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О ВОЗМОЖНОСТИ МГД МОДЕЛИРОВАНИЯ В РЕАЛЬНОМ МАСШТАБЕ ВРЕМЕНИ КОРОНАЛЬНОГО МАГНИТНОГО ПОЛЯ НАД АКТИВНОЙ ОБЛАСТЬЮ

On the Possibility of Real Time Scale MHD Simulation of the Coronal Magnetic Field Above an Active Region

Abstract. Механизм солнечной вспышки, основанный на накоплении энергии в магнитном поле токового слоя, объясняет первичное выделение энергии в солнечной короне и основные проявления вспышки. МГД моделирование предвспышечной ситуации в короне над реальной активной областью осуществляется без каких-либо предположений о механизме солнечной вспышки. Все условия задаются из магнитных карт SOHO MDI. Моделирование в реальном масштабе времени необходимо для определения точного положения вспышки в пространстве и её прогнозирования. Специальные численные методы разработаны и реализованы в программе ПЕРЕСВЕТ для увеличения скорости счёта. В реальном масштабе времени рассчитана начальная стадия образования токового слоя. Показана возможность моделирования предвспышечной ситуации.

1 Introduction

The solar flare electrodynamical model (Podgorny A.I. and Podgorny I.M., SolPh, 1992, **1**39, 125; AsRep, 2006, **50**, 842) based on energy accumulation in the current sheet created above the active region explains the primordial energy release in the solar corona revealed from X-ray observations of limb flares (Lin R.P. et al., 2003, ApJ, **595**, L69). The electrodynamical model explains also appearance of H_α ribbons and X-ray sources on the photosphere and the absence of strong magnetic field changes on the photosphere during a flare (Podgorny A.I. and Podgorny I.M., JASTP, 2013, **92**, 59). When disturbances that propagated from the photosphere arrive to the vicinity of an X-type singular line, the magnetic forces cause plasma motion, which deforms the magnetic field into the configuration corresponding to a current sheet. After quasistationary evolution the current sheet becomes unstable (Podgorny A.I., SolPh, 1989, **123**, 285; Plasma Phys. Cont. Fus., 1989, **31**, 1271), and instability causes an explosive energy release.

The MHD simulations for the real active region are carried out without any assumptions about the solar flare mechanism. The magnetic field observations are used to construct initial and boundary conditions. Such simulations are done independently of the existing flare models. The simulation is initiated several days before the flare, when strong disturbances in the corona are absent. Here, we do not consider processes inside the current sheet in detail according to the principle of limited simulation (Podgorny I.M., Fund. Cosmic Phys., 1978, **1**, 1).

All our previous MHD simulations (including Podgorny A.I. and Podgorny I.M., AsRep, 2008, **52**, 666) have been performed in the strongly compressed timescale. The magnetic field on the photosphere has been changed $10^4 - 10^5$ times faster than in the reality. This can cause some unrealistic structures with strong current, which mask the current sheet appearance. Also, coincidence of the real current sheet positions and positions obtained from simulations for the small timescale can be not very good, because the X-type singular line slowly moves during changing of the magnetic field configuration.

The general goal of our investigation is to simulate the flare situation in the corona above the active region in the real timescale. The aim of presented here simulations is to study situation near a singular X-line in a short time interval, when MHD disturbances arrive to the singular X-point, but the main plasma flow does not reach it.

2 Numerical methods implemented in the PERESVET code

The MHD simulation of the magnetic field and plasma evolution in the corona above the active region NOAA 10365 is performed. The system of MHD equations for compressible plasma with all dissipative terms is solved numerically in the computational domain with size $L_0 = 4 \times 10^{10}$ cm. L_0 is used as the dimensionless unit of length. The numerical methods are implemented in the PERESVET code (Podgorny A.I. and Podgorny I.M., Comput. Math. Math. Phys., 2004, **44**, 1784).

Knowledge of the initial magnetic field in the corona and photospheric magnetic field change before the flare permits us to determine the field evolution in the corona by solving of the MHD equation system. During the evolution the magnetic field above an active region becomes nonpotential due to the appearance of a current system in the corona.

The potential magnetic field in the initial moment of time should be known for setting the initial condition. Physically it means that the calculation begins before the appearance of strong disturbances on the photosphere, which can cause current generation in the corona. The potential magnetic field configurations have been calculated using magnetograms observed on May 24, 2003. The method of potential magnetic field calculation in the corona is described by Podgorny A.I. and Podgorny I.M. (Geomag. Aeron., 2012, **52**, 150). The initial plasma density and temperature are set to be constant in the space, and the initial velocity is zero.

To solve the set of MHD equations it is necessary to set two magnetic field components parallel to the boundary on all boundary of a computational domain in each moment of time. The magnetic field component normal to the boundary is found from $\mathrm{div}\mathbf{B} = 0$. SOHO MDI (`http://soi.stanford.edu/magnetic/index5.html`) observes on the photosphere only the distribution of the line-of-sight magnetic field component. For setting boundary conditions two parallel to the photosphere magnetic field components are taken from the calculated potential magnetic field obtained by solving the Laplace equation. Such a method is valid because the magnetic field on the photosphere is determined mainly by currents under the photosphere, but not by currents in the corona. It should be verified when the data about distributions of all three field components on the photosphere are available for setting boundary conditions for the magnetic field directly from observations.

For the chosen size of the computational domain on the photosphere $L_0 = 4 \times 10^{10}$cm, which is 4 times larger than the active region size, the magnetic field on the nonphotospheric boundary is weak. It does not influence strongly the solution of MHD equations. The results of calculation performed with three types conditions for parallel to the boundary magnetic field components on the nonphotospheric boundary are virtually the same: (1) the parallel to the boundary magnetic field components are unchanged on the nonphotospheric boundary; (2) the parallel to the boundary magnetic field components are set from the condition of zero current density on the boundary ($\mathrm{rot}\mathbf{B} = 0$); (3) the parallel to the boundary magnetic field components are set from the condition of zero derivative of the current density normal to the boundary ($\partial\, \mathrm{rot}\mathbf{B}/\partial n = 0$). Other values on the boundaries are approximated by free-exit conditions.

New numerical methods have been developed for solving the set of MHD equations so that main previous effective methods (Podgorny A.I. and Podgorny I.M., AsRep, 2008, **52**, 666) are also used. The absolutely implicit finite-difference scheme is used, which is conservative relative to the magnetic flux. The right part of the equation for the magnetic field $\frac{\partial \mathbf{B}}{\partial t} = \mathrm{rot}\,(\mathbf{V} \times \mathbf{B}) - \mathrm{rot}\,(\nu_m\, \mathrm{rot}\, \mathbf{B})$ is approximated in such a way that the finite-difference analog of $\mathrm{div}\mathbf{B}$ ($[\mathrm{div}\mathbf{B}]$) is zero to a high accuracy. The calculated current density $[\,\mathrm{rot}\mathbf{B}]$ tends to zero during the magnetic field relaxation providing stabilization of slowly growing instabilities.

In previous simulations (Podgorny A.I. and Podgorny I.M., AsRep, 2008, **52**, 666) the dissipation term was approximated as $[-\,\mathrm{rot}(\mathrm{rot}\mathbf{B})]$. The scheme presented here and implemented in the PERESVET code contains the dissipation term in the form $[\Delta\mathbf{B}]$. In this scheme, the conservation of $[\mathrm{div}\mathbf{B}]$ is not performed to a very high accuracy as in (Podgorny A.I. and Podgorny I.M., AsRep, 2008, **52**, 666). But this scheme is more stable because the dissipative term works in such a way that $|[\mathrm{div}\mathbf{B}]|$ decreases with time, which is more important for the scheme stability. The time of calculation decreases by the factor of 10.

3 Results of real time scale simulations on a short time interval

Here we present the first results of simulation of the magnetic field behaviour above the active region NOAA 0365 during the first 7 minutes of the evolution in the real time scale. Figures 1a, b show two X-points ($x = 0.427$, $y = 0.174$) and ($x = 0.546$, $y = 0.053$). At ($x = 0.546$, $y = 0.053$) X-point current concentration occurs, e. g., the current formation begins.

The magnetic field configuration and levels of current density distribution at time moment $t = 7$ min in the central plane $z = 0.505$ (Figure 1) show the trend of current sheet formation due to disturbances focusing in the X-type singular-line vicinity. The X-point does not precisely coincide with the current density maximum position (Figure 1a, b). It means that the singular line and the plane of creating current sheet are not precisely perpendicular to the plane of the figure $z = 0.505$. The X-point position and the position of the point of intersection of the singular X-line with this plane exactly coincide only if the X-line crosses this plane normally. If the X-line intersects the plane at some angle, then the field configuration in the plane is changed, and the X-point position is shifted relative to the position of the intersection point.

According to the procedure described by Podgorny A.I. et al. (JASTP, 2008, **70**, 621), the singular line is found as a magnetic line passing through the point of the absolute current density maximum. The current sheet is better pronounced in the plane perpendicular to the singular line, as it is shown in Figure 1c, d in a large scale. The field of velocities shows an

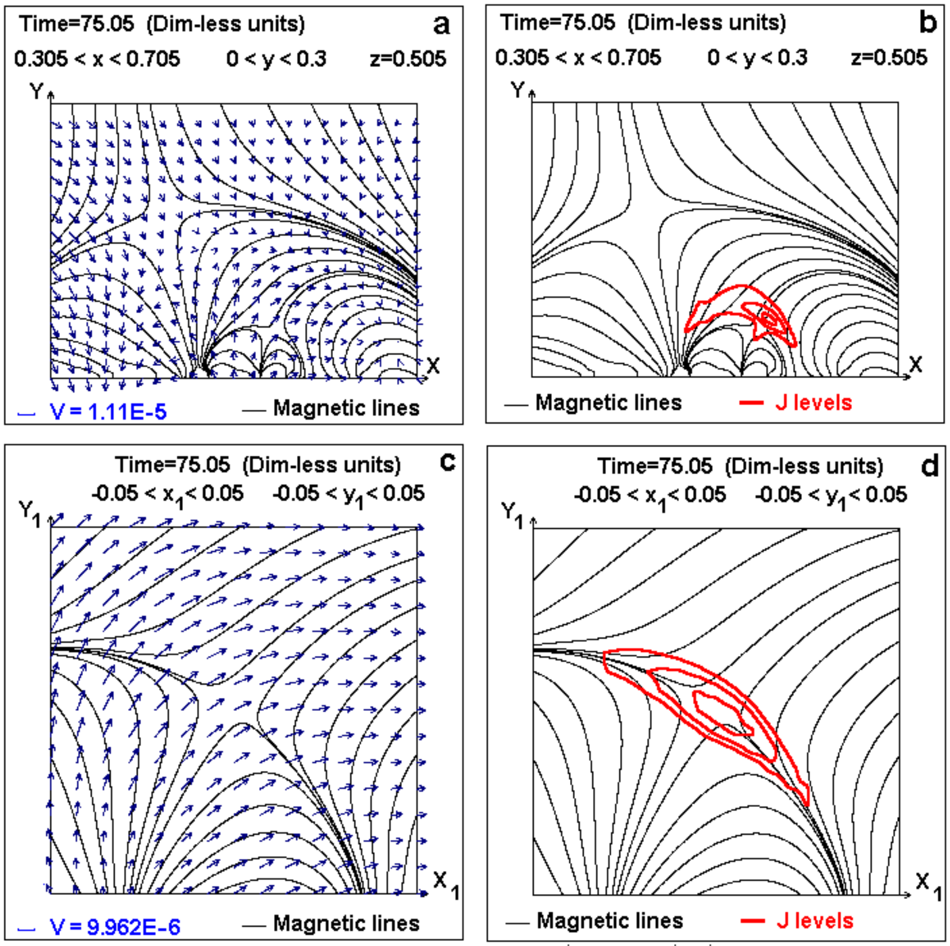

Рис. 1: Magnetic lines, velocity vectors, and lines of the constant current density obtained by real time scale MHD simulation for the active region NOAA 0365 for time moment $t = 7.5$ min. (a, b) – in the central plane $z = 0.505$; (c, d) – in the plane including the point of current density maximum $(x, y, z) = (0.5650, 0.065, 0.4998)$ and perpendicular to the magnetic vector at this point $\mathbf{B} = (0.001977, 0.01244, -0.03279)$.

upward and rightward X-line motion as a whole. Lines of the constant current density show the current sheet creation.

In Figures 1c, d the turnabout of the current sheet around the X-point (in 3D space the turnabout around the X-line) is seen clearly. The possibility of such a turning can be explained by the existence of magnetic field component B_r, directed toward the X-point in the plane of the figure. The component B_r can appear due to change of the magnetic field of photospheric sources along the X-type singular line. Such magnetic field configuration in the vicinity of the singular X-line is studied by Podgorny A.I. (SolPh, 1989, **123**, 285). The force jB_r in this case would cause the turning of the current sheet around the X-line.

Figures 2 and 3 help to visualize of the current sheet position in the 3D space. The current sheet begins to be created in the vicinity of the X-type singular line. This result is obtained using the developed system of numerical results visualization, which permits us to create images in an arbitrary chosen plane. Magnetic field configurations and lines of the

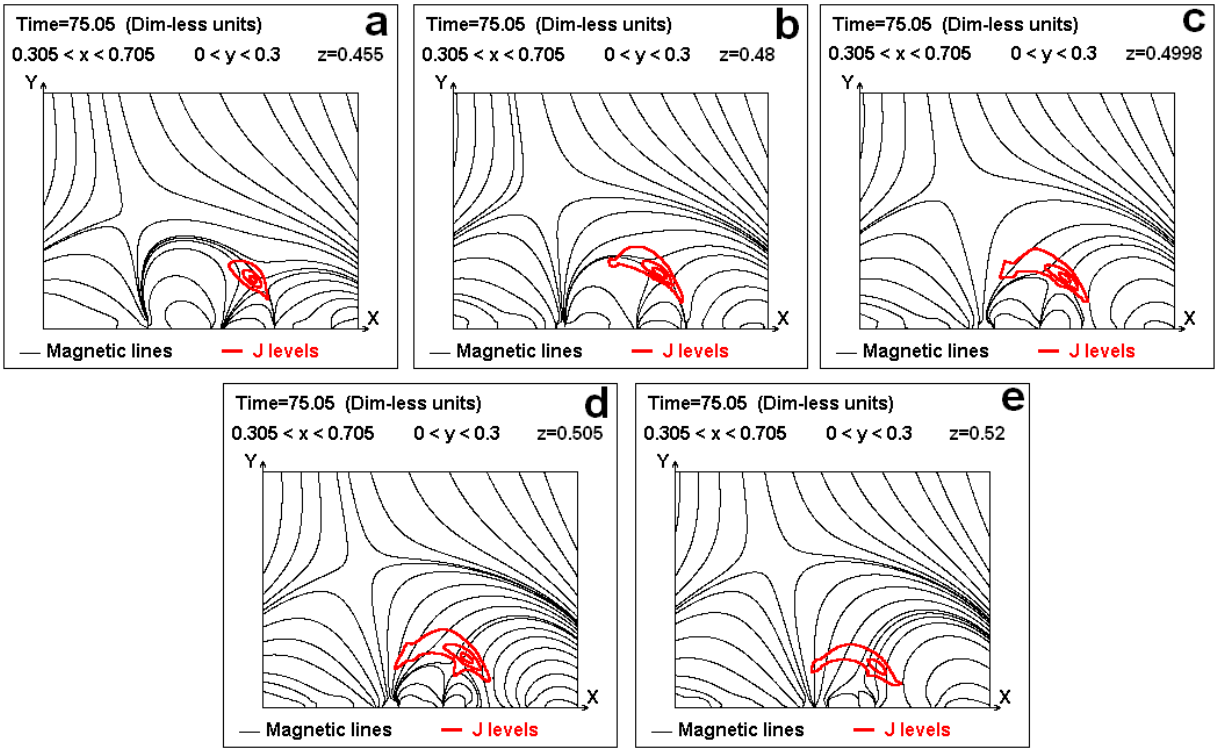

Рис. 2: Magnetic lines and lines of constant current density for time moment $t = 7.5$ min in the planes parallel to the central one.

constant current density in the planes $z = 0.455$, $z = 0.48$, $z = 0.4998$, $z = 0.505$, $z = 0.52$, are shown in Figure 2. In the ($z = 0.48$) plane the position of the current density maximum coincides with the X-point, and in the ($z = 0.4998$) plane it is situated close to the X-point. It means that the current sheet is perpendicular or almost perpendicular to these planes. In other planes ($z = 0.455$; $z = 0.505$; $z = 0.52$) the current density maximum does not coincide with the X-point, which means that the current sheet is inclined to the figure plane at some angle. Figure 3 helps to visualize the position of the line of current density maximums in the current sheet in the 3D space. Two magnetic lines (1 and 2), passed through the points of current density maxima in different parallel planes, are close to each other inside the current sheet (Figure 3a). Line (1) passes through the ($x = 0.575$, $y = 0.06$, $z = 0.455$) point, which is the point of the current density maximum in the ($z = 0.455$) plane. Line (2) passes through the point ($x = 0.565$, $y = 0.065$, $z = 0.4998$), which is the position of the current density maximum in the ($z = 0.4998$) plane. The good coincidence of magnetic lines 1 and 2 means that each of these lines is close to the line of current density maxima.

The lines are situated rather far from each other outside the current sheet (in the region $z > 0.52$). For the magnetic field component along the current sheet, the magnetic lines concentration takes place in the sheet. To show better the position of line (1), its part in front of the ($z = 0.455$) plane is drawn by light red color, and its part behind the plane ($z = 0.455$) by light green color. This line is shown separately in Figure 3b. Similarly, Figure 3c shows the red part of line (2) in front of the ($z = 0.4998$) plane and its green part

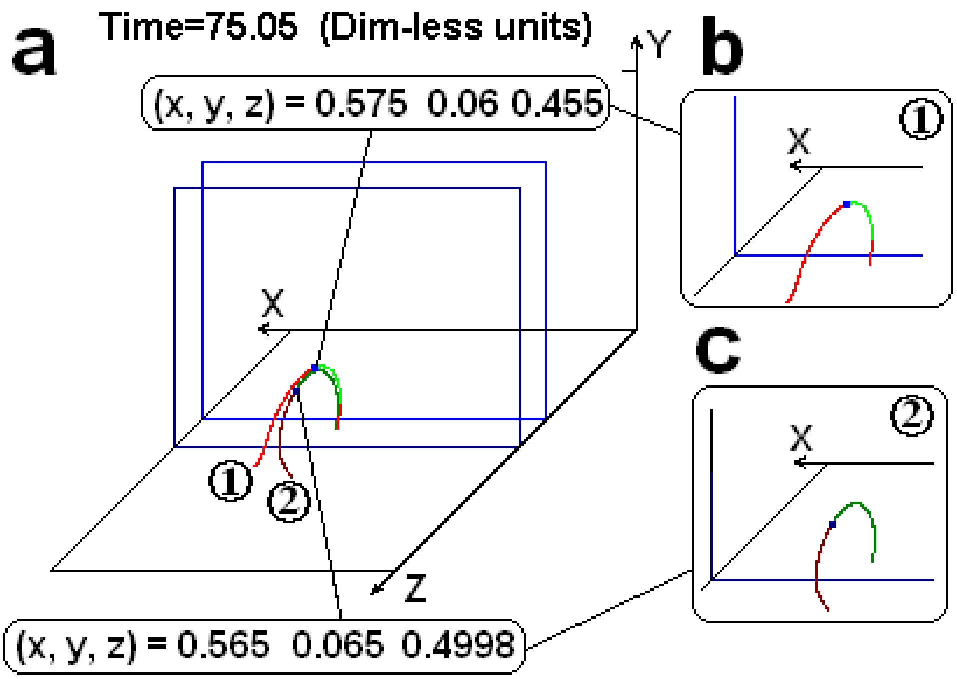

Рис. 3: Magnetic lines in the 3D space that pass through the positions of current density maxima.

behind it. To represent the lines better, they are drawn in the coordinate system with the inverted X axis, otherwise the far parts of lines would be hidden.

From Figure 3 one can imagine the behavior of the line of current density maxima inside the current sheet, which is close to magnetic lines 1 and 2. The line of current density maxima has a form of an arch with its top located at a height of ∼0.07 dimensionless units of length, which means $\sim 3 \times 10^9$ cm.

4 Conclusion

The new version of the Peresvet code has been developed. The first results of the simulation of an actual active region show the possibility of MHD simulation in real time scale using modern supercomputers. For solving this problem it is necessary to parallelize computations when using a supercomputer. Such simulation should permit us to search for locations of X-ray radiation sources and to compare these numerical results with observations.

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