Investigation of the mechanism of solar flare and acceleration of solar cosmic rays in real conditions of the solar corona

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Abstract. The generation of solar cosmic rays occurs during explosive energy release in a solar flare, so in order to understand this phenomenon it is necessary to study both the mechanism of the solar flare and the process of particle acceleration by the generated electric field. During a solar flare in the solar corona above the active region (AR), the energy stored in the magnetic field of the current sheet is released. Using the results of numerical simulation and observations, I.M. Podgorny proposed an electrodynamic model of a solar flare, explaining its main observational manifestations, in particular, the appearance of X-ray emission on the surface of the Sun. The acceleration of protons occurs along a singular line of the magnetic field of the current sheet by the electric field \( \mathbf{E} = -V \times \mathbf{B}/c \). To obtain accurate results it is necessary to carry out MHD simulation in the real scale of time, which is only be done using parallel calculations. The parallelization of the program PERESVET carried out using graphics card (GPU), the calculations were accelerated by ~ 120 times. As a result of optimization of the approximation of the boundary conditions of free exit at the non-photospheric boundary, instability near the boundary was stabilized. The first results of MHD simulation in the real scale of time above the AR 10365 showed the appearance of a plasma flow near singular X-type lines, which have to cause to the formation of a current sheet.

1. Introduction. Solar cosmic rays and solar flares.

Solar cosmic rays (SCR) are fluxes of charged accelerated particles up to energies of ~ 20 GeV, mainly protons, appearing during solar flares. However, not all solar flares are accompanied by SCR. Only ~ 30% of the most powerful X-ray class X flares cause SCR. During a flare, the SCR flux can exceed the background flux of galactic cosmic rays by ~ 3 orders of magnitude and reach ~ 10^2 particles cm^-2 s^-1 sr^-1 for energies above 100 MeV. Prognosis of appearance of SCR is an important practical problem, since they can cause radiation exposure to astronauts. Since SCR are caused by solar flares, in order to study the physics of this phenomenon and improve the quality of its prognosis, it is necessary to simultaneously study the processes occurring during solar flares and the acceleration of charged particles.

During a solar flare, 10^{32} erg of magnetic energy is released during several tens of minutes. Flares occur above active regions (ARs) with a high magnetic field (several thousand G) at altitudes of 15,000 km - 30,000 km, which is ~ 1/40 - 1/20 of the solar radius. This has been proven by measurements of thermal X-ray emission from flares on the limb [1], the invariability of the magnetic
field on the solar surface during flares [2], and other observations [3]. The main flare process high in the corona can be explained by the mechanism of S.I. Syrovatskiy [4]: the accumulation of magnetic energy in the field of the current sheet, which is formed in the vicinity of a singular X-type magnetic field line and in the course of quasi-stationary evolution transfers into an unstable state. The release of energy is accompanied by the observed manifestations of the flare, which are explained by the electrodynamic model of the solar 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 [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 longitudinal currents caused by the Hall electric field in the current sheet.

2. Acceleration of SCR during a flare. The need for MHD simulation in the real scale of time.

Solar cosmic rays are accelerated in the current sheet by an induction electric field caused by a fast change in the magnetic field during the flare process. This electric field is equal to \( \mathbf{E} = -\mathbf{V} \times \mathbf{B}/c \). For a typical inflow velocity into the current sheet \( \mathbf{V} = 2 \times 10^7 \text{ cm/s} \), magnetic field \( \mathbf{B} = 100 \text{ G} \), and sheet length \( l = 10^7 \text{ cm} \), we obtain the potential difference \( E = 2 \times 10^{10} \text{V} \), after passing which the particle gain an energy of 20 GeV. The SCR spectrum for the Bastille flare on July 14, 200 [5] was determined by calculating the trajectories of particles in an electric and magnetic field, obtained by MHD simulation in the solar corona above AR. The calculated spectrum of cosmic rays coincided with the spectrum obtained by observations on the worldwide network of neutron monitors.

When performing MHD simulation, all conditions were taken from observations and no assumptions about the flare mechanism were made when setting the problem [7]. In order to speed up the calculation, an absolutely implicit finite-difference scheme, conservative relative to the magnetic flux, was specially developed [7, 8]. Despite the use of specially developed methods, it was possible to carry out MHD modeling in the corona on a usual computer (Intel (R) Core (TM) I7 CPU 920 @ 2.67GHZ) only in a greatly reduced \( (10^4 \text{ times}) \) scale of time. In order to get the correct development of processes in time, it is necessary to carry out MHD simulation in the real scale of time. Such simulation is necessary for calculation the trajectories of particles to study particles acceleration and the possibility of their exit from the field above the AR, i.e., the possibility of SCR appearance for a given flare [9]. Calculations have shown that MHD simulation in the real scale of time requires that the time step on the main part of the calculated interval does not exceed \( 4 \times 10^7 \text{ days} \). Such simulation cannot be carried out on a usual computer, it would require 8 years of calculation.

To study of the mechanism of generation and propagation of solar cosmic rays and their prognosis it is necessary:

1) Study of the mechanism of a solar flare and the position of a flare in the corona above the active region by numerical MHD simulation of a flare situation in the solar corona above the active region, in which the magnetic field distribution observed on the solar surface is taken as boundary conditions.
2) Study of the mechanism of particles acceleration during a flare and the possibility of their escape from the region of a strong magnetic field in the corona above the active region by calculating the trajectories of particles in electric and magnetic fields obtained as a result of MHD simulation.
3) Since there is no information about plasma inhomogeneities, and, therefore, the diffusion coefficient in the equation for the propagation of accelerated particles is unknown, the prediction of the appearance in interplanetary space of cosmic rays capable of causing radiation to astronauts is supposed to be carried out on the basis of the analysis of observational data for SCR time delay and front rise time carried out by I.M. Podgorny [10].

3. Methods needed for MHD simulation in the real scale of time. 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.

These values depend on:

- **Mathematical method**: The type of difference scheme (within a given type of schemes, which are absolutely implicit and conservative with respect to the magnetic flux) and the parameters of the difference scheme, first of all, ordinary and artificial magnetic viscosity, which is used mainly near the boundary (where difficulties always arise with the correct setting of all boundary conditions).

- **The computation speed of a given processor**, for us, is, first of all, the computation speed of graphics card (GPU) threads, which perform parallel computations.

- **Algorithm for parallelizing computations**, in particular, the location and transfer of arrays on the graphics card, which are, in essence, copies of the arrays of distributions of all quantities in the computational domain contained in the main memory of the computer.

![Image](image_url)

**Figure 1.** Current density in the central plane of computational domain. Propagation, initialization and stabilizing instability on the non-photospheric boundary

**4. Stabilization of the instability arising at the non-photospheric boundary**

But first, it is necessary to get rid of sufficiently strong disturbances caused by instabilities at the non-photospheric boundary. Calculations in the real scale of time have shown that such instabilities (figure 1) 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.

**5. Parameters of the difference scheme; equipment; and optimization of parallel computations**

For implicit finite-difference scheme time step \( \tau \) in principle can be larger than the time from Courant condition \( \tau < h/(V_{MV} + V_{MA}) \). 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. Calculations showed, that time for proposed difference scheme step \( \tau \) must be less then \( \tau_K \), in spite of that the absolute implicit scheme is used. Apparently, it is due to that the system of equations with cross-terms.

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

- Time step \( \tau = 0.4 \times 10^{-7} \) days (Courant step \( \tau_K \) varies from \( 0.45 \times 10^{-7} \) to \( 0.79 \times 10^{-7} \) in the process of calculation, and depending on the details of the rules for its determination near the boundary)
- Artificial viscosity (usual and magnetic) \( \nu = 3 \times 10^{-3} \).
- Precision of solution of implicit scheme $\varepsilon = 10^{-7}$, at which 3 iterations are performed.

Figure 2. The appearance and disappearance of instability near the photospheric boundary

Figure 3. Evolution of current density distribution in the central plane.

The selected computing equipment and the parallelization algorithm give the fastest computation time of one iteration 0.0282 - 0.0302 sec (Titan V). As a result, now we can get the time for calculation the evolution during the day above the AO, equal to $\sim$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 the grid 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 (figure 2). 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.

![Figure 4](image)

**Figure 4.** 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.

Time of calculation of one iteration depends on:
- Computing speed of this processor
- Algorithm for parallelizing computations

It is necessary to solve the following problems (basically, they have been solved, but in the future, the methods will need to be improved in order to increase the calculation speed):

1) **Choice of computing equipment**

The problem was set on GPU computers rented "in the clouds" with modern graphics cards (GPU) for parallel computing Titan-V (Volta), V100 (Volta-100), P100 (Pascal-100). They have a high computation speed for each thread. The use of the modern language Fortran PGI made it possible to apply the methods of optimizing the parallelization algorithm for computations presented in 2)

2) **Optimization of the parallelization algorithm**

For optimization of the algorithm parallelization calculations it was performed more than 20 modernizations of the code, as the result of which the speed of calculation increase in 7.5 times and became 120 times faster than the calculation speed of a non-parallel program.

The following methods were used:
1) Parallel computation at spatial grid points in sequentially selected 3D blocks
2) Passing a large number (≈ 100) parameters in subroutines that perform parallelization on graphics cards
3) 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.

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.
6. Formation of singular X-type lines with the plasma flow

The evolution of the current density in the central plane of computational domain for MHD simulation in the corona above AR 10365 during the first 1.2 days of evolution, when there were no flares yet, is presented in figure 3. During the evolution of magnetic field and plasma, described by the results of MHD simulation, 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 figure 4. 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.

7. Conclusion

1. Solar cosmic rays are accelerated by the electric field $E = \mathbf{V} \times \mathbf{B}/c$ in the current sheet in the solar corona during a solar flare; therefore, to study the mechanism of SCR generation, it is necessary to study the mechanism of solar flares.
2. The development of MHD methods for simulating the flare situation in the solar corona over the active region, necessary for studying the mechanism of solar flares, has been continued. The proposed methods make it possible to carry out MHD simulations in the corona in real scale of time for the foreseeable time (for MHD simulations of one day of evolution in the corona, ~21 days of calculation are now required).
2a. Optimization of the parallel computation algorithm is carried out.
2b. The optimal parameters are selected for the used absolutely implicit finite-difference scheme, conservative with respect to the magnetic flux.
3. The evolution of the plasma and the field in the corona above AR 10365 was calculated during the first 1.2 days of evolution, when there were no flares yet. The calculation did not show the appearance of pronounced current sheets even with sufficiently strong disturbances in 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 lead to the formation of a current sheet; however, in the course of further evolution, such configurations disappeared (possibly, microflares appeared).
4. The work carried out revealed the possibilities for further optimization of the methods in order to further reduce the calculation time.

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