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MHD simulation in the solar corona to obtain conditions for the acceleration of cosmic rays during solar flares

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Solar cosmic rays are generated during the primordial energy release in solar flares. This explosive process takes place in the solar corona above the active region at altitudes of 15 000 to 70 000 km. It represents the fast release of the magnetic field energy of the current sheet, which is formed near a singular magnetic field line under the influence of disturbances propagating from the solar surface. Solar cosmic rays appear as a result of acceleration of charged particles, mainly protons, by an inductive electric field in the current sheet, equal to the field $\mathbf{E} = \mathbf{V} \times \mathbf{B}/\mathbf{c}$ near the current sheet. To study the mechanism of solar flares, the process of formation of a current sheet and the accumulation of energy in its magnetic field for each specific flare, and to obtain the possibility of improving the prognosis of solar flares based on an understanding of their physical mechanism, it is necessary to carry out magnetohydrodynamic (MHD) simulation of a flare situation in the solar corona above a real active region. The electric and magnetic fields obtained by MHD simulation above a real active region at the site of the primordial flare energy release and near it are necessary for studying the generation of solar cosmic rays. The acceleration of charged particles and the possibility of their exit from the acceleration region must be studied by calculating the trajectories of charged particles in electric and magnetic fields obtained by MHD simulation. The first results of studying the acceleration of charged particles were obtained by calculating trajectories in electric and magnetic fields, found by MHD simulation above the active region under simplified conditions.

When setting the conditions for MHD simulation, no assumptions were made about the physical mechanism of the solar flare; the boundary conditions were taken from observations. Experience has shown that the physical mechanism of a solar flare can be studied by MHD simulation only if the calculation starts a few days before the appearance of flares, when magnetic energy for the flare has not yet accumulated in the corona. For MHD simulation in the real scale of time, a significant computational speed is required, which is achieved only through the use of parallel computing on supercomputers. Parallelization of calculations was carried out by computational threads on graphic cards (GPU).

The MHD simulation above a real active region is continued, the results of which were presented at previous ICPPA conferences. The conditions for setting the problem of MHD simulation are refined, the developed method for the numerical solution of the equations of magnetohydrodynamics is improved. Simulation above the active region of AO 10365 in real time showed the appearance of a numerical instability near the boundary of the computational region, which has time to develop over a fairly long (about 3 days) time interval, despite use of the finite-difference scheme which is developed for our purposes. The scheme is absolutely implicit and conservative with respect to the magnetic flux. Methods for stabilizing emerging numerical instabilities were developed, which made it possible to solve the problem for relatively large usual and magnetic viscosities (usual and magnetic Reynolds numbers are $Re = 10^4$; $Re_m = 3 \times 10^5$). These methods made it possible to partially solve the problem of stabilization of instabilities for relatively low usual and magnetic viscosities ($Re = 10^7$; $Re_m = 10^9$), at which the perturbation propagating from the solar surface is weakly suppressed by the viscosity, which allows the formation of sufficiently powerful current sheets with high magnetic energy, accumulated for flare. The results obtained made it possible to understand how to further develop methods for stabilizing numerical instabilities.

MHD simulations showed the appearance of current sheets in the vicinity of X-type singular magnetic field lines. The configuration of the magnetic field above the active region is so complicated that the positions of singular lines and current sheets can only be found using a specially designed graphic search system. A

divergent magnetic field can be superimposed on the X-type magnetic field configuration near the singular line. The divergent magnetic field may dominate, so that the resulting configuration will not resemble an X-type field. However, due to the presence of an X-type configuration in the superimposed fields, MHD simulations show the formation of a current sheet. At the sites of the flares on May 26 and 27, 2003 above AR 10365, the X-type configuration is strongly distorted by the diverging magnetic field. Perhaps for this reason, the solar flares on May 26 and 27, 2003 were not very strong. The coincidence of the position of the flare thermal X-ray source with the places on singular lines where the current sheet was formed confirms the solar flare mechanism based on the accumulation of energy in the magnetic field of the current sheet.

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