MODELLING OF FORCE-FREE ELECTRIC CURRENTS IN THE SOLAR ATMOSPHERE

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Abstract. Using the 3-D numerical code with quasi-particles representing electric currents the force-free current paths for 4 current filaments and corresponding magnetic fields are computed. The initial dipole magnetic field in a flaring active region and the virtual mirror current representing the effect of the inertial photosphere are considered. Then a structure of the magnetic loop with current filaments is analyzed, e.g. through the computation of quasi-separatrix layers and lengths of magnetic field lines.

1. Numerical model

The model used was described in the paper by Karlický [1]. A basic assumption in this model is that the electric current is force-free, i.e. the electric current is parallel to the local magnetic field. The currents are represented by numerical particles. First some initial magnetic field of arbitrary form (potential or force-free) is prescribed. Then from the bottom surface of the numerical box, which represents the photosphere, numerical particles (no mass, no forces, no equation of motion are considered) are injected upwards along the local magnetic field line. These particles change their position with the constant "velocity" $\mathbf{v} \parallel \mathbf{B}$ ($\mathbf{B}$ is the magnetic field) throughout the space above the photosphere. During the "time" step Δt, they change their position by the propagation vector $\mathbf{dl} = \mathbf{v}\Delta t$, which simultaneously represents the force-free electric current, whose intensity is prescribed by a numerical constant. Because the particles are injected successively, one particle every time step Δt along one current path, they are after some time distributed regularly (with the $\mathbf{dl}$ distance between neighbouring particles) along a line above the photosphere, thus depicting the electric current path. For small currents these paths correspond to the initial magnetic field lines. If particles penetrate back below the photosphere then these particles are excluded from further computations. Prescribing to each particle some electric current and using the Biot and Savart law

$$d\mathbf{B} = \mu_0 I \frac{d\mathbf{l} \times \mathbf{R}}{4\pi \mid \mathbf{R} \mid^3}, \tag{1}$$

where $\mathbf{R}$ is the distance from the current element to where $\mathrm{d}\mathbf{B}$ is evaluated and $\mathrm{d}\mathbf{l}$ is the element of length in the current direction (which, in our case, is equal to the particle propagation vector - see above), we compute the current magnetic field, which changes the initial magnetic field as well as the current particle trajectories. Namely, at every time step, at particle positions we compute the magnetic field directions, which are then used as directions of the particle propagation. This procedure is repeated every time step. At some specific times the magnetic field is also available at any point of the computational box, e.g. for field-line drawings. The relation (1) is singular for $\mid \mathbf{R} \mid= 0$. Moreover, the electric current is flowing in some finite area. On the other hand, there is the finite distance between numerical particles. To solve this problem, we define $\mathbf{R_0}$ as the minimum interaction distance; while for the magnetic field calculations at distances $\mid \mathbf{R} \mid > \mid \mathbf{R_0} \mid$ the relation (1) is valid, for the case $\mid \mathbf{R} \mid \leq \mid \mathbf{R_0} \mid$ a modified relation in the form

$$d\mathbf{B} = \mu_0 I \frac{d\mathbf{l} \times \mathbf{R}}{4\pi \mid \mathbf{R_0} \mid^3} \tag{2}$$

is used (in this relation $d\mathbf{B}$ decreases to zero for $\mid \mathbf{R} \mid \rightarrow 0$). Thus $\mid \mathbf{R_0} \mid$ roughly corresponds to the radius of the electric current cross-section. (In principle, Eq. (2) can be replaced by some cylindrical or other approximation. But we think that these changes cause only slight effects on global equilibria. The reason why Eq. (2) was used is the simplicity of its numerical form, which is important in the case with many numerical particles.) Simultaneously, this procedure represents some smoothing of electric current. Namely, in the force-free case, the curved, infinitesimally thin electric current always forms a helical structure. This effect is also found for smoothed electric currents, but with much larger structures. To describe this helical structure with the appropriate precision, we need the smoothing distance $\mathbf{R_0}$ to be several times greater than the distance between successively injected particles. Otherwise, we have more helical circles, which are not sufficiently described by particles. This smoothing procedure is a little artificial and can be considered as appropriate only if we are interested in the global aspects of electric current and magnetic field. More precise computations can be done only if one localized electric current is represented by many close current paths. When the minimum interaction distance $\mathbf{R_0}$ is shorter than the distances between numerical particles dl, then the procedure with $\mathbf{R_0}$ becomes irrelevant and the smoothing of currents is given by dl. More precision can be obtained only by the shortening of dl. Therefore, according to the type of our task, we need to select the appropriate dl, $\mathbf{R_0}$, number of current paths and number of particles.

Our computations start from a low electric current which is then slowly and continuously increased to the specific value of electric current. Then it is useful to keep this current constant for some time and thus to relax the resulting structure. The method can be generalized for an arbitrary number of injection positions, i.e. for arbitrary current distribution. It enables us, for example, to simulate the current flowing through a finite cross-section by more sub-currents and thus to increase the computation precision.

Applying this method to currents in the solar atmosphere we need to consider the effect of the inertial photosphere. We included this effect using the virtual mirror current as suggested by Kuperus and Raadu [2]. This current causes that no magnetic field created by the coronal currents can penetrate the photospheric layers.

2. Computed magnetic field and its analysis

As the initial magnetic field of a simplified active region (i.e. without computed currents), we take the dipole magnetic field:

$$B_x = C\frac{3x^2 - r^2}{r^5}, \tag{3}$$

$$B_y = C\frac{3xy}{r^5}, \tag{4}$$

$$B_z = C\frac{3x(z - z_0)}{r^5}, \tag{5}$$

where C is a constant, z_0 is the position of the magnetic source below the photosphere (z_0 = - 5 $\times$ 10^7 m in our case), r is the distance from the magnetic source position to the position where the magnetic field is calculated. The constant C is chosen to give the maximum of this field as 100 G. This maximum is situated in the bottom-surface centre of the computational box. Then using our model with the increasing electric current we computed force-free current paths for four current filaments having the distances of 4 $\times 10^6$ m at injection positions with $\mid \mathbf{R_0} \mid$ = 2 $\times 10^6$ m. The current cross-section area is 5 $\times 10^{13}$ m^2. The distance between particles is 5 $\times$ 10^5 m, the particle "velocity" is 5 $\times$ 10^5 m s^{-1}, and the "time" step is 1 s. In computations the electric current was increased up to a specific value and then kept constant for some relaxation time. The resulting current filaments and corresponding magnetic field for the total electric current of 10^{11} A is shown in Fig. 1.

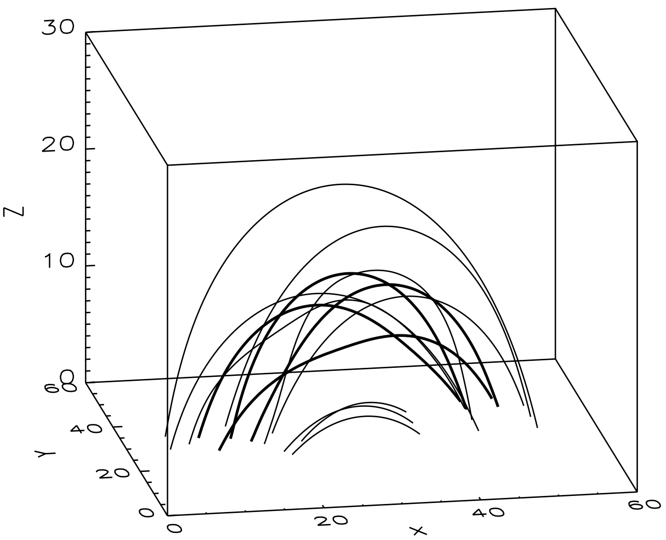

Figure 1. The electric current rope with four electric current filaments (thick lines) and corresponding magnetic field (thin lines) for I_{total} = 10^{11} A. Distances are expressed in Mm.

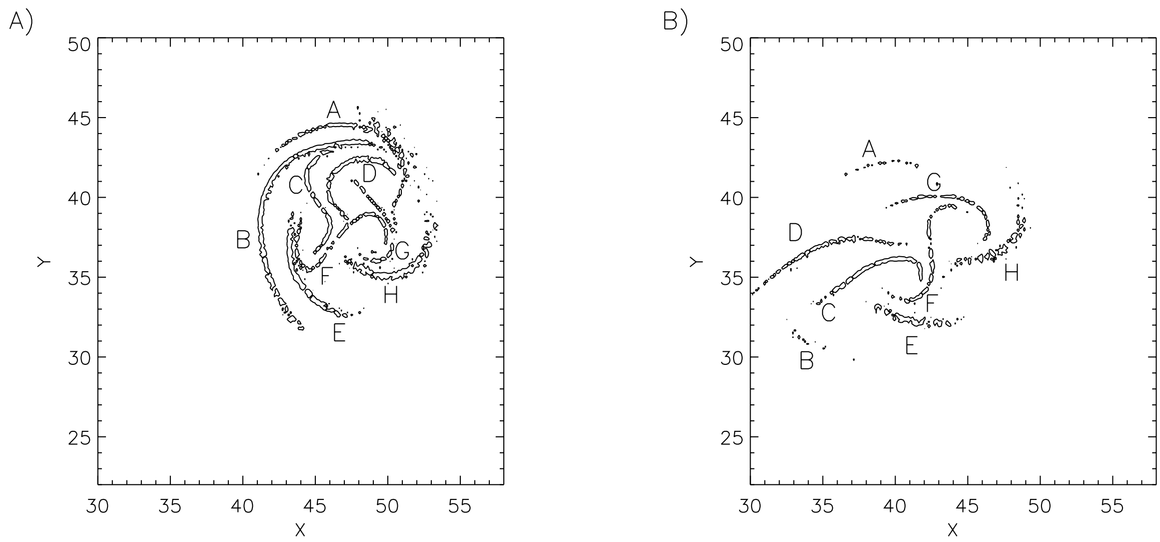

Figure 2. The distribution of intersections of quasi-separatrix layers with two horizontal planes in the solar atmosphere: A) Z = 0 Mm, and B) 7 Mm. N = 10. Letters A-H designate corresponding layers.

Then we started to analyze the structure of this magnetic field from the point of view of 3-D reconnection. Firstly, we used the classical description expressing local parameters, e.g. magnetic field vectors and electric current densities. Then we analyzed global characteristics of this magnetic field configuration. In accordance with Démoulin et al. [3] we computed intersections of quasi-separatrix layers with a prescribed plane. These computations are based on a determination of the function N(x,y) which is the norm of the displacement gradient tensor of magnetic field lines. Results for two horizontal planes (Z = 0 and Z = 7 Mm) and for N = 10 are shown in Fig. 2. The relationship between two specific intersections are expressed by letter A-H.

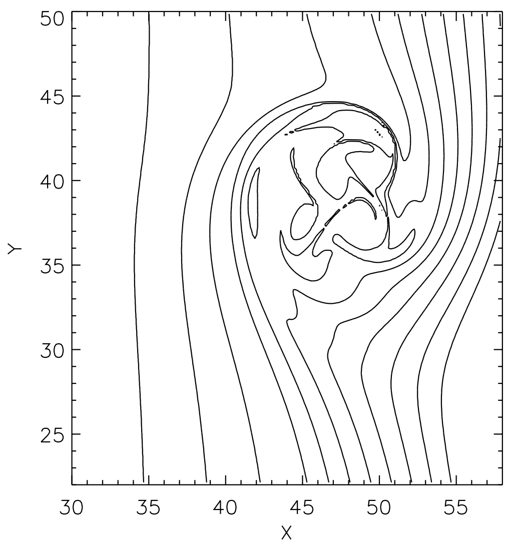

Figure 3. The structure of magnetic field lines expressed in their lengths. The equidistant lines corresponding to magnetic line lengths of 10, 20, 30, 40, 45, 50, 55, 60, 65, 70, and 75 Mm are depicted.

But, there are further possibilities how to describe the global characteristics of the magnetic field. For example by lengths of magnetic field lines. In initial dipole field the field line length increases with the increase of a distance of the photospheric line intersection from the neutral line. The addition of the electric current into the dipole field represents a twist and prolongation of magnetic field lines in space of the electric current rope (Fig. 3).

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References

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