*"Physics of Auroral Phenomena", Proc. XXXII Annual Seminar, Apatity, pp. 127 - 130, 2009*


Polar Geophysical Institute

# SOLAR FLARE MODEL – COMPARISON WITH COMPLEX SPACECRAFTS OBSERVATION

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**Abstract.** The solar flare model obtained from 3D MHD numerical simulation has been discussed in previous Apatity conferences. The main point of this model consists in primary energy release in the corona due to magnetic energy dissipation in a current sheet. Now a possibility appears for detail comparison of this model with simultaneous observations of a flare by several spacecrafts (RHESSI, Stereo A and B, and GOES). The unusual position of the active region and spacecrafts permits to obtain new information about a flare event. The M2 flare 25.11.2007 has been produced above the active region situated behind the solar limb. This active region was observed by Stereo A and Stereo B. RHESSI can measure thermal X-ray emission from the current sheet and X-ray radiation above the flare current sheet. RHESSI space craft has been shielded from powerful X-ray radiation generated in legs of the flare loop by the Sun body that permits to detect very weak radiation from the corona. The weak flux of hard X-ray from corona (above the thermal source) is revealed together with III-type radio emission. The electrons with energy order of 50 keV responsible for these radiations are moving along magnetic lines. They reach the Earth orbit and are observed by GOES. This hard pulse of X-ray shows a thin target spectrum. Electrons producing these radiations are accelerated in field-aligned currents generated by the Alfven wave which is excited by the Hall electric field in the current sheet. The field-aligned currents are connected due to the Alfven conductivity. Another system of field-aligned currents is connected in the chromosphere, where accelerated electrons produce the thick target power spectrum. This strong flux of hard X-ray radiation is measured by Stereo spacecrafts. All scenario of solar flare development is in agreement with the electrodymamical solar flare model prediction.

## Introduction

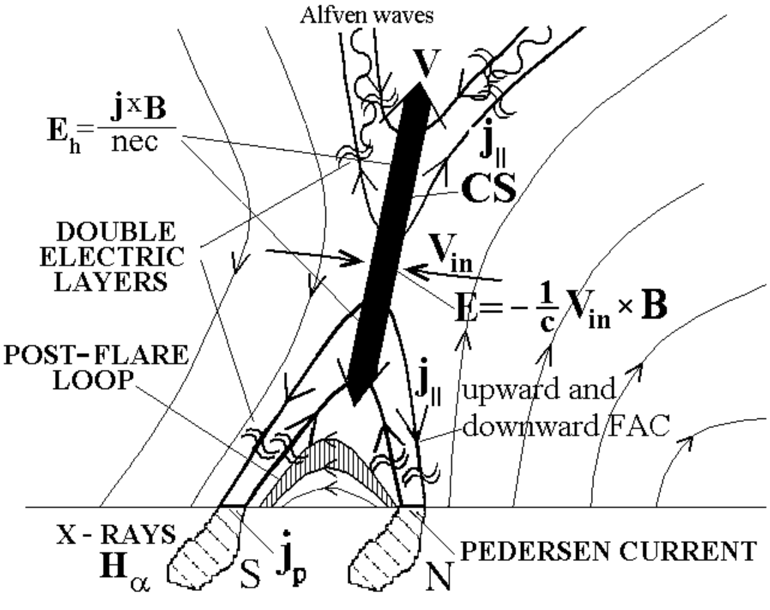
The "solar flare" term was introduced in 1945 year for a phenomena of suddenly appearing two visible bright ribbons on the solar surface that accompaniment by the strong magnetic distortion (magnetic storm) on the Earth. In that time a solar flare could be considered as some type of syndrome, because there were no date about flare nature and conditions of flare appearance. Now, valuable information about these phenomena is obtained, and the syndrome definition becomes unacceptable. Early observations in the visible light have caused a wrong impression about flare location, and flares have been often considered as an effect appearing on solar surface (chromospheric flare). S. I. Syrovatsky was the first one who pointed out that magnetic energy can be accumulated above an active region in a current sheet. Numerical MHD simulation has demonstrated [1 - 3] that the current sheet is created in the corona before the flare, when an active region magnetic field slowly changes in 2 – 3 days before the flare. The stable current sheet can be transferred into unstable state, producing explosive energy release in the corona [4]. The spacecraft measurement in the X-ray region opens a new era in solar flare physics understanding. They demonstrate that primary energy release indeed occurs in the current sheet appeared in the corona above an active region heating plasma up to temperature order of several keV. During flare development electron beams with energy of several hundreds keV are generated. The pulse of solar cosmic ray is reached the Earth orbit [5]. Part of accelerated particles heats the solar surface producing nuclear reaction with $\gamma$–ray emission. Total big flare energy is order of $10^{33}$ erg. The visible spectra in such condition are not representative for flare investigation.

## The electrodynamical model for an elementary flare

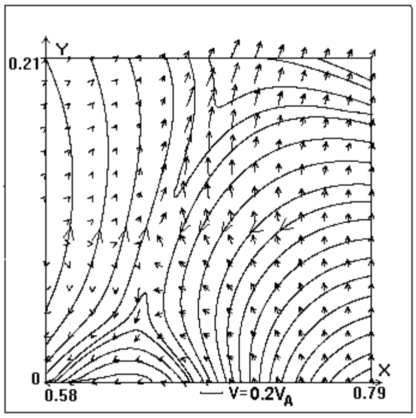
Usually a series of elementary flares appears above an active region during several hours. The numerical simulation demonstrates several current sheet creation in a preflare state [6]. Each of the current sheet can be responsible for one of elementary flare. At setting 3D MHD numerical simulation in the previous works the photospheric magnetic field has been approximated by local magnetic sources (magnetic charges or dipoles). Such method does not permit to reproduce properly a magnetic field configuration above the active region. For exact simulation of energy accumulation for a solar flare the magnetic field dynamics on the photospheric is set from magnetic maps obtained in the preflare state [6]. The electrodynamical model for an elementary flare and typical configuration of the current sheet magnetic field together with velocity vectors are shown in fig. 1. Thin lines and thin arrows show magnetic field lines. Thick lines and thick arrows show field-aligned current generated by the Hall electric field. The Hall electric field appears because $\mathbf{j}\times\mathbf{B}/c$ force applied to electrons. Charges separation produces the Hall electric field

$E_h \sim \dfrac{j_{cs} B_n}{nec}$ directed along the current sheet [7]. The Hall electric field is also responsible for ions acceleration together with electrons producing plasma ejection from the current sheet (Coronal Mass Ejection).

The field-aligned currents are generated below the magnetic X-line, because of the plasma conductivity anisotropy in the magnetic field. They are closed in the chromosphere by the Pedersen currents. The electrons accelerated in these field-aligned currents precipitate downward producing flare ribbons, and hard X-ray on the solar surface [8]. This phenomenon is similar to field-aligned current generation in the Earth magnetic tail that produce aurora in the polar oval. The energy of X-ray depends on current sheet parameters. In a typical solar flare it should be order of 100 keV. The fast electron precipitation initiates local heating and chromosphere evaporation. As a result the postflare loop is fulfilled by chromospheric plasma. [9].




Electrons accelerated in FAC produce hard X-ray.




Magnetic lines of a current sheet created in numerical MHD simulation. and vectors of plasma velocity. A sheet appears above an active region in the preflare state. Plasma inflows into a current sheet. Inside the sheet plasma acceleration takes place by **j**×**B** force producing CME.

**Figure 1**

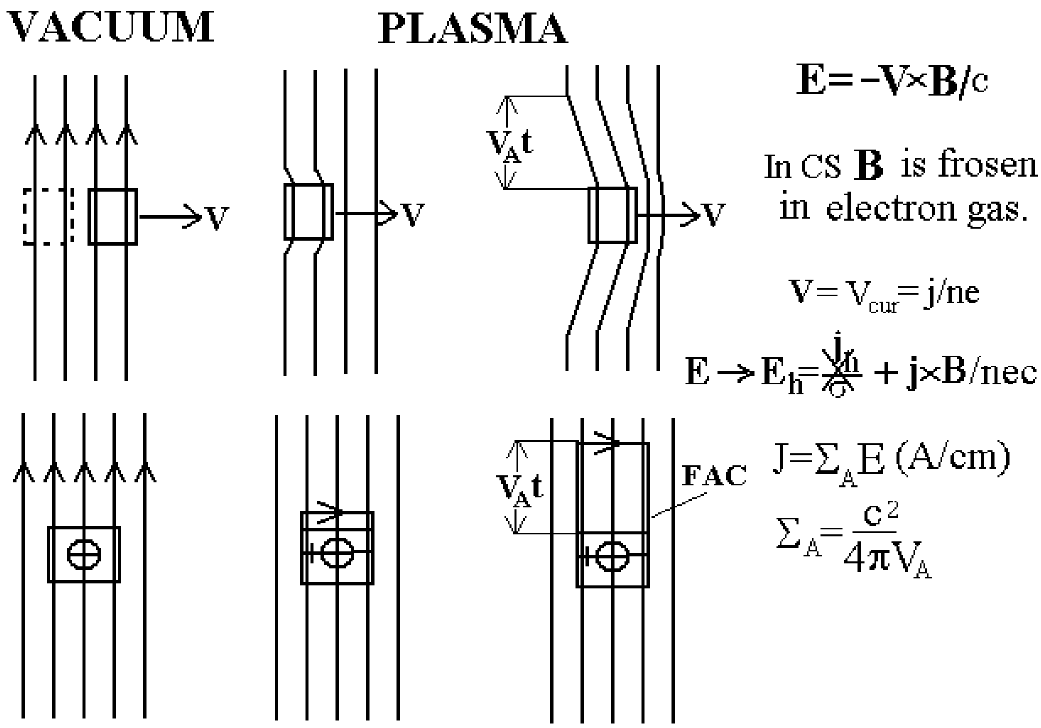



**Figure 2**

The field-aligned currents generated by the Hall field above the magnetic X-line are propagated upward with Alfven wave in the interplanetary space. The electrons accelerated in these currents produce III-type microwave radiation. The shame of field-aligned currents generation in the Alfven wave and closing by the Alfven conductivity $\Sigma_A$ are shown in fig. 2.

The force **j**x**B**/c accelerates plasma along the CS, and ejected plasma produces coronal mass ejection. Alternative solar flare mechanism is based on primary magnetic rope ejection, and current sheet creation at the rope interaction with a magnetic loop [10]. But no trace of a magnetic rope is found in 3D MHD simulation for a real preflare active region. The creation of coronal mass ejection has been investigated in details by RHESSI and LASCO measurements of the limb flare 15.04.2002. It is clearly seen that coronal mass ejection occurs after appearing of the hot plasma thermal X ray `emission from the current sheet. The photo of current sheet thermal emission and the trajectory of coronal mass ejection [11, 12] are presented in fig. 3.

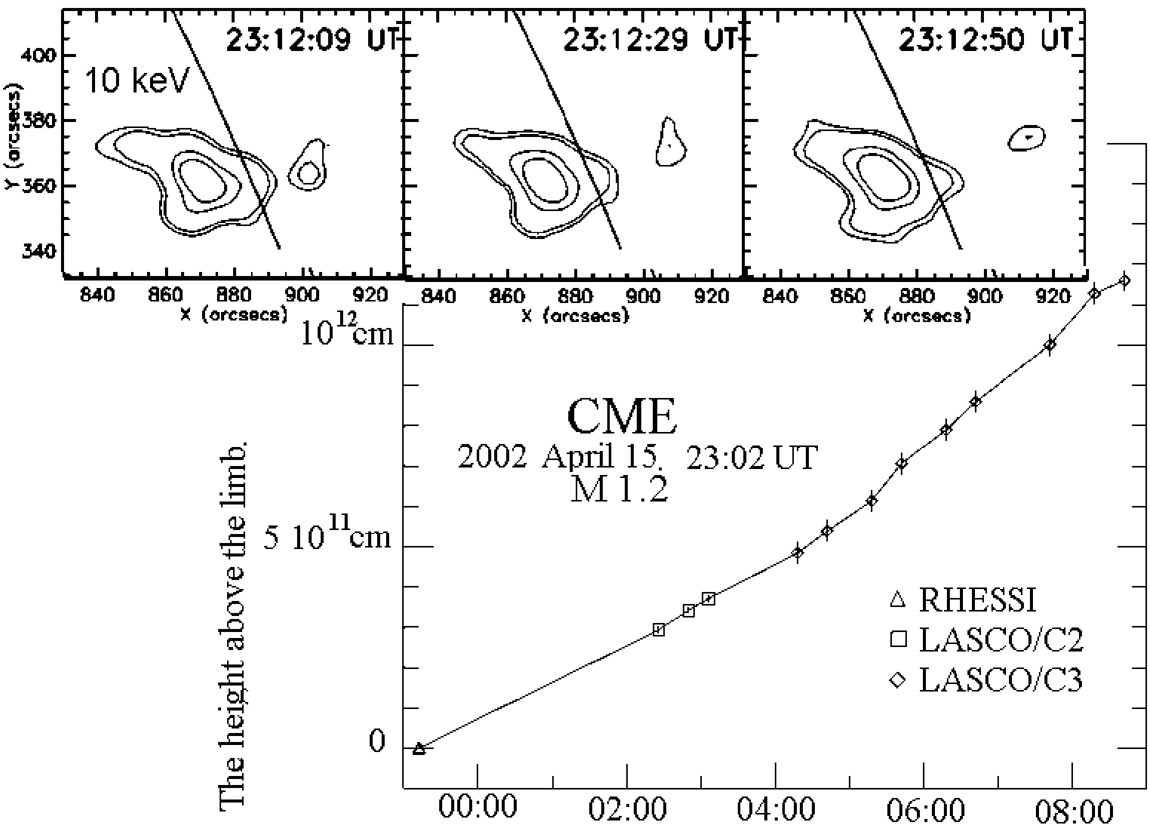



**Figure 3**

## Hard X-ray from corona and electron beams accelerated in FAC of Alfven wave

The fast electron beams that accelerated in field-aligned currents produced by the Alfven wave are moving along interplanetary magnetic lines in the solar wind. In low density plasma they produce hard X-ray very weak intensity. This radiation is very difficult to detect on the background of the strong thick target X-ray from the solar surface. Indirect evidence of such electron beams creation follows from III-type radio emissions at the flare appearance. But the coronal X-ray has been observed by RHESSI in C8 (GOES) December 31, 2007 flare, because of occultation 16 arcsec. The powerful hard radiation has been shielded by the Sun body. The flare real class was M2. Positions of space craft is shown in fig. 4a [13]. Results of X-ray measurements in such situation are shown in fig. 4b. Above the current sheet the thermal X-ray source the RHESSI spacecraft has observed hard radiation with the power spectrum ~ $(h\nu)^{-\gamma}$, where $\gamma$=4.1±0.4. The space craft WIND on the Earth orbit has observed the electron beam from the flare. The electron beam reveals the power spectrum $E^{-\delta}$, where $\delta$=2.9±0.3. The spectrum of X-ray created by the power spectrum electron beam in thin target approximation can be presented in the form:

$$I(h\nu) = \int_{h\nu}^{\infty} E^{-\delta}\sigma(h\nu, E)dE \sim (h\nu)^{-(\delta+1)}.$$

Here $E$ is electron energy, $\sigma(h\nu, E) \sim \frac{1}{Eh\nu}$ - is section of quantum creation with energy $h\nu$ at electron –ion collision. Within errors of measurement one can conclude, that electron beam accelerated in the Alvfen wave field-aligned current is propagated in the solar wind and is detected by WIND on the Earth orbit. This beam is also responsible for plasma wave radiation well known as III-type radio emission.

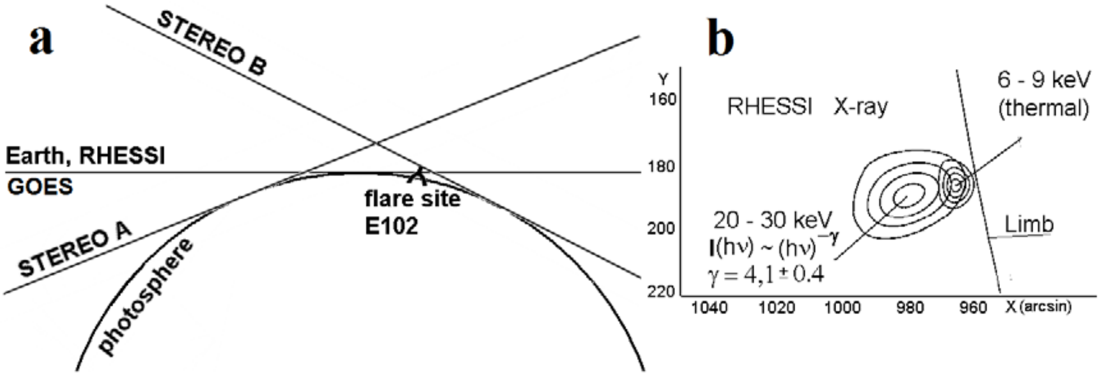



**Figure 4.**

## Conclusion

The electrodynamical model is based on results of 3D MHD numerical simulation that demonstrates a current sheet creation above an active region due to new magnetic flux flowing up from the photosphere. Usually several current sheets appear before a set of elementary explosive flare events. X-ray space measurements confirm primary energy release accumulated in the current sheet. The authors [12] declared that they found strong evidence for the existence of large-scale current sheet on 2002 April 15 flare. The plasma density in the current sheet order $10^{11}$ $cm^{-3}$ at electron temperature ~3 kev is typical for the flare explosion. This plasma is ejected in the interplanetary space with the velocity of several hundred km/s. The generated fast electron beams are moving along the magnetic lines downward. They hit the photosphere and produce strong X-ray power spectrum typical for a thick target. Apparently beam acceleration takes place in field-aligned currents generated by the Hall electric field in the current sheet. The upward and downward field-aligned currents are connected in chromospheres due to Pedersen conductivity, where charged particle can collide with neutral atoms. The Hall electric field has to generate the Alfven wave. Electrons accelerated in field-aligned currents in the Alfven wave moving in the corona produce also hard radiation with a power X-ray spectrum. But this spectrum is corresponding to a thin target. The intensity of the coronal X-radiation is very low. These electrons are also responsible for plasma frequency radiation (III-type radio emission). Another important effect consists in solar flare cosmic ray production [7].

***Acknowledgments***. This work was supported by RFBR grant № 09-02-00043.

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