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Study of the physical mechanism of a solar flare using MHD modeling over an active region: the onset of an extended surface of magnetic lines passing through a chain of current density maxima

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Abstract. The primary release of solar flare energy in the corona at altitudes of 15,000 – 70,000 km is explained by the physical mechanism of S.I. Syrovatsky, based on the rapid release of energy accumulated in the magnetic field of the current layer. The observed manifestations of the solar flare are explained by its electrodynamic model proposed by I.M. Podgorny. The model uses analogies with the electrodynamic model of a substorm, previously developed by its author. Since it is impossible to obtain the magnetic field configuration in the corona from observations, it is necessary to conduct MHD modeling. When setting the problem, no assumptions were made about the mechanism of the solar flare. For the numerical solution, an upwind absolutely implicit finite-difference scheme, conservative with respect to magnetic flux, was developed. The scheme is realized in the PERESVET computer program. A detailed study of the pre-flare state over the active region AR 10365 was conducted. The study revealed the emergence of an extended current sheet 50,000 km wide, which is a surface of magnetic lines passing through a chain of closely spaced current density maxima. The magnetic lines of the surface are in the form of arches located in the bright region of the flare emission. At the center of such a current sheet, a 3D maximum of current density does not necessarily have to be achieved. An appearance of a flare in such an arcade is explained by the fact that the main part of the surface of the magnetic arcs has properties that contribute to the development of flare instability.

Keywords: solar flare; current sheet; MHD simulation; active region

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1 Introduction

Numerous observations show the primary release of solar flare energy in the corona at altitudes of 15,000 to 70,000 km (Lin et al. (2003) and others). This can be explained by a physical mechanism of Syrovatskii (1966) based on the accumulation of energy in the magnetic field of a current sheet formed near a singular magnetic field line. The fast release of the magnetic energy of the current sheet leads to the observed manifestations of the flare, which are explained by the electrodynamic model of the solar flare proposed by Podgorny I. et al. (2010). The model was developed based on the results of observations and MHD simulation and uses analogies with the electrodynamic model of a substorm, previously developed by its author (Podgorny I. et al. 1988).

Since it is impossible to obtain the configuration of the magnetic field in the corona from observations, to study the flare situation it is necessary to carry out MHD simulations in the solar corona. When setting the problem, no assumptions were made about the mechanism of the solar flare. All conditions were taken from observations. To study the physical mechanism of a solar flare, calculations must begin several days before the flare, when magnetic energy for the flare has not yet accumulated in the corona.

2 Problem statement and developed methods of solution

MHD simulation is performed over the active region AR 10365 during the time interval from 24.05.2003 20:48 to 27.05.2003 20:48. The computational domain in the corona has the form of a rectangular parallelepiped ($0 \leq x \leq 1$, $0 \leq y \leq 0.3$, $0 \leq z \leq 1$) ($L_0 = 4 \times 10^{10}$ cm). The lower boundary of the computational domain y=0 (XZ) contains the active region.

For the numerical solution of MHD equations, the absolutely implicit upwind finite-difference scheme, conservative relative the magnetic flux, has been developed (Podgorny A. & Podgorny I. 2004). Special methods have been developed to construct a scheme that remains stable over the longest possible time step. The magnetic field setting at the photosphere boundary was calculated from the potential magnetic field using the line-of-sight field component at the photosphere measured by SOHO MDI (http://soi.stanford.edu/magnetic/index5.html). Parallelization of calculations was carried out by computing threads on the GPU using CUDA technology.

The magnetic field configuration obtained by MHD simulation is so complex that it is often impossible to determine the positions of special lines and the current sheets appearing near them. For this purpose, a graphical search system (Podgorny A. & Podgorny I. 2013) was developed, based on the determination of the

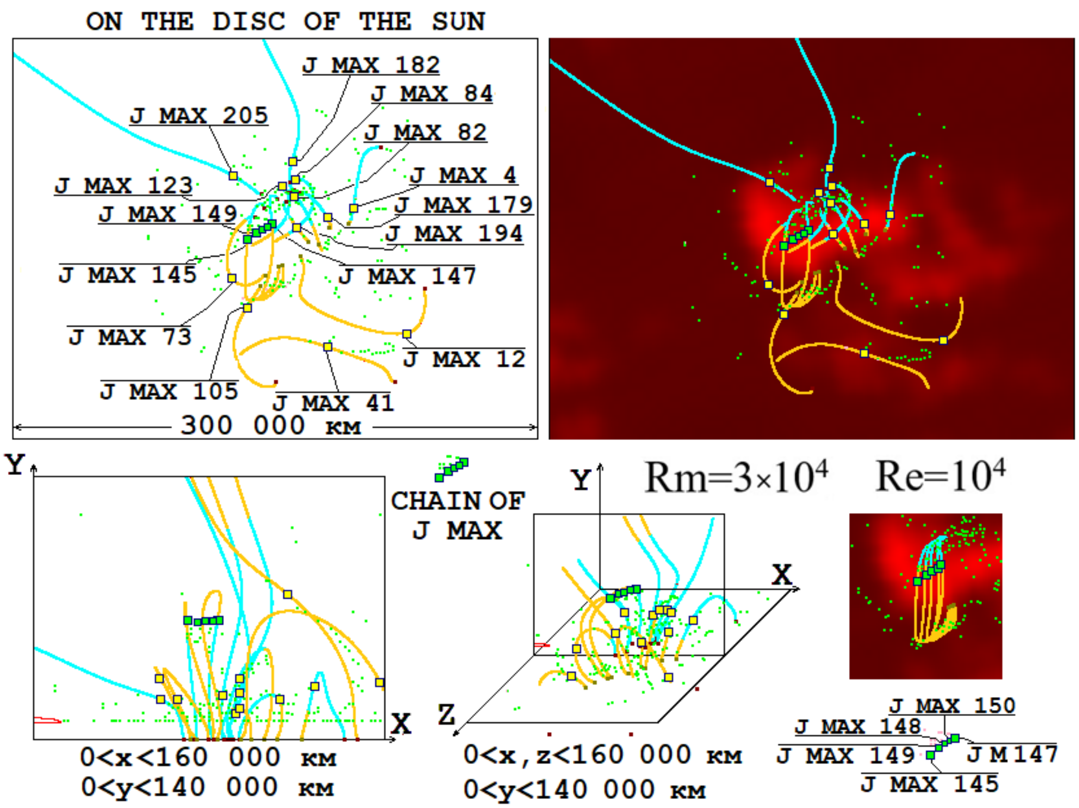

Fig. 1. The positions of the current density maxima in the calculated region of the corona in space and their projections onto the central plane of the calculated region (the plane passing through the center of the calculated region, located parallel to the solar equator and perpendicular to the solar surface) and onto the picture plane (perpendicular to the line of sight). The distribution of microwave radio emission at a frequency of 17 GHz, obtained on the solar disk using the Nobeyama radioheliograph, is superimposed on the picture plane. The magnetic field configuration is represented by magnetic lines passing through the selected current density maxima, and their projections onto the planes. The chain of maxima consists of points marked in green.

positions of the current density maxima that are achieved in the centers of current sheets.

3 Extended surface of magnetic lines passing through the chain of current density maxima

The detailed study of pre-flare state over the active region AR 10365 at 02:32:05 on May 26, 2003, three hours before the M 1.9 flare was carried out by comparing the results of numerical MHD simulation in the corona with observations of radio emission at a frequency of 17 GHz obtained at the Nobeyama Radioheliograph (NoRH). Magnetic field configuration is represented by lines passing through maxima of current density with the numbers 145, 147, 194, 179, 4, 73, 105, 41, 12, 205, 123, 82, 84, 182 (Fig. 1.). The current density maxima are numbered in descending order of current density. 3D magnetic lines in the computational domain in the corona, and projections of magnetic lines onto the central plane of the computational domain are shown. Also, the intensity distribution of microwave radiation at a frequency of 17 GHz observed on the solar disk using the Nobeyama radiheliograph (NoRH) is superimposed on the projections of magnetic lines onto the picture plane.

The magnetic field configurations at the selected points of current density maxima indicate favorable conditions for the occurrence of flares at some maxima located in the region of bright flare emission. There is no significant dominance of the diverging magnetic field in the vicinity of these maxima. At the same time, maxima with such properties also occur outside the bright region of flare emission.

The problem of coinsidence of bright flare emission regions with flare positions found from MHD simulation results can be solved by the occurrence of a surface of high current density, the current passing through a chain of current density maxima. The maxima of this chain with numbers 145, 149, 148, 150 and 147 in Fig. 1 are shown by green dots. Magnetic lines on the solar disk passing through the maxima of this chain are shown separately on an enlarged scale.

The 2nd row of Fig. 2 shows the plane and three-dimensional configurations near the chain maxima in a square and in a cube of 12,000 km. These configurations do not have properties that could significantly promote the flare release of energy. In plane configurations, the divergent magnetic field dominates over the X-type field, and in three-dimensional configurations, the field lines do not diverge much along the singular line, which means a relatively large longitudinal component of the magnetic field, stabilizing explosive instability.

The study of plane and three-dimensional configurations in a square and in a cube with a larger size of 80,000 km with the center at the 148th maximum located

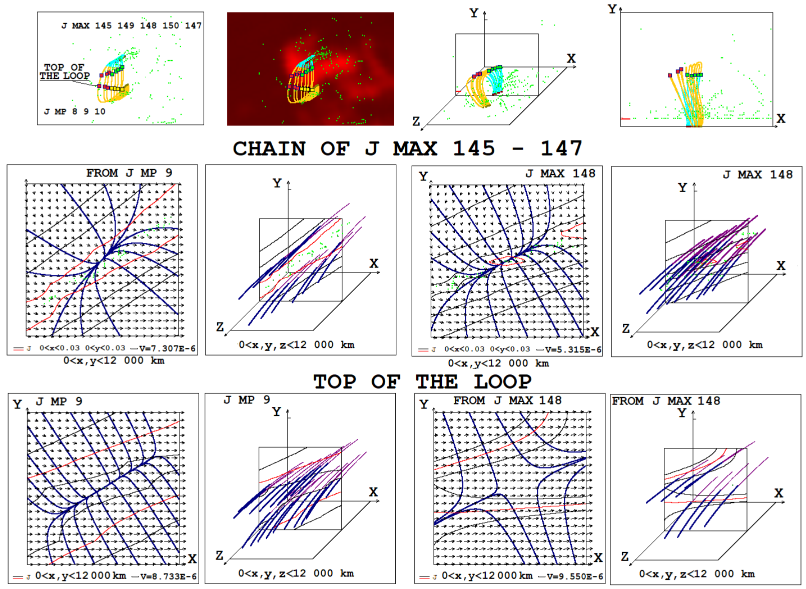

Fig. 2. Plane and spatial configurations in regions of 12,000 km in size with centers at the points of the chain of maxima and at the points at the top of the arch located on magnetic lines coming out of the points of the chain of maxima.

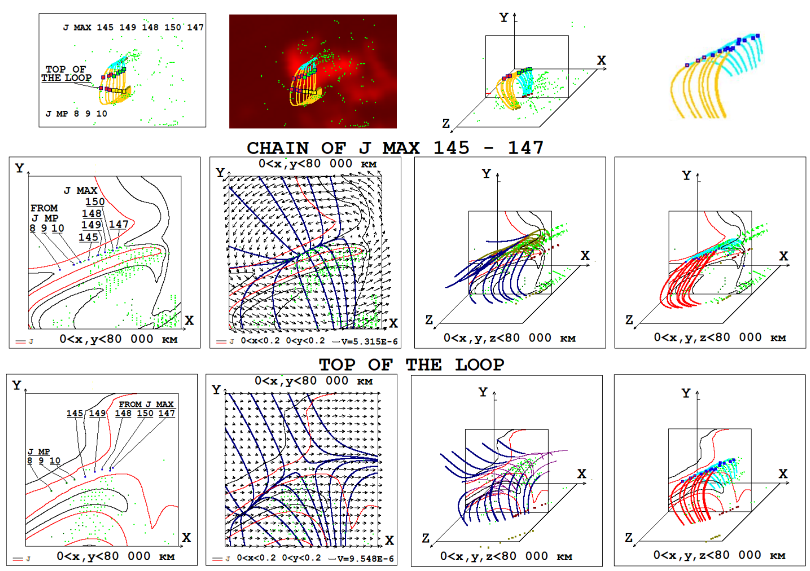

Fig. 3. Plane and spatial configurations in large regions of 80,000 km. In the central part of one of these regions there is a chain of maxima. In the central part of another region there are points at the top of an arch located on magnetic lines coming out from the points of the chain of maxima.

in the middle of the chain (Fig. 3, the second row) showed that all the chain maxima belong to the same current sheet of considerable width (50,000 km). Magnetic lines in a cube passing through the chain maxima form an arcade (Fig. 2, the last figure of the second row). In the upper rows of Fig. 2 and 3, the chain maxima points are marked in green, and the points on the tops of the loop located on magnetic lines, passing through the chain maxima points, are marked in yellow.

Magnetic field configurations (3rd row in Fig. 2) near the loop top points in the central plane of 12,000 km in size have properties that promote the development of flare instability. In most of these small regions, the X-type field dominates, while in other regions, the diverging field dominates very weakly. In the three-dimensional configuration, the field lines diverge significantly in the direction along the singular line, which means that the longitudinal component of the magnetic field is relatively weak, so that it will not be able to stabilize flare instability.

A comparison of two-dimensional and three-dimensional configurations in small regions of 12,000 km for the points of the chain of maxima and the points at the top of the arcade (Fig. 2) shows a much more favorable situation for the occurrence of flare instability at the tops of loops than at the points of the chain of maxima. The same result is obtained by comparing the magnetic field configurations in large regions (80,000 km in size) at the location of the chain of maxima and at the top of the arch (Fig. 3).

4 Conclusion

The problem of coinciding the positions of flares found as a result of MHD modeling with the observed bright region of flare radiation can be solved by the found arcade of magnetic lines passing through a chain of current density maxima. The arcade is entirely located in the bright region of pre-flare emission at a frequency of 17 GHz, obtained by the Nobeyama Radioheliograph (NoRH).

Extended version of this article is available at https://sites.lebedev.ru/ru/podgorny/file/7096.

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