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MHD SIMULATION OF FLARE SITUATION ABOVE THE ACTIVE REGION AR 10365 IN THE REAL TIME SCALE

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Abstract. Since the configuration of the magnetic field in the corona, where solar flares appear, cannot be determined from observations, to study the flare situation, a numerical magnetohydrodynamic (MHD) simulation is carried out above the active region. MHD simulation performed in a greatly reduced (10 000 times) time scale permit to obtain results on the study of the solar flare mechanism, but the magnetic field configuration was distorted, especially near the photospheric boundary, due to the unnaturally rapid change in the field on the photosphere. For a more accurate study of the flare situation, MHD simulation in the real time scale was performed above the active region of AR 10365, which was made possible through the use of parallel calculations. The MHD simulation in the real scale of time above the AR 10365 during the first day of evolution showed the appearance of current density maxima with singular X-type line and plasma flow, which have to cause to the formation of a current sheet.

Introduction. Accumulation and of magnetic energy for solar flare and its fast release

The study of the physical processes occurring during the slow accumulation of magnetic energy, and then its explosive release during a solar flare, is an important fundamental problem that will help to solve a practical problem to improve the quality of solar flare prognosis. During a flare the energy of 10^{32} erg is released in a few tens of minutes. Since flares occur above active regions (ARs) with a large magnetic field (the value of the field in the active region on the solar surface reaches several thousand G), there is now no doubt that magnetic energy is released during flares. The primordial energy release from the flare occurs high in the solar atmosphere (in the lower corona) at altitudes of 15,000 km - 30,000 km. First of all, this has been proven by direct measurements of the thermal X-ray emission of flares on the limb [1]. Evidence of the appearance of a flare in the corona is also the invariability of the magnetic field on the solar surface [2], and change in plasma temperature in time at the site of the flare inferred from the observation of ultraviolet radiation in the lines of multiply ionized iron ions [3].

The main flare process high in the corona can be explained by the mechanism of S.I. Syrovatskii [4]: the accumulation of magnetic energy in the field of a current sheet, which is formed in the vicinity of a X-type singular line of magnetic field. As a result of quasi-stationary evolution, the current sheet transfers into an unstable state. Instability causes a flare release of energy with all the observed manifestations of a flare, which are explained by the electrodynamic model of a flare proposed by I.M. Podgorny [5]. The model was developed based on the results of observations and numerical MHD simulation and uses analogies with the electrodynamic substorm model proposed earlier by the author on the basis of Intercosmos-Bulgaria-1300 satellite data [6]. The hard X-ray beam radiation on the surface of the sun during a flare is explained by the deceleration in the lower dense layers of the solar atmosphere of electron fluxes accelerated in field aligned currents caused by the Hall electric field in the current sheet.

Since the configuration of the magnetic field in the corona cannot be obtained from observations, in order to study the physical mechanism of the flare, as well as improve the prognosis of flares, it is necessary to carry out magnetohydrodynamic (MHD) simulation in the corona above the active region (AR), in which all conditions are taken from observations. When performing MHD simulations, no assumptions about the flare mechanism were made at setting of the problem [7], the purpose of the simulation was to determine the mechanism of the solar flare. For setting the conditions, we used the magnetic field distribution observed in the photosphere. In order to speed up the calculation, a finite-difference scheme was specially developed, which had to remain stable for the largest possible time step [7, 8]. The scheme was realized in the PERESVET program. The scheme is upwind, absolutely implicit, and conservative with respect to the magnetic flux, it is solved by the iteration method. Despite the use of specially developed methods, it was possible to carry out MHD simulations in the corona on a usual computer only on a greatly reduced (by a factor of 104) time scale. At the same time, instability arose at the photospheric boundary, caused by an unnaturally rapid change in the magnetic field, however, thanks to the application of the developed methods, it did not propagate into the calculated region of the corona and did not increase to infinity. In order to get rid of this instability, as well as to obtain the correct development of processes in time, it is necessary to carry out MHD simulations in real scale of time. In view of the impossibility of MHD simulation in the real scale of time on the usual computer in the foreseeable time [9], it is necessary to carry out parallel computations.

Choice of the numerical method for solving MHD equations and optimization of the parallelization algorithm

To increase the computation speed when carrying out parallel computations, the choice of the numerical method should be such as to maximize the time step at which the difference scheme remains stable and the number of iterations at each time step was minimal. In our case, the choice of the numerical method means the choice of the type of the difference scheme within a given type of schemes, which are absolutely implicit and conservative with respect to the magnetic flux, and the choice of the parameters of the difference scheme, first of all, the usual and magnetic artificial viscosity, which is used mainly near the boundary (where difficulties always arise with the correct setting of all boundary conditions). In addition, the parallelization algorithm has been optimized for these purposes. Also, to increase the computation speed, the computation time of one iteration was reduced [9] due to the correct choice of computing equipment and software and the use of the capabilities of the selected equipment for parallelizing the computation.

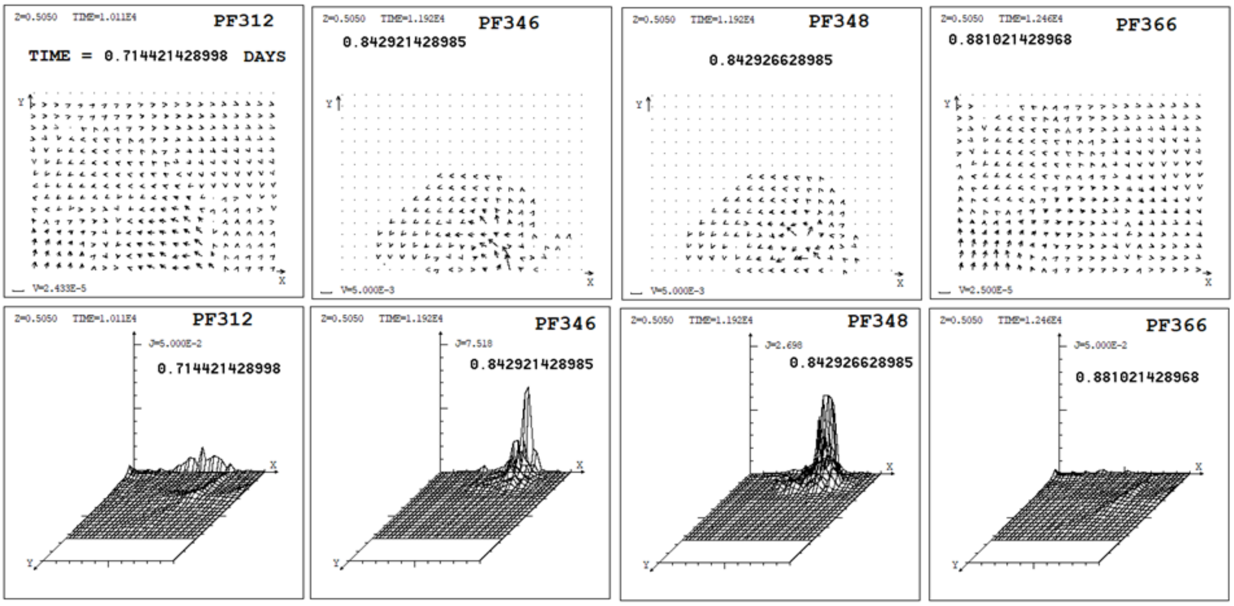

Figure 1. The appearance and disappearance of instability near the photospheric boundary.

For implicit finite-difference scheme time step τ in principle can be larger than the time from Courant condition τ_K: $\tau < h/(V_{MV}+V_{MA})$. Here h is space step, V_{MV} is the maximal of absolute value of velocity and V_{MA} is the maximum of absolute values of magnetosonic and Alven velocities.

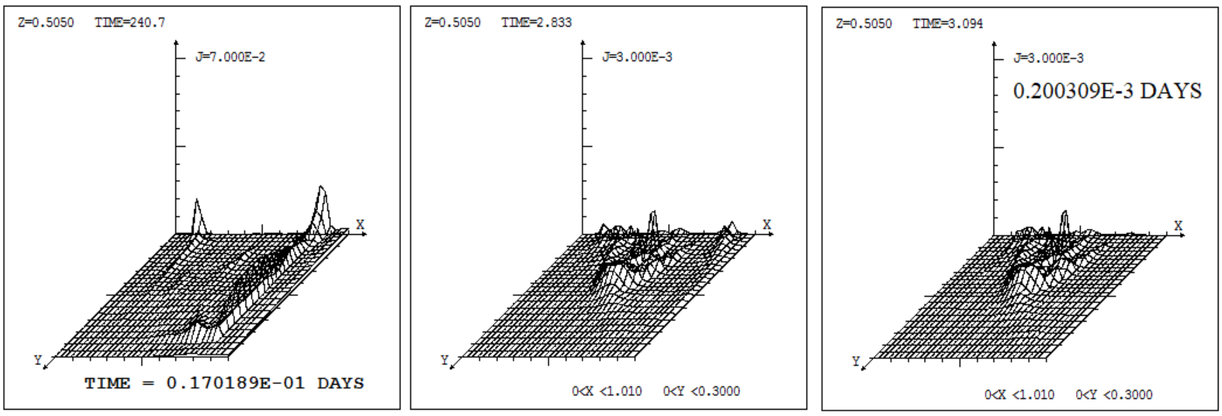

Figure 2. Current density in the central plane of computational domain. Propagation, initialization and stabilizing instability on the non-photospheric boundary.

Calculations showed, that time for proposed difference scheme step τ must be less then τ_K, in spite of that the absolute implicit scheme is used. Apparently, it is due to that the system of equations with cross-terms. Also it can be due to solving of implicit scheme by the iteration method, and the first iteration is in fact the solution of explicit scheme. To solve the proposed implicit difference scheme without using the iteration method, the alternating direction method should be applied. However, with a sufficiently large acceleration by the magnetic tension force (which appears at the place of plasma outflow from the current sheet), the use of the alternating direction method leads to numerical instabilities even for the Courant time step.

It is difficult to choose the most optimal parameters during the calculation, because there are several parameters and the step τ_K changes during the calculation. Calculations have shown that the currently used set of parameters is quite optimal:

- Time step $\tau = 0.4\times10^{-7}$ days (Courant step τ_K varies from 0.45×10^{-7} to 0.79×10^{-7} in the process of calculation, and depending on the details of the rules for its determination near the boundary).
- Artificial viscosity (usual and magnetic) $\nu = 3\times10^{-3}$.
- Precision of solution of implicit scheme $\varepsilon = 10^{-7}$, at which 3 iterations are performed. In this case, in order to avoid instability, from time to time it is necessary to set for a short interval (~ 100 time steps) $\varepsilon = 10^{-10}$, for which ~ 60 iterations will be performed.

In order to optimize of the parallelization algorithm minimization of transfers of arrays of distributions of all values in the computational domain and auxiliary arrays, between the memory on the graphics card (arrays with the DEVICE attribute) and the main computer memory was performed. After all the upgrades, during the entire numerical solution of the MHD equations, there is no transfer between the memory of the graphic card and the main memory of the computer (such transfer cannot be avoided only when the calculation results are written to a file, it can be carried out only from the main memory, and occurs every several thousand steps, so it almost does not take calculation time).

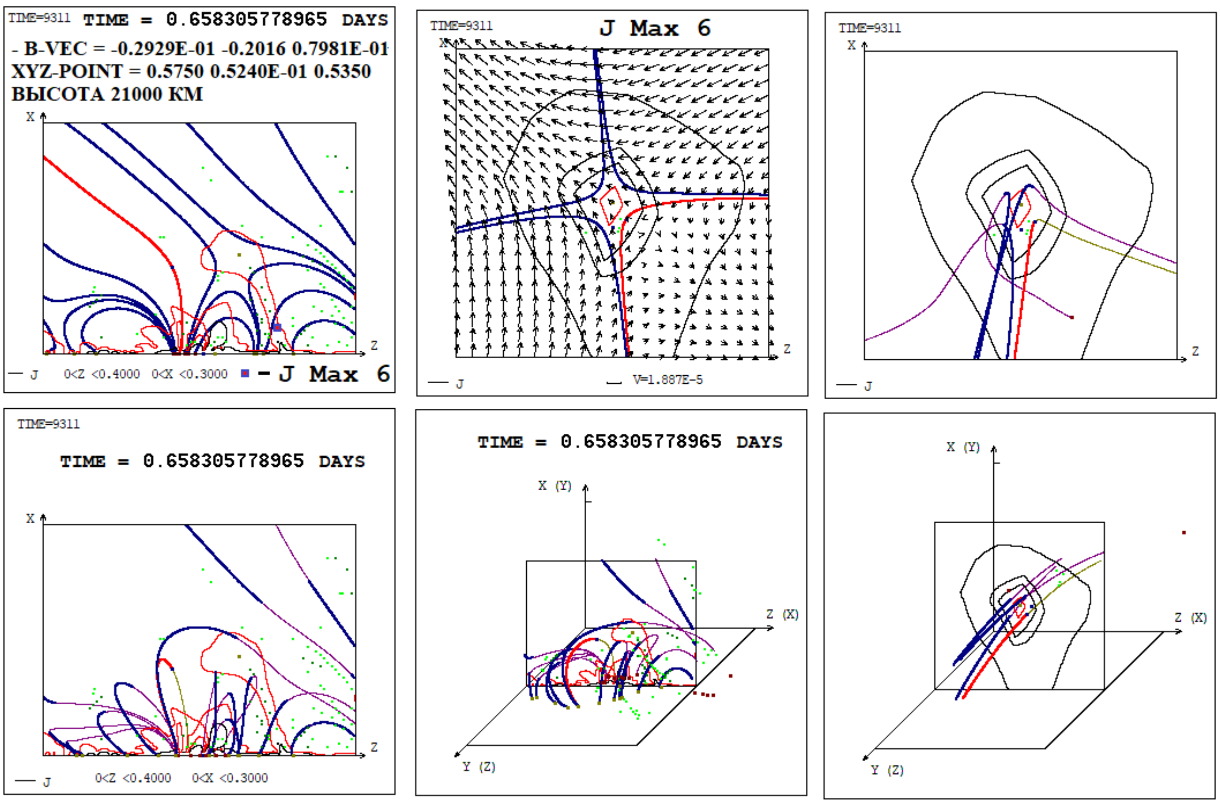

Figure 3. Magnetic configuration in main part of computational domain of corona in 3D space and in the central plane. Local current density maximums, which are the candidates on the places of flares are shown as the green points. Magnetic field configuration and plasma flow near the 6-th maximum of current density.

As a result of choosing the numerical method for solving MHD equations and optimization of the parallelization algorithm and also due to the correct choice of computing equipment and software [9] and the use of the capabilities of the selected equipment for parallelizing the calculation, now we can get the time for calculation the evolution during the day above the AR, equal to 21 days. Under less favorable conditions it can be increased by 7% - 10%. For the prognosis, this time should be less than a day, it is necessary to work on further optimization, the reserves are existing.

If the conditions on difference scheme parameters are not fulfilled (first of all, if the time step is too large), a numerical instability arises near the photospheric boundary, as a result of which an unnaturally large disturbance propagates into the corona (Fig. 1). However, if, after the onset of instability, we return to the selected parameters of the difference scheme, then the instability stabilizes and the strong disturbance in the corona caused by the instability will disappear. This indicates the quality of the proposed difference scheme.

Stabilization of the instability arising at the non-photospheric boundary

Calculations in the real scale of time have shown appearance of sufficiently strong disturbances caused by instabilities at the non-photospheric boundary. Such instabilities (Fig. 2) can lead to a halt in the calculation due to a strong increase in the values or to an obviously incorrect solution due to the appearance of strong nonphysical perturbations.

This problem was solved by using the following methods:

1. Limiting the velocity of plasma inflow into the computational domain.
2. Application of artificial viscosity (usual and magnetic) near the non-photospheric boundary.
3. The invariability of the magnetic field at the edges of the boundary of the computational domain, relative to the potential field used to set the boundary conditions.

Formation of singular X-type lines with the plasma flow, contributing to the accumulation of flare energy

During the first one day of evolution of magnetic field and plasma, described by the results of MHD simulation in the real scale of time, from time to time the current density maximums appear with X-type configuration and plasma flow as for 6-th maximum at the moment 0.658 days presented in Fig. 3. The plasma flow near such maximums in principle can cause to the current sheet creation. Some of such configurations later disappear, possible, the microflares occur in such configurations.

Conclusion

1. Primordial energy release during the solar flare takes place high in corona. To study physical mechanism of flare it is necessary to carry out MHD simulation above AR in the real scale of time.

2. Parallelization of the calculation for solving a specially developed finite-difference scheme of MHD equations is carried out. The optimal parameters of the difference scheme were selected for calculations in the real scale of time.

3. The methods have been developed to stabilize the numerical instability arising at the non-photospheric boundary.

4. When the selected parameters of the difference scheme change (first of all, an increase in the time step), numerical instability can appear at the photospheric boundary, causing to the propagation of a strong nonphysical disturbance into the computational domain of the corona. When returning to the selected optimal parameters of the difference scheme without performing a new calculation from an earlier time instant before the onset of instability, the instability stabilizes, and the disturbance propagating from it into the corona disappears, which confirms the quality of the developed difference scheme.

5. The optimization of the parallelization algorithm has been carried out, first of all, the data exchange (values in the computational domain of the corona) between the main memory of the computer and the memory of the graphics card on which the computation is parallelized is minimized. As a result of the optimization performed, the calculation speed increased 7.5 times.

6. The calculation of the evolution of the plasma and the field in the corona above AR 10365 at the initial stage did not show the appearance of pronounced current sheets even with sufficiently strong disturbances on the photosphere (exceeding the real disturbances that appeared due to numerical instabilities in the process of choosing the optimal parameters of the difference scheme). At several current density maxima, an X-type configuration was found, with a plasma flow, which should cause to the formation of a current sheet; however, in the course of further evolution, such configurations disappeared (possibly, microflares appeared).

7. As a result of the work carried out, the possibility of further optimization of the methods was revealed in order to further increase the calculation speed, which will be necessary when using MHD simulation to improve the flares prognosis.

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