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Problems Arising in Studying the Mechanism of a Solar Flare by the Way of Comparing the Results of MHD Simulations Above the Real Active Region with Observations

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1. Abstract.
The primordial release of solar flare energy in the solar corona above the active region can be explained by the mechanism according to which flare energy is accumulated in magnetic field of the current sheet. MHD simulation above the real active region is continued to study the mechanism of a solar flare. For this purpose, the calculation should start a few days before the flare, when the flare energy has not yet accumulated in the corona. A general agreement between the flare positions found from the results of MHD simulations and observations is shown. However, a detailed comparison raises problems. Comparison of the MHD simulation results with observations showed the need to modernize the MHD simulation methodoы and ways of its implementation.

Keywords: Solar flare; current sheet; magnetohydrodynamic simulation.

2. Introduction

Numerous observations ([Lin et al., 2003] and others) indicate that the primordial release of solar flare energy occurs in the solar corona at an altitude of 15,000–70,000 km. It becomes necessary to explain the slow accumulation of magnetic energy, so that it can be able to release fast. These processes are explained by the solar flare model, according to which the flare energy is accumulated in the magnetic field of the current sheet formed in the vicinity of the singular line [Syrovatskii 1966]. Further, in the process of quasi-stationary evolution the current sheet transfers into an unstable state [Podgorny and Podgorny 2012]. The instability in the current sheet causes a flare release of energy with all the observed manifestations, which are explained by the electrodynamic model of the flare proposed by I.M. Podgorny in [Podgorny et al., 2010]. The model was developed based on the results of observations and numerical magnetohydrodynamics (MHD) simulations and uses analogies with the substorm electrodynamic model proposed earlier by its author [Podgorny et al., 1988].
Since the configuration of the magnetic field of the corona cannot be found from observations, to study the mechanism of a solar flare, it is necessary to carry out MHD simulations above a real active region, in which the conditions for the magnetic field on the solar surface are taken from observations.

3. Setting of problem and MHD simulation methods

The system of MHD equations in a dimensionless form was numerically solved for the region of the solar corona above active region 10365, which has the shape of a rectangular parallelepiped ($0<x<1$, $0<y<0.3$, $0<z<1$), the lower side of which XZ ($y=0$) is located on the solar surface contains the active region. The y-axis is directed from the Sun perpendicular to the photosphere. The x-axis is directed from East to West, and the z-axis from North to South. The units of length, magnetic field, plasma density and temperature are chosen to be their typical values $L_0=4\times10^{10}$ cm, $B_0 = 300$ G, $n_0=\rho_0/m_i=10^8$ cm^{-3} and $T_0=1\text{MK}=10^{6\text{o}}$K. The unit of plasma velocity is the Alfvén velocity $V_0 = V_A = B_0/\sqrt{4\pi\rho_0}$ = 0.65×10^{10} cm/s.

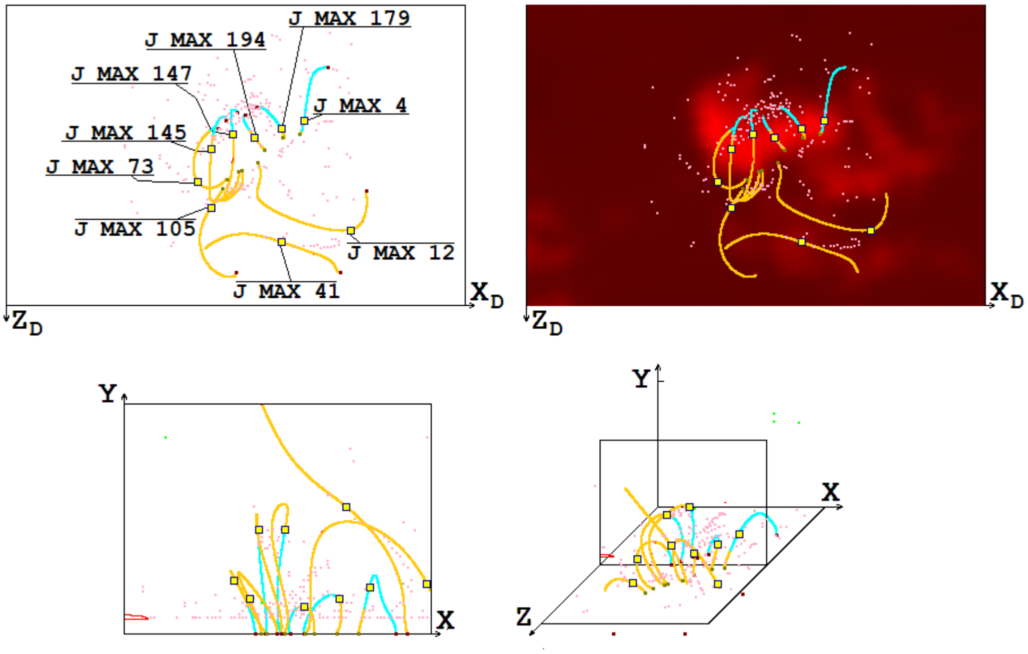

Figure 1. Comparison of the magnetic field configuration and the positions of the current density maxima with the distribution of radio emission intensity at a frequency of 17 GHz on 26 May 2003 at 02:32:05, three hours before the M1.9 flare for simulation with high viscosities (Re_m= 3×10^4, Re= 10^4). The positions of the current density maxima are shown as green points. The magnetic field configuration is presented by magnetic lines which pass through selected current density maxima (J MAX) with the numbers 4, 12, 41, 73, 105, 145, 147, 179 and 194. Three-dimensional magnetic lines in the computation domain and their projections on the picture plain and on the central plane of the computation domain (z = 0.5) The magnetic lines in front of the central plane are shown as bold light brown lines and behind the central plane of the computational domain as light blue lines.

To select dimensionless parameters the principle of limited simulation [*I.M. Podgorny 1978*] was used, according to which much larger or much smaller unit, dimensionless parameters remain much larger or smaller than unit when simulated without their exact preservation. The main parameters characterizing the influence of ordinary and magnetic viscosity are the Reynolds numbers Re and Re_m, which are the inverse values of dimensionless viscosities ($Re_m=V_0L_0/\nu_{m0}$, $\nu_{m0}=c^2/4\pi\sigma_0$; $Re = \rho_0 L_0 V_0/\eta$,). Large viscosities (Re_m= 3×10^4, Re= 10^4) stabilize numerical instabilities well, and at low viscosities (Re_m= 10^9, Re= 10^7) disturbances propagating from the solar corona are practically not suppressed, which makes it possible to accumulate sufficient magnetic energy for a solar flare in the corona.

For the numerical solution, an upwind, absolutely implicit finite-difference scheme was developed which is conservative with respect to the magnetic flux [*Podgorny and Podgorny 2004*]. The methods were applied with the aim of constructing a scheme that remains stable for the maximum possible time step. The scheme was realized in the computer program PERESVET. The simulations were carried out by means of parallel computing threads on graphics cards using CUDA technology. For low magnetic viscosities numerical instabilities arise near the boundary of the computational domain, for the stabilization of which methods have been developed.

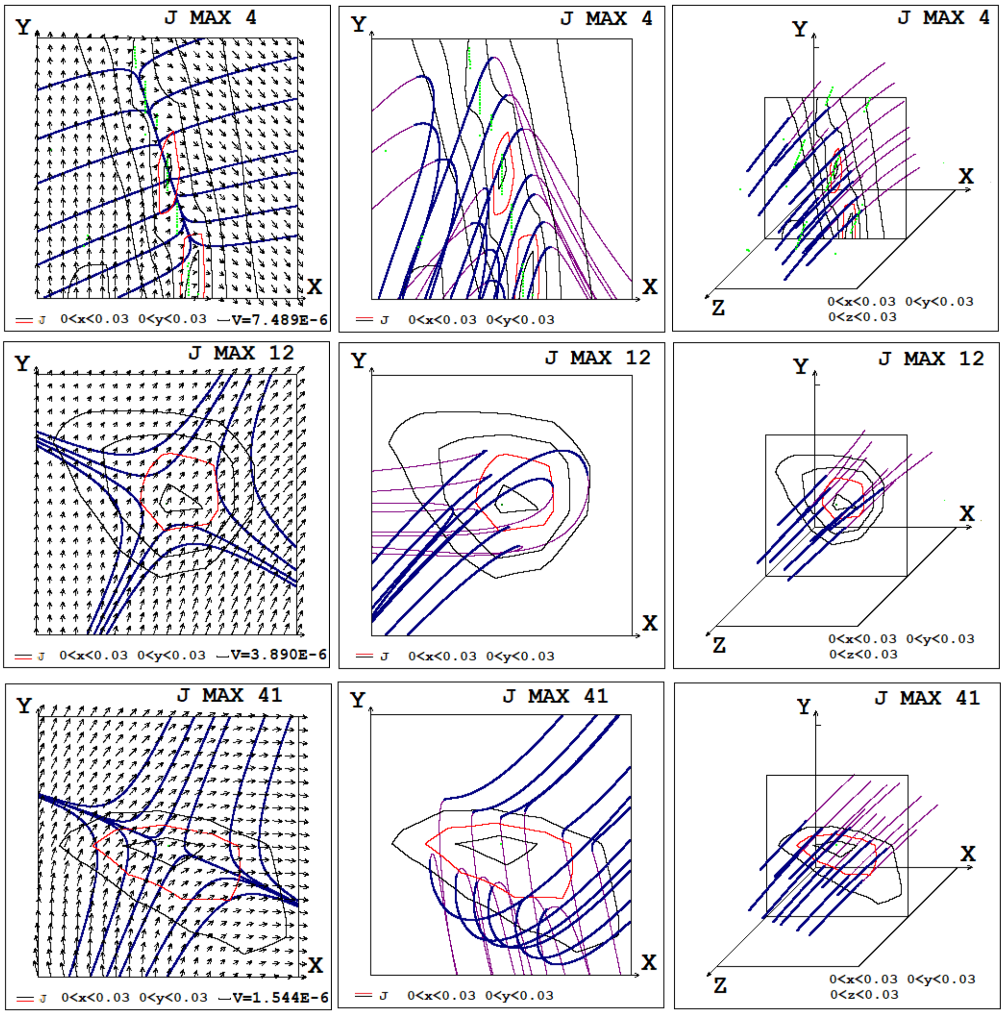

Figure 2. The configurations of the magnetic field and plasma flow near the selected 4th, 12th and 41th current density maxima on 26 May 2003 at 02:32:05 for simulation with high viscosities ($Re_m= 3\times10^4$, $Re= 10^4$). The configurations are shown by plane magnetic lines which are tangential to projections of magnetic vectors on the plane of the current sheet configuration (this plane is perpendicular to the singular line on which the current density maximum is situated; in this plane, the configuration of the current sheet is most distinctly pronounced), by projections of magnetic lines on the plane of configuration and by 3-dimensional magnetic lines.

The configuration of the magnetic field obtained by MHD simulation is so complex that it is impossible to determine the positions of singular lines and the current sheets appearing near them from it. For this purpose, a graphical search system of flare positions has been developed [*Podgorny and Podgorny 2013*]. The system is based on the search for current density maxima, which are reached in the middle of the current sheets. The current density maxima are located on the singular lines of the magnetic field.

4. Results: comparing of flare positions obtained from results of MHD simulation for different viscosities with observations

The Figures (1-3) present the results of MHD simulations for high magnetic and ordinary viscosities (Re_m= 3×10^4, Re= 10^4) and for low viscosities (Re_m= 10^9, Re= 10^7), as well as a comparison of these results with observations of radio emission at frequency of 17 GHz obtained with the Nobeyama Radioheliograph (https://solar.nro.nao.ac.jp/norh/index.html). The results are presented for 02:32:05 on May 26, 2003, three hours before the M1.9 flare, when the magnetic field energy for the flare was accumulating in the corona. The currents, which that stores magnetic energy for the flare, heat up the corona, which cause radiation.

There are differences in the location of the current density maxima for calculations with high and low viscosities (Figures 1, 3). At the same time, for both variants, a sufficiently large number of maxima are located in the bright region of strong preflare radiation, which confirms the flare mechanism based on the accumulation of energy in the magnetic field of the current sheet. For low viscosities, a smaller part of the maxima is located in the bright region, and the total number of maxima is several times greater than in the calculation for high viscosities. This behavior of the current density maxima in calculations for two sets of parameters is apparently largely due to the appearance of a numerical instability, the stabilization of which is a significant problem if the viscosity is low. The current density in the created maxima under low viscosity conditions is 100 to 1000 times less than the current density under high viscosity conditions. The velocity of the plasma flow near current sheet for low viscosities is ~ 100 times higher than the velocity for high viscosities (Fig. 2,3). These results are a consequence of the low suppression of perturbations under conditions of low viscosity and confirm the need for MHD simulations under such conditions, despite the difficulties that arise due to the appearance of numerical instability.

Figures 1, 2 show the positions of nine selected current density maxima numbered 4, 12, 41, 73, 105, 145, 147, 179 and 194 (the maxima are numbered in order of decreasing current density in them) and the magnetic field configurations near these maxima for calculation with high viscosities. The remaining maxima are depicted by purple dots. The magnetic field configuration is represented by magnetic lines passing through the selected maxima. In the picture plane, the positions of the current density maxima and magnetic lines are superimposed on the intensity distribution of radio emission at a frequency of 17 GHz, obtained with the Nobeyama radioheliograph. To compare the positions of the six current density maxima numbered 8, 16, 19, 20, 47 and 234, the magnetic lines passing through them, and the magnetic field configurations in the calculation for low magnetic viscosities are briefly shown in Figure 3. The remaining current density maxima are shown as green dots. These results are presented in detail in the figures in [*Podgorny and Podgorny 2023*]. The flare release of energy is most likely in the current sheet formed at the current density maximum, which has the following properties. The diverging magnetic field should not strongly dominate over the X-type field [*Podgorny et al., 2021*]. The longitudinal magnetic field should not significantly exceed the field in the plane of the current sheet configuration (i.e., the plane perpendicular to the magnetic field vector at the point of maximum current density); this is expressed in the fact that the magnetic lines in space (3rd column of figures in Figure 2), located near a singular line passing through the point of maximum current density, should diverge, significantly different from straight lines. The point of maximum current density should be located near the top of the magnetic loop. As can be seen from Figures 1, 2 and 3, the current density maxima with such properties are located both in the bright region of flare radiation or near it, and far from the bright region of flare radiation for both calculation options. At the same time, a greater number of maxima with such properties are located in the region of bright flare radiation for calculations with high viscosities ($Re_m= 3\times10^4$, $Re= 10^4$), which, apparently, is also associated with the conditions for the appearance of numerical instabilities.

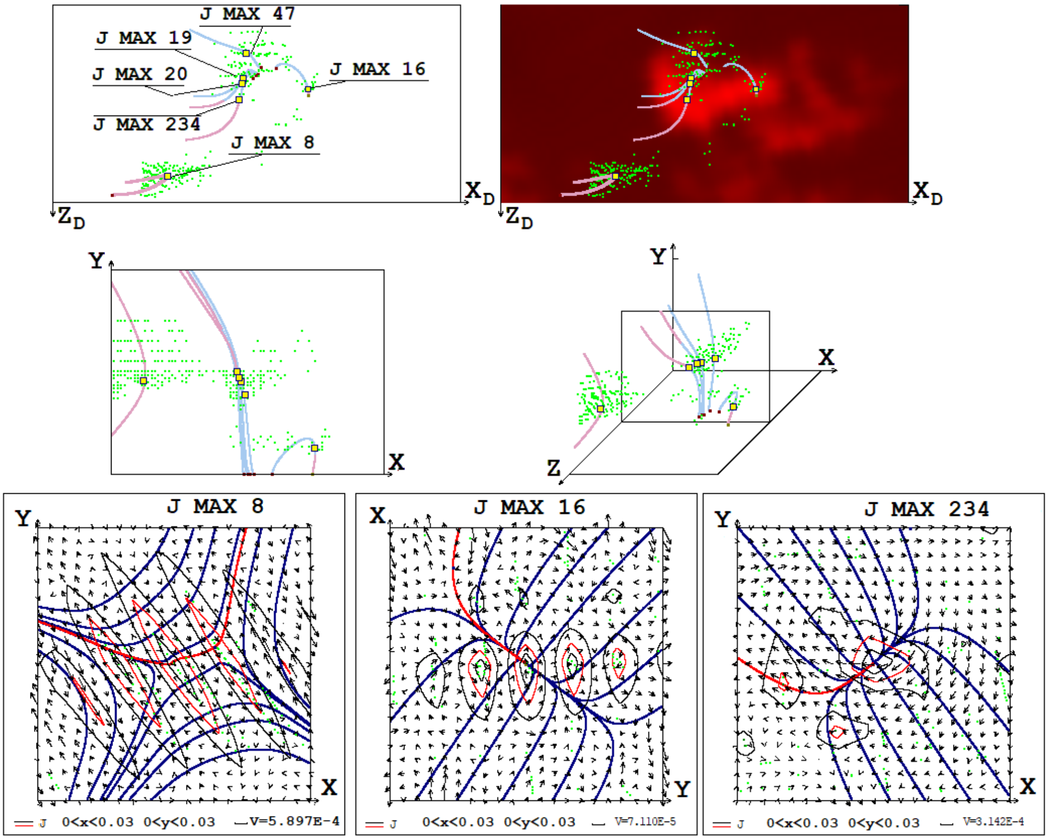

Figure 3. Comparison of the magnetic field configuration and the positions of the current density maxima with the distribution of radio emission intensity at a frequency of 17 GHz on 26 May 2003 at 02:32:05, three hours before the M1.9 flare for simulation with low viscosities ($Re_m= 10^9$, $Re= 10^7$). The positions of the current density maxima are shown as green points. The magnetic field configuration is presented by magnetic lines which pass through selected current density maxima (J MAX) with the numbers 8, 16, 19, 20, 47 and 234. The configurations of the magnetic field and plasma flow near the selected current density maxima.

5. Conclusions

1. A numerical simulation technique has been developed and modernized, including the development of a finite-difference scheme, methods for stabilizing the numerical instability that occurs near the boundary of the computational domain, and methods for solving a number of auxiliary problems.

2. It is shown that a large number (about a hundred) of current density maxima, which are located in the places of formation of current sheets on singular lines, are in the region of bright flare radiation, which confirms the mechanism of a solar flare based on the accumulation of energy in the magnetic field of the current sheet.

3. However, a sufficiently large number of current density maxima are located far from the bright region of the flare radiation (at a distance of more than 10 Mm). Moreover, many current

density maxima located far from the bright region of the flare radiation have properties that contribute to the appearance of a flare (the relatively small effect of a divergent magnetic field superimposed on the X-type configuration; a relatively small component of the longitudinal magnetic field; the location of the current density maximum near the top of the magnetic loops). This problem could arise due to an inaccurate numerical solution, and further improvement of numerical methods is necessary to solve it.

4. MHD simulations for relatively high viscosities (conventional and magnetic) showed suppression of the perturbation propagating into the corona from the solar surface, this inhibit the accumulation of large energy for a solar flare. At the same time, at high viscosities, the solution is much more stable and the position of a relatively larger number of current density maxima is in the region of bright flare radiation or near it (in this case, for calculations with high viscosities, the total number of current density maxima is less than for calculations with lower viscosities). Carrying out MHD simulations above the active region for low viscosities and for high viscosities and comparing the results of these variants of calculation makes it possible to better study the flare situation. The results obtained for sufficiently low viscosities ($Re_m= 3\times10^4$, $Re= 10^4$), at which a numerical instability arose, which significantly complicated the calculations, and for sufficiently high viscosities ($Re_m= 10^9$, $Re= 10^7$), at which weak current sheets only began to formed indicate the need for simulations for intermediate values between the indicated viscosities. It may be necessary to perform several calculations for a number of sets of intermediate viscosities in order to select the optimal MHD simulation parameters.

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