

CORONAL CLOSURE OF SUBPHOTOSPHERIC MHD CONVECTION FOR THE QUIET SUN

T. Amari ¹, J.F. Luciani ¹, J. J. Aly ²

ABSTRACT

We use our Resistive Layer Model (RLM), which stresses the importance of the resistivity at the photospheric interface, to study the evolution of a solar coronal quiet region driven by subphotospheric convection. The initial version of the RLM is improved by introducing a new Boussinesq MHD model for the upper part of the convection zone (CZ), while the low beta corona is still described by a MHD model. We compute the evolution of a weak magnetic field introduced initially in the CZ. We observe its amplification by the turbulence, the concentration of the photospheric flux at the boundaries of the convection cells, the coalescence and the cancellation of flux elements, and the transfer of about 10% of the magnetic energy into the corona. The currents associated to the nonpotential coronal field are found to be organized in filament-like localized structures due to the photospheric vortices and the complexity of the magnetic topology. Their resistive dissipation contributes to the heating of the quiet corona.

Subject headings: MHD – Sun: corona – Sun: magnetic fields

1. INTRODUCTION

About 90% of the magnetic flux in the quiet Sun emerges as ephemeral regions. Each emerging pole fragments into pieces which migrate towards the boundary of the supergranulation cells, along which they move and suffer cancellation and coalescence (Priest et al. 2002). The flux tubes connected to them are thought to play an important role in the heating of the quiet corona, a topic which has been much studied theoretically by using a generic model in which a coronal configuration is submitted to changing photospheric boundary conditions

¹CNRS, Centre de Physique Théorique de l'Ecole Polytechnique, F-91128 Palaiseau Cedex, France – amari@cpht.polytechnique.fr

²AIM - Unité Mixte de Recherche CEA - CNRS - Université Paris VII - UMR n^o 7158, Centre d'Etudes de Saclay, F-91191 Gif sur Yvette Cedex, France

chosen to mimic the effects of the underlying convection zone (CZ) motions. The resulting evolution is thus found to lead to the formation of small scale structures (current layers, filaments) in which magnetic energy dissipation into heat occurs efficiently (see Klimchuk (2006) for a recent review). On the other hand, extensive magnetohydrodynamic (MHD) studies of the underlying CZ have lead to important results on the turbulent amplification and rising of weak magnetic tubes, but with the imposed upper boundary conditions preventing the emergence of structures (Meneguzzi & Pouquet 1989; Cattaneo 1999; Cattaneo et al. 2003). To go a step further towards a full understanding of the formation of quiet Sun coronal structures and of their role in the plasma heating, it thus appears at this stage that a global model is needed in which the approaches from above and from below get connected. Clearly, it is necessary for completing this task to elucidate the physics of the photospheric transition region, which can be done essentially by developing extensive numerical simulations. This is not easy as the very different physical properties of the CZ and the corona, and the stiff changes occurring at their interface, impose severe constraints on the schemes.

In this Letter we report a contribution to the solution of that problem which is complementary to some related recent works (e.g., Abbett (2007); Cheung et al. (2007); Martinez-Sykora et al. (2008); Steiner et al. (2008)). It rests on the use of the *Resistive Layer Model* (RLM) introduced in Amari et al. (2005). The RLM couples the subphotospheric convection to the low beta corona through a turbulent resistive layer in which the effective resistivity is larger than in these two regions, and it allows the transfer of flux, helicity, and energy, between them, with the key quantity controlling this process being the parallel component of the electric field. With respect to our initial approach, we keep the full MHD model for describing the corona, but we introduce an important improvement for describing the CZ. We replace indeed the simple kinematic picture by a more consistent model based on an idealized incompressible Boussinesq approximation of the MHD equations. The latter, which is similar to the one used in Cattaneo (1999), is valid only for weak fields. Then it was not possible to use it in the strong field context dealt with in Amari et al. (2005), but it is adequate here for studying how an horizontal remnant field that has risen from the bottom of the CZ evolves in the upper part of the latter.

2. GLOBAL MODEL PROBLEM: THE RLM

In the RLM, the CZ, the corona, and their interface are represented, respectively, by the upper half-space $\Omega_+ = \{z > 0\}$, the lower half-space $\Omega_- = \{z < 0\}$, and the plane $\Gamma = \{z = 0\}$. Two MHD models are assumed to be available for computing the evolution of the state of the plasma in Ω_+ and Ω_- , respectively. The normal component of the velocity is

required to vanish on Γ ($v_z = 0$). Of course, it is well possible that this particular assumption does not allow to grasp the whole physics of the emergence process, and that we have to get rid off of it in a latter step of our program – e.g., by treating both the corona and the CZ by a single MHD model –, but we feel that the RLM is worth being studied as an intermediate step. In order to get a transfer of magnetic flux through Γ , we require the presence at the top of Ω_- of a thin resistive boundary layer (RBL) Ω_{RBL} of width z_{RBL} – i.e., a region of nonzero resistivity which may be thought to mimic the turbulent photosphere in which an effective resistivity enhancement is expected. The RBL is thus comprised between the plane $\Gamma_{RBL}^u = \Gamma$ and the new interface $\Gamma_{RBL}^l = \{z = -z_{RBL}\}$. A crucial quantity in the model is the horizontal component of the electric field, $\mathbf{E}_s = \hat{\mathbf{z}} \times (B_z \mathbf{v}_s - v_z \mathbf{B}_s) + \eta \mathbf{j}_s$ (Ohm’s law in a plasma with magnetic diffusivity η), which is continuous in the whole space.

In this Letter, we use the full set of MHD equations (see Sect. 4.1 of Amari et al. (2003)) in Ω_+ , as we did in Amari et al. (2005), but we introduce a newly developed MHD Boussinesq approximation in Ω_- . The latter leads to the nondimensionalized system

$$\partial_t \mathbf{v} + \nabla \cdot (\mathbf{v} \otimes \mathbf{v}) = -\nabla \cdot [(p + B^2/2) \mathcal{I} - \mathbf{B} \otimes \mathbf{B}] + \nabla \cdot (\sigma \nabla \mathbf{v}) + \sigma R_a \theta \hat{\mathbf{z}}, \quad (1)$$

$$\partial_t \mathbf{B} = \nabla \times (\mathbf{v} \times \mathbf{B}) - \nabla \times [(\sigma/\sigma_m) \nabla \times \mathbf{B}], \quad (2)$$

$$\partial_t \theta + \mathbf{v} \cdot \nabla \theta = \mathbf{v} \cdot \hat{\mathbf{z}} + \Delta \theta, \quad (3)$$

$$\nabla \cdot \mathbf{B} = 0 \quad \text{and} \quad \nabla \cdot \mathbf{v} = 0, \quad (4)$$

$$\Delta p = -\nabla \cdot [\nabla \cdot (\mathbf{v} \otimes \mathbf{v})] + \nabla \cdot [-\nabla \cdot (B^2 \mathcal{I}/2 - \mathbf{B} \otimes \mathbf{B}) + \sigma R_a \theta \hat{\mathbf{z}}], \quad (5)$$

$$\partial_n p = \left\{ -\sigma \hat{\mathbf{n}} \cdot \nabla \times \nabla \times \mathbf{v} + \hat{\mathbf{n}} \cdot [-\nabla \cdot (B^2 \mathcal{I}/2 - \mathbf{B} \otimes \mathbf{B}) + \sigma R_a \theta \hat{\mathbf{z}}] \right\}_\Gamma, \quad (6)$$

where standard notations have been used. It is solved by a third order Adams-Bashford time integration which is implicit for all the dissipation terms. This linear system (5)-(6) ensures the incompressibility of the flow (Eq. (4)₂), and it is solved at each time step by the efficient preconditioner developed in Amari et al. (1999). The convective terms are treated by a second-third order non oscillant upwind scheme. Our spatial discretization uses a staggered mesh in which \mathbf{v} and \mathbf{B} are evaluated on the faces of the cubic cells, while the pressure p and the temperature increment θ (defined as in Cattaneo (1999)) are evaluated at the cell centers. This insures, along with equation (2), that equation (4)₁ is satisfied. Horizontal periodicity of all the fields is assumed. Vertically, we impose free-slip and stress-free conditions for the velocity as in Meneguzzi & Pouquet (1989) and Cattaneo (1999): $\mathbf{v}_n = 0$ and $\partial_n \mathbf{v}_t = 0$ (the subscript n (t) indicates a normal (tangential) component). The tangential component of \mathbf{B} at the bottom of the box in Ω_- is fixed to its initial value indicated below. At the top boundary, this quantity depends on its value at the base of Ω_+ . The normal component of \mathbf{B} has not to be prescribed. None of these tangential boundary conditions intervene for solving Faraday equation, due to the conditions imposed on \mathbf{v} , but they are needed for solving the momentum equation. As for θ , we impose the vertical boundary condition $\theta = 0$. In Ω_- the

size of the numerical box representing the upper layer of the convection zone (down to 30 Mm) is taken to be in our units 10×10 in the horizontal directions, and 1 in the vertical one, with a spatial resolution $256 \times 256 \times 25$. The Prandtl number is fixed to $\sigma = 1$ and its magnetic counterpart to $\sigma_m = 5$, and we set the Rayleigh number R_a to a value between 50000 and 100000. In Ω_+ the domain size is $10 \times 10 \times 30$, the larger vertical value being required for ensuring that the coronal structures stay unconstrained by boundary effects. The choice of the parameters in Ω_- leads to a viscous coefficient $\nu = 1$, and a resistivity $\eta = .2$. The initial coronal density is set to be of the order of 10^{-3} . As an initial condition, we take \mathbf{B} to vanish in Ω_+ , and to be in Ω_- of the form $B_y \hat{\mathbf{y}}$, with B_y decreasing linearly to zero with height from a maximum value $B_{max} = 1 - 3$ at the base. The latter field is supposed to be a residual remnant of the toroidal field at the bottom of the CZ (Moreno-Insertis 1992). For the initial temperature in Ω_- we choose a random perturbation of magnitude 10^{-3} .

The RLM model: (i) first performs in Ω_- an ideal step which determines in particular the tangential component of the velocity at its top, (ii) thus effects an ideal step of the MHD coronal model in Ω_+ , and (iii) finally solves a purely resistive step for the domain $\Omega = \Omega_- \cup \Omega_+$. In that step, the resistivity is taken to be of the form $\eta(x, y, z) = \eta_0 \exp[-(z - z_c)^2 / \sigma_z^2] + \eta_{bg}$ – as in Amari et al. (2005) –, with $\eta_0 = 1$, $z_c = -.1$, and a value $\eta_{bg} = .2$ of the background resistivity compatible with the value of the resistivity in Ω_- and Ω_+ . Actually, it is this prescription which defines the RBL, which then has $z_{RBL} = \sigma_z = .1$.

3. RESULTS AND DISCUSSION

The following features are observed during a run. (a) Thermal convection sets up, with a moderate number of cells being formed. The convective dynamics induces an amplification of the magnetic field. (b) Although the initial magnetic field in the CZ is small and horizontal, vertical field concentrations appear at the border of the convective cells. This results from the emergence of flux at the hot cell centers followed by its transport by the diverging motions up to the cooler intercell layers. Coalescence and cancellation of flux elements are observed along the interfaces as shown in Figure 1. (c) Mutual interactions among various surface flows lead to the creation of the photospheric vortices shown in Figure 1. These characteristic structures, also found by Cattaneo (1999), are consequences of subphotospheric motions. (d) The photospheric vortices are the traces of coronal filaments, as well as of current concentrations (see Fig. 2). Slightly above the photosphere, these structures exhibit a well organized network, linked by the current/field concentrations, which keeps information about the photospheric cell structure. The existence of these currents contradicts the standard picture of a quiet Sun carpet simply made of quasi-potential complex topology

structures and is in agreement with results obtained independently by Abbett (2007). (e) Most of the flux closes down at low altitude as shown on Figure 3 (see also Priest et al. (2002)). However (in accordance with the previous point) the coronal configuration is far from being in a potential state: We observe that more than 10% of the magnetic energy created by convection is transferred to the corona along with electric currents, the latter being subsequently subject to continuous dissipation as shown on the left panel of Figure 4. (f) In the duration of the simulation, the system exhibits a dynamical evolution. The coronal response is not a quasi-equilibrium state, but rather a nonequilibrium one in which vertically oriented "winds" are generated by the dynamic ram-pressure gradient, ∇v^2 , which is much increased in the front of the corona and tends to generate a front shock. This can be seen in the panel (b) of Figure 4 comparing the various components of the kinetic energy.

In spite of the possible limitation of the RLM related to the $v_z = 0$ assumption, we feel that it is already interesting to apply our results to the problem of the heating of the quiet coronal regions. The solution to that problem has been often ascribed to the generation of DC currents in the type of structures we have obtained in the corona. What our work shows in this respect is that the latter may be of subphotospheric origin, and that their continuous coupling to the underlying motions leads to a non negligible amount of the magnetic energy generated in the CZ by the magnetoconvection being transferred to the corona, where it gets dissipated through the formation of current-sheets. We also note that our model is likely to give at least a lower bound to the transfer of flux and energy to the corona, insofar as we may expect this transfer to be increased by a nonzero v_z . Finally we quote some points which will be addressed in a forthcoming paper: The possible effects of a preexisting large scale coronal poloidal field, and the precise budget and the nature of the dissipation in the closed carpet structures.

We thank M. Menneguzzi and F. Cattaneo for interesting exchanges. Our simulations have been performed on the NEC SX5 supercomputer of the Institute I.D.R.I.S of the CNRS.

REFERENCES

- Abbett, W. P. 2007, *ApJ*, 665, 1469
- Amari, T., Luciani, J. F., & Aly, J. J. 2005, *ApJ*, 629, L37
- Amari, T., Luciani, J. F., Aly, J. J., Mikic, Z., & Linker, J. 2003, *ApJ*, 595, 1231
- Amari, T., Luciani, J. F., & Joly, P. 1999, *SIAM J. Sci. Comput.*, 21, No. 3, 970

- Cattaneo, F. 1999, *ApJ*, 515, L39
- Cattaneo, F., Emonet, T., & Weiss, N. 2003, *ApJ*, 588, 1183
- Cheung, M. C. M., Schüssler, M., & Moreno-Insertis, F. 2007, *A&A*, 467, 703
- Klimchuk, J. A. 2006, *Sol. Phys.*, 234, 41
- Martinez-Sykora, J., Hansteen, V., & Carlsson, M. 2008, *ApJ*, 679, 871
- Meneguzzi, M. & Pouquet, A. 1989, *Journal of Fluid Mechanics*, 205, 297
- Moreno-Insertis, F. 1992, in *NATO ASIC Proc. 375: Sunspots. Theory and Observations*, ed. J. H. Thomas & N. O. Weiss, 385–410
- Priest, E. R., Heyvaerts, J. F., & Title, A. M. 2002, *ApJ*, 576, 533
- Steiner, O., Rezaei, R., Schaffenberger, W., & Wedemeyer-Böhm, S. 2008, arXiv:0801.4915v3 [astro-ph]

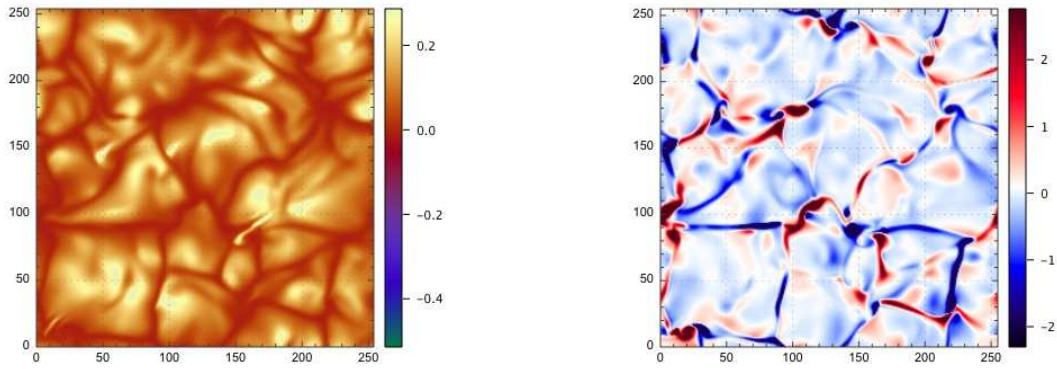


Fig. 1.— Horizontal cuts of the profiles of temperature (left panel) and vertical component of the magnetic field (left panel) at the photospheric level. They show a reasonable agreement between the positions of the cool (hot) regions and the centers of the cells (the intercell edges).

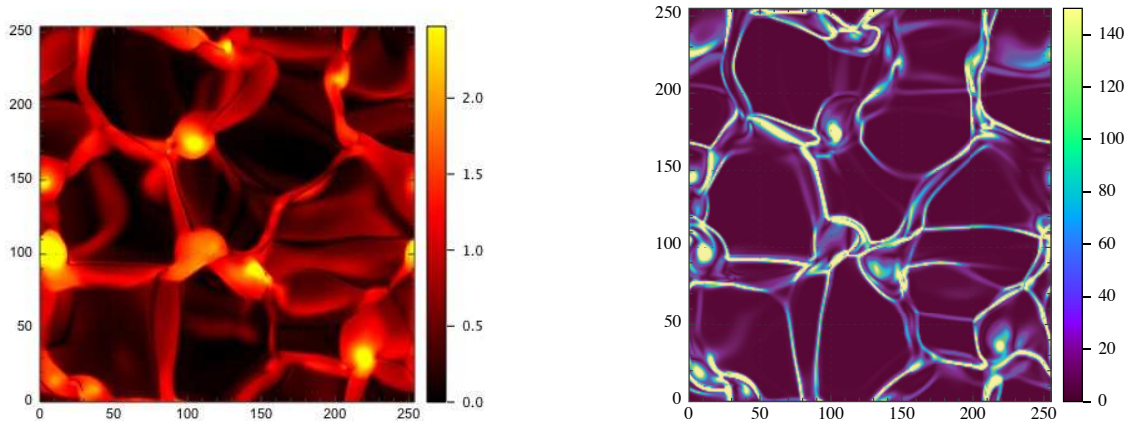


Fig. 2.— Horizontal cuts above the photosphere of the magnetic field norm (left panel) and of the electric current squared norm (right panel). The structures still have memory of the underlying network structure. Vortices shown on the left panel of Figure 1 are associated with coronal current filament structures, and interconnect through sheets.

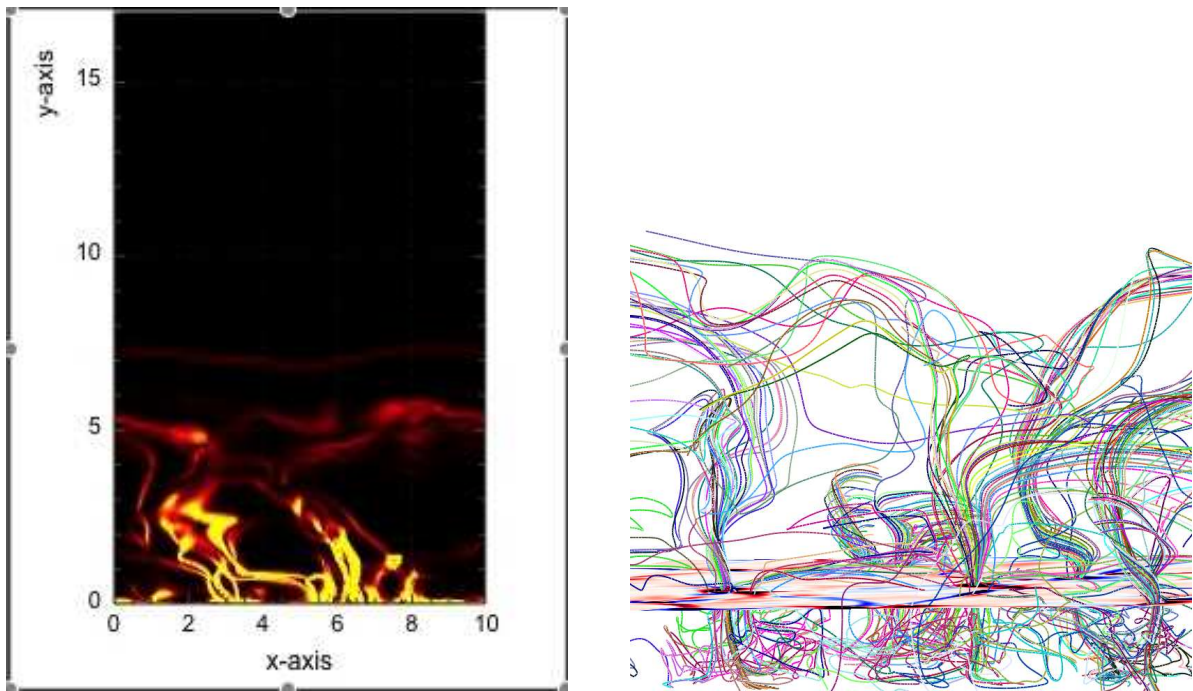


Fig. 3.— Vertical cut of the electric current squared norm (left panel) and partial view of the field lines organization (right panel), showing electric current concentrations in filament-like emerging structures concentrated at the boundaries of the cells that they do interconnect, as well as CZ part. Weaker field areas in the CZ are much less organized than those prolonging downwards the flux filaments.

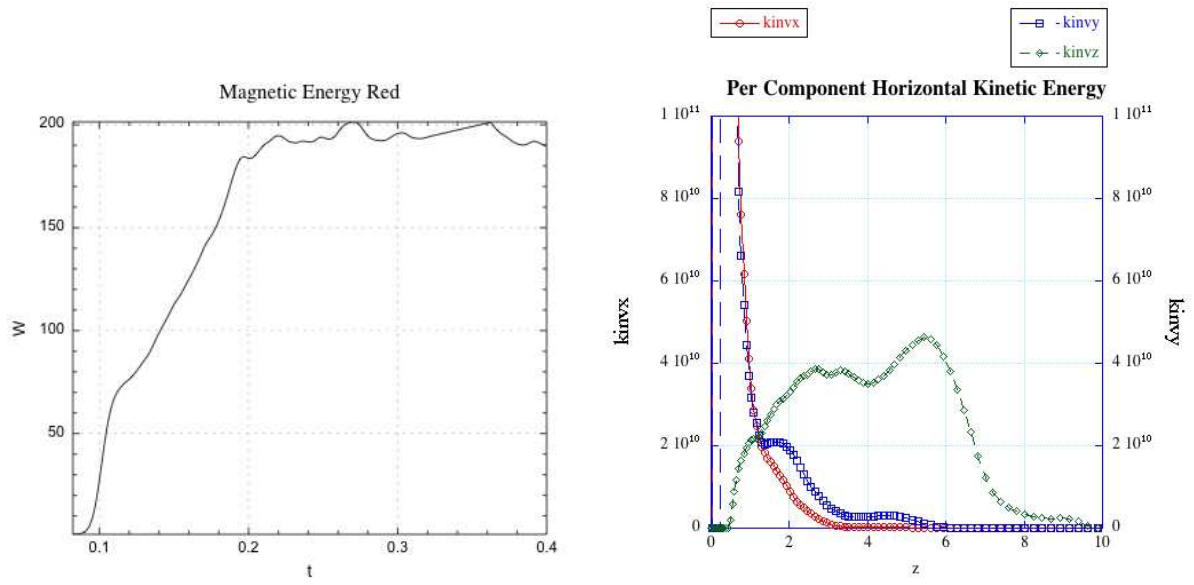


Fig. 4.— Evolution of the magnetic energy in the corona (left panel) and distributions of the various components of the kinetic energy around $t=0.39$ (right panel).