MHD Simulation of Solar Flare Current Sheet Position and Comparison with X-ray Observations in active region NOAA 10365

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Abstract. The solar flare electrodynamical model based on energy accumulation in the current sheet magnetic field explains the main flare manifestations. The magnetic field configuration and plasma behavior are simulated numerically above the active region NOAA 10365 which produced the flare M1.4 May 27, 2003 at 02:40. The full system of 3D MHD dissipative equations is solved using the Peresvet code. No assumptions are employed about the mechanism of flare production. The initial and boundary conditions are set using SOHO MDI measurements. The result of simulation demonstrates current sheet creation above AR NOAA 10365 before the flare M1.4 May 27, 2003. The comparison with RHESSI X-ray observations during the flare May 27, 2003 at 02:40 is made. It is shown that the projection on the photosphere of the calculated current sheet position coincides rather good with the source of 3 - 6 keV X-ray measured by RHESSI. According to the RHESSI data 3 - 6 keV X-ray emission is produced by thermal plasma source in corona above an active region.

Keywords: sun, solar flare, current sheet, MHD simulation

Introduction

The Yohkoh and RHESSI X-rays observations on the solar limb (Masuda et al., 1994; Lin et al., 2003) demonstrated that the primordial flare energy release takes place in the solar corona above an active region at the altitude 15000 – 30000 km. The MHD simulation with the real initial conditions on the photosphere (Podgorny, Podgorny, 2008, 2008) 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 (Podgorny, 1989). As a result, explosive instability develops, which cause the flare energy release. The 3D MHD simulations (Podgorny, Podgorny, 2008, 2008) and comparison with RHESSI X-ray measurements permit to create solar flare model based on current sheet creation before the flare (Figure 1) (Podgorny, Podgorny, 2006; Podgorny et al., 2008). 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 chromosphere 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.

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 (Podgorny, Podgorny, 2012, 2012). The most widely used mechanism is based on the assumption of magnetic rope appearance (Forbes, 1991). 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 equilibrium configuration with big amount of free energy, that suddenly becomes unstable.

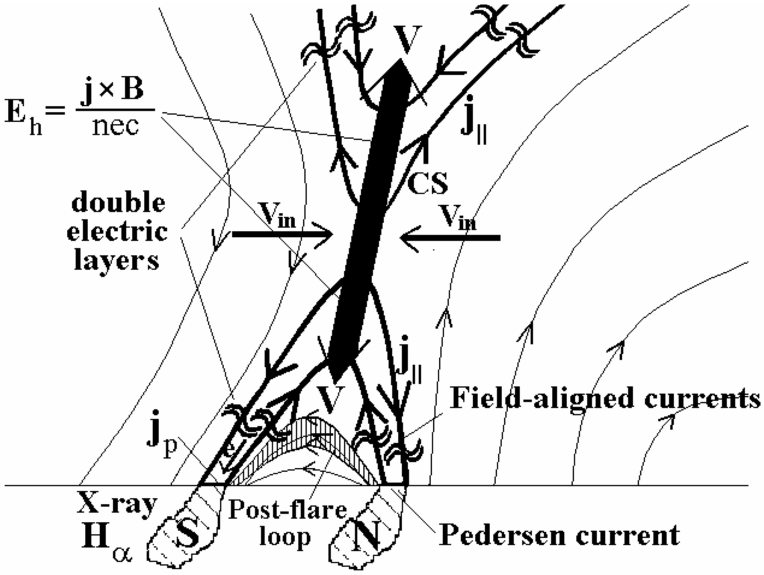

Figure 1. Solar flare electrodynamical model (Podgorny, Podgorny, 2006; Podgorny et al., 2008). The magnetic lines are shown by thin lines.

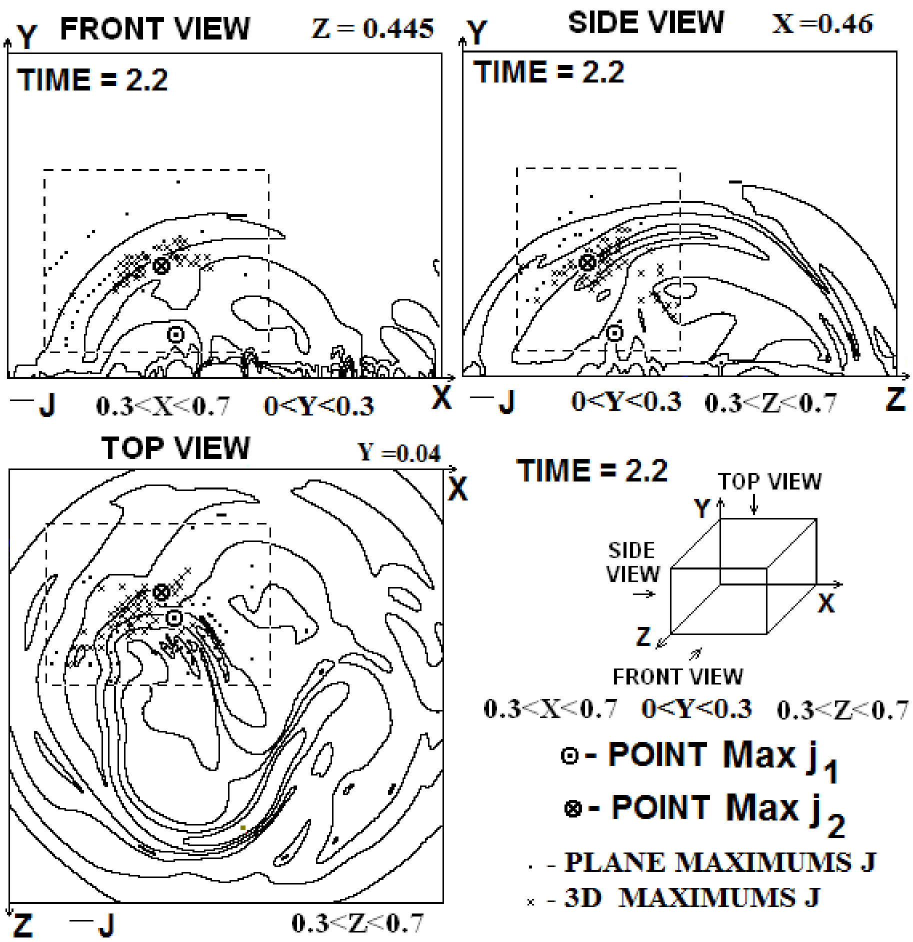

Figure 2. The lines of the constant current density and plane current density maximums marked in the plains containing the point Max j_1 : Front View z=0.445, Top View y=0.04, Side View x=0.46. The projections of 3D current density maximums are marked by crosses. The maximums are marked only in the subregion 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 possibility of creation such a system at slow evolution of an active region is not considered. Until now, nobody has been able to demonstrate the appearance of a magnetic rope in simulation at the real observed 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 simulations are 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. The simulation presented here is initiated from field configuration measured more than two days before the flare M1.4 May 27, 2003 at 02:40 in the active region NOAA 10365. 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.

Search of the Current Sheet Position

The analysis of magnetic field configurations in the different planes, which was fulfilled using MHD simulation results for the active region NOAA 10365 (Podgorny, Podgorny, 2006; Podgorny et al., 2008), showed formation of several current sheets above this active region. Each of them can cause a flare. In this paper the 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 soft X-ray sources in the corona the graphical system developed by authors is used. To find the position of a 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 for 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 3D 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 current density 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 magnetic field configuration 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 current density maximum, which is situated perpendicular to the magnetic field vector (Podgorny et al., 2007).

For comparing of observed X-ray sources positions with the results of MHD simulations the strongly reduced time scale (Podgorny, Podgorny, 2006; Podgorny et al., 2008) are used because even calculating a powerful personal computer, simulation in the real time scale should demand too large time for calculation. 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. Such fast magnetic field change on the photosphere can cause disturbances with large current, but calculations show that the plasma velocity in such disturbances never exceeds the Alfven velocity. However, the places of current sheets creation in any case must be X-type singular lines. The X-type singular lines are defined by potential field configuration which does not depend on how fast the field on the photosphere is changed in time.

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 M1.4 May 27, 2003 at 02:40 above the active region NOAA 10365. The dimensionless moment 2.2 corresponds to the moment May 27, 2003 at 02:53 near the maximum of the M1.4

flare when the distributions of X-ray emission are measured by RHESSI. So this moment is chosen for comparison with X-ray observations.

The Figure 2 presents lines of the equal current density and positions of its maximums in planes, which are perpendicular to the 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, Z-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 the 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 the length. Y-axis is directed perpendicular to the photosphere from the Sun. The size of the computational domain along the Y-axis is 120 000 km (0.3 in dimensionless units). The coordinate origin is located in the Northern Eastern corner of the computational domain, which is a rectangular parallelepiped ($0<x<1$, $0<y<0.3$, $0<z<1$). Figure 2 presents the part of the computational domain with linear size of the 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.

As the active region is situates near the solar disk center (S6 W5), the images in the picture plane (perpendicular to line-of-sight) presented in Figure 3, approximates well the projection on the plane y=const which is marked as Top View in Figure 2. But this plane y=const is not parallel precisely to picture plane (it should be parallel to picture plane if the active region is situates in the solar disk center (S0 W0) and the tilt of the solar North rotational axis toward the observer $B_0=0$). The unit line-of-sight vector for active region position and $B_0= -1.266^o$ is (-0.124, 0.988, -0.0899) which slightly differs normal to the photosphere vector (0, 1, 0). It is impossible to compare precisely picture in the Top View plane in Figure 2 with the picture plane in Figure 3. For orientation, the region in Figure 3 20" <x< 150", -165" <y< -35" have size $\Delta x=\Delta y=130"$ which corresponds to 0.236 dimensionless units, and the center of down boundary of computational domain in picture plane is situated in point with solar disk coordinates (x= 118.3", y= -87.27"). Figure 3 presents images of X-ray intensity for the flare May 27, 2003 at 02:53 in soft (1-10 KeV) and in hard (>10 KeV) spectrum ranges obtained on RHESSI spacecraft (http://rhessidatacenter.ssl.berkeley.edu). Figure 3 shows that the source of soft X-ray is situated in the area $0.3389 <x< 0.5456$, $0.355 <z< 0.505$ ($\Delta x=0.2067=114"$, $\Delta z=0.15=83"$), the boundary of this subdomain is marked by dashed lines in the projection y=const in Figure 2. 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 situated 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 Figure 2 in all three projections. The boundaries of this subdomain are also marked in Figure 2 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 Figure 2 as Max j_1. In the vicinity of this local current density maximum in the plane, which is perpendicular to the magnetic field vector, the magnetic field configuration corresponds to the pronounced current sheet distinctly (see Figures 4a, b). Taking into account that on such small height the magnetic field is large, the position of such current sheet, apparently, corresponds to the solar flare place. Therefore, for clarity, the planes in all three projections in Figure 2 are drawn through the point of this local current density maximum (0.46, 0.04, 0.445). In the picture plane perpendicular to the line-of-sight in geocentric coordinate system with the origin in the solar disk center the position of Max j_1 point is (x, y) = (96", -56") in arc seconds (see Figure 4c). It coincides well with position of soft X-ray intensity maximum (x, y) = (99", -64"). Slight difference can appear due to uncertainty of time moment definition at simulation in reduced time scale and due to approximation of the numerical method.

In all three projections (Figure 2) the group of the current density local maxima are seen in the considered subdomain located at the altitude of 30 000 – 40 000 km (see projections z=const and x=const). For points of this group the field configuration in the plane, which is perpendicular to magnetic field vector, is similar to the configuration for the point of this group marked in Figure 2 as Max j_2 (see Figure 5a, b). This field configuration is a stretched spiral (see Figure 5a). 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 Figure 5c) near this point one can see the configuration of the current sheet that created in the vicinity of singular X-type point. In principle it is possible the appearance of another flare of this series near this point, which is weaker than considered here the flare M1.4.

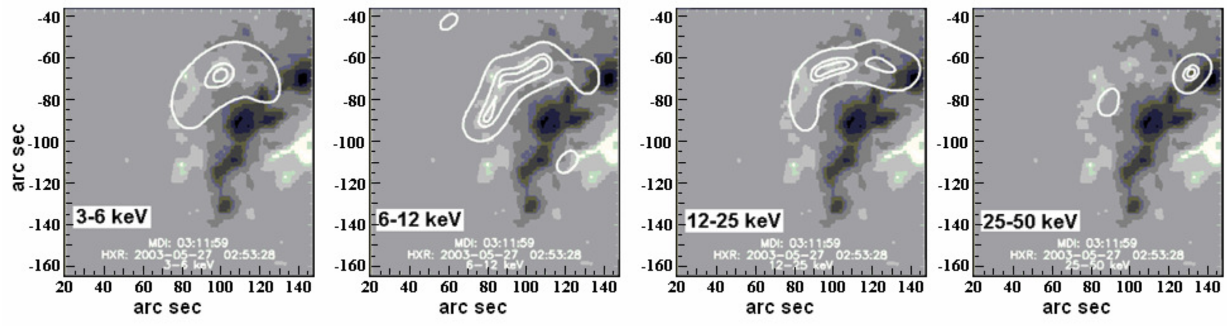

Figure 3. Distributions of X-ray emission for the flare May 27, 2003 at 02:53 in soft and hard ranges obtained on RHESSI spacecraft (http://rhessidatacenter.ssl.berkeley.edu).

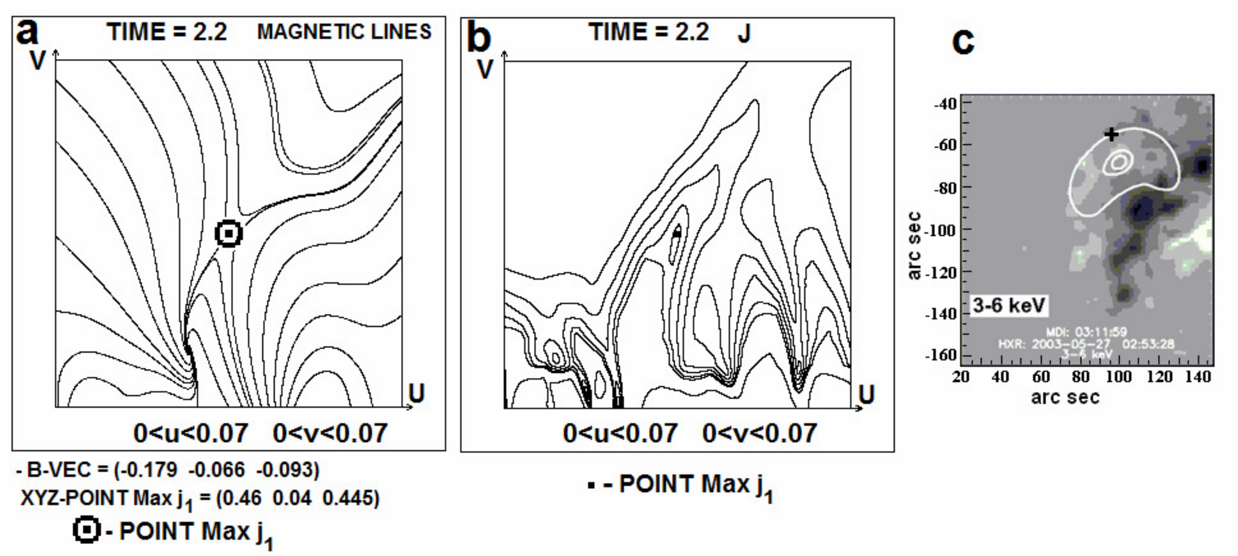

Figure 4. a, b - Magnetic field configuration and lines of equal current density in the plane which contains the point Max j_1 with coordinates (0.46, 0.04, 0.445) and which is situated perpendicular to the magnetic field vector B=(0.179, 0.04, 0.445). c - + is the position of the calculated current density maximum (x, y) = (96", -56") on the image of distribution of soft X-ray emission obtained by RHESSI (http://rhessidatacenter.ssl.berkeley.edu). The position of the soft X-ray intensity maximum is (x, y) = (99", -64").

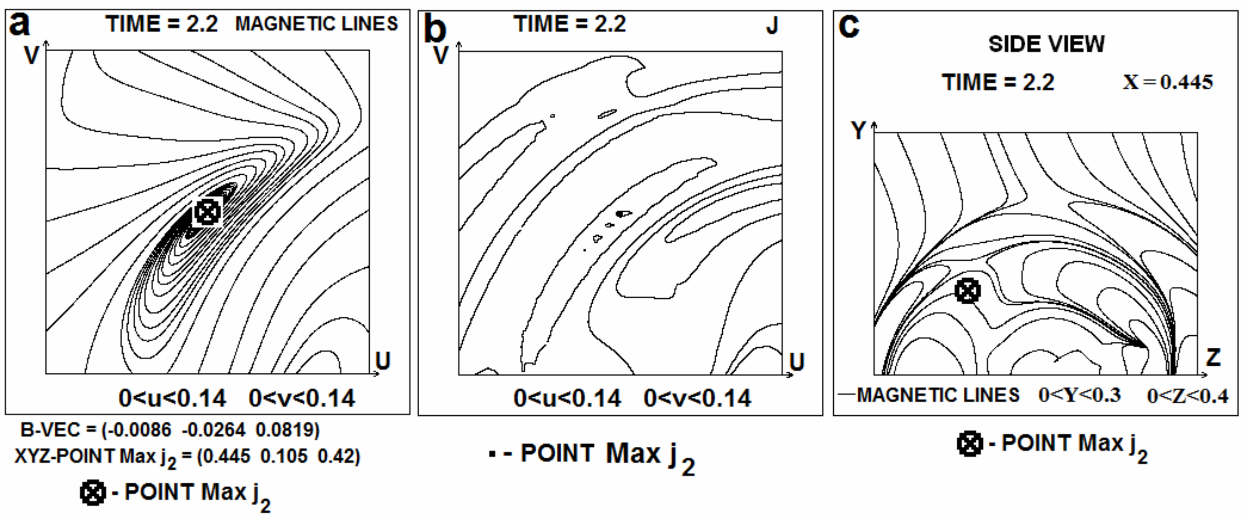

Figure 5. a, b – Magnetic field configuration and lines of equal current density in the plane which contains the point Max j_2 with coordinates (0.445, 0.105, 0.42) and which is situated perpendicular to magnetic field vector B=(-0.0086, 0.0264, 0.0819). c - Magnetic field configuration in the plane x=0.445 which contains the point Max j_2.

Conclusion

3D MHD numerical simulation shows formation of the current sheet above the active region NOAA 10365 before the flare of May 27, 2003 at 02:53. The initial and boundary conditions are set using the magnetic field measurements on the photosphere. The projection of the current position detected during the flare coincides with the position of the 3 - 6 keV X-ray source, as measured on the spacecraft RHESSI. According to the RHESSI measurements the spectrum of emission at the energy 3 - 6 keV has a typical thermal spectrum and thermal X-ray source is recorded above the magnetic arches. Thus we have obtained independent evidence of the solar flare mechanism, based on the accumulation of the flare energy in the current sheet magnetic field in the corona. The data presented here have been obtained in the calculations with a reduced time scale. The next stage of this research is to develop methods that will receive data in real time.

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