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MHD Simulation of a Flare Situation in Real Scale of Time Above AR 10365: Development of a Technique, Choice of Parameters, The Appearance of Field Singularities at Flare Sites

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Abstract. The mechanism of release of the magnetic energy of the current sheet formed in vicinity of singular X-type magnetic field line explains the observed primordial release of solar flare energy in corona. The observed manifestations of the flare are explained by the electrodynamic model of a solar flare proposed by I.M. Podgorny. The study of the flare mechanism is impossible without performing MHD simulations above a real AR, MHD simulation in the solar corona in real time can only be carried out thanks to parallel calculations using CUDA technology. To select the conditions for the numerical solution of MHD equations under which various viscosities. Mainly, the configuration of the magnetic field at the maxima of the current density is the configuration of the X-type singular line, which is strongly distorted by superimposed diverging magnetic field.

Introduction.

The mechanism of S.I. Syrovatskii [*Syrovatskii 1966*], accor ding to which, during a solar flare, the magnetic energy of the current sheet formed in the vicinity of the X-type singular line of the solar corona magnetic field is released, explains the observed primordial energy release of the flare above the active region (AR) at an altitude of ~ 1/40 - 1/20 of the solar radius. The primordial release of energy high in the corona is evidenced by observations of thermal X-ray emission from flares on the limb [*Lin et al., 2003*], the invariability of the magnetic field during flares on the solar surface [*Podgorny et al., 2015*], changes in the corona temperature at the flare site according to observations of ultraviolet radiation of highly ionized iron ions [*Podgorny and Podgorny 2018*] and other observations. The flare release of the energy of the current sheet causes the observed manifestations of the flare, which are explained by the electrodynamic model of the flare proposed by I.M. Podgorny [*Podgorny et al., 2010*]. According to this model 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. 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 [*Podgorny et al*., 1988].

The results of the studies lead to the conclusion that the study of the flare mechanism is impossible without carrying out MHD simulations above a real AR, in which the magnetic fields observed in the photosphere are taken as boundary conditions, and the calculation begins several days before the appearance of flares. When setting the problem, no assumptions were done about the flare mechanism.

Method for the numerical solution of MHD equations

In order for the finite-difference scheme approximating the system of MHD equations to remain stable for the maximum possible time step, which is necessary to increase the calculation speed, an absolutely implicit upwind finite-difference scheme, conservative with respect to the magnetic flux, was developed. The scheme is solved by the iteration method.

To obtain the correct development of physical processes in time, it is necessary to carry out MHD simulation in the real scale time. Despite the use of specially developed methods, the calculations are slow. **There is a need to use parallel computing.** The time of calculation of evolution of the field and plasma in the solar corona above the active region is determined by:

1) The size of the time step (at which the scheme remains stable)
2) The number of iterations
3) The time of calculation of one iteration

Choice of parameters of MHD equations. Stabilization of instabilities arising near the boundary

Due to the difficulties in matching the solution in the computational domain with the values specified at the boundary, a calculation in the real scale time can lead to the development of a strong instability that has time to develop during a long time interval, both near the photosphere and non-photospheric boundaries. The strongest instabilities arise at low viscosities The problem of stabilization of instabilities arising at the boundaries of the computational domain was almost completely solved [*Podgorny at al., 2020*], for which artificial limitation of the rate of plasma inflow into the computational domain through the non-photospheric boundary, the setting of artificial viscosity near the non-photospheric boundary, and other stabilization methods were used. The viscosities were set in accordance with the principle of limited modeling [*I.M. Podgorny 1978*], according to which much larger or much smaller units, dimensionless parameters remain much larger or smaller than units when simulated without their exact preservation.

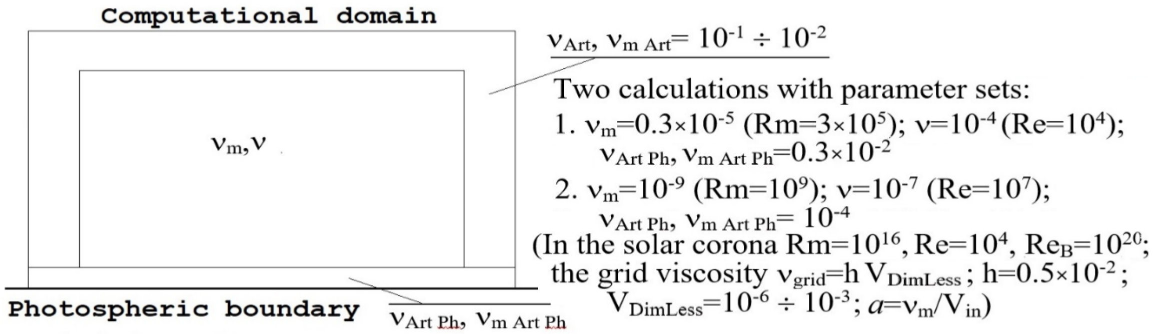

Fig. 1. Viscosity and artificial viscosity for two calculation variants.

For the active region AR 10365, two calculations were carried out for two sets of parameters corresponding to relatively high and low viscosities within three days (see Fig. 1.). In both calculations near the non-photospheric boundary, to stabilize the numerical instability, sufficiently large artificial viscosities were taken, their dimensionless values (inverse to the Reynolds numbers) are ν_{Art}=$\nu_{m\ Art}$=10^{-1}÷10^{-2}.

In the first variant, the viscosities were taken equal to ν_m=0.3×10^{-5} (Rm=3×10^5); ν=10^{-4} (Re=10^4), the artificial viscosity near the boundary was taken relatively high $\nu_{Art\ Ph}$, $\nu_{m\ Art\ Ph}$=0.3×10^{-2}. With these parameters, due to the suppression of the perturbation propagating from the photosphere by the artificial viscosity, a sufficiently intense accumulation of the flare energy does not occur in the region; therefore, a calculation with the second set of parameters with significantly lower viscosities was required. The calculation results with these parameters are given in [*Podgorny et al. 2020*].

In the second variant of the calculation, a set of parameters was selected ν_m=10^{-9} (Rm=10^9); ν=10^{-7} (Re=10^7); $\nu_{Art\ Ph}$, $\nu_{m\ Art\ Ph}$= 10^{-4}, the simulation results with these parameters are presented in the next chapter. If instabilities did not arise at the boundary, then, proceeding only from the need to obtain a stable solution inside the region, it is possible to make the following estimate of the computation time of one day of evolution in the solar corona above the active region. The time step from the Courant condition $\tau_K=h/(V_{MV}+V_{MA})$ in the calculations is $\tau_K = 10^{-8} \div 10^{-7}$ days. To estimate the computation time with a step τ_K : the computation time of one iteration on graphics cards using the CUDA technology is 2×10^{-2} sec, for 5 iterations the computation time of one step is 0.1 sec, so that (day ~ 10^5 sec) the computation time of one day of evolution in the solar corona is 10 - 100 days.

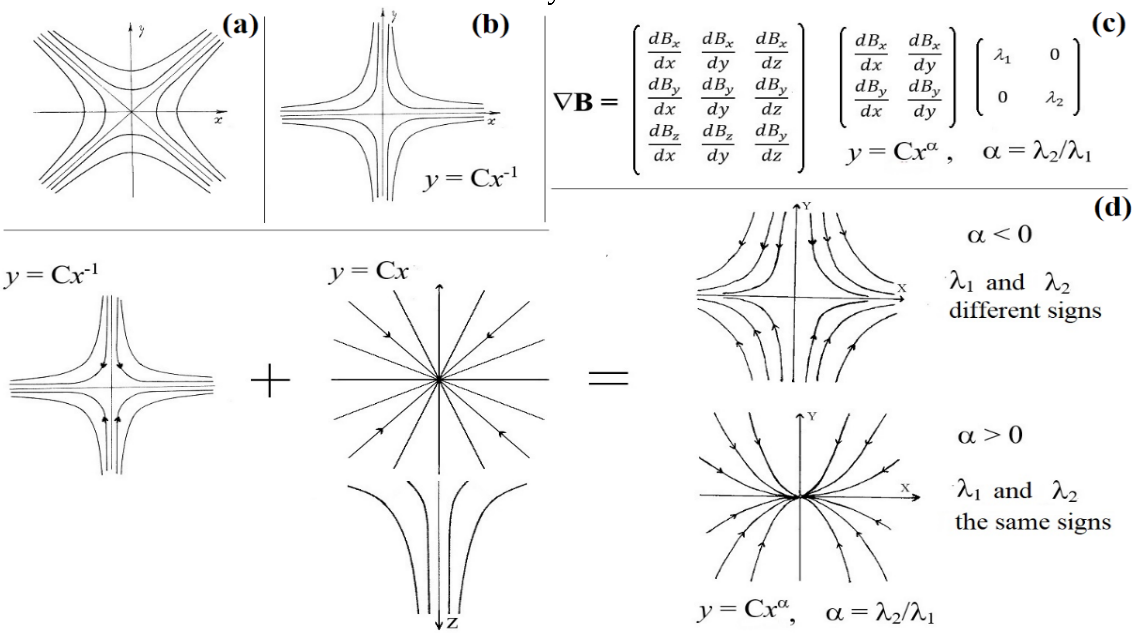

Fig. 2. Superposition of X-type magnetic field and diverging magnetic field.

At low viscosities, strong disturbances arise in some places of the computational domain. These disturbances are propagating towards the boundary. The perturbations are so strong that, despite setting a large artificial viscosity near the boundary, they cause numerical instability. For this set of parameters to stabilize the instabilities, it is also necessary to decrease the step (less than 10^{-8} days) and increase the number of iterations (in the calculations, their number reached 60 and more). As a result, the calculation time is greatly increased, reaching several months.

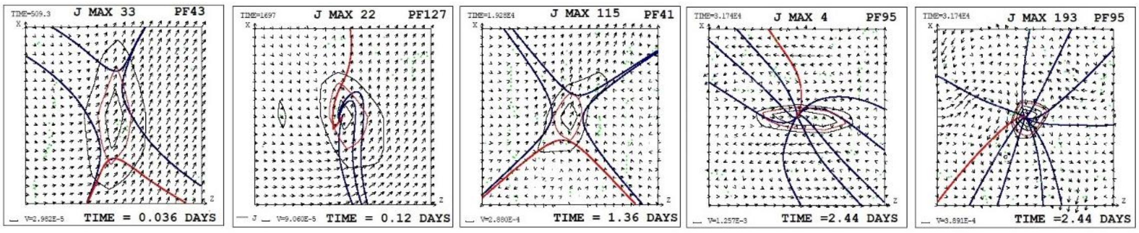

Fig. 3. Examples of superposition of X-type and diverging magnetic field obtained from MHD simulation.

MHD simulation results. Flare M1.4 27.05.2003 at 2:43

MHD simulation above AR 10365 showed the appearance of special lines in which a diverging magnetic field is superimposed on the configuration of the X-type magnetic field (Fig. 2, 3). The diverging magnetic field can be large, it can dominate the X-type field, fundamentally distorting its configuration However, even in this case, the presence of the X-type configuration leads to the accumulation of perturbations with the formation of a current sheet, in the magnetic field of which the flare energy is accumulated. In this case, even with a significant dominant diverging magnetic field, a sufficiently powerful current sheet may appear (Fig. 3, J Max 4), leading to the appearance of not only a weak flare, but also a flare of medium power.

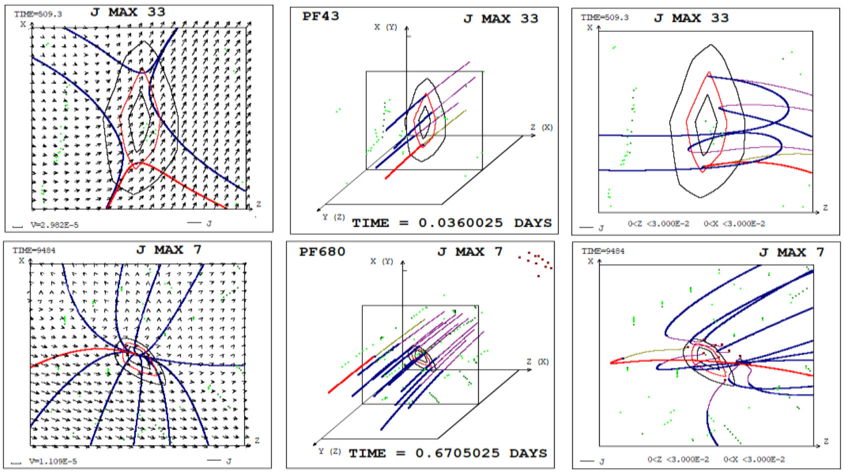

Fig. 4. Field configurations near singular lines. Flat magnetic lines, three-dimensional configurations, projections of field lines on the plane of configuration.

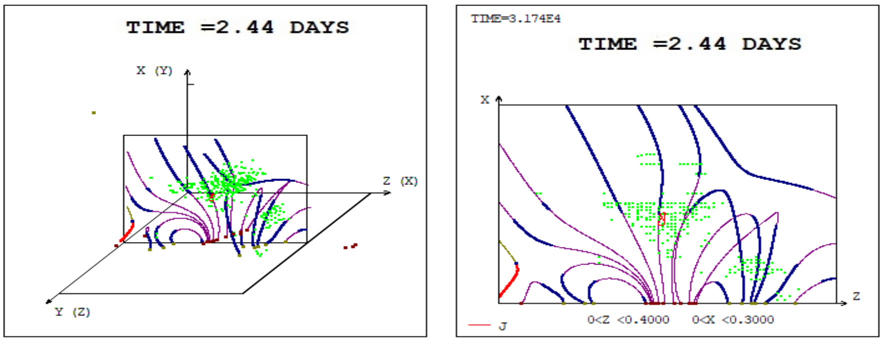

Fig. 5. Three-dimensional configuration of the magnetic field in the computational domain and the projection of the magnetic lines on the central plane.

When the X-type field and the diverging field are superimposed (Fig. 2d), the magnetic lines of the resulting field have the form $y = Cx^{\alpha}$, where $\alpha = \lambda_2/\lambda_1$, λ_1 and λ_2 are the eigenvalues of the matrix ($\nabla\mathbf{B}$) [*Podgorny 1989*]. If the X-type field dominates, then the magnetic lines have the form of hyperbolas ($\alpha < 0$, λ_1 and λ_2 have different signs). If the diverging field dominates, then the magnetic lines have the shape of parabolas ($\alpha > 0$, λ_1 and λ_2 of the same sign). Most often, the three-dimensional configuration of the magnetic field in the vicinity of the singular line is complex (examples are shown in Fig. 4), from this configuration it is impossible to determine that the line is singular. Therefore, a specially developed system for finding points through which singular line pass is required [*Podgorny et al., 2013a,b, 2017*].

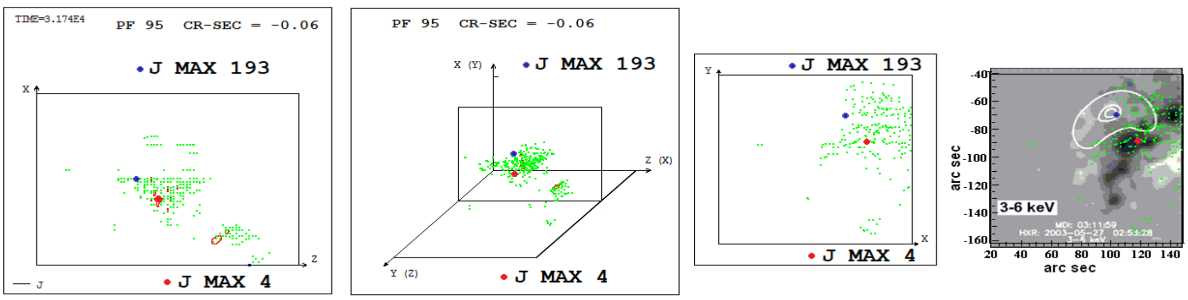

Fig. Flare-M1_4-2. The location of the current density maxima in the region, their projections onto the central plane, the picture plane (perpendicular to the line of sight), and the distribution in the picture plane of soft X-ray emission of 3-6 keV, received by the RHESSI spacecraft during the M 1.4 flare on May 27, 2003 (http://rhessidatacenter.ssl.berkeley.edu).

In Fig. 5. shows the configuration of the magnetic field in the computational domain of corona at the time of the M 1.4 flare on May 27, 2003 at 2:43 am, which corresponds to 2.44 days from the beginning of the calculation. The current density maxima found by the graphical search system through which singular magnetic field lines can pass are indicated by green dots in Figures 5, 6. The positions of the current density maxima in the region are shown, their projections onto the central plane, which passes through the central point of the computational region and is located perpendicular to the photosphere and parallel to the solar equator. Fig. 6 shows the location of many of the current density maxima in the picture plane close to the thermal X-ray source. The 193rd maximum of the current density is located in the central region of the source (all the maxima are numbered in decreasing order). The 4th maximum near the source of thermal X-ray radiation has the most powerful current sheet. The field configurations near the 193rd and 4th current density maxima (Fig. 7) show the dominance of the diverging magnetic field over the X-type field. MHD simulation showed the coincidence of the positions of some current density maxima with the position of the source of the flare thermal X-ray radiation; the maximum of the current density with a sufficiently powerful current sheet is located at a distance of ~ 10" from the source. In the future, it will be necessary to try to more accurately select the parameters for a more precise calculation.

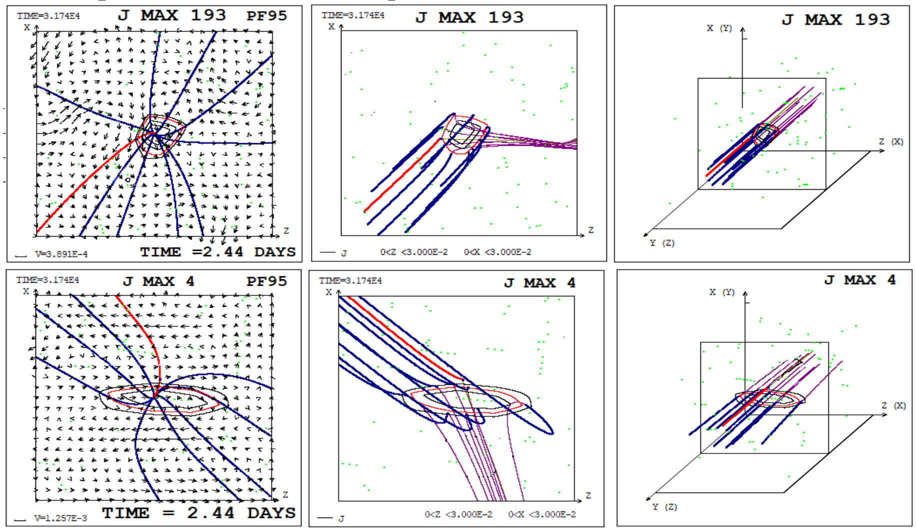

Fig. 7. Magnetic field configurations near the193rd and 4th current density maxima.

Conclusion.

To understand the physical processes causing the flare situation, simulation in the real scale of time is necessary, and the calculation should begin several days before the flare, when the magnetic energy of the flare has not yet been accumulated in the corona.

1. A technique has been developed for the numerical solution of MHD equations in the solar corona in real scale of time, which is impossible without the use of parallel computations. Boundary conditions are taken from observations.

1.1 In order to reduce the calculation time, an absolutely implicit upwind finite-difference scheme was developed, which is conservative with respect to the magnetic flux in order to maximize the spatial step at which the scheme remains stable.

1.2 Methods for stabilizing instabilities near boundaries have been developed. Mainly, this is an application of artificial viscosity near the boundary, both magnetic and ordinary, as well as other methods of stabilization.

2. The simulation performed above AR 10365 showed the formation of local maxima of the current density on singular lines of the magnetic field.

2.1. Some current density maxima did not appear on singular X-type magnetic field lines.

2.2 In addition, a large number of current density maxima arise in places where the configuration of the X-type singular line is significantly distorted by the diverging magnetic field superimposed on it. Apparently, in the places of current density maxima with such a configuration, the appearance of low-power flares is possible.

2.3. Comparison of the calculation results with observations showed the appearance of current density maxima at the flare sites with a field configuration strongly distorted by the superimposed diverging magnetic field. Perhaps for this reason, solar flares over AR 10365 on May 26 and 27, 2003 were not very large.

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