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TYPES OF MAGNETIC FIELD CONFIGURATIONS IN WHICH ENERGY ACCUMULATION FOR FLARES IS POSSIBLE ACCORDING TO THE RESULTS OF MHD SIMULATION ABOVE THE ACTIVE REGION IN THE REAL SCALE OF TIME

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Abstract
To study the mechanism of a solar flare, it is necessary to perform MHD simulations in the corona above a real active region, in which all conditions are taken from observations and the calculation begins several days before the appearance of flares, when the energy for the flare has not yet accumulated in the corona. When setting the problem, no assumptions about the mechanism of the solar flare are made. The MHD simulation continued in this paper confirmed the solar flare mechanism based on the release of energy accumulated in the magnetic field of the current sheet. The fast release of the magnetic energy of the current sheet leads to the observed manifestations of the flare, which are explained by the electrodynamic model of the flare proposed by I. M. Podgorny. In addition to those found in the previous work, the configurations of the magnetic field near singular lines, in which the current sheet is created, are obtained and studied.

Introduction
The mechanism of a solar flare [1], according to which during a flare there is a release of energy accumulated in the magnetic field of the current sheet, explains the primordial release of flare energy in the solar corona above the active region, which follows both directly from the observations [2] and from numerous considerations derived from the analysis of observational data. The current sheet, which is formed as a result of the accumulation of plasma disturbances near the singular line of the magnetic field, transferes into an unstable state in the process of slow evolution (see, for example, [3]). The instability causes a flare release of energy, accompanied by observational manifestations of a flare, which are explained by the electrodynamic model of a solar flare proposed by I.M. Podgorny [4].

The study of the physical mechanism of solar flares is carried out by magnetohydrodynamic (MHD) simulation of a flare situation in the corona above a real active region [3]. To solve this rather complex problem, special methods are being developed without which it is impossible to perform MHD simulation under the set conditions [5]. MHD simulation above a real active region and the development of mathematical methods necessary for its implementation are continued in this work.

Conditions and goals of MHD simulation
When setting the conditions for MHD simulation above a real active region, no assumptions were made about the mechanism of a solar flare. All conditions were taken from the observations. The solar flare mechanism must be determined from the results of such simulations. MHD simulation should make it possible in each particular case to understand how the processes occurring in the current sheet arose and to determine the configuration of electric and magnetic fields at the flare site. Such information should be needed in the future to improve the prediction of solar flares based on understanding their physical mechanism and studying the mechanism of acceleration of solar cosmic rays (SCR) by the electric field of the current sheet by calculating the trajectories of protons in the fields obtained by MHD simulation. This problem was solved in [4] for fields obtained by MHD simulation under simplified conditions. The solution of this problem should be continued under real conditions, its solution should allow predicting the appearance of SCRs during a flare.

In addition to us, several groups in foreign countries are engaged in the study of processes in the solar corona by means of numerical MHD simulation (see, for example, [6-11]). Experience has shown that the mechanism of a solar flare can be correctly studied only if the calculation begins several days before the appearance of solar flares, when energy for the flare has not yet been accumulated in the corona. At present, MHD simulation in this setting of the problem is carried out only by us.

Setting of the problem and developed methods for numerical solution

MHD simulation is carried out over the active region of AR 10365. The computational domain in the corona is a rectangular parallelepiped ($0 \le x \le 1$, $0 \le y \le 0.3$, $0 \le z \le 1$) (the size $L_0 = 4 \times 10^{10}$ is chosen as the unit of length). The lower boundary of the computational domain $y=0$ (XZ) is located on the surface of the Sun (photosphere) and contains the active region, the Y axis is directed from the Sun perpendicular to the photosphere. The three-dimensional system of MHD equations for a compressible plasma, taking into account dissipative terms and anisotropic thermal conductivity, is solved numerically in a dimensionless form:

$$\frac{\partial \mathbf{B}}{\partial t} = \mathrm{rot}(\mathbf{V} \times \mathbf{B}) - \frac{1}{\mathrm{Re}_m} \mathrm{rot}\left(\frac{\sigma_0}{\sigma} \mathrm{rot}\mathbf{B}\right) + \mathrm{rot}\left(\nu_{m\_\mathrm{Art}}\, \mathrm{rot}\mathbf{B}\right) \quad (1)$$

$$\frac{\partial \rho}{\partial t} = -\mathrm{div}(\mathbf{V}\rho) \quad (2)$$

$$\frac{\partial \mathbf{V}}{\partial t} = -(\mathbf{V},\nabla)\mathbf{V} - \frac{\beta}{2\rho}\nabla(\rho T) - \frac{1}{\rho}(\mathbf{B} \times \mathrm{rot}\mathbf{B}) + \frac{1}{\mathrm{Re}\rho}\Delta\mathbf{V} + G_g\mathbf{G} + \nu_{\mathrm{Art}}\Delta\mathbf{V} \quad (3)$$

$$\frac{\partial T}{\partial t} = -(\mathbf{V},\nabla)T - (\gamma-1)T\mathrm{div}\mathbf{V} + (\gamma-1)\frac{2\sigma_0}{\mathrm{Re}_m \sigma \beta_0 \rho}(\mathrm{rot}\mathbf{B})^2 - (\gamma-1)G_q \rho L'(T) +$$

$$+\frac{\gamma-1}{\rho}\mathrm{div}\left(\mathbf{e}_{\|}\kappa_{dl}(\mathbf{e}_{\|},\nabla T) + \mathbf{e}_{\perp 1}\kappa_{\perp dl}(\mathbf{e}_{\perp 1},\nabla T) + \mathbf{e}_{\perp 2}\kappa_{\perp dl}(\mathbf{e}_{\perp 2},\nabla T)\right) \quad (4)$$

To select the parameters, the principle of limited simulation was used [12], according to which, the dimensionless parameters which are much larger and much smaller then unit are set in calculations to be much larger and much smaller unit without accurately preserving their values.

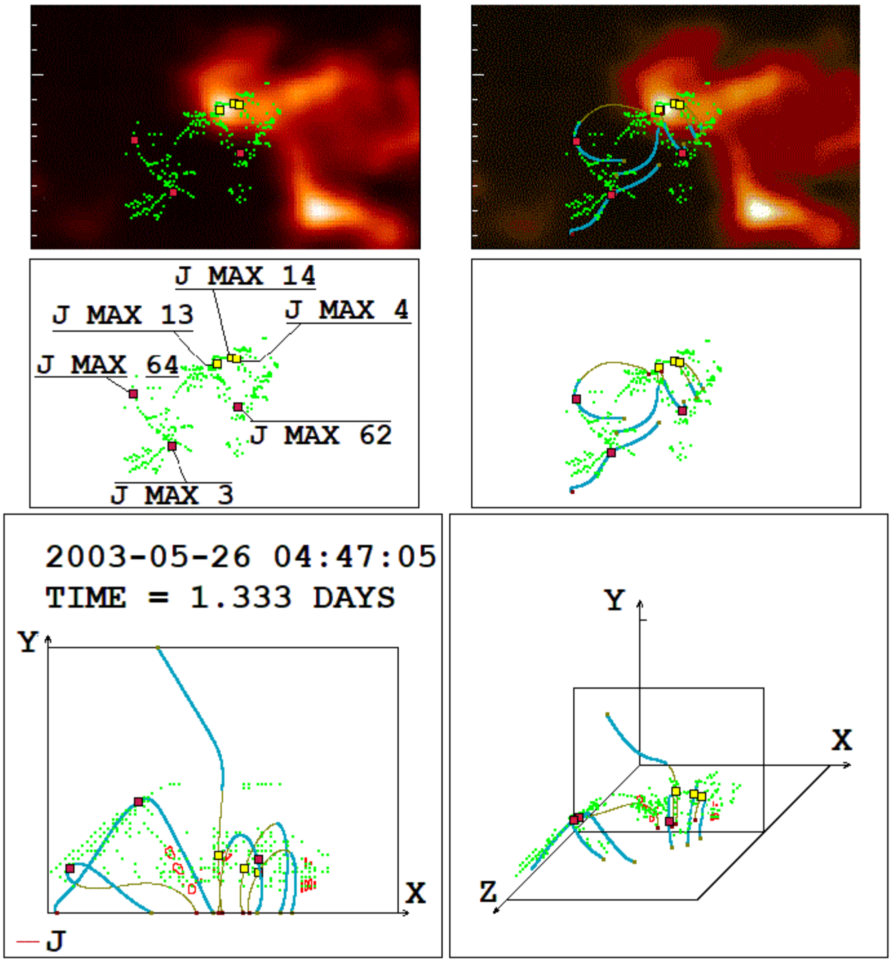

Figure 1. Comparison of the results of MHD simulation with the intensity distribution of radio emission at a frequency of 17 GHz obtained with the Nobeyama Radioheliograph (NoRH). The configuration of the magnetic field is represented by magnetic lines in the computational domain, passing through the selected current density maxima. The projections of these lines onto the central plane of the computational domain (z=0.5) and onto the picture plane perpendicular to the line of sight are presented.

The main parameters are the magnetic and ordinary Reynolds numbers, which are inverse to the dimensionless values of viscosities ($Re_m = \nu_{m\_dl}^{-1}$, $Re = \nu_{dl}^{-1}$). Dimensionless values of artificial viscosities ($\nu_{m\_Art\_Ph}$ and ν_{Art_Ph}) were set mainly near the boundary of the region to stabilize the numerical instabilities.

For the numerical solution, an upwind absolutely implicit finite-difference scheme, conservative relative to the magnetic flux, was developed [13, 14]. The scheme is solved by the method of iterations. The use of special methods was aimed at constructing a scheme that remains stable for the maximal possible time step. Despite the use of special methods that made it possible to significantly speed up the calculation, the numerical solution took a long time, so simulation in the real scale of time is possible only with the help of parallel calculations, which were carried out by parallel computational threads on graphics cards using CUDA technology [15, 16]. After a series of upgrades to the parallel computing algorithm, mainly related to minimizing data exchange between the graphics card memory (GPU) and the central processing unit (CPU) memory, it was possible to increase the calculation speed by 120 times through the use of parallel computing.

The main problem of MHD simulation above a real active region is the numerical instabilities that arise near the boundary of the computational region. The instability stabilization methods developed in [5] are improved in this paper. The methods are based on the use of artificial viscosity and a special selection of values at the boundary; they made it possible to partially solve the problem, which made it possible to carry out simulations for low viscosities ($Re_m = 10^9$, $Re = 10^7$), at which the perturbation propagating from the photosphere is not suppressed and, therefore, a sufficiently large energy can be accumulate in the corona for a flare. Thanks to the use of the developed methods, it was possible to conduct MHD simulations for low viscosities during a period of almost three days. On the basis of the results obtained, ways were found for further improvement of methods for stabilizing numerical instabilities that arise near the boundary of the region.

Results of MHD simulations and their comparison with microwave observations of preflare plasma

The configuration of the magnetic field obtained by MHD simulation is so complex that it is often impossible to determine the positions of special lines and the current sheets appearing near them from it. For this purpose, a graphical search system [17, 18] was developed, based on determining the positions of the current density maxima that are reached at the centers of the current sheets.

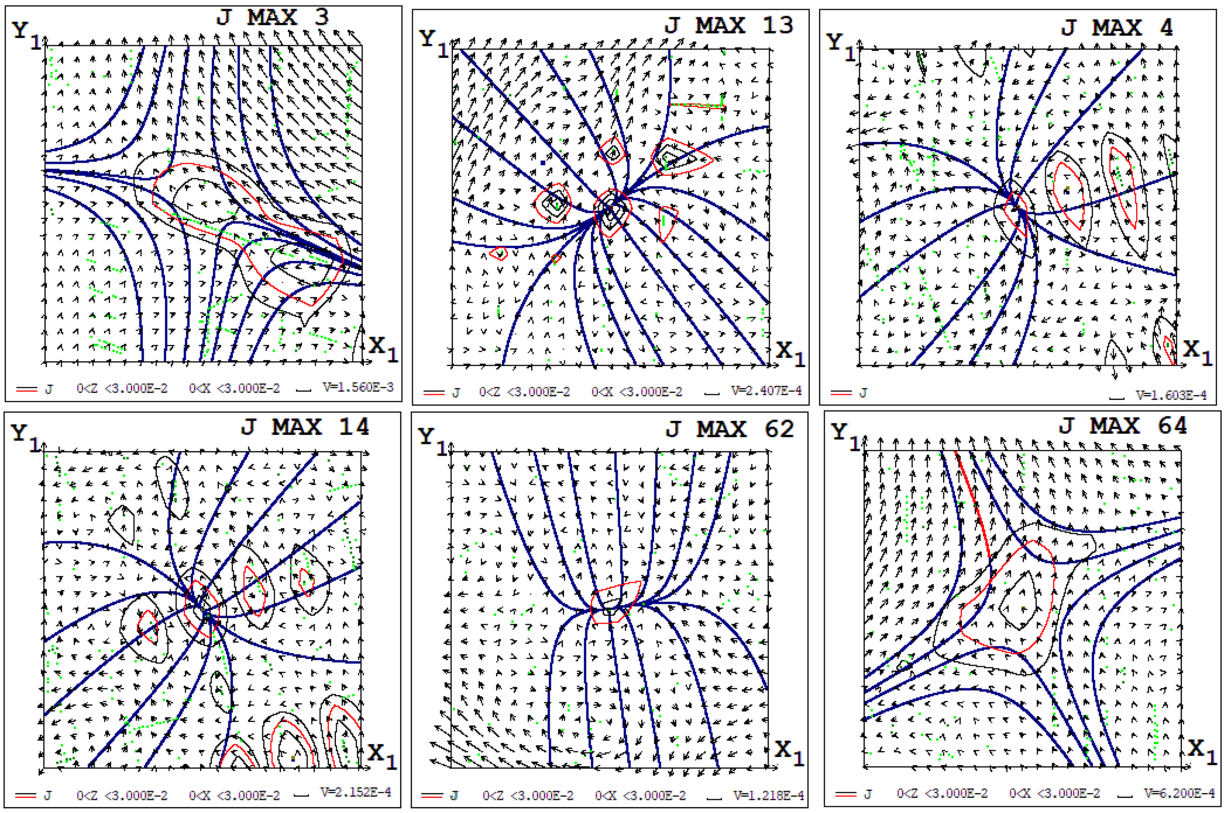

Figure 2. Magnetic field configurations in the vicinity of the 3rd, 4th, 13th, 14th, 62nd and 64th current density maxima in the plane perpendicular to the singular line. Velocity fields and current density level lines are also shown.

Figure 1 compares the results of MHD simulations with observations of radio emission at a frequency of 17 GHz obtained with the Nobeyama radio heliograph (NoRH) one hour before the class M 1.9 flare in AR 10365, when the energy for the flare is accumulated in the magnetic field of the current sheets, which are formed near singular lines, and preflare heating of the plasma by the emerging currents occurs. This comparison complements comparisons with observations during flares [5]. The 3rd, 4th, 13th, 14th, 62nd, and 64th current density maxima are highlighted, the remaining maxima are marked by green dots (the maxima are numbered in descending order of the current density in them).

Figure 1 indicates the coincidence with some accuracy of the positions of microwave emission sources with the positions of singular lines. Several tens of current density maxima, in which current sheets are formed, are located in the region of high intensity microwave emission or are close to it, which confirms the flare mechanism based on the release of energy accumulated in the magnetic field of the current sheet. The accuracy of agreement between the simulation results and observations cannot be called very high, since a significant number of current density maxima are located at a rather large distance (~10 Mm) from the region of power radio emission. Possibly, this inaccuracy is related to the error of the method caused by a rather rough spatial grid step of the difference scheme (2 Mm), which is exacerbated by the appearing numerical instability. In the future, it is necessary to try to improve the accuracy of the calculation by both improving mathematical methods and, if such an opportunity presents itself, as a result of using more powerful supercomputers, which permit to reduce the spatial step.

The configurations shown in Figure 2 near the singular lines, on which the selected current density maxima are located, confirm the earlier conclusion ([5]), according to which the configuration in the vicinity of the singular line in the general case is a superposition of an X-type configuration and a diverging magnetic field. Even if the divergent magnetic field dominates, so that a deformed diverging field is obtained as a result of the superposition, due to the presence of an X-type field in the superposition, the disturbances are accumulated to form a current sheet, the plasma is heated by the generated current, so that, as the simulation results show, the corresponding current density maximum is in the region of strong microwave emission. This result indicates the possibility of the formation in the vicinity of a singular line with a dominant superimposed diverging magnetic field of a current sheet, which can cause a sufficiently powerful solar flare.

Conclusion

1. The use of improved methods made it possible to partially solve the problem of stabilizing numerical instabilities that arise near the boundary of the computational domain and to carry out MHD simulations for low viscosities during a period of almost three days. The results obtained showed the ways of further improvement of the instability stabilization technique.
2. The study of the magnetic field configuration in the preflare state confirmed the existence of a large number of singular lines, near which a divergent magnetic field is superimposed on the X-type magnetic field configuration. In this case, even if the divergent magnetic field dominates, due to the presence of an X-type field in the vicinity of the singular line, a current sheet can arise, which will cause a sufficiently powerful flare.
3. The location of a large number of current density maxima, near which current sheets are formed, in the region of strong microwave radiation confirms the flare mechanism based on the release of energy accumulated in the magnetic field of the current sheet.

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