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HARD SOLAR FLARE RADIATIONS

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Abstract. The space craft measurements during a solar flare demonstrate thermal X-ray *radiation* inside a current sheet above an active region and electron acceleration in the field-aligned currents up to hundreds keV. Precipitation of these particles on the solar surface is analogous with particle precipitation in aurora. Two components of solar cosmic rays are shown in neutron monitors measurements. The prompt cosmic ray component is generated during main energy release. The exponential spectrum of these protons is in agreement with particle acceleration by Lorenz electric field along the magnetic singular line in a current sheet. The similar effect has been observed in the laboratory experiments with high power discharge - pinch discharge. The flares produce also a delayed component. Apparently, it can be associated with spectrum deformation during diffusion in the turbulent magnetic field.

Introduction

The electrodynamical solar flare model is based on MHD numerical simulation of a current sheet creation above the active region [1 – 2]. It is shown that the 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 the new magnetic field emergence near pre-existing loop, if the polarity of the new field is opposite to the old field [2]. The full system of resistive MHD equations has been solved above an active region before the flare. It is important to emphasize that no assumption about the mechanism of current sheet creation is taken into account in these numerical experiments. Distribution of the magnetic field in the corona is calculated using the preflare magnetic field measured on the photosphere as boundary conditions. No magnetic flux ropes generation is observed prior the flare. Current sheet stability is conditioned by a normal magnetic component and plasma velocity along the current sheet. The stored energy is fast dissipated during a flare, when the current sheet transfers into an unstable state [3]. Current sheet is very stable for a long time, and energy is accumulated in the current sheet magnetic field. The electrodynamical solar flare model is shown in Fig. 1a. 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 the initial magnetic field configuration and the character of photosphere disturbances in the preflare state. For a vertical current sheet shown in Fig. 1a 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 into the current sheet. The energy flux $V_{in}B^2/8\pi$ is transferred into the current sheet. As a result plasma heating and acceleration along the current sheet take place. After reconnection, plasma flows along the current sheet upward and downward. The force $\mathbf{j}\times\mathbf{B}/c$ accelerates plasma, and upward flux produces coronal mass ejection.

Field-aligned currents

An important feature of a coronal current sheet is the Hall effect that produces the Hall current and the Hall electric field:

$$\mathbf{E} = \frac{\mathbf{j}}{\sigma} - \frac{\mathbf{V}\times\mathbf{B}}{c} + \frac{\mathbf{j}\times\mathbf{B}}{nec} - \frac{\nabla(nT_e)}{en} \qquad (1)$$

$$E_h = \frac{j_h}{\sigma} + \frac{j_{cs}B_n}{nec} \qquad (2)$$

The last term in (1) is a small for the long current sheet. The Hall electric field E_h appears because $\mathbf{j}\times\mathbf{B}/c$ force applied to electrons. Charges separation takes place. The E_h electric field is directed along the current sheet. Hall electric field is responsible for ions acceleration together with electrons producing plasma ejection from the current sheet (Coronal Mass Ejection). The powerful CME, the measurements of the Earth magnetotail electric field and field-aligned currents [4], comparison of the Hall current and the current in the current sheet, and measurements of Hall electric field in laboratory simulated magnetosphere present convenient evidence that in a real current sheet in the space the term E is much bigger than j_h/σ. So, for the Hall electric field estimation the formula $E_h \sim \frac{j_{cs}B_n}{nec}$ can be used. The Hall electric field produces field-aligned currents because of the plasma conductivity anisotropy in the magnetic field.

These currents are closed in the chromosphere by Pedersen currents. The electrons accelerated in upward field-aligned currents precipitate downward producing flare ribbons, and hard X-ray radiation on the solar surface. This phenomenon is similar to field-aligned current generation in the Earth magnetic tail that produce aurora in the polar ovals [4]. The energy of this X-ray depends on current sheet parameters. In a typical solar flare it should be order of 100 keV. The hard X-ray in the legs of magnetic loop produced fast electron beams precipitation has been demonstrated in RHASSI space measurement. The thermal X-ray sours with the temperature ~3 keV appears in the corona in the place of magnetic lines reconnection [5]. These date confirm the flare electrodynamical model prediction that energy dissipation should takes place in a current sheet in the corona.

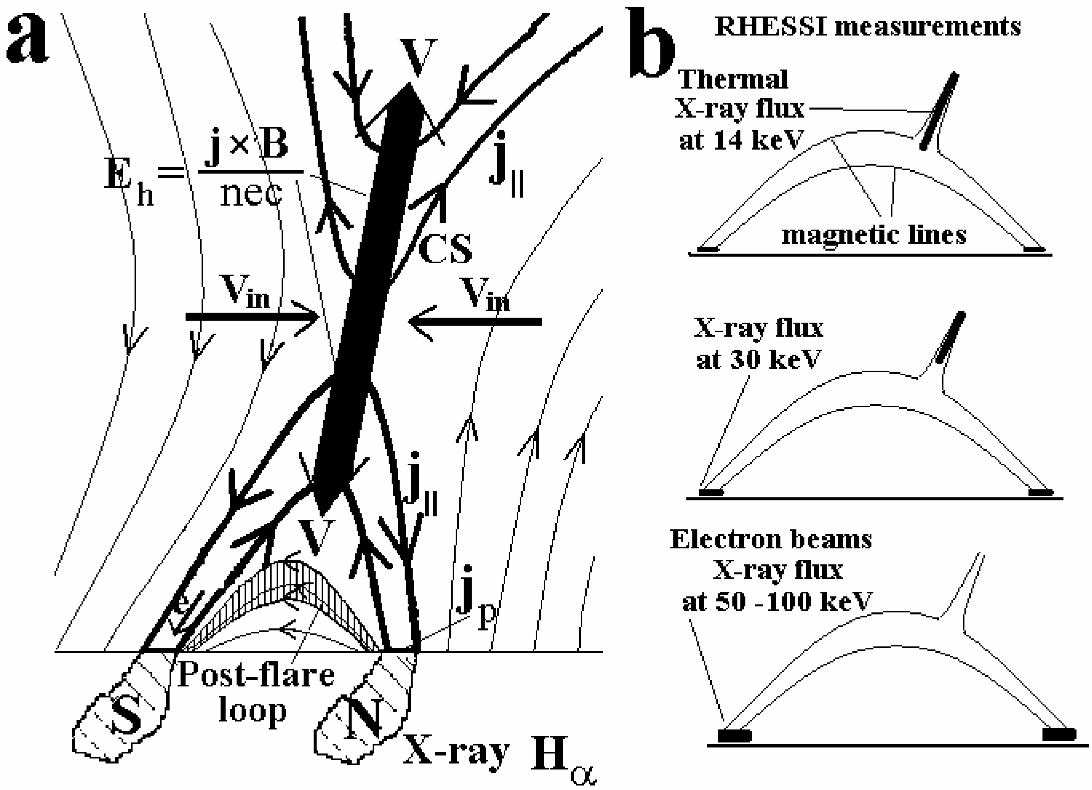

Figure 1. a) The flare electrodynamical model. b) Positions of X-ray sources according to RHESSI data.

Solar cosmic rays

The possibility for proton acceleration up to relativistic energy by Lorenz electric field $-\mathbf{V}\times\mathbf{B}/c$ takes place in vicinity of a X- type neutral line. Here $\mathbf{V}$ is plasma velocity inflow into a current sheet during magnetic reconnection. The neutral line is directed perpendicular to the picture Fig. 1. During explosive reconnection the inflow velocity can reach Alfven velocity, which corresponds to E~100 V/cm.

The spectra in energy range 1 -20 GeV have been obtained by analyzing of responses of the network of ground based neutron monitors [6, 7]. Each detector responses on neutrons created above its position in the Earth atmosphere due to incident cosmic ray protons. A proton with given energy reaches the magnetosphere from the certain asymptotic direction (the certain point of the celestial sphere) and moves in the Earth magnetic field before entering the atmosphere, where it creates neutrons. All neutron monitor stations work as a united multidirectional relativistic proton spectrometer. About 30 proton flares were developed. The typical example of the solar flare cosmic ray monitor responses (event 13.12.2006) is presented in Fig.2. The temporal profiles of the signals for two ground level neutron monitors at Calgery (Canada) and Mawson (Antarctica) for the event October, 22 1989 are shown. The smooth growth in the count rate at Mawson indicates that this station is detected primary the slow component, while a rather sharp initial increasing corresponds to the prompt component has been recorded at the Calgary monitor. The arrows labeled 1 and 2 mark the maximum of the count rate recorded by these monitors. Fig. 2b and 2c present energy spectra relativistic protons for these times. The spectra were derived by fitting the data for 27 neutron –monitor station. These data are presented on semilog and log-log scales. The spectrum 1, which was obtained at initial phase of the event (the prompt component) is described well by a linear dependence on semilog scale (Fig. 2c) i. e. relation is the exponential $dI_1/dE \sim \exp(-E/E_0)$ with $E_0 \sim 0.6$ GeV. This prompt spectrum corresponds to the particle that directly reach Earth orbit with the delay of time of flight along the Arhimed magnetic line. The prompt spectrum brings undisturbed information about mechanism of relativistic particle generation in the current sheet. The spectrum 2, which was taken 30 min later, has a different character. It is described by a linear dependence on the log-log scale. It is power-low dependence $dI_2/dE \sim E^{-\gamma}$ with $\gamma \sim 5$.

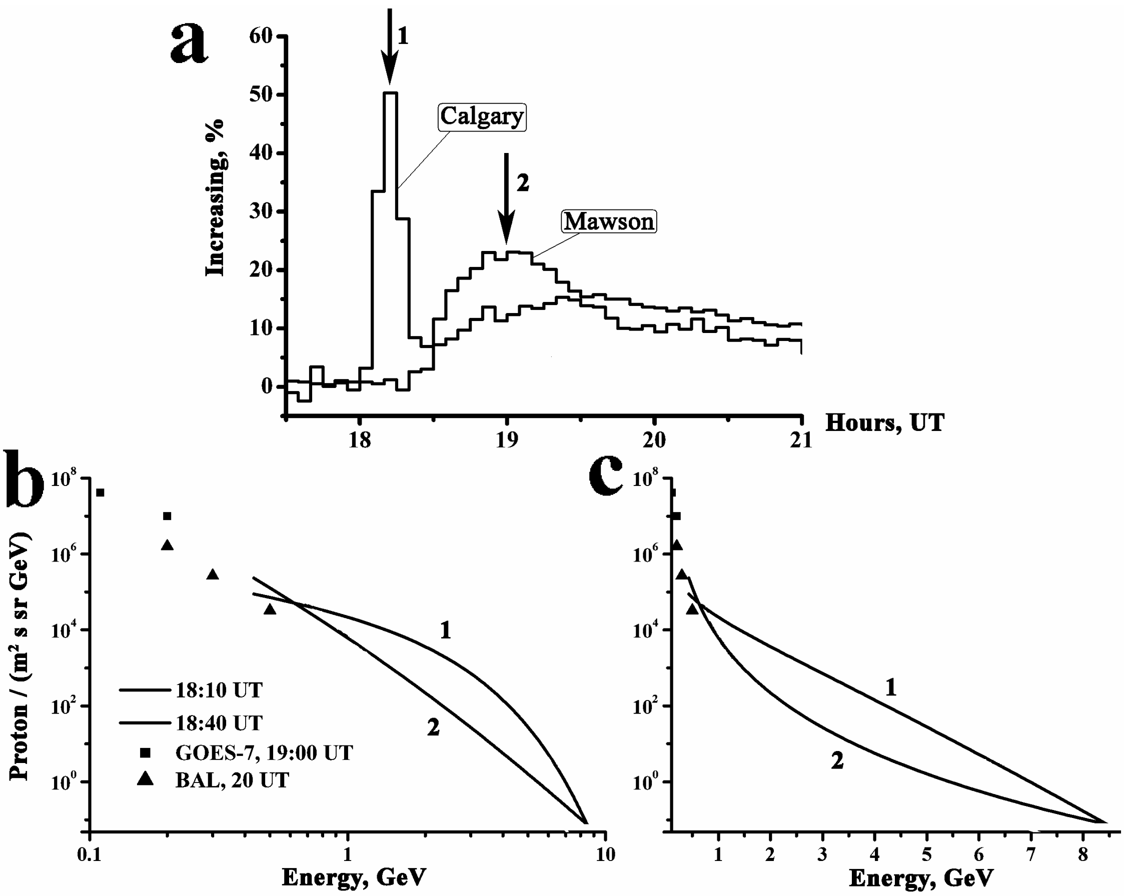

Figure 2. ***(a)*** Temporal profiles of the neutron monitors signals at Calgary and Mowson neutron monitor during the event October 22, 1989. (**b,c**) Solar proton spectra in the log-log (**b**) and semilog scales (**c**). (1) is spectrum of the prompt component, (2) is spectrum of the delayed component. Crosses are the direct solar proton data measured by balloons.

The mechanism of particles acceleration along a singular line.

The possibility of particle acceleration along a singular magnetic line by the Lorenz electric field was demonstrated in the laboratory experiments directed to plasma heating for controlled thermonuclear research **[8, 9].** The powerful discharge in hydrogen and deuterium was investigated. The discharge was produced in a cylindrical chamber with the 20 cm diameter and the 100 cm length, which is situated inside a coaxial feeder. The voltage was applied from low induction capacity 36 μF. The initial gas pressure was order of 5×10^{-2} mm Hg, and the rate of current increasing was $\sim10^{11}$ A/sec. After gas breakdown the current density is located near chamber walls, and the current magnetic field compresses plasma to the axis (pinch effect).

The radial current distribution changes with time. The pinch boundary moves with acceleration. It reaches velocity $\sim10^7$ cm/s at the discharge radius ~1 cm. At that time the magnetic field is $B = 0.2I/r \sim 4\times10^4$ ***Gauss***, and the electric field directed along the discharge axis becomes $\mathbf{E} = -\mathbf{V}\times\mathbf{B}$ ~4000 V/cm. The initial discharge and compressed pinch (at 3 μs) are shown in Fig. 3. The radial distribution of current density is presented below. The magnetic configuration in the axis vicinity possesses the O-type magnetic singular line. The electric field $-\mathbf{V}\times\mathbf{B}$ accelerates ions and electrons along the axis in opposite directions. Particle acceleration takes place along this ***O-type*** line. Here magnetic field prevents particle escape from the axis vicinity, because the every deflected particle is returned to the axis by the $e\mathbf{V}\times\mathbf{B}/c$ force.

The experiment [8] demonstrated fast particles (electrons and ions) acceleration along the chamber axis (O-type magnetic singular line). They gain energy W>300 keV at the voltage applied from the capacity order of 10 - 15 kV. The particle acceleration was discovered because of X-ray emission and neuron radiation at discharge in deuterium. For direct energy measurements of accelerated electrons an energy analyzer is used. The energy analyzer has been placed above the anode with a hole, as it is shown in Fig 3. The acceleration time in laboratory experiment is very short order of 0.5 μs. Particle acceleration is ceased when pressure of hot compressed plasma stops the compression. The similar mechanism of particle acceleration should manifest itself also in vicinity of X-type line of a current

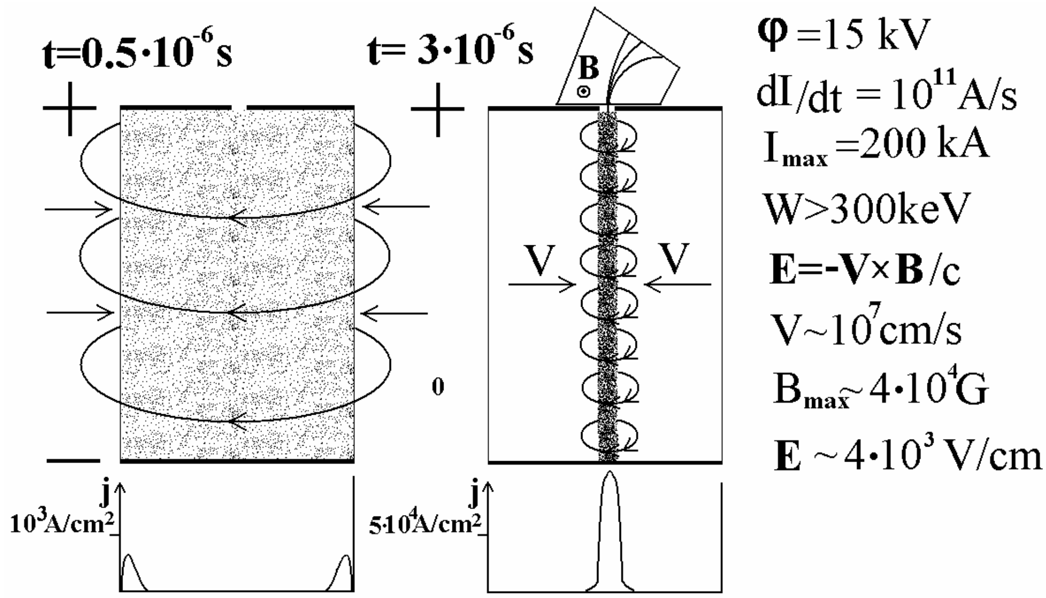

Figure 3. Lorenz electric field generation in pinch discharge. The radial current distribution is shown below.

sheet at fast plasma inflow into the sheet (Fig. 1). In this case plasma flowing into the sheet moves after magnetic reconnection along the sheet, and plasma pressure in the sheet does not prevent plasma inflow. The particle acceleration takes place during all time of fast reconnection. But the e**V**×**B**/c force in vicinity of X-type line of a current sheet prevents particle to escape from the acceleration region only in one direction (perpendicular to the current sheet). In another direction (along the sheet) particles can escape from the acceleration region. Only a part of particles traveling along the axis can gain big energy. Such mode of acceleration reveals exponential spectrum, which is typical for the prompt component of solar flare cosmic rays.

The spectrum of protons accelerated by the constant electric field applied along X-type singular line of potential magnetic field has been numerically investigated [6]. The main parameters of this numerical experiment are taken from MHD numerical simulation of the current sheet that has appeared in the corona before the Bastille Day flare. Initially the particles are numerically generated according to three dimensional spatially uniform Maxwellian distribution inside a parallelepiped with magnetic field. The parallelepiped has been divided in 1250000 layers. Each layer contains 16257024 particles distributed at t=0. The constant electric field is applied along singular line. These calculations demonstrate an exponential spectrum. Now such calculations are in progress ***for*** a real magnetic and electric field configurations obtained for a real preflare configuration.

Conclusion

The prompt component of relativistic proton brings direct information about particle acceleration during the flare. The prompt component spectrum reviles exponential dependence dI/dE~exp(-E/E_0) with E_0 order of 0.5 GeV. This spectrum fits very well with the mechanism of particles acceleration along a singular line of X-type during magnetic reconnection in the current sheet.

The delayed component arrives to the Earth orbit several tens minutes later. There is a temptation to explain the delayed component by acceleration in interplanetary shock wave excited by CME. But it is difficult to explain power spectrum dI/dE~ $E^{-\gamma}$ with so high γ as order of 5 in a shock. Apparently both components appear in the current sheet, but spectrum of delayed component is formed during diffusion across the magnetic field due to scattering with irregularities. During such scattering the anisotropy of angular distribution decreases.

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