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SOLAR FLARE MULTIWAVE INVESTIGATIONS AND PHYSICAL MODEL

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Abstract. New observations justify the flare scenario predicted by the electrodynamical model based on numerical 3D MHD simulations. X-ray RHESSI measurements show plasma heating above an active region in the place, where current sheet (CS) has been created due to disturbances focusing. The measured plasma parameters above an active region during the flare correspond to plasma heating (T~3 keV) in CS due to magnetic reconnection. Phenix-2 radio telescope measurements show high frequency continuum appearing simultaneously with hard X-ray pulse (t~1min). The radio continuum frequency (1.5 – 15 GHz) corresponds to plasma density obtained from X-ray measurements. CS magnetic field obtained from MHD numerical simulation is in agreement with the observed plasma pressure. The photospheric hard X-ray sources seem to be created by electrons accelerated in the electric field applied along the loop magnetic lines. Applications of solar flare models that used magnetic tubes interaction and magnetic ropes ejection with appearance are also discussed.

Introduction

The solar flare is a complex of high power phenomenon that appears in the corona above an active region. The observations carried out for several decades in the visible light do not permit to understand the physics of the flare, because the plasma temperature in the place of energy release exceeds several keV, and the matter at such temperature is completely ionized. The flare visible radiation, mostly hydrogen H_α line, can be generated by neutral atoms in rather cold plasma outside the place where explosive energy releases. The ribbon radiates because of neutral atoms in the chromosphere are excited by fast electron that precipitate along loop magnetic lines. But visible radiation from the chromosphere and photosphere has been often considered by mistake as an indication of the primary energy release on the Sun surface.

The bright visible and ultraviolet loops above an active region represent the magnetic line shape. The temptation arises to consider such a loop as a magnetic tube filled with plasma. At encounters of two tubes with opposite directed powerful magnetic fluxes approach each other, the reconnection is assumed to be a source of energy released for a flare. But such consideration is not correct, because even in the potential approximation (zero plasma pressure) for equilibrium of such isolated magnetic flux tube, the force of the magnetic pressure inside the tube $\nabla B_i^2/8\pi$ must be equal to the force of magnetic line tension $B_i^2/8\pi R$. Here B_i is the magnetic field inside the tube and R is the curvature radius of a field line. This condition is not fulfilled for a magnetic tube where sign of the magnetic tension force is not directed to the tube axis, and does not compensate the magnetic pressure that tries to expand the tube (Fig. 1a). So the isolated magnetic tube can not exist even in potential approximation. In the plasma presence the plasma pressure is added to the magnetic pressure, and the equilibrium of isolated plasma tube with the magnetic flux is impossible. For existence of equilibrium it is necessary to apply the strong magnetic pressure $\nabla B_e^2/8\pi$ outside a tube, but not inside it. For big R the magnetic tension can be neglect, and the pressure balance looks as $B_i^2/8\pi + nkT = B_e^2/8\pi$. So, for equilibrium it is necessary that $B_i < B_e$ - the tube has to be a <u>diamagnetic one</u> (Fig. 1b). Such a tube appears when dense plasma fills a tube, and as a result plasma pressure pushes the field lines out of the tube, but diamagnetic tube can not serve for solar flare energy accumulation in the magnetic field.

The magnetic tube can exist only in presence of strong current I directed along the tube axis (Fig. 1c). In such magnetic configuration (rope) the tube confinement is supplied by the strong magnetic field of a longitudinal current. In this case pressure equilibrium looks as $I^2 = (B_i^2 - B_e^2)r_0^2 c^2/4\pi + 2c^2 NkT$. Here, N is the number of particles per unit of the tube length, T is the plasma temperature, r_0 is the tube radius. If a rope appears above the photosphere, it should be pushed away due to magnetic interaction with the image current under the photosphere.

The rope repulsion from the photosphere by the current magnetic field is very popular for explanation of CME and solar flares [1]. A series of studies is dedicated to MHD simulation of the repulsion of the rope that is orthogonal to magnetic arch. As a rope (CME) is ejected the lines of arched magnetic field are stretched, CS appears, and free magnetic is accumulated for a solar flare in CS magnetic field. But it is impossible to realize a stable equilibrium in the process of the rope creation. Because of that the rope current should increase faster than rope ejection takes place [2]. To release typical energy for a flare and CME, it is assumed to be fast (t~10 c) appearance of the rope with the current of the order of 10^{12} A. This strong current must produce tremendous magnetic disturbances in the active region before a flare. However, no strong disturbances are observed on the photosphere before the flare. The mechanism of prompt appearance of a current of orders of 10^{12} A remains an unsolved problem. The

electrodynamical model does not meet this problem - solar flare energy is accumulated in the CS magnetic field during several hours before the flare.
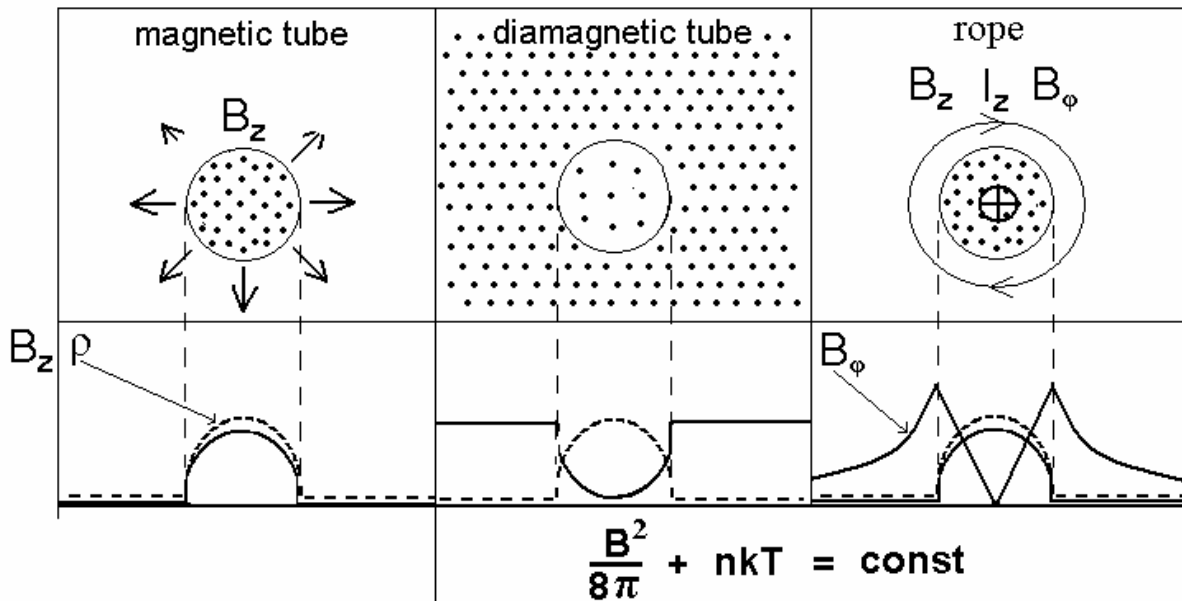

Figure 1. **a)**. Nonequilibrium magnetic tube in the corona. **b)**. Equilibrium diamagnetic tube. **c)**. Equilibrium magnetic tube with strong longitudinal current (rope). The points show magnetic lines perpendicular to the figure.

The modern flare observation.

Every flare possesses its own peculiarity. Usually, the flare appears together with coronal mass ejection order of 10^{15} g. Here we consider a most typical single flare or according to Benz terminology [3] a standard flare. The most representative radiations of high temperature plasma in explosive phenomena are X-rays and radio emission at the frequency order of the plasma or the synchrotron frequency. The first incontestable evidences that flare energy release occurs in corona has been obtained from the X-ray photographs of Yohkoh space craft. The X-ray photographs taken on the solar limb show a coronal source above the active region. The efficiency of plasma heating in the corona due to magnetic energy dissipation is obvious. The magnetic field in the corona above an active region is the only source of accumulated energy. Here the ratio of particles energy to the magnetic energy is very small $\beta = 8\pi nkT/B^2 \ll 1$, and magnetic energy transformation in the particle energy (heating or/and plasma stream kinetic energy) can be very effective. But energy of the active region magnetic field can not be quickly transformed into heat and plasma streams because photospheric magnetic sources (solar spots) only slightly change during flare energy release. The potential magnetic field of an active region is a "dead" one. The real source of energy accumulated in the corona that can be transformed into kinetic energy or plasma heating is the magnetic field of a coronal current system, which is slowly generated before the flare and fast dissipated during the flare. Two possibilities of a current system creation are considered in theoretical solar flare models: The linear current that is directed along the magnetic line was proposed by A. Severny (now this idea is developed into rope configuration – the powerful field-aligned current that accelerates plasma due to magnetic repulsion from the photosphere) and S. Syrovatsky idea of CS creation in the vicinity of a singular magnetic line above the active region due to magnetic disturbances focusing. The observations [4] show that new magnetic flux emerges 2 – 3 days before the flare. A set of numerical MHD simulations above a real active region shows CS creation during several tens of hours – the preflare state due to such photospheric disturbances, but still we do not know any evidence of rope repulsion from the photosphere.

The convinced evidence of energy release in the corona above an active region has been obtained on the RHESSI space craft. The typical X-ray spectrum measured by the RHESSI during a flare is shown in Fig. 2a. One can see an overlapping of two different spectra. In the region of 1 – 20 keV the obtained dependence fits very well with an exponential X-ray spectrum created by thermal electrons distribution in plasma with the density of $n \sim 10^{11}$ cm^{-3} and the temperature 3.1 keV [5]. This hot coronal source is observed at height $\sim 3 \times 10^9$ cm, where typical plasma parameters are the plasma density $n \sim 10^7$ cm^{-3} and the temperature about 100 eV. For confinement of such hot and dense plasma cloud it is necessary to have magnetic field B = 110 Gauss, estimated from the pressure balance $B^2/8\pi = nkT$.
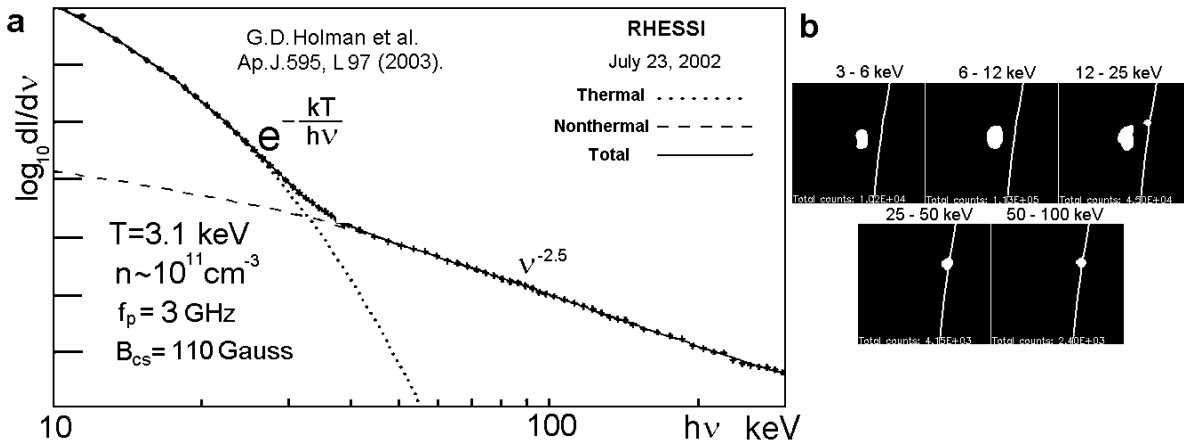
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Figure 2. a) X-ray solar flare spectra by RHESSI. **b)** X-ray photo of the solar flare. White line shows limb position.

At higher energy $h\nu \gg 20$ keV a power spectrum with $\gamma = -2.5$ is manifested. This power spectrum corresponds to bremsstralung at electron beam hitting a target. Apparently, electrons accelerated in the corona precipitate on the solar surface. Two different types of X-ray emissions during a flare are also seen in X-ray photos obtained by RHESSI in different spectral intervals for a flare appeared on the solar limb. The photos shown in Fig. 2b are taken at the maximum of hard X-ray emission with time resolution of 1 min and angular resolution of 1 arcsec. The white line shows the limb position. The coronal source that radiates thermal X- ray spectrum ($h\nu < 20$ keV) is seen in the corona above an active region, but the high energy ($h\nu > 50$ keV) power X-ray spectrum are generated from the solar surface source located at the foot of the flare loop. The surface source can appear as a result of electron acceleration along magnetic field line or escaping from the corona, as has been proposed in Internet RHESSI page. They assume that electron acceleration takes place in the magnetic cusp region where closed arch lines transfers into open line of a neutral CS. The magnetic field configuration with cusp at the top of magnetic loops is presented in Fig. 3a. But such suggestion contradicts to absence of X-ray with energy $W > 20$ keV emitted from the corona, e. g. such energetic electrons do not exist in the cusp. It is not clear either how such configuration with a neutral CS can be generated in spite of its instability.

The resent microwave investigations by Phenix-2 radio telescope [3] discovered a high frequency solar flare continuum spectrum appearing above the active region. This spectrum is observed at the maximum of high energy X-ray emission in the spectral region $h\nu \sim (1 - 10)$ GHz. The continuum spectrum emission duration order of 1 min is the same as the hard X-ray pulse. If this spectrum is emitted from CS where the normal component does not exceed 10 Gauss the plasma frequency f_p has to be much bigger of the cyclotron frequency f_b. In such conditions the observed frequency is $f = (f_p^2 + f_B^2)^{1/2} \sim f_p$. Here $f_p = (ne^2/\pi m_e)^{1/2}$. The density 10^{11} cm^{-3} obtained from X-ray measurements corresponds $f_p = 3$ GHz. So there is agreement with X-ray measurements. The solar flare continuum spectrum is determined by density distribution in CS.
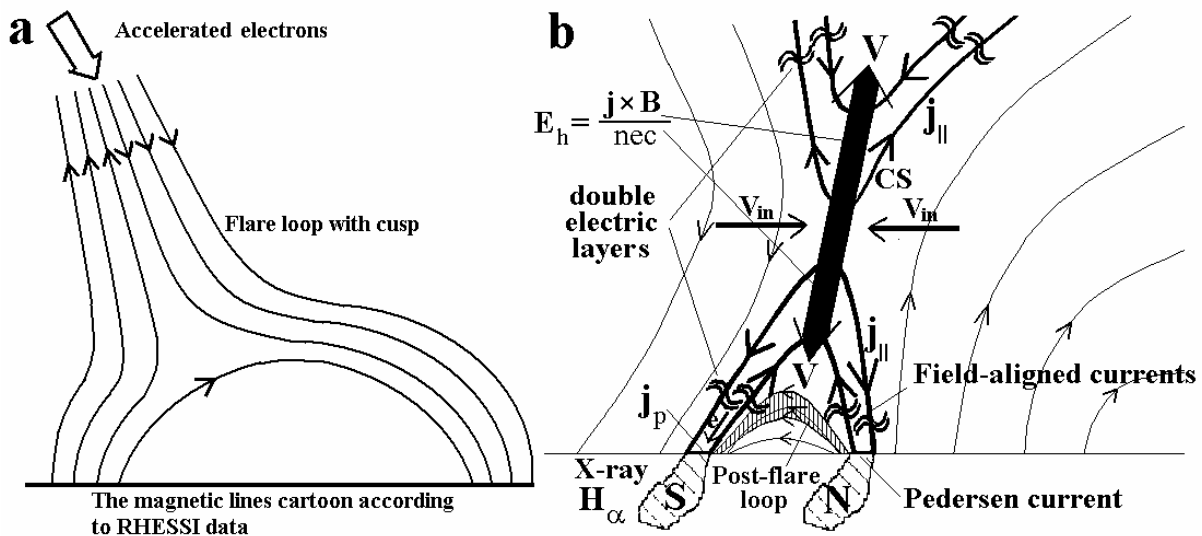

Figure 3. a) Magnetic field cartoon from RHESSI. **b)**Elecrtrodynamical solar flare model.

The flare model

The results of X-ray and radio emission high frequency continuum described hereby confirm the solar flare electrodynamical model [2, 6] that had been discussed in the previous Apatity seminars [7]. The model based on 3D MHD simulation demonstrated CS appearance above an active region due to disturbance focusing in the vicinity of a singular line. In the simplest case CS is created, if the new magnetic flux emerges whose magnetic field is opposed to the old magnetic flux. It is necessary to emphasize that the created CS is not a Harris type sheet. It contains the normal magnetic component, and plasma flows inside the sheet in both directions from the neutral line. The solar flare electrodynamical model is shown in Fig. 3b. CS separates two opposed directed magnetic fluxes, as at the high temperature the magnetic field is frozen in the plasma. The plasma moves with frozen-in magnetic lines, which reconnect and flux of magnetic energy $V_{in}B^2/8\pi$ is transferred into heat due to reconnection. The hot plasma in CS has to produce X-ray emission in the corona. Simultaneously the force $\mathbf{j}\times\mathbf{B}/c$ accelerates plasma upward and downward along the sheet. Upward acceleration produces coronal mass ejection. The downward flow together with frozen-in magnetic lines creates the post flare magnetic loop. The Hall electric field $\mathbf{E}_h = \mathbf{j}\times\mathbf{B}/(nec)$ is directed along CS. The Hall electric field appears due to electric charges separation because the force $\mathbf{j}\times\mathbf{B}/c$ is applied to the electron gas. The ion gas is heavier, and ions move in the electric field behind electrons. This electric field generates a system of field-aligned upward and downward currents in the corona that are connected in the chromosphere. The mode of this field-aligned current generation and electron acceleration in the upward currents are similar to the phenomena observed in the Earth polar region [8]. The accelerated electrons hit the solar surface in the regions of foots of a magnetic arch. They produce X-ray sources on the solar disk. Such scenario is revealed in RHESSI X-ray measurements. The Lorenz electric field $\mathbf{V}\times\mathbf{B}/c$ is applied along the singular line that is perpendicular to the figure. The total voltage along this line can be more than 100 GV. The protons accelerated in the vicinity of a singular line have an exponential spectrum. Such spectrum is indeed a typical one for relativistic protons appearing during the explosive phase of a flare [9].
Another evidence of the electrodynamical model is obtained by comparison of the position of calculated CS and the position of the maximum temperature of radio emission during the flare [10].

Conclusion

The resent 3D MHD simulations for a real active region before the flare demonstrate the current sheet creation before the flare [10], but no rope appearance show numerical simulation or magnetic field measurements carried out on the photosphere. Apparently electrodynamical model can be considered as the most acceptable for description of solar flare development.

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