"Physics of Auroral Phenomena", Proc. XXIX Annual Seminar, Apatity, pp. 207 - 210, 2006

Polar Geophysical Institute

HARD X-RAYS GENERATION AT A SOLAR FLARE

I. M. Podgorny[1], A. I. Podgorny[2]

[1]*Institute for Astronomy RAS, Moscow, Russia, podgorny@inasan.ru,*
[2]*Lebedev Physical Institute RAS, Moscow, Russia*

Abstract. A solar flare spends the main part of its energy for X-rays generation. The observations near the solar limb (Yohkoh and RHESSI spacecraft) demonstrated that three powerful hard X-rays sources usually appear. One source is located in the corona above a loop. The legs of the loop coincide with other two sources that observed on the solar surface in Northern and Southern spots of an active region. The X-rays energy distribution of the coronal source is well-fitted by a thermal spectrum with the electron temperature of ~3 keV. The two surface sources demonstrate a power spectrum typical for X-rays produced by electron beams with energy up to 200 keV in a thick target. These results show that fast energy release occurs in the corona with heating coronal plasma and creation of electron beams precipitating along the magnetic field lines into the chromosphere. According to the electrodynamical solar flare model electron beams are accelerated in the field-aligned currents produced by the Hall electric field in the current sheet. The hard X-ray data and solar cosmic rays data discussed at the last year Apatity seminar are in agreement with the scenario predicted by the electrodynamical solar flare model. The general magnetic field configuration and the geometry of electron precipitation during a solar flare permit us to conclude about analogy with electron precipitation in aurora.

Introduction

The electrodynamical solar flare model is based on MHD numerical simulation of a current sheet creation above an active region [1 – 3]. It is shown that a current sheet appears in the solar corona in the vicinity of an X-type magnetic singular line due to disturbances focusing that are arriving from the photosphere. In particular, the current sheet appears at a new magnetic loop emergence near pre-existing loop, if the polarity of the new loop is opposite to that of the old loop [2]. It is important to emphasize that no assumption about the mechanism of a current sheet creation is taken into account in these numerical experiments. Just distribution of the magnetic field in the corona is calculated using the preflare magnetic flare measured on the photosphere as boundary conditions. No magnetic flux ropes generation is observed prior the flare.

Current sheet is very stable for a long time, and energy is accumulated in the current sheet magnetic field. The high current sheet stability is conditioned by a normal magnetic component and plasma flow along the current sheet. The stored energy is fast dissipated during a flare, when a current sheet transfers into an unstable state [4].

The main mechanism of explosive energy release is magnetic reconnection. The primary energy release occurs in the corona due to energy dissipation that has been stored in the current sheet magnetic field. As a result coronal plasma heating takes place in the X-type singular line vicinity. The electrodynamical solar flare model is shown in Fig. 1. Thin lines show the magnetic field lines, thick lines show the magnetic lines with field-aligned currents. Thick arrows show field-aligned current direction. The position of a current sheet depends on initial magnetic field configuration and the character of photosphere disturbances in the preflare state. For a vertical current sheet shown in Fig. 1 a solar flare and coronal mass ejection appear simultaneously in the same explosive event. Plasma inflows into a current sheet with the velocity V_{in} from the both sides of the sheet. This plasma flow brings frozen-in magnetic lines that reconnect in the current sheet. The energy flux $V_{in}B^2/8\pi$ is transferred into plasma heating and acceleration along the current sheet. After reconnection, plasma flows along the current sheet upward and downward. The force **j**x**B**/c accelerates plasma, and upward flux produces coronal mass ejection.

Plasma accelerated downward moves together with shortening magnetic lines and produces a postflare loop. New lines with hot plasma pile up on the loop top gaining impression of magnetic arch expansion. The downward ("supra-arcade flow") plasma stream from the reconnection site has been demonstrated in [5]. If downward plasma flow is accelerated up to the Alfven velocity, a shock can appear on the loop top. The results of MHD simulation of plasma flow in a current sheet are shown in Fig. 2. Plasma accelerated upward is ejected from the current sheet producing coronal mass ejection. Hot plasma accelerated downward brings frozen-in magnetic line on the magnetic arch top.

An important feature of a coronal current sheet is the Hall **j**x**B**/nec electric field generation that directed along the accelerated plasma flow in the current sheet. The Hall electric field produces field-aligned currents because of the plasma conductivity anisotropy in the magnetic field. The field lines with the field-aligned currents and current directions are shown in Fig. 1 by thick lines. These currents are closed in the chromosphere by Pedersen currents. The electrons accelerated in upward field-aligned currents precipitate downward producing flare ribbons

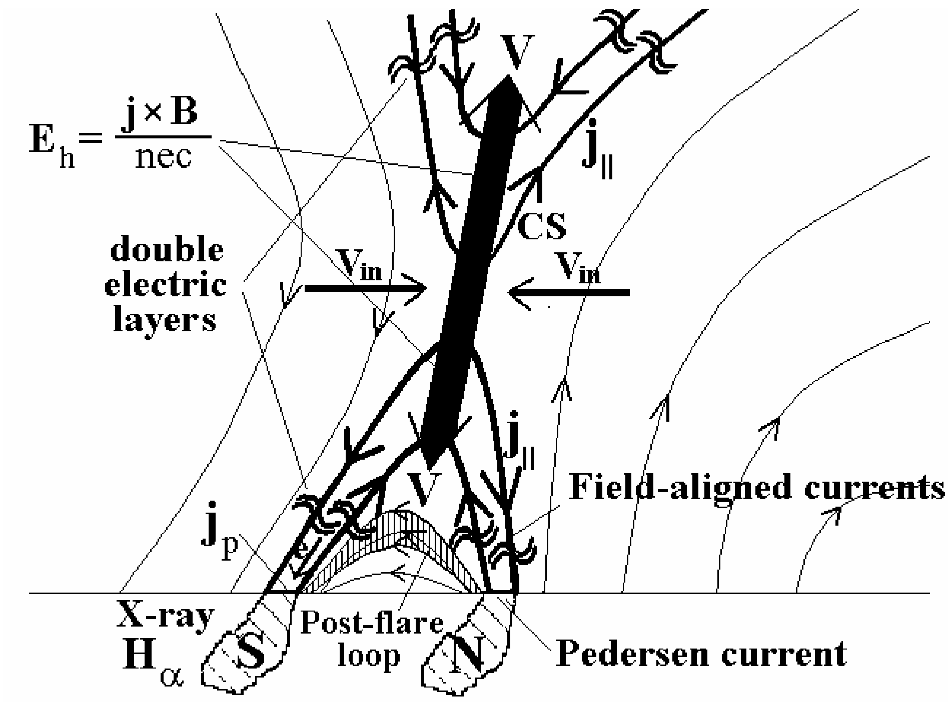

Figure 1. The flare electrodynamical model. Thin lines and thin arrows show magnetic field line. Thick lines and thick arrows show field-aligned current generated by the Hall electric field.

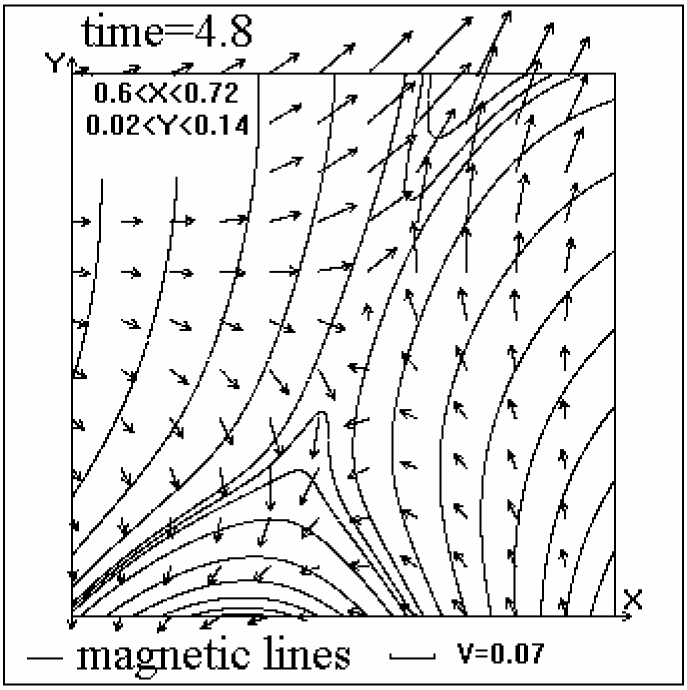

Figure 2. Plasma flow and magnetic line around a current sheet.

and hard X-ray radiation on the solar surface. This phenomenon is similar to aurora generation in the Earth polar ovals [3]. The energy of this X-ray depends on current sheet parameters. In a typical case 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. [6].

Magnetic energy dissipation should produce the loop legs moving apart, while plasma and magnetic lines inflow into a vertical current sheet. Indeed, at arriving the new magnetic lines the loop legs should go away together with field-aligned currents, flux of precipitating electrons and flare ribbons. For the solar flare produced at a horizontal current sheet decay the ribbons draw together [1].

X-ray emissions

The primary energy release in the corona above an active region has been demonstrated in the Yohkoh spacecraft hard X-ray measurements. The coronal source of flare X-ray emission is seen in the corona for a flare that appeared near the solar limb. The coronal source is situated above the magnetic arc in the place, where current sheet creation takes place according to the flare electrodynamical model. This source expected to be created due to plasma heating at magnetic reconnection in the current sheet. Another two hard X-ray sources were appeared in the places of the Northern and Southern magnetic spots. These two sources are produced by precipitation of electron beams that gain their energy in field-aligned currents.

Yohkoh data have been confirmed by valuable measurements on the RHESSI spacecraft [7, 8]. Positions of X-ray sources and their typical energy are shown in Fig. 3. Two chromospheric and one coronal X-ray sources are presented. The magnetic field lines that correspond to magnetic spots are shown also. There is a temptation to put the coronal source in singular line vicinity. The measurements permit to get spectrum of sources. The comparison of RHESSI and GEOS data show that the coronal source X-ray spectrum in the 2002 July 23 solar flare corresponds to thermal radiation with the temperature T~3keV at an emission measure of $\sim 5\times 10^{49}$ cm^{-3}. The plasma density is order of $10^{11} cm^{-3}$. From the pressure balance $nkT=B^2/8\pi$ one gets the magnetic field B~100G, corresponding to the typical flare current sheet value obtained in the numerical MHD simulation [3]. The plasma density $n=10^{11} cm^{-3}$ correspond to plasma frequency at the wave length $\lambda \sim 10$ cm. The emission of high frequency radio continuum at $\lambda \lesssim$ 10cm is associated with hard X-ray emission [9]. These data can be considered as an additional indirect evidence of energy dissipation accumulated in the current sheet magnetic field. The power X-ray spectrum $\sim \nu^{-2.5}$ of the surface ("footpoint") sources obtained by RHESSI shows that this radiation is produced by electron beams with energy of 100-200keV hitting the thick target (chromosphere). The minimum of total energy deposited into the flare plasma by non thermal electron (footpoint sources), 2.6×10^{31} erg, is on the order of the energy in the thermal plasma.

For obtaining a direct evidence of energy release in the current sheet it is necessary to calculate position of the sheet by solving MHD equation above the active region. For setting boundary conditions the evolution of preflare magnetic field should be used. Recently, such investigation has been performed for the flare May 27, 2003. It is shown that the flare radio emission at λ=5.2 cm is generated from the current sheet that appears in the preflare state [10].

Solar cosmic ray spectrum

The independent data confirming the electrodynamical solar flare model has been obtained by analyzing spectra of relativistic protons associated with a flare. The results of development of neutron monitors measurements show that protons arriving on the front of a solar cosmic rays pulse (prompt component) possess an exponential spectrum. The delayed component arrives several tens minutes later. It reveals a power spectrum. A possible explanation of this fact consists in different mechanisms of these components generation. Numerical calculations carried out for particles acceleration by electric field along the X-type singular line show an exponential spectrum [11]. In these calculations at t=0 the particle density set constant in the singular line vicinity, and electric field has been applied. As for the delayed component, it can be explained by acceleration in the shock wave that appears at CME. However, in another numerical experiment a power spectrum is demonstrated [12]. The main difference of this work consists in consideration of particles trajectories that at t=0 have been generated in a region of particle adiabatic drift. In the current sheet the particle is moving in crossed **E** and **B** to the singular line and gains energy in the singular line vicinity. The particles that situated at t=0 in vicinity of singular line are not considered. Apparently, the result of [11] (exponential spectrum) corresponds for particles initially located around a singular line, where the magnetic field is too weak, and particles are accelerated along the singular line. Such particles belong to the prompt component. The power spectrum of [12] describes delayed component. The delayed component must appear on the later flare phase, when particle density around the singular line is exhausted, and new particles arrive to the singular line vicinity drifting from the adiabatic region. Of course, it is impossible to reject another mechanism of delayed component creation.

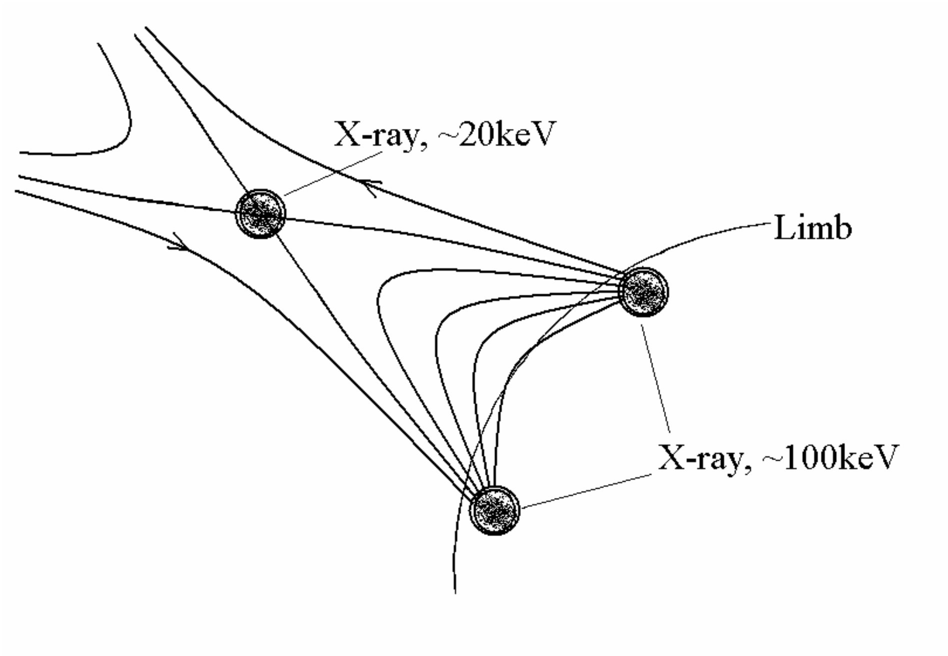

Figure 3. Flare X-ray emissions.

Conclusion

There are many observations that confirm the electrodynamical flare model. The most important of them are based on fast particle generations. It is shown plasma heating in corona and electron precipitation on the solar surface. But till the last time no one has demonstrated directly that energy release occurs in a current sheet. Now such evidence is obtained via comparison position of the calculated current sheet and distribution of microwave radio emission at a flare [10].

Acknowledgments. This work was supported by RFBR grant № 06-02-16006.

References

1. Podgorny A. I. and I. M. Podgorny. *Solar Phys*. **139**, 125 (1992).
2. Podgorny A. I. and A. I. Podgorny. *Astronomy Reports*. **45**, 60 (2001).
3. Podgorny I. M., A. I. Podgorny and S. Minami. Astron. *Astroph. Trans.* **22**, 585 (2003).
4. Podgorny A.I. *Solar Phys.* **123**, 285 (1989).
5. McKenzie D. E. and H. S. Hudson. *Earth Planet Space*. **53**, 577 (2001).
6. Podgorny A. I. and A. I. Podgorny. *Astronomy Reports.* **43**, 6o8 (1999).
7. Lin R. P., S. Krucker, G. J. Hurford, *et al*. *Astrophys. J.* **595**, L69 (2003).
8. Holman G. D., L. Sui, R. A. Schwariz, A. G. Emslie. *Astrophys. J.* **595**, L97 (2003).
9. Benz A. O., P. C. Grigis, A. Csillaghy, P. Saint-Hilaire. *Solar Phys*. **226**, 121 (2005).
10. Podgorny A. I., I. M. Podgorny, N. S. Meshalkina. Proc. of the 29th Annual Seminar. Apatity. 2006. P. ???.
11. Balabin Yu. V., E. V. Vashenyk,. O. V. Mingalev, A. I. Podgorny and I. M. Podgorny. *Astronomy Reports*. **49**, 837 (2005).
12. Wood P. and T. Neukirch. *Solar Phys*. **226**, 73 (2005).