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Arcade of magnetic lines passing through the chain of density maxima: the result of MHD simulation above active region in order to obtain conditions for acceleration of solar cosmic rays

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In order to study the physical mechanism of solar cosmic ray acceleration, it is necessary to simultaneously study the physical mechanism of a solar flare, since solar cosmic rays are generated during solar flares. Numerous observations, the most important of which is the direct observation of the source of thermal X-ray emission of a flare at the edge of the solar disk, indicate that flares occur in the solar corona at altitudes of 15,000-70,000 km (1/40 - 1/10 of the solar radius). The results of MHD simulation confirm the occurrence of flares at these altitudes. The slow accumulation of energy for a solar flare in a stable magnetic field configuration in the corona, and then its transition to an unstable state, explains the physical mechanism of S. I. Syrovatsky, based on the accumulation of energy in the magnetic field of the current sheet formed in the vicinity of a singular magnetic line. The fast release of magnetic energy of the current sheet leads to the observed manifestations of a flare, which are explained by the electrodynamic model of a solar flare proposed by I. M. Podgorny. In the current sheet, due to the dissipation of magnetic energy, the plasma is heated to a temperature of several tens of millions of degrees, resulting in the appearance of a source of thermal soft X-ray emission with energies of 3 - 25 keV. The Hall electric field in the current sheet creates an electric circuit consisting of field-aligned currents along magnetic lines exiting from the current sheet, which are closed by the Petersen current on the photosphere. Electrons accelerated in field-aligned currents, interacting with the lower dense layers of the solar atmosphere, cause beam hard X-ray emission with energies of 50 - 100 keV and higher on the surface of the Sun. The ejection of plasma under the action of magnetic tension force in the current sheet, the appearance of flare arches, and a number of other manifestations of a solar flare are also explained by the electrodynamic model. Generation of solar cosmic rays occurs as a result of acceleration of charged particles (mainly protons) by the induction electric field, which arises due to fast change of magnetic field during flare instability, which is equal to the field $V \times B/c$ near the current sheet (the product of the velocity of plasma inflow into the sheet and the magnetic field created by the sheet current). An estimate of the measured energies of solar cosmic rays up to 20 GeV is obtained if we take a typical field above the active region of 100 G, the velocity of plasma inflow into the sheet of 2×10^7 cm/s and the length of the sheet on which acceleration occurs of 10^9 cm. During superflares on the star dwarfs of the class G, the power of which is four orders of magnitude greater than the power of solar flares, acceleration of galactic cosmic rays to energies of 10^{15} eV can occur. This estimate will be obtained if we take the magnetic field and the velocity of plasma inflow into the sheet to be 100 times greater, and the length of the current sheet to be 10 times greater compared to the values of these quantities for solar flares.

Since it is impossible to obtain the magnetic field configuration in the corona from observations, it is necessary to carry out MHD simulation above the active region to study the mechanism of solar flares. MHD simulation will also allow us to obtain the configurations of the electric and magnetic fields to study the acceleration of cosmic rays by calculating the trajectories of test charged particles in these fields. Calculations of particle motion in fields obtained under simplified conditions have made it possible to obtain an idea of the mechanism of generation of solar cosmic rays. Now it is necessary to carry out more accurate MHD simulation using maps of the observed magnetic field on the solar surface.

When setting the problem of MHD simulation, no assumptions were made about the physical mechanism of solar flares. All conditions were taken from observations. The aim of MHD simulation is to find the physical mechanism of a solar flare, and not to verify a hypothesis regarding the proposed mechanism. To properly study the physical mechanism of a solar flare, when performing of MHD simulation, the calculation should begin several days before the appearance of flares, when the energy for the flare has not yet accumulated in corona (otherwise we do not know whether the magnetic field configuration with which the calculation begins can be formed in the corona).

An absolutely implicit upwind finite-difference scheme, conservative with respect to magnetic flux, has been developed for numerical solution of magnetohydrodynamic equations. Numerical methods which have been developed have the purpose to obtain a difference scheme that will remain stable for the maximum possible time step to accelerate the calculation. The implicit scheme is solved by the iteration method, in which the values at the central point of the template are taken at the next iteration for better convergence. The scheme is realized in the PERESVET computer program written in FORTRAN. To speed up the computations, parallel calculations are performed by computing threads on modern graphic cards (GPU) using CUDA technology. Carrying out the calculation in a reasonable time is complicated by numerical instabilities that arise, first of all, near the boundary of the computational domain, both photospheric one (on the surface of the Sun) and non-photospheric one. The developed methods for stabilizing these instabilities, including the use of artificial viscosity and special matching of quantities at the boundary, made it possible to partially solve this problem. The development of methods for stabilizing numerical instabilities near the boundary of the computational domain continues. The magnetic field configuration above the active region is so complicated that it is practically impossible to determine the positions of the singular lines and the current sheets formed in them directly from the magnetic field configuration. Therefore, a graphical search system based on the appearance of a current density maximum in the middle of the current sheet has been developed for this purpose. Local current density maxima are searched for, then the magnetic field configuration is analyzed in the vicinity of each of them. The longitudinal component of the magnetic field (directed along the singular line perpendicular to the plane of the current sheet configuration) can be small compared to the field in the plane of the configuration and not hinder the instability of the current sheet, thereby promoting the appearance of a flare. In this case, the magnetic lines in three-dimensional space can diverge significantly along the special line. Also, the magnetic lines in three-dimensional space can be close to parallel, which means a comparatively large longitudinal component of the magnetic field. In this case longitudinal magnetic field will stabilize the instability of the current sheet, thereby hindering the flare release of magnetic energy.

In the vicinity of the singular magnetic field line, a divergent magnetic field (the mirror field created in plasma installations designed to solve the problem of controlled thermonuclear fusion) can be superimposed on the X-type configuration. It creates a rotational motion around the singular line, preventing the occurrence of a flare. The superposition of fields can be dominated by the X-type field or the divergent field.

MHD simulation above the active region AR 10365 showed the appearance during flares and before flares in the bright region of flare or pre-flare emission of a significant number of current density maxima with configurations promotable for the occurrence of solar flares. In the vicinity of these maxima, there is a diverging magnetic field in space along a singular magnetic line, and there is no significant dominance of the diverging magnetic field above the X-type field in the plane of the current sheet. The problem is that maxima with such properties also occur outside the bright region of flare emission, and in the bright region there are not very many such maxima compared to their total number. This problem of the coincidence of the flare positions found from the MHD simulation results with the observed flare positions can be solved by the appearance of a surface of increased current density passing through a chain of current density maxima. To solve this problem, we performed a detailed comparison of the MHD simulation results above the active region AO 10365 at 02:32:05 on May 26, 2003, three hours before the M 1.9 flare, with the 17 GHz radio emission observations obtained with the Nobeyama Radioheliograph. At this moment, the energy for the flare is accumulated in the magnetic field of the solar corona and the plasma is heated by the currents that create this field. Near the boundary of the region of bright pre-flare emission, a chain of current density maxima with field configurations that are not promote for flares appearance. The surface of increased current density passing through this chain of current density maxima is actually a large current sheet of ˜ 50,000 km. This surface is an arcade of magnetic lines that is completely located in the region of bright pre-flare emission. At the top of the arcade, there are no current density maxima, but the current density there is quite high, differs little from the current density at the maxima, and plane current density maxima arise. At the top of the arcade, the field configuration has properties that promote the appearance of flare instability: the dominance of the X-type field in the plane of the current sheet configuration over the diverging magnetic field and a significant divergence of magnetic lines in three-dimensional space along the direction of the singular line, meaning a small value of the longitudinal component of the current sheet. The location of the arcade in the bright region of flare emission confirms the possibility of the appearance of flare instability at the top of the arcade, which will propagate to a significant part of the arcade.

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