effective resistivity in the model. The diffusion is particularly strong where the gradients of the magnetic field are important, *i.e.* at current sheets, which induces reconnections there.
◇ ARMS is based on modified **flux corrected transport algorithms** (DeVore 1991). The time-dependent equations are solved on a **dynamically solution-adaptive grid**. The code uses the adaptive mesh toolkit PARAMESH (MacNeice et al. 2000). The grid is refined (or de-refined) adaptively during the simulation. When the relative difference, between two contiguous points of the mesh, of a given criteria is above (below) a value of 0.5 (0.125) then the mesh is refined (de-refined) by dividing locally the grid size by 2 (0.5). In these simulations the criterion for refinement is based on the value of the ratio $||\nabla \times \mathbf{B}||/||\mathbf{B}||$. The grid is refined preferentially where the thin current layers responsible for null-point reconnection build-up.

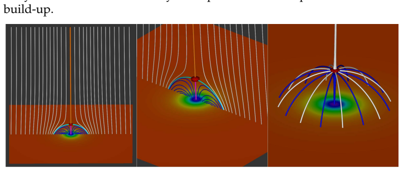

Figure 1 : 3D view of the initial magnetic configuration over a $z = 0$ cut of the distribution of B_z. The field lines belonging to the inner connectivity domain (the closed domain) are plotted in blue whereas those belonging to the outer volume (the open field) are displayed in white. The red isosurface locates the position of the magnetic null. **Left and middle panels :** *Magnetic field lines are plotted along the $x = 0$ & $z = 0$. The cyan field line locates the position of the fan surface. The orange field line materialize the outer Spine whereas the pink one represent the inner spine.***Right panel :** *3D view of the inner and outer fan surface.*

◇ The initial magnetic configuration (**see Fig. 1**), is given by the potential field formed by a magnetic dipole, with intensity is $\mu_0 m_0/2\pi = 50$ and directed along the vertical axis, and a uniform volumetric magnetic field $B_v = 1$ of opposite direction. The dipole is located at $(0, 0, z_0 = -1.5)$. The vertical field in the volume is thus given by

$$B_z(x,y,z) = \frac{\mu_0 m_0}{4\pi} \frac{2(z-z_0)^2 - (x^2+y^2)}{(x^2+y^2+(z-z_0)^2)^{5/2}} - B_v \tag{5}$$

◇ This configuration creates an intense **axisymmetric positive magnetic polarity** at the bottom boundary ($z = 0$) surrounded by weak negative magnetic fields. The plasma density is initially set to 1 and the plasma pressure to 0.01 in order to simulate the coronal conditions. The numerical Alfvén velocity is around 3.9 in the inner polarity. Thus the Alfvén time at the scale inner loops is of the order of 2 time units.
◇ A **null point**, initially exist along the central axis $(x = 0, y = 0)$ at $z_n = (\mu_0 m_0/2\pi B_v)^{1/3} + z_0 \simeq 2.2$. This null point divide the space in two volumes of distinct connectivity. The inner volume is formed of closed field lines linking the magnetic polarity with his surrounding environment. The outer volume is composed of open vertical field lines. We are studying the **interactions between closed and open magnetic fields**.
◇ The fields lines going through the magnetic null form particular topological features known as the **Spine-Fan topology** (Cowley 1974, Longcope 2005). This topology defines preferential sites for reconnection to occur.
◇ The boundary conditions are defined such that the top boundary is open and **line-tied** conditions apply at the bottom boundary ($z = 0$). This implies that the bottom boundary is infinitively conducting and has infinite inertia: it evolves only due to the prescribed motions. The aim is to simulate the behavior of the lower layers of the solar atmosphere.
◇ In order to store free magnetic energy and to study reconnection, we constrained the magnetic configuration by applying a twisting motion at the bottom boundary, within the positive magnetic polarity. The prescribed horizontal motion, $\mathbf{v}_\perp = \mathbf{v}$(z=0) is defined by:

$$\mathbf{v}_\perp = \frac{v_0}{2}\left[1 - \cos\left(2\pi \frac{t - t_l}{t_r - t_l}\right)\right] \frac{B_r - B_l}{B_z} \tanh\left(k_B \frac{B_z - B_l}{B_r - B_l}\right) \mathbf{z} \times \nabla B_z \tag{6}$$

for $t \in [t_l = 100; t_r = 1100]$ and $B_z \in [B_l = 0.1; B_r = 13]$. The constraint is thus only applied after a small relaxation time. This motion induces flows along the contours of $B_z(z = 0)$, and therefore preserves its distribution at the bottom boundary. $B_z(z = 0)$ being axisymmetric, $\mathbf{v}_\perp$ corresponds to a purely **axisymmetric azimuthal flow**. The maximum velocity is only equal to 1% of the local Alfvén velocity.

3 Magnetic evolution

◇ We performed several runs, with different intensity for the twisting motions. Three different phases could be observed. **Fig. 2** presents the evolution of the configuration at different times for a particular run. The evolution of the integrated energies for this run are displayed on **Fig. 3**.

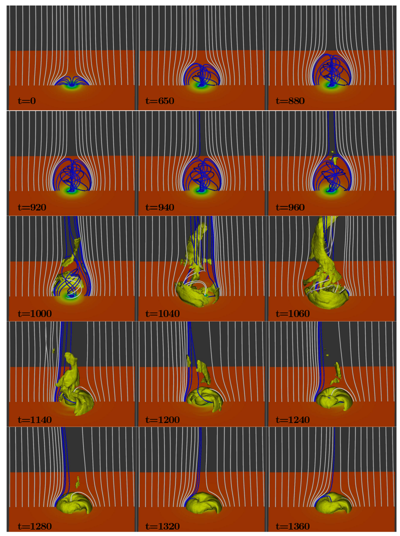

Figure 2 : Evolution of the magnetic configuration. The 2D plane displays the distribution of B_z at the bottom boundary. The field lines are plotted starting from the bottom boundary along the y axis at fixed position. The white ones are initially belong to the open connectivity domain whereas the blue ones are in the close connectivity domain. The yellow isocontours are those of the mass density and represent surface where ρ equal 1.25 .

☞ **Energy build-up (from t $= 100$ to t ~ 940) :.** The slow twisting increases the azimuthal component of the magnetic field, and thus the magnetic field intensity within the inner connectivity volume. During this phase the axisymmetric is well-preserved. **The axisymmetric properties of the magnetic configuration forbids reconnection to occur** and free magnetic energy slowly accumulates.

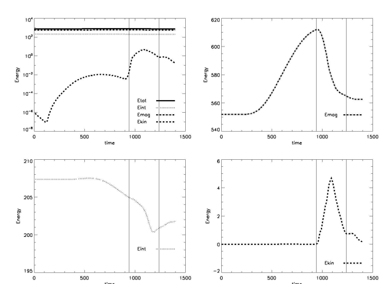

Figure 3 : Evolution of the Energies during the simulation. The two vertical lines at $t = 940$ and $t = 1240$ separate the three different phases. **Top left :** *Total, Kinetic, intern and magnetic energies in a log scaled plot.* **Top right :** *Magnetic energy.* **Bottom left :** *Intern energy.* **Bottom right :** *Kinetic Energy.*

☞ **"Instability" ($\sim$ t ~ 940) :** Eventually, the axis of the twisted flux tube starts to deforms itself under a **kink-like instability**. The twisted magnetic structure starts to writhe. **The axisymmetry broken, substantial reconnection is allowed**. Very thin and intense current layers develop along the separatrices. The instability only appears when a sufficient amount of magnetic helicity has been injected, *i.e*, a sufficient number of turns. Performing several simulations, we found that the critical values for the instability to appear, lies between 1.5 and 2 turns The magnetic energy decreased by 12% during this phase.

☞ **Jet generation (from t ~ 940 to t ~ 1240) :** Reconnection allows the transfer of magnetic energy and helicity from the inner domain to the outer domain. The ejection of helicity is done by the mean of a torsional wave. This leads to the **a jet generation** (see **Fig. 4**). Materials is accelerated and ejected up in the open field. The free energy is partly transformed to kinetic energy and to magnetic energy transported away by the torsional wave. Reconnections occurring at the null points lead to a decrease of the magnetic energy of 8% (80% of the free energy initially stored). **The jet formation due to magnetic reconnections is extremely effective at removing the magnetic energy and helicity stored.**

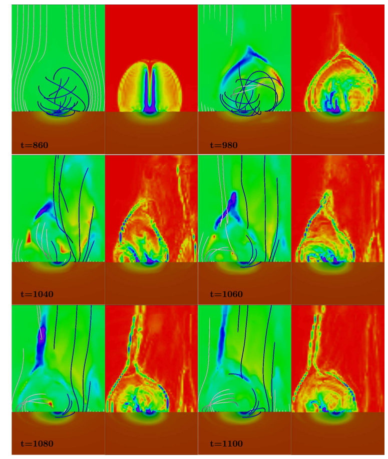

Figure 4: **At each time : Left :** *2D cut (in the plane yz) of the vertical component of the velocity field. The field lines are piloted starting from the bottom boundary along the y axis at fixed position: white field lines initially belongs to the open connectivity domain whereas the blue ones are in the close domain.* **Right :** *2D cut (in the plane yz) of the total current density.*

☞ **Relaxation (from t ~ 1240) :** The topology is now strongly modified. The inner and the outer spines are no longer coaxial as predicted by the reconnection models. Initially closed field lines are now open. Intense and thin current layers develop along the line joining the intersection of the spines with the Fan surface. Reconnections allow the system to relax. The final state is in equilibrium with a null point and some lightly twisted structures in the inner domain.

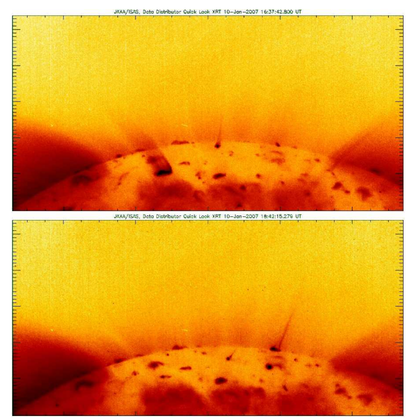

Figure 5: Examples of X-ray polar jets observed by XRT/HINODE on Jan 10, 2007. (image courtesy of J. Cirtain)

4 Conclusion

◇ The applications to solar activity and to the solar atmosphere is particularly straightforward. This simulation presents the evolution, in a coronal-like plasma of a closed magnetic structure interacting with an open one, by motions applied at the lower boundary and leads to the acceleration and ejection of coronal plasma. This type of configuration, with a null point, is frequently observed in the solar atmosphere in particular at the solar pole where magnetic polarity are linked with polar jets (see **Fig. 5**). Our axisymmetric calculations represent a firts step towrd understanding more realistic, complex configurations.

References

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