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THE PHYSICAL MECHANISM OF THE SOLAR FLARE, STUDIED ON THE BASIS OF THE RESULTS OF OBSERVATIONS AND MHD SIMULATION

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Abstract. According to numerous indications obtained from observations primordial energy release during solar flares takes place in the solar corona above the active regions. Emission in the lower layers of the solar corona, as well as processes in interplanetary space and in the Earth's magnetosphere are the consequence of the primordial flare process in the solar corona. The flare is explained by the release of energy accumulated in the magnetic field of the current sheet formed in the corona. An electrodynamical model of a solar flare is proposed, which explains its main observational manifestations, in particular, the appearance of X-ray emission on the surface of the Sun. The first results of MHD simulation in the real scale of time show the appearance of current sheets in the corona above the active region, which confirms the proposed solar flare mechanism.

Introduction. The physical mechanism of solar flare

During the solar flare, in a few tens of minutes, ~ 10^{32} erg of magnetic energy is released, which transforms into the energy of solar cosmic rays (protons accelerate to energies of ~ 20 GeV), into the thermal energy of a heated plasma, the kinetic energy of the plasma ejection, and the energy of electromagnetic emission in a wide the range (from radio, optical, ultraviolet to X-ray and γ-emission) caused by heated and accelerated electrons and accelerated protons. One of the most interesting properties of a flare is its appearance high in the solar corona - at altitudes of 15000 - 30 000 kilometers (1/40 -1/20 of the solar radius). This is evidenced by numerous observations. These include the appearance of a thermal X-ray source in the corona at the said heights when observing the on the limb of solar disk [1]. The appearance of a region of strongly heated plasma in the corona during the flare is demonstrated by the emission of FeXXIV ions in the line 193 Å, which arise at a temperature of 20 MK, and in other high-temperature lines [2, 3]. Numerous studies [4, 5] showed the invariability of the magnetic field on the solar surface during flares, which indicates the release of magnetic energy high in the corona.

The appearance of a flare in the corona can be explained by the mechanism, according to which the flare energy is stored in the magnetic field of the current sheet formed in the vicinity of a singular X-type line [6]. Such a singular line is formed in the magnetic field of the corona, when the sources of the magnetic field on the solar surface are located with alternating polarities. When current along the singular line arises due to plasma disturbances, magnetic forces directed along one axis of coordinates to a singular line, and along another axis from a singular line, cause to the accumulation of disturbances, propagating from the solar surface, with the formation of the current sheet. During quasi stationary evolution, during which the total plasma mass of the sheet decreases [7], the current sheet transforms into unstable state. Observations of high-temperature plasma emission in the lines of multiply ionized iron ions revealed structures that do not coincide with the magnetic lines. Such structures can be current sheets. The coincidence of the position of the current sheet obtained by numerical magnetohydrodynamic (MHD) simulation [8, 9] with the position of the observed flare source of thermal X-ray emission provides independent evidence of the mechanism of the current sheet.

The most common of the alternative flare mechanisms is the mechanism in which the flare energy is stored in the field of a magnetic rope. From the very beginning, the rope is set in an unstable or non equilibrium state [10] or is formed as a result of too fast or too complex plasma motion on the photosphere [11-13]. Simulation of the flare situation over the active region [14] in a statement of a problem close to ours confirmed the formation of a current sheet at the site of flare energy release. At the same time, the appearance of rope or any other signs of alternative flare mechanisms was not detected, as also in our simulation. The mechanism of current sheet is the only one capable of explaining the slow accumulation of flare energy in a stable configuration, followed by its transition to an unstable state.

Based on the mechanism of releasing the energy of the magnetic field of the current sheet, using the results of numerical MHD simulation in the corona above the active region and observations, an electrodynamic model of a solar flare has been proposed [15]. Beam hard X-ray emission during a flare on the surface of the Sun is explained by the deceleration of electrons, accelerated in field-aligned currents along the magnetic lines coming out of the sheet, in the lower dense layers of the solar atmosphere. Field-aligned currents are caused by the Hall electric field, which is formed in the current sheet due to the interaction of the current carried by the electrons with the magnetic field component normal to the sheet.

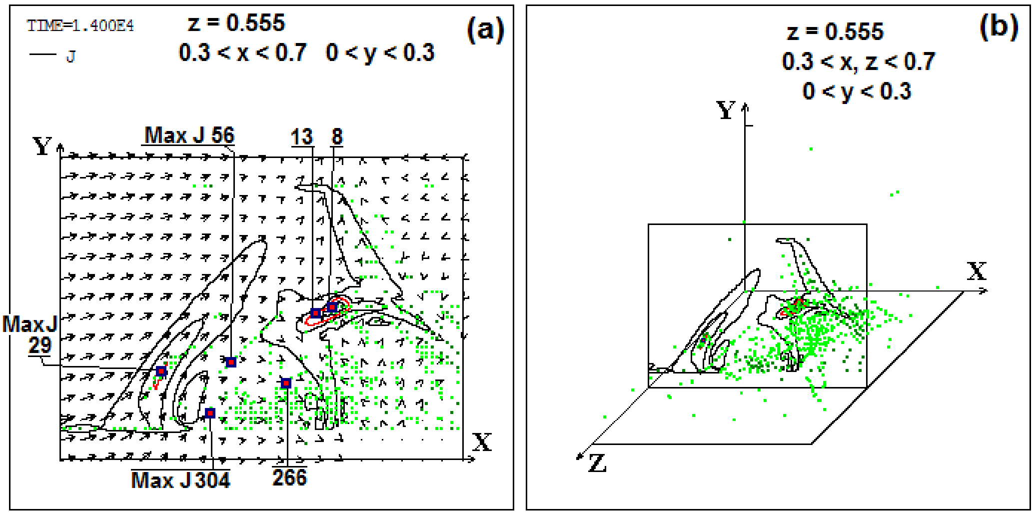

Figure 1. The plane z = 0.555 in the region of 0.3 <x, z <0.7; 0 <y <0.3. The Y axis is directed from the Sun perpendicular to the photosphere, the XZ plane (y = 0) is located on the photosphere, the X axis is directed from the East to the West, the Z axis from the North to the South.

On the necessity for MHD simulation in the corona in the real scale of time

Prior to this work, MHD simulation in the corona over the active region was only possible on a greatly reduced scale of time (in 10^4 times), in which the evolution of the magnetic field on the solar surface in 1 day in the calculations takes ~ 10 seconds. MHD simulation in the real scale of time is caused by the following reasons. During MHD simulation in the corona near the photospheric boundary, where there is a strong magnetic field gradient, numerical instabilities appear. These difficulties are especially exacerbated when simulation on a greatly reduced scale of time, due to unnaturally rapid changes in the magnetic field. The numerical methods used made it possible to limit the instability growth near the boundary and prevent its propagation into the region, which made it possible to obtain the field configuration in the corona. However, to determine the positions of the sources of beam X-ray emission at the intersection of the magnetic field lines outgoing from the current sheet with the photosphere, it is necessary to know sufficiently accurately the field configuration near the photosphere. The first results of simulation in the real scale of time during the day showed the appearance of weak instability near the photospheric boundary, which should not greatly distort the magnetic field. Simulation in the real scale of time also allows one to get rid of the appearance of current density maxima in the corona near the photospheric boundary, caused by unnaturally rapid changes in the field at the boundary, which mask current sheets.

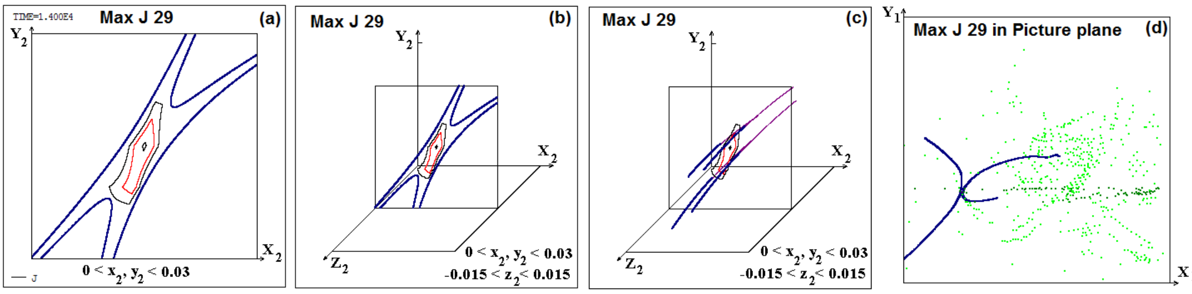

Figure 2. Magnetic lines and lines of equal current density (thin red and black) in the plane of the configuration of the current sheet of the 29th current density maximum (***a, b, c***). The plane magnetic lines (lines tangent to the projections of the magnetic field vectors onto the plane of current sheet configuration) are shown in bold blue (***a, b***), the lines of the magnetic field in three-dimensional space (***c***) in front of the configuration plane are shown in bold blue, behind the configuration plane, thin violet. (***d***) - The 29th maximum in the picture plane, the projections of plane magnetic lines shown on (a,b), and projections of the positions of the maxima of the current density in space (light green points) and the maxima of the current density in the plane z = 0.555 (dark green points).

When simulation in the real scale of time, a plasma with a magnetic field propagating upward even at a relatively low speed of ~ 10^4 cm/sec will rise to a height of ~ 10 000 thousand kilometers during a day. When simulating in the reduced scale of time, only relatively weak disturbances propagating at Alfven speed can reach such heights. Therefore, simulation in the real scale of time will make it possible to more accurately determine the configuration of the magnetic field and to establish the time of formation of the current sheet with the flare energy stored in its magnetic field.

Flare position search system on the results of MHD simulation

Even for sufficiently powerful flashes, the configuration of the magnetic field near the current sheet, distorted by the longitudinal field, can be so complicated that it is almost impossible to determine the position of the current sheet from the location of the magnetic lines in space. A graphic system for searching the current sheet position (flare position) on the results of MHD simulation is developed. The flare position search method is based on the fact that the maximum of absolute value of the current density is located in the current sheet. The maxima of the current density are searched, then an analysis of the magnetic field configuration is carried out near them. The graphic search system is described in detail in [8].

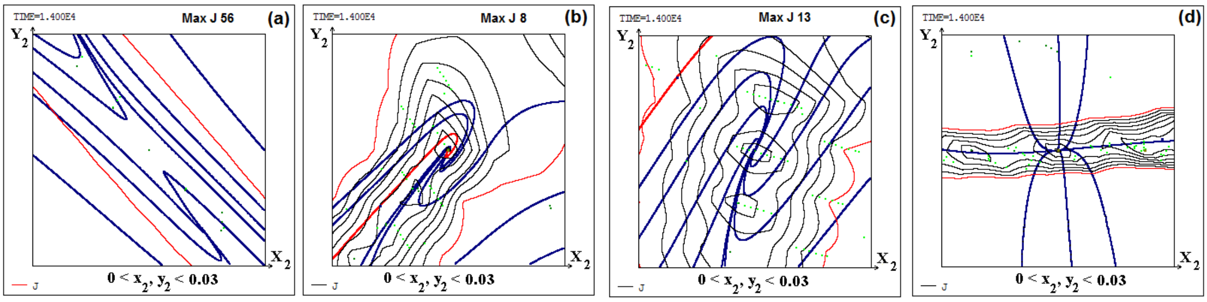

Figure 3. Magnetic lines and lines of equal current density in the plane of the current sheet configuration for the 56th (***a***), 8th (***b***), 13th (***c***) and 266th (***d***) current density maxima.

The first results of MHD simulation in the real scale of time

In order to exclude the influence of the non-photospheric boundary, the conditions at which should best approximate the conditions of free exit, the size of the computational domain significantly exceeded the size of the coronal region with a strong magnetic field, in which it is necessary to determine the places of magnetic energy accumulation for solar flares. The photospheric boundary of the computational domain has the shape of a square with a side length L = 400 000 km, which is taken as a unit of length. This size is more than 3 times larger the linear size of the active region (~ 120 000 km) with a strong magnetic field (100 - 1000 G) located in the middle of the photospheric boundary of the computational domain. The height of the computational domain of 120,000 km was approximately two times larger the height of the region with a sufficient strong magnetic field (10 - 1000 G), it was ~ 60 000 km. It was assumed that in the region with a small magnetic field (1–3 G) surrounding the region of a large magnetic field, strong disturbances will not appear when the condition $\partial \mathbf{V}/\partial n=0$ is set at the non-photospheric boundary. The calculations showed the absence of strong disturbances when the plasma flows out of the computational domain. In some places of the non-photospheric boundary, there appear velocities directed inward to the region, which in some cases lead to fast (more than 10^6 cm/sec) plasma motion in a part of the region with a small magnetic field. These results indicate the need for further calculations with other types of approximations of the conditions for free exit at the non-photospheric boundary in order to find out the possibility of avoiding disturbances with high speeds. However, at the same time, the calculations showed that fast flows arising near the region of a strong magnetic field transfer a very rarefied plasma and do not have any significant effect on the processes in the part of the calculation region with a large magnetic field. Therefore, the results obtained at present in the first stage can be used to analyze the flare situation above the active region.

Figure 1 depicts the situation in the region $0.3 < x, z < 0.7$; $0 < y < 0.3$, i.e. in a subregion in the central part of the computational region with a linear size of the photospheric border of 160 000 km., which completely contains the region in the corona with a large field above the active region of the solar surface. In the plane $z = 0.555$, located near the center of the selected region perpendicular to the photosphere and crossing the photosphere along a line parallel to the solar equator, the velocity field and lines of equal current density are shown. This figure, together with the image of the velocity field and lines of equal current density in the $z = 0.44$ plane in [16], gives an idea of the behavior of the values in the main part of the computational domain. Light points (light green points in color variant of paper on the Apatity seminar website *http://pgia.ru/seminar/*) show the positions of the first 450 local maxima of the current density in space, numbered in decreasing order of the current density in maximum. Dark dots (dark green) indicate the plane maxima of the current density in the plane $z = 0.555$, however, the graphical system makes it easy to move the plane along the Z axis perpendicular to it, so that it is easier to determine the position of the selected current density maximum. At the center of each current sheet formed in the corona, there should be one of the marked maxima of the current density. In order to establish whether a current sheet is formed in the vicinity of the selected maximum current density, it is necessary to construct a magnetic field configuration in the plane of the current sheet configuration, i.e. in the plane perpendicular to the magnetic field vector at the point of this current density maximum. The analysis showed the existence of a pronounced configuration of the current sheet in the vicinity of the 29th current density maximum located at an altitude of 32 000 km (Fig. 2). The configuration plane of this current sheet is perpendicular to the unit vector 0.502, 0.4, 0.767. The lines of equal current density on the left side of the plane $z = 0.555$ in Fig. 1 show the intersection of the current sheet with this plane.

The current sheet appears also in the vicinity of the 56th maximum of the current density (Fig. 3a). At most current density maxima, there is no pronounced configuration of the magnetic field of the current sheet with oppositely directed magnetic lines on either side of the sheet. The configuration of the magnetic field in the vicinity of such a maximum of the current density is the superposition of the field of a singular X-type line and a diverging field, which can form in the plasma trap of the mirror tube type. In addition to the accumulation of magnetic disturbances under the action of magnetic forces near a singular X-line, in a configuration with diverging magnetic lines, a twisting of the magnetic field occurs, which does not contribute to the formation of the current sheet and can weaken this process, distorting the plasma flow, which brings the magnetic field. As a result, a deformed spiral of magnetic field lines may appear near the sheet (we mean “flat” lines of a three-dimensional magnetic field, to be absolutely precise - lines tangent to the projections of the magnetic field vectors onto the plane of the current sheet configuration). Several current density maxima can form in the current sheet, as is seen for the configurations of the 8th and 13th current density maxima (Fig. 3b, 3c). A deformed configuration of a diverging field with a squashed current can also arise, the shape of which slightly resembles a sheet, as in the vicinity of the 266th maximum (Fig. 3d). In the available calculation, such a maximum of 304 [16] also appeared near the position of the flare on May 27, 2003, which was found from the calculation in a reduced scale of time [8, 9]. The flare will occur more than a day after the moment for which the configuration analysis was carried out, so there is still time for the evolution of the field near this maximum.

Conclusion

The mechanism of a solar flare, according to which the magnetic field energy of the current sheet is released in the corona, is confirmed by the results of numerical MHD simulation and numerous observations made both in the solar corona and near the solar surface. The first results of MHD simulation in the real scale of time during the first day of the evolution of the magnetic field and plasma above the active region of AO 10365 showed the appearance of current sheets in the vicinity of singular X-type lines in the corona, confirming the proposed flare mechanism. In addition, the MHD simulation showed the appearance of structures with current formed in the places where the field configuration near a singular X-type line was superimposed with a diverging magnetic field arising in a plasma trap of the mirror tube type. The appearance of additional magnetic forces caused by the interaction of the current along the axis of the singular line with the diverging magnetic field leads to a twisting of the magnetic field, and such away preventing the accumulation of high magnetic energy. Possibly, the appearance of low power flares and microflares is explained by such structures, which, as shown by the simulation, are formed much more than current sheets. The calculations carried out indicate the need for further simulation of the flare situation in the corona in the real scale of time both for a more detailed study of the flare mechanism and for the further use of the results of MHD simulation to improve the forecast of solar flares and their consequences.

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