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THE METHOD OF SEARCH FOR POSSIBLE SOLARE FLARE POSITIONS IN THE CORONA AND FIRST RESULTS OF REAL-TIME MHD SIMULATION OF PREFLARE SITUATION

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Abstract. To perform MHD simulation of preflare situation in a real active region it has not be done any assumptions about the solar flare mechanism. All conditions for simulation are taken from observations. In previous simulations magnetic field distributions on the photosphere sequentially better and better approximate the boundary conditions which must correspond to real observed magnetic field. But in such simulations the time scale of field changing is 4-5 orders smaller than in reality. The simulation in real time scale is needed to define better the flare position in space and to predict the moment of flare. Here the special numerical methods developed and realized in program PERESVET to accelerate MHD simulation are described. The first results of real time scale MHD simulation during several first minutes are presented. It is shown that near X-line the process of disturbances focusing begins which cause the current sheet creation. Using the methods developed earlier the position of future current sheet creation and distribution of parameters is found. The possibilities of real-time and near real-time MHD simulation of preflare situation on modern computers using the latest developed here mathematical methods are discussed.

Introduction

The electrodynamical model of the solar flare [1, 2] based on explosive energy release in the current sheet created in solar corona above the active region explains the primordial energy release in corona obtained by X-ray observations on the solar limb [3, 4], appearance two or more H_α ribbons and X-ray sources on the photosphere, and the absence of strong magnetic field changes on the photosphere during the flare. The current sheet is created by focusing of disturbances in the vicinity of the magnetic field X-type singular line in the corona. After quasi-stationary evolution the current sheet becomes unstable [5], and the instability causes the explosive energy release.

The alternative solar flare mechanism is connected with the magnetic rope appearance in the corona. Such mechanism meet difficulties in explanation of week field change on the photosphere during the flare because the rope must strongly pushed out of the sun by magnetic force, and its fast motion must cause strong field disturbance on the photosphere. Also it is not clear how the rope can appear in corona. The MHD simulations for rope flare mechanisms (for example [6]) assume the rope existence from the very beginning or the rope creates by strong twisting of arc footprints [7] that means strong magnetic disturbance on the photosphere which is not observed. All MHD simulations performed till now for a real active region do not show the rope appearance, but the current sheets appear during such simulations.

The MHD simulation for real active region means that it has not be done any assumptions about the solar flare mechanism during setting conditions for simulation. All conditions for simulation are taken from observations. Such simulations should be done to study the processes during the flare independent of flare mechanism should it be current sheet or rope or something else. The magnetic field distribution observed on the photosphere is used for setting of the boundary conditions. The simulation initiates several days before the flare when strong disturbances in the corona are absent, and the potential magnetic field calculated from observed field distribution on the photosphere is set as initial condition. The space step of the finite-difference scheme is several orders larger, than the thickness of a real current sheet, so the principle of limited simulation [8] is used.

In the first simplest such type simulations the observed magnetic field is approximated by field of several dipoles [9] or magnetic charges situated under the photosphere. The field of each dipole or charge approximates the field of spot. Typical observed magnetic field distributions on the photosphere (Fig. 1) show that the field of dipoles can be used only as a rough approximation. So in [10-12] observed field distributions are used directly for setting boundary conditions. Calculation showed that field configuration in corona is essentially defined by observed field distribution in the large area near the active region. So in [13-15] the simulations have been performed in the computation domain with the size 4 times larger than the active region size.

All previous MHD simulations have been fulfilled in strongly compressed time scale. The magnetic field on the photosphere has been changed in $10^4 - 10^5$ times faster than in reality. This can cause the unrealistic structures with strong current which mask the current sheets. Also coincidence of the real current sheet positions and obtained from simulations for such small time scale can be not very well because X-type singular line slowly moves during

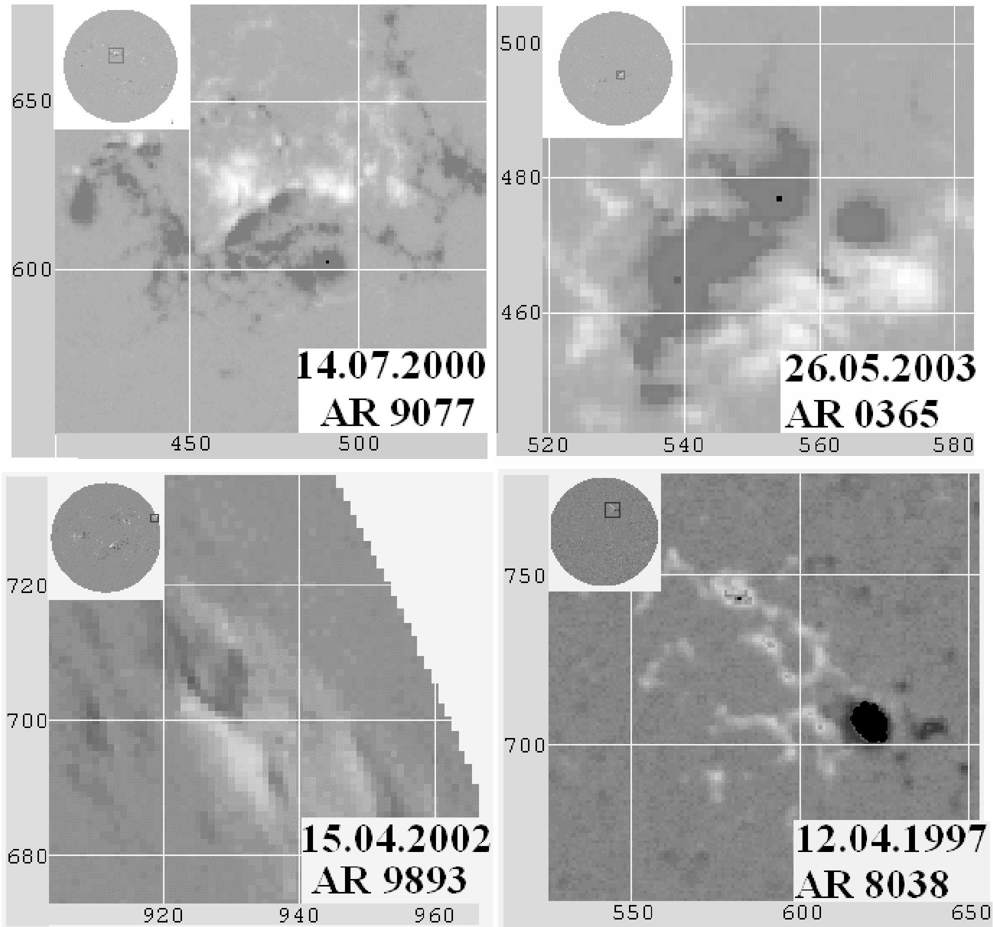

Fig1. Observed by SOHO MDI line-of-sight magnetic field component distributions on the photosphere for different active regions.

changing of the magnetic field configuration. This singular line motion is defined by two time scales. First of them is given by wave propagation with Alvenic velocity, and the second one is given by plasma motion with its velocity. To avoid inaccuracies of such simulations and to have possibility to define the moment of solar flare appearance from calculation, the simulation must be done in the real time scale or at least the time scale must be not so small (decreased in 10 – 100 times). For this purpose the mathematical methods are developed to have a stable numerical solution for large time step and such away to accelerate simulations.

The latest numerical methods realized in program PERESVET

The new numerical methods are added for finite-difference scheme construction for solving of the MHD equations system so that main previous effective methods are remained. As in previous work the absolutely implicit finite-difference scheme is used. All terms with space derivatives are taken on the next time step and such finite-difference equations are solved by iterations [16]. This scheme is conservative relative to magnetic flux. The implicit scheme provides such combination of parameters that the error of numerical solution does not grow strongly in time even if the Kourant condition ($\tau < h/(V_{MV}+V_{MA})$ is violated. Here τ is the time step, h is the space step, V_{MV} is the maximum of plasma velocity absolute value, and V_{MA} is the maximum of absolute values of velocities of all magnetosonic waves and alvenic wave propagation. In the conservative relative to magnetic flux scheme the magnetic fluxes through the boundaries of numerical greed cells averaged per unit of square are used instead of magnetic field vectors in each point of the greed. In the conservative relative to magnetic flux scheme the right part of equation for magnetic field $\frac{\partial \mathbf{B}}{\partial t} = \text{rot}(\mathbf{V}\times\mathbf{B}) - \text{rot}(\nu_m\ \text{rot}\mathbf{B})$ is approximated such a way that finite-difference analog of div**B** ([div**B**]) is equal to zero with high precision. Difference of |[div**B**]| from zero is defined by the error of iteration convergence and by the error of numbers representation in computer. Equality of [div**B**] to zero means equivalence of finite-difference analogs of -rot(rot**B**) and Δ**B** ([-rot(rot**B**)] = [Δ**B]**), due to which during the magnetic field relaxation [rot**B**] (calculated current density) tends to zero providing stabilization of slow growing instabilities.

In previous simulations [10-15] the dissipation term have been approximated as [-rot(rot**B**)] that provide high accuracy of [div**B**] conservation during transferee from the given time step to the next one. The scheme presented here and realized in program PERESVET contains the dissipation term in the form [Δ**B**]. In the two dimensional case the scheme for constant magnetic viscosity ν_m for B_x equation has a form:

$$\frac{\overset{(i_t+1)}{B^{j+1}_{x,i_x,i_y}} - B^{j}_{x,i_x,i_y}}{\tau} = \left[\mathrm{rot}(\mathbf{V}\times\mathbf{B})\right]_x + \\ +\nu_m\left(\frac{\overset{(i_t)}{B^{j+1}_{x,i_x,i_y-1}} - 2\overset{(i_t+1)}{B^{j+1}_{x,i_x,i_y}} + \overset{(i_t)}{B^{j+1}_{x,i_x,i_y+1}}}{h^2} + \frac{\overset{(i_t)}{B^{j+1}_{x,i_x-1,i_y}} - 2\overset{(i_t+1)}{B^{j+1}_{x,i_x,i_y}} + \overset{(i_t)}{B^{j+1}_{x,i_x+1,i_y}}}{h^2}\right) \quad (1)$$

Here τ is the time step, h is the space step, j is number of time step, i_x, i_y are the numbers of space steps in x- and y-directions, i_t is the iteration number. Scheme (1) can be easily generalized on 3D case and dependence of ν_m space coordinates for all B-components equations. In this scheme [div**B**] conservation is not fulfilled with high accuracy during transferee from a current space step to next one. But dissipation term works such away that ||[div**B**]|| decreases in time which is more important for scheme stability. Also in scheme (1) the convergence of iterations is better than in scheme with ([-rot(rot**B**)] as the dissipative term.

Definition the of initial potential magnetic field is modernized to minimize ||[div**B**]||. After solving of the Laplace equation for the field potential with tilted derivative as boundary condition (see [13-15]), it is done two corrections of field. The first of them is solving of diffusion equation for **B** $\frac{\partial \mathbf{B}}{\partial t} = \Delta\mathbf{B}$ with the scheme (1). The second one is inserting magnetic charges in the center of cells of the numerical greed with the value q=-[div**B**]$V_{cell}/4\pi$ (V_{cell} is the cell volume). As a result of using of this method the maximum of |div**B**| for the initial potential field becomes 0.25×10^{-7} in dimensionless coordinates, where as [13-15] it have been 0.45×10^{-3} in previous calculations.

The presented methods permit to accelerate simulations in ~ 30 times. But it is not enough for real-time simulation on the modern personal computer during one day of active region evolution by calculation during several days. Such calculation during several days can be performed only if the simulation time scale is in 100 times decreased comparing with real one. The calculations during several days in real time scale can simulate the active region evolution during ~ 15 minutes.

First results of real-time MHD simulation of preflare situation

Here we present first results of real time simulation of active region the AR 0365 during its first 3 minutes evolution. The sizes and position of the computational domain, dimensionless units and all other conditions except the time scale of photospheric magnetic field changing are the same as in [13-15]. MHD simulations are performed in the computational domain ($0\le x \le 1$, $0\le y\le 0.3$, $0\le z \le 1$, in dimensionless units). The unit of the length is chosen as $L_0=4\times10^{10}$ cm. The Y-axis is directed away from the Sun normally to the photosphere. The XZ (y=0) plane is the photospheric plane with X-axis in the East to West direction and with the Z-axis in the North to South direction. The unit of the magnetic field B_0=300 Gauss is taken. The dimensionless units of the plasma density and the temperature are taken to be equal to their values in the initial moment of time $\rho_0=10^8$ cm^{-3}, $T_0=10^6$ °K. The dimensionless unit of the plasma velocity is taken as correspondingly the Alfvenic velocity $V_0 = V_A = B_0/\sqrt{4\pi\rho_0} \approx 0.5\times10^{10}$ cm/s.

The magnetic field configuration and levels of current density distribution in time moment t=3 min in the central plane z=0.5 (Fig. 2a, b) show tendency to creation of a current sheet by disturbances focusing in the vicinity of X-type singular line. The X-point and the current density maximum positions do not coincide precisely. It means that singular line and the plane of future current sheet are not precisely perpendicular to the plane of figure z=0.5. According to the procedure described in [15] the singular line is found as magnetic line passing through the absolute value current density maximum point. In the plane perpendicular to the singular line (Fig 2c, d) the future current sheet is better pronounced. The field of velocities shows overlay of X-line motion as whole upward and rightward with disturbances focusing by plasma motion toward and outward X-line with different directions.

Discussion and conclusion

The firs results of real time simulation of active region after all numerical methods modernizations show that to calculate during several days of the active region evolution during one day it is necessary to have supercomputer using the system of parallel computations which calculates 100 times faster than modern personal computer (double core processor 1.6 GHz). To use simulations for improving the solar flare prognosis the simulated evolution must be faster than real active region evolution, so it should be used supercomputer 10^4 times faster than ordinary computer.

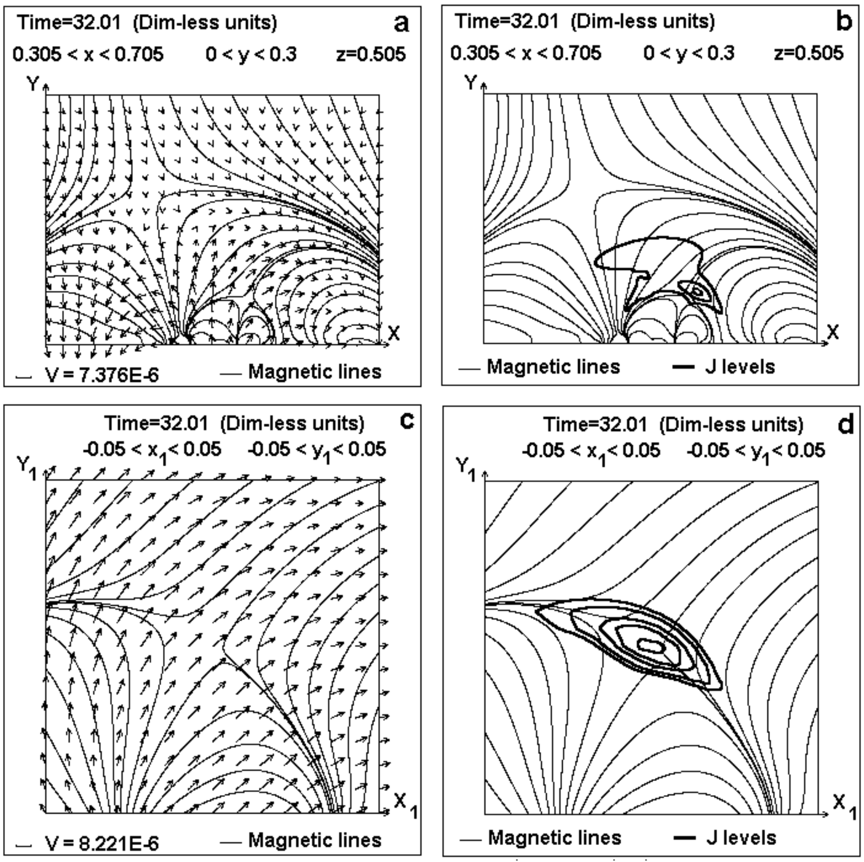

Fig 2. Results of real time MHD simulation for active region AR 0365 for time moment t=3 min. (a, b) – in central plane z=0.505; (c, d) – in the plane contained point of current density maximum (x, y, z) = (0.5628, 0.06, 0.505) and situated perpendicular to magnetic vector in this point **B** = (0.00103, 0.01658, -0.03915).

But it is possible that real processes near the current sheet and the time moment of flare can be derived from simulation with time scale in 10 or 100 times smaller than real time scale. In this case to understand situation it should be enough to use not so fast supercomputer or even the personal computer. Calculations performing with such time scale will show how real such a possibility.

The real time simulation shows the tendency to current sheet appearing in the vicinity of X-type singular line by disturbances focusing during first 3 minutes of active region evolution.

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