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POSITION OF THE PRIMORDIAL RELEASE OF SOLAR FLARE ENERGY AT THE EXTENDED SURFACE OF MAGNETIC LINES WITH INCREASED CURRENT DENSITY: RESULTS OF MHD SIMULATION

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Abstract. The study of magnetic field configurations near the points of the arcade of magnetic lines with increased current density continued with the aim of studying the physical mechanism of solar flares. An analysis of the constructed configurations, taking into account new configurations in the vicinity of points in the middle of the bright pre-flare region, showed that the flare release of energy occurs in magnetic field configurations that promote the appearance of explosive instability, where current density maxima may not appear. The obtained result is necessary for searching for flare positions based on magnetic field configurations found by MHD simulation, and, subsequently, for forecasting flares based on understanding their physical mechanism.

Introduction

The premordial release of solar flare energy in the solar corona at an altitude of 15,000 km - 70,000 km, indicated by numerous observations ([1] and others), explains the physical mechanism of the flare (S.I. Syrovatsky, [2]), according to which the energy of the magnetic field of the current sheet, created in the vicinity of a singular magnetic field line as a result of the accumulation of disturbances propagating from the solar surface, is released in the corona. The fast release of the current sheet magnetic energy leads to the observed manifestations of the flare, which are explained by the electrodynamic model of the solar flare proposed by I.M. Podgorny [3]. The appearance of hard X-ray radiation on the surface of the Sun during a flare is explained by the acceleration of electrons in field-alighned currents caused by the Hall electric field in the current sheet. The electrodynamic model of a solar flare uses analogies with the electrodynamic model of a substorm, previously proposed by its author based on measurements on the Intercosmos-Bulgaria-1300 spacecraft [4].

Since it is impossible to obtain the magnetic field configuration in the corona from observations, to study the mechanism of a solar flare it is necessary to perform MHD simulations in the solar corona above the active region, in which the magnetic field measured at the solar surface is used to set the boundary conditions. The physical mechanism of a solar flare can only be studied if calculations begin several days before the flare, when the magnetic energy of the flare has not yet accumulated in the corona. Setting of the problem of the MHD simulation is described in detail in [5-11]. This work is a continuation of the work [11], in which general ideas about the mechanism of a solar flare and methods of studying it are described in more detail.

The configuration of the magnetic field above the active region can be quite complex, so it is practically impossible to find the positions of the singular lines and the current sheets formed near them directly from the magnetic field configuration obtained by MHD simulation. To solve this problem, a graphical system for searching for flare positions using the magnetic field configurations found by MHD simulation was developed, based on determining the positions of local current density maxima [12]. Previously, the system was used under the assumption that the current density is achieved in the middle of the current sheet, however, as the results presented here show, this assumption is not always fulfilled. In this case, the positions of the flares are associated with the positions of the current density maxima; in particular, the flares can be located on magnetic lines passing through the current density maxima. Therefore, the existing graphical system is useful for finding flare positions in any case, but for more convenient use, it should be modernized.

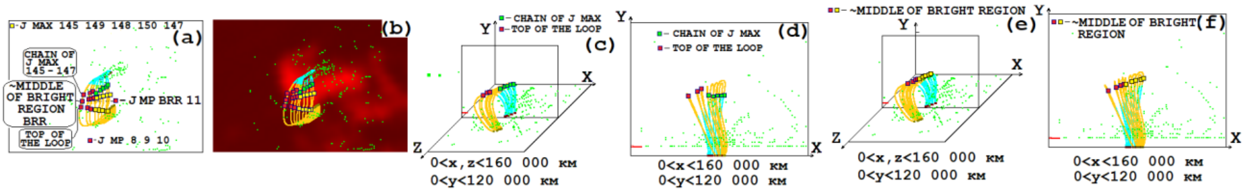

Figure 1. The chain of current density maxima, marked in green, and the magnetic lines of the arcade.

As the results of calculations [8-10] have shown, during flares and before flares, a large number of current density maxima are located in the bright region of flare or pre-flare emission. However, at the same time, a fairly large number of maxima are located outside the bright region of flare or pre-flare emission; their relative number compared to the total number of maxima can be quite large.

In order to understand why such an arrangement of current density maxima occurs, a detailed study of the pre-flare situation at 02:32:05 on 26.05.2025, three hours before the M 1.9 class flare above the active region AR 10365, which was started in [11], was continued. A comparison is made of the configuration obtained by MHD modeling with the distribution of the observed microwave radiation at a frequency of 17 GHz over the solar disk, obtained with the Nobeyama radioheliograph. As noted, of particular interest is the chain of closely spaced current density maxima with numbers 145, 149, 148, 150 and 147, represented by green dots in Figure 1 (all maxima are numbered in descending order of current density at the maximum). The magnetic lines, passing through these maxima of the chain, belong to an arcade with increased current density. The projections of these lines onto the plane of the solar disk are shown in Figure 1a, b (the distribution of microwave radiation at a frequency of 17 GHz is also superimposed on Figure 1b), their spatial location in the computational domain of the solar corona is shown in Figure 1c, e, their projections onto the central plane of the computational domain of the solar corona (the plane passing through the center of the calculated region and located parallel to the solar equator and perpendicular to the surface of the Sun) are shown in Figure 1d, f.

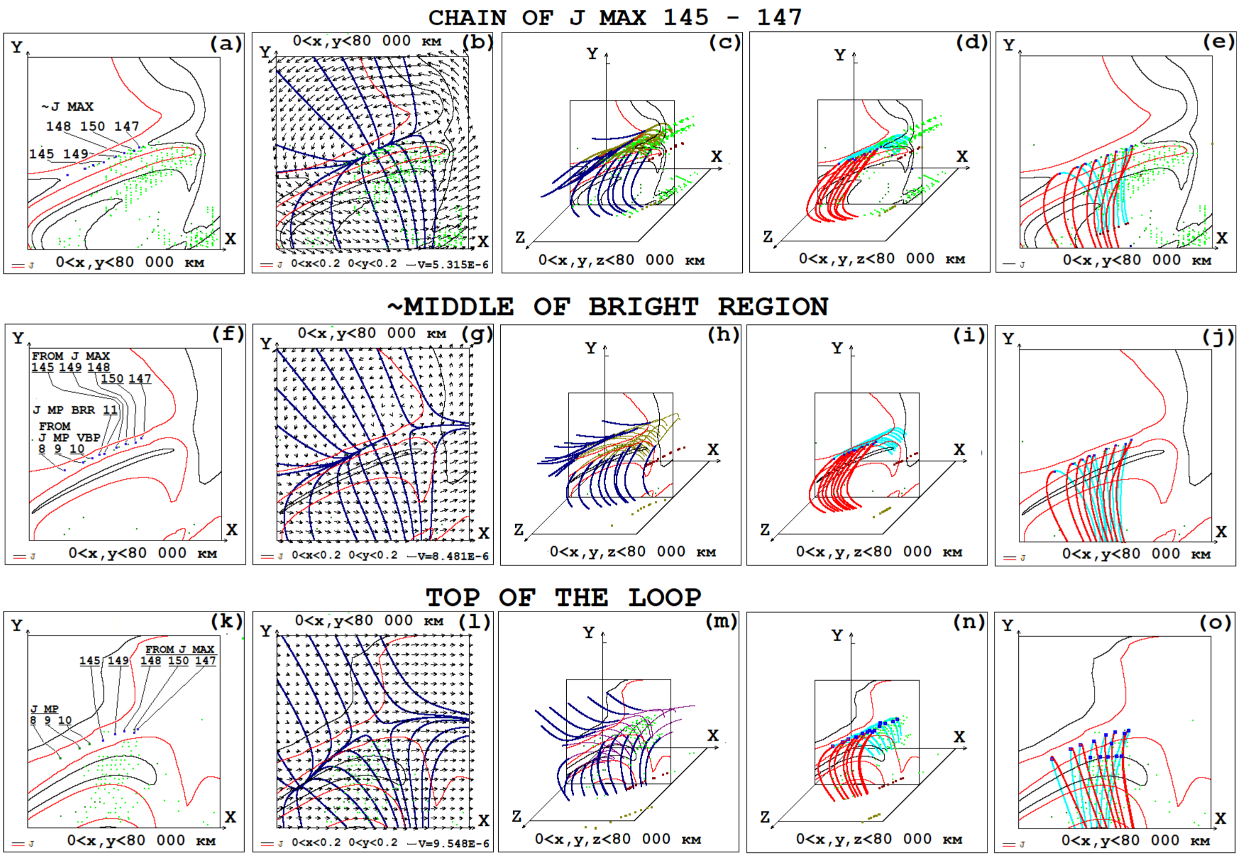

Figure 2. Plane and spatial configurations of the magnetic field in regions of large size 80 Mm.

Selection of regions with centers at points on the arcade of magnetic lines for the research of magnetic field configurations

For a better understanding of the obtained results of the study of the mechanism of solar flares and how to correctly search for the positions of solar flares, in comparison with the previous study [11], a study of configurations in areas with centers at points located on the arcade under study in the middle of the bright pre-flare region in projection onto the solar disk has been added.

To better understand the methodology for studying the field above the active region, we will describe in detail the choice of magnetic lines of the arcade and the regions in which the magnetic field configurations are studied. These regions are cubes of large size 80 mm and small size 12 mm, the central points of which lie on the arcade lines. The central plane of each cube (both large and small) is understood to be the plane passing through the center of the cube, located parallel to two faces of this cube with which it does not intersect, and perpendicular to two other faces of the cube with which this plane intersects. All cubes are oriented in space so that their central plane is perpendicular to the magnetic field vector at the central point of the cube. Larger cubes are constructed with centers at the middle maximum of the chain with number 148 and at two more points located on the magnetic line passing through this middle maximum: at the point of the loop top of this magnetic line (at which the magnetic field vector is parallel to the solar surface) and at the point whose projection onto the plane of the solar disk (perpendicular to the line of sight) is located near the middle of the bright region of pre-flare emission. The results of MHD simulation in large regions of size 80 Mm are presented as spatial images in cubes (Fig. 2c,d,h,i,m,n) and as plane images in large squares in the central planes of these cubes (Fig. 2a,b,e,f,g,j,k,l,o). Plane current density maxima are sought in the central planes of the cubes with centers at the loop top and near the middle of the bright region of pre-flare radiation. The arcade of magnetic lines (Fig. 1a-f) consists of lines passing through the maxima of the chain. To the arcade lines are added also magnetic lines passing through the plane maxima of the central planes of large cubes of 80 Mm with centers at the top of the loop (three plane maxima with numbers 8, 9 and 10, depicted in this plane in a large square in Figure 2k, the remaining plane maxima coincide with the points of intersection of the magnetic lines passing through the maxima of the chain with this plane) and near the middle of the bright region of pre-flare radiation (one plane maximum with number 11, Fig. 2f, for the rest, there is also a coincidence with the already constructed magnetic lines). The arcade size is ~50 Mm, in regions of large size 80 Mm it is represented by magnetic lines in three-dimensional space (Fig. 2d,i,n) and their projections onto the central plane (Fig. 2e,j,o). As can be seen from plasma density distributions, presented by the lines of equal density of plasma, in the central planes of large size 80 Mm, which are sections of the arcade (Fig. 2a, f, k), the arcade is a surface of increased current density, i.e. an extended current sheet. The centers of the small cubes are located at the maxima of the chain with numbers 145, 149, 148, 150 and 147 (green dots in Fig. 1) and at the intersection points of the magnetic lines of the arcade with the central planes of the large cubes (in Fig. 1, yellow dots for the lines passing through the maxima of the chain, and red dots for the added lines passing through the plane maxima). The results of MHD simulation in small-sized areas of 12 Mm are presented as spatial images in small-sized cubes (Fig. 3d, e, i, j) and as plane images in small-sized squares in the central planes of these cubes (Fig. 3a, b, c, f, g, h, k, m).

Properties of magnetic field configurations in selected regions and the location of their centers in projection onto the plane of the solar disk

At the points at the top of the arcade and near the center of the bright region of pre-flare emission, the maximum current density is not reached, but here it is possible to accumulate energy for the flare, pre-flare heating of the plasma, and then a fast release of energy during the flare due to the fact that the properties of the magnetic field configuration near these points contribute to the formation of a current sheet, and then the appearance of flare instability. These properties are possessed by configurations in large and small selected regions with centers located at the top of the arcade and near the center of the bright region of pre-flare emission. These properties of the configuration include the dominance of the X-type field, or at least almost equal influence of the X-type magnetic field and the divergent magnetic field (Fig. 2g,l for large-size regions of 80 Mm and Fig. 3f,g,h,k,l,m for small-size regions of 12 Mm) and a significant divergence of magnetic lines in three-dimensional space along the direction of the singular line (Fig. 3h,m for large-size regions of 80 Mm and Fig. 3i,j,n,o for small-size regions of 12 Mm), which means a small value of the longitudinal component of the current sheet. In this case, the current density at these points with configurations promotable for the appearance of flares is not much less than the current density at the chain maxima, and plane current density maxima appear. At the same time, for the chain of maxima located near the upper boundary of the bright pre-flare region, the field configuration is not very favorable for the development of flare instability, since in the plane configuration the diverging field dominates (Fig. 2b and Fig. 3f,b,c) and the lines diverge slightly in space (Fig. 2c and Fig. 3d,e).

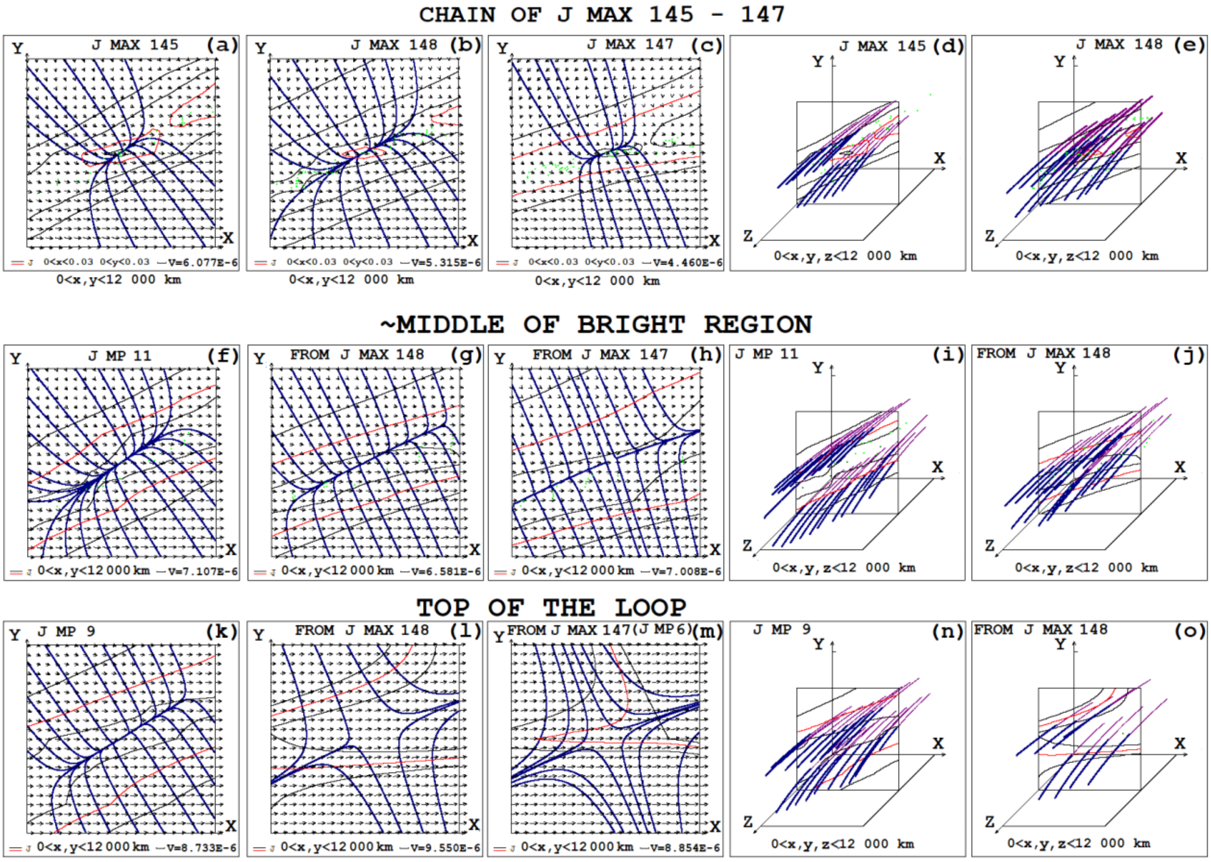

Figure 3. Plane and spatial configurations of the magnetic field in regions of small size 12 Mm.

Discussion and conclusion; the possibility of using the obtained results to search for the positions of flares based on the magnetic field configuration obtained by MHD simulation

The study of magnetic field configurations near points on the magnetic lines of the arcade that appeared before the M1.9 flare on May 26, 2003, made it possible to gain insight into the physical processes that lead to the accumulation of magnetic energy that should be released during the flare, and to determine where the flare should occur. The arcade of magnetic lines with an increased current density of a large size of ~50 Mm is an extended current sheet. Somewhat unexpected is the fact that the accumulation of magnetic energy of the flare, pre-flare heating of the plasma due to dissipation of the magnetic field, and the fast release of magnetic energy during the flare do not occur in the place where the current density reached its maximum. However, understanding this process makes it possible to find the position of the flare.

In the place where processes occur that lead to the fast release of magnetic energy, the current density is not much less than its maximum value, and plane maxima of the current density often appear in the plane perpendicular to the magnetic field vector at a given point. The magnetic field configuration in this place, due to magnetic forces directed in a certain way, should contribute to the creation of a current sheet, and then the appearance of flare instability. The achieved understanding of the magnetic field configurations in which a flare should occur should make it possible to more accurately find the positions of solar flares with the aim of, in the future, improving the forecast of flares. To achieve this goal, it will be necessary to perform a more detailed study of this and other pre-flare and flare magnetic field configurations using an modernized MHD simulation technique and a technique for searching for flare positions based on the field configuration found by MHD simulation.

The performed research showed that the positions of solar flares do not necessarily have to be in the places of current density maxima, but they are associated with these places, in particular, they most likely should be on the same magnetic lines on which the current density maxima are located. The existing search system based on finding current density maxima can be used to search for flare positions, but given the latest results, its use becomes more labor-intensive. In order to better automate the process of searching for flare positions and make it more convenient, it will be necessary to modernize the existing graphical search system. The simplest method of modernization consists in searching for plane maxima of the current density in planes perpendicular to the magnetic field vectors at the points of maxima. It is possible to select only plane maxima at the tops of magnetic loops, i.e. in places where the magnetic field vector is parallel to the solar surface. It is possible to use the definition of how the magnetic field configuration in the vicinity of the found point is promote for flare instability, for which, in particular, it will be necessary to analyze the signs and ratios of the absolute values of the eigenvalues of the matrix $\nabla \mathbf{B}$ with the appropriate choice of the coordinate system in the plane perpendicular to the magnetic field vector. There are also other ways to modernize the graphical search system; combinations of several approaches are possible.

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