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POSITIONS OF X-RAY EMISSION SOURCES OF SOLAR FLARE OBTAINED BY MHD SIMULATION

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Abstract. Several mechanisms of solar flare production are considered by different authors. Usually the initial conditions are artificially set such a way that it is required for development of the proposed mechanism. The problem of used condition formation during evolution of a real active region is not considered in such approach. In our MHD simulation we does not use any hypotheses about the flare mechanism, but the flare mechanism is found from the numerical MHD simulations in which all the conditions are taken from observations. It is shown that flare energy accumulation occurs in the current sheet magnetic field created by disturbances focusing in the vicinity of an X-type singular line. The electrodynamical model of the solar flare based on current sheet mechanism, which explains main flare manifestations, has been developed. Using this electrodynamical model the positions of sources of thermal X-ray radiation is found for the flare occurred May 27, 2003 at 02:53. To find positions of sources of soft X-ray radiation in the corona the graphical system is developed. The comparison with RHESSI X-ray observations is made.

Introduction

The primordial flare energy release takes place in the solar corona above an active region at the height 15 - 30 thousands kilometers. It is proved by flare X-rays observations on the solar limb [1, 2]. MHD simulation with the real initial conditions on the photosphere [2, 3] show that flare energy accumulation can occur in the current sheet magnetic field created by disturbances focusing in the vicinity of an X-type singular line. After the quasi-steady evolution the current sheet transfers into an unstable state [5]. As a result, explosive instability develops, which cause the flare energy release. A number of papers consider several other mechanisms of solar flare: magnetic reconnection between the twisted magnetic flux tubes (helicity); compression of plasma by the self current (pinch-effect); different instabilities of current in plasma (see review [6, 7]). The most widely used mechanism is based on the assumption of magnetic rope appearance [8]. If the rope current crosses the arch magnetic lines, then the 1/c $\mathbf{j}\times\mathbf{B}$ force accelerates plasma upward and stretches magnetic lines. As a result the current sheet appears under the rope. This sheet is analogous to one is created by disturbances focusing in the vicinity of X-type singular line. Occurrence of magnetic rope or other alternative mechanism requires appropriate conditions in the solar corona. It is difficult to explain how such conditions can appear due to slow evolution of magnetic field, which is observed on the solar surface. It is impossible to get instantly a powerful rope in the process of slow active region evolution before a flare. Slow grows of the rope current in equilibrium state demands self-consistent grows of the arch magnetic field to conserve the stable equilibrium state, which really cannot be fulfilled. Usually simulations are performed in the assumption of existence some powerful equilibrium configuration with big amount of free energy, that suddenly becomes unstable. The possibility of creation such a system at slow evolution of an active region is not considered.

Until now, nobody has been able to simulate the appearance of magnetic rope for a real change of the magnetic field on the photosphere. Here another approach is proposed. Instead of hypothesizing, we find the flare mechanism directly from the numerical MHD simulations in which all the conditions are taken from observations. In such approach no assumption about the physical mechanism of investigated phenomenon is used.

MHD simulation is carried out in the solar corona in the computational domain in the form of a parallelepiped, the lower boundary of which is located on the photosphere in the active region. The size of the computational domain is several times larger than the size of the active region of the Sun, so the photospheric boundary is located far from strong magnetic field sources and it produces no errors in the numerical simulation.. This small field adjacent to the active region can influence the field in the corona, as it is situated in a large area.

The calculations are initiated several days before the flare, when strong disturbances in the corona are absent. Therefore, the potential magnetic field in the corona, calculated from the field distribution observed on the photosphere, is used for setting initial conditions. The magnetic field distributions measured on the photosphere are used for setting boundary conditions during period of simulated active region evolution. Others boundary conditions are approximated by free-exit conditions. The special numerical methods are developed to stabilize numerical instabilities. The methods are realized in the PERESVET code on the FORTRAN language. The absolutely implicit finite-difference scheme with upwind approximation of transport terms is used. This scheme is also conservative relative to the magnetic flux. It is solved by the iteration method.

The results of 3D MHD simulation [3, 4] and comparison of with X-ray observations on spacecrafts Yohkoh and RHESSI permit to create the solar flare electrodynamical model [9, 10]. The model explains main flare manifestations. The flare occurs because of fast release of energy accumulated in the magnetic field of the current sheet, created in the preflare state above an active region. The plasma, heated by fast dissipation of the magnetic field, emits X-ray radiation with thermal spectrum for the temperature, which equal to several keV. In this model the Hall electric field in the sheet generates field-aligned electric currents in the corona along the magnetic field lines that are crossing a current sheet. The hard X-ray emission is the bremsstrahlung emission in the chromospheres of electrons, which are accelerated in field-aligned currents. The positions of sources of X-ray radiation can be found, if the magnetic field configuration is known from results of MHD simulation. According to the solar flare electrodynamical model the position of thermal X-ray emission is situated in the current sheet, and positions of nonthermal hard X-rays are places of crossing of the photosphere with the magnetic lines, which are going out of the current sheet. The aim of present work is investigation of the possibility of finding of the current sheet position in the numerical experiment and comparison this position with positions of the thermal X-ray radiation.

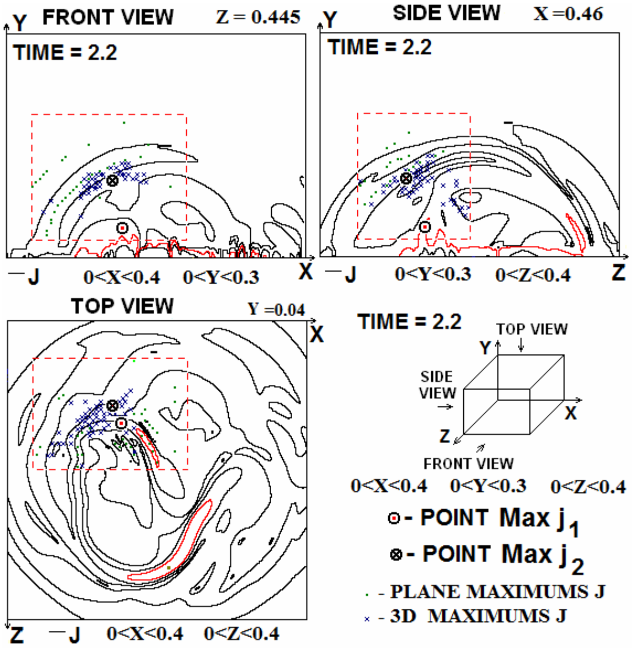

Fig. 1 The lines of the constant current density and plane current density maximums marked in the plains containing the point Max j_1 : Front View z=0.445, Top View y=0.04, Side View x=0.46. The projections of 3D current density maximums are marked by crosses. The maximums are marked only in the subregion $0.3389 < x < 0.5456$, $0.02362 < y < 0.1919$, $0.355 < z < 0.505$, which boundaries are marked by dashed lines. The chosen points Max j_1 and Max j_2 are marked.

The method of search current sheets positions

The analysis of magnetic field configurations in the different planes, which was fulfilled for MHD simulation results in the active region 10365 [9,10], showed the formation of several current sheets above this active region. Each of them can case the flare. In this paper an attempt is made to find the position of X-ray sources of the flare, which occurred May 27, 2003 at 02:53 in the active region NOAA 10365, using the results of the MHD simulations, and to compare with the X-ray observations.

To find positions of sources of soft X-ray radiation in the corona the graphical system developed by authors is used. To find the position of the current sheet, its property is used, according to which the local maximum of the absolute value of the current density is located in the center of a current sheet. In any selected plane, which can be placed arbitrarily in the space in the computational domain, the lines of level of absolute values of current density are constructed. Furthermore, in this plane all positions of local maxima of the current density in the plane and projections of all positions of the local maxima of the current density in the space on the plane are marked. Marked points are located at the intersection of the current sheets with the plane, or they are corresponded to centers of current sheets. The program can easily obtain information about any marked point of the maximum. It can be outputted coordinate value of that point in any chosen coordinate system and the all calculated variables (magnetic field vector, plasma density, and plasma temperature, etc.) in this point. In order to determine whether a given point of the current density maximum correspond the current sheet center or simply corresponds to an increase of the current density as a result of some disturbance, the program offers the possibility to build the configuration of the magnetic field in the vicinity of the selected point in any arbitrarily rotated coordinate system. Typically, in first turn it is expected to build the magnetic field configuration in a plane containing the selected point of the maximum current density which is situated perpendicular to the magnetic field vector. [11].

For comparing of observed X-ray sources positions with the results of MHD simulations the strongly reduced time scale [9, 10] are used because even using a powerful personal computer, simulation in the real time scale should demand too large time for calculation. Such fast magnetic field change on the photosphere can cause disturbances with large current. However, the places of current sheets creation in any case must be X-type singular lines.

Comparing of calculated position of the current sheet with the measurements of thermal X-ray emission

The time interval τ=6.108 s is taken as the unit of time. For simulation in a reduced time scale the field evolution on the photosphere during the time τ corresponds to real evolution during a day. The simulation is initiated from field configuration measured two days before the flare May 27, 2003 at 02:53. The moment 2.2 corresponds to the moment of flare May 27, 2003 at 02:53 in the active region NOAA 10365. So this moment is chosen as for comparison with X-ray observations.

The Fig. 1 presents lines of the equal current density and positions of its maximums in planes, which are perpendicular to axis of the computational domain, in the moment t=2.2. X-axis and Z-axis are situated on the photosphere, X-axis is directed from East to West, Y-axis directed from North to South. The photospheric boundary of the computational domain is a square with the side of 400 000 km, which is ~ 4 times bigger than the size of active region. The active region situates in the central part of this square. The length of the square side is taken as the unit of length. Y-axis is directed perpendicular to the photosphere from the Sun. The size of computational domain along the Y-axis is 120 000 km (0.3 in dimensionless units). The coordinate origin is in the Northern Eastern corner of the computational domain, which is rectangular parallelepiped of the form ($0<x<1$, $0<y<0.3$, $0<z<1$). Fig. 1 presents the part of computational domain with linear size of photospheric boundary 160 000 km (0.4 dimensionless units) of form ($0.3<x<0.7$; $0<y<0.3$, $0.3<z<0.7$) where the main magnetic field is situated.

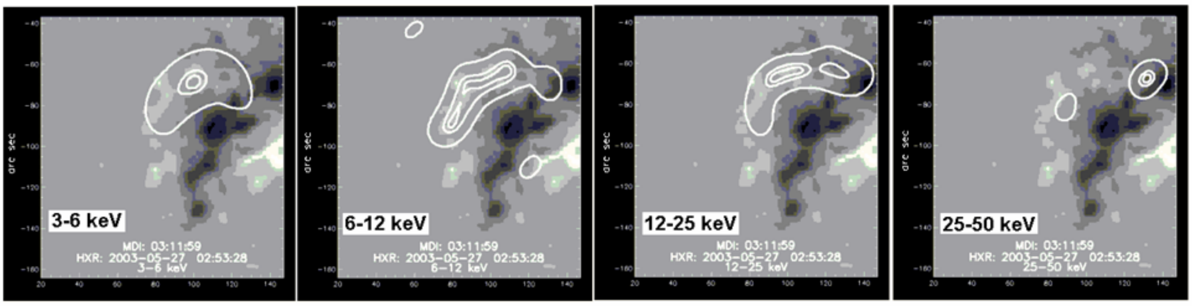

Fig. 2 Distributions of X-ray emission for the flare May 27, 2003 at 02:53 in soft and hard ranges obtained on RHESSI spacecraft (http://rhessidatacenter.ssl.berkeley.edu).

As the active region is situates near the solar disk center (S6 W5), the images in the picture plane (in perpendicular to line-of-sight plane) presented in Fig. 2, approximates well the projection on the plane *y*=const. Fig. 2 presents images of X-ray intensity for the flare May 27, 2003 at 02:53 in soft (1-30 KeV) and in hard (>30 KeV) ranges obtained on RHESSI spacecraft (http://rhessidatacenter.ssl.berkeley.edu). Fig. 2 shows that the source of soft X-ray situated in the area $0.3389 < x < 0.5456$, $0.355 < z < 0.505$, the boundary of this subdomain is marked by dashed lines in the projection *y*=const in Fig. 1. As the observations of soft X-ray on the limb shows that the flare takes place on heights from 15 000 km to 30 000 km (from 0.0375 to 0.075 in dimensionless units) we can be practically sure that the position of our flare is inside the interval of heights from 0.02362 to 01919 in dimensionless units. So one can see that the current density maximums are situated in the subdomain ($0.3389 < x < 0.5456$, $0.02362 < y < 0.1919$, $0.355 < z < 0.505$), their positions are marked on Fig. 1 in all three projections. The boundaries of this subdomain are also marked in Fig. 1 in all three projections.

The local current density maximum in the considered subdomain on the height ~ 16 000 km is assigned in all three projections in Fig. 1 as Max j_1. In the vicinity of this local maximum in the plane, which is perpendicular to magnetic field vector, the magnetic field configuration corresponds to the pronounced current sheet distinctly (see Fig. 3a). Taking into account that on such small height the magnetic field is large, the position of such current sheet must correspond to the solar flare place. Therefore, for clarity, the planes in all three projections in Fig. 1 are drawn through the point of this local maximum (0.46, 0.04, 0.445).

Also in Fig. 1 in the considered subdomain in all three projections the group of current density local maxima located is seen at the altitude of 30 000 – 40 000 km (see projections *z*=const and *x*=const). For points of this group field configuration in the plane, which is perpendicular to magnetic field vector, is similar to the configuration of the point of this group marked in Fig. 1 as Max j_2. This field configuration is a stretched spiral (see Fig. 3b). It can occur due to strong disturbance appeared because of the shortened time scale. Also, stretch of the spiral may be caused by focusing of disturbances, which are typical for the current sheet, because in the projection *x*=const (see Fig. 3c) near this point we see the configuration of the current sheet created in the vicinity of singular X-type point.

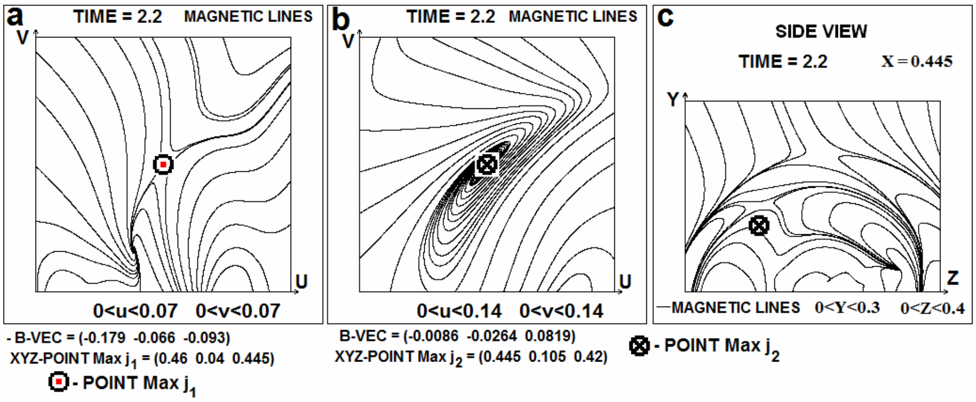

Fig. 3 a – Magnetic field configuration in the plane which contains the point Max j_1 with coordinates (0.46, 0.04, 0.445) and which is situated perpendicular to magnetic field vector **B**=(0.179, 0.04, 0.445). **b** – Magnetic field configuration in the plane which contains the point Max j_2 with coordinates (0.445, 0.105, 0.42) and which is situated perpendicular to magnetic field vector **B**=(-0.0086, 0.0264, 0.0819). **c** – Magnetic field configuration in the plane *x*=0.445 which contains the point Max j_2.

Conclusion

The analysis of current sheets appearance in the magnetic field obtained by MHD simulations in the corona above the active region showed that the most likely the flare occurred May 27, 2003 at 02:53 in the active region NOAA 10365 is produced by the current sheet with center in Max j_1 (Fig. 1). Now, however, we can not exclude the appearance of this flare or another flare of this series, which is weaker, due to a current sheet in the vicinity of one of the points in the group that is located at an altitude of 30,000 - 40,000 km (Fig. 1). For a more precise answer to the question about the position of the flare May 27, 2003 at 02:53 it is required a similar graphical analysis of the results of the MHD simulations carried out in real time.

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