The spectrum of solar relativistic cosmic ray measurements and numerical simulation

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Abstract. The solar relativistic protons are measured with the worldwide network of neutron monitors. The big pulses of relativistic protons appeared after the flares occurring in the West side of the Sun disk. They arrive to the Earth along Archimedean magnetic lines without collisions in ~15 min after a flare. This prompt anisotropic flux contains information about the exponential ~exp(–E/E₀) spectrum of protons ejected from the solar cosmic ray source. After delay of 15 - 20 min the proton flux becomes isotropic with power spectrum E⁻γ where γ ~ 5. Apparently, beam instability is developed. The protons accelerated in eastern flares can reach the neutron monitor due to diffusion across the magnetic lines. The magnetic field energy accumulation in the current sheet in the solar corona above the active region is proved by MHD simulations and the position of observed flare thermal X-ray source. During a flare the magnetic field energy is transferred into the particle energy. Proton acceleration up to relativistic energy can occur in the electric field applied along the singular line in a current sheet. The electric field E = -V×B/c is created due to the fast rate of reconnection V. At typical V = 2×10⁷ cm/s the measured spectrum coincides with the calculated spectrum.

1. Introduction

The most popular mechanisms of cosmic ray acceleration considered 100 years in the theory is based on shock waves. The untested assumptions are used. In 1942 S. Forbush have discovered the sharp pulses of energetic proton emission from the Sun, which is not associated with cosmic ray that arrived from far region of the space. The modern experimental method and theory of solar flare permit to get evaluative information about physics of solar flare and mechanism of proton acceleration at solar flare appearance. The principal problem arises, if the solar cosmic rays are generated by a similar mechanism, as a cosmic ray that arrived from far cosmic space. So far any reliable information on mechanism of particles acceleration in the outer space is not available. However, analysis of a number of observational data relating to solar cosmic rays provides the valuable information about the particle acceleration in actual solar flares. This information is useful for understand the physics of cosmic rays. The most important information about solar cosmic ray has obtained from worldwide network of neutron monitors, which operate as a multy channel analyzer of the energy. Solar cosmic rays are caused by solar flares. Particles acceleration takes place during the explosive energy release in the solar flare. So to understand the physics of solar cosmic rays origin and also, possibly, for prognosis of
solar cosmic rays events, it is necessary to study directly the explosive process in the solar flare and the process of particle acceleration, which takes place during it.

**Figure 1.** Electrodynamical model of the solar flare which used the results of numerical simulation of the current sheet creation (at left).

2. **Solar flare**

Primordial energy release of the solar flare takes place in the solar corona at the altitudes 15 000 - 30 000 km. The flares appear above the active regions with magnetic field about 3000 G. The flux of magnetic field of active region increases in several times during 2 - 3 days before the flare. It reaches $\sim 10^{22}$ Mx [1]. The numerical solving of magnetohydrodynamical (MHD) show that change of magnetic field in active region before the flare produces a current sheet with energy accumulation for a flare ($\sim 10^{33}$ erg). So the magnetic energy of a flare is stored in the solar corona.

For precise study of the flare situation when setting of conditions for MHD simulation no assumptions about the mechanism of solar flare have been done. The calculations are performed for dynamic of the boundary conditions are taken from photospheric measurements. The magnetic field configuration and plasma parameters in the corona above an active region is obtained in the numerical solving of equations using the observed magnetic field distribution on the photosphere for setting of the boundary condition on the photosphere. For setting other values on the photospheric and nonphotospheric boundaries the approximation by free-exit conditions is used. The solution is started several days before the flare, when there are no strong disturbances in the corona, and so the potential magnetic field that calculated using distribution of magnetic field on the photosphere is used for setting the initial condition. To accelerate calculation the finite-difference scheme, which is stable for large steps, is developed by authors [2]. This scheme is upwind one, absolutely implicit one, and it is conservative relative to the magnetic flux.

MHD simulation in the solar corona above the active region NOAA 10365 shows appearance of the current sheet which position during the flare May 27, 2003 at 02:53 coincides with the position of the flare source of thermal X-ray emission [3]. The fact of a such coincidence is an independent confirmation of the flare mechanism, according to which there is an explosive release of the magnetic energy of a current sheet formed in the solar corona. During quasi-stationary evolution of the current sheet the plasma density near it decreases in time. Then the current sheet transforms into an unstable...
state, and explosive release of its magnetic energy takes place [4, 5]. The energy released at the current sheet decay produces a flare. For precise study of the flare situation at setting of conditions for MHD simulation no assumptions about the mechanism of solar flare been done.

**Figure 2.** (a) - registration of relativistic solar protons by two neutron monitors, (b) - Energy spectrums calculated for relativistic protons accelerated in a current sheet (points) and measured by worldwide network of neutron monitors (solid line).

Basing on the mechanism of energy release in the current sheet and using the results of numerical simulation the electrodynamical model of solar flare (figure 1) is developed which explains the main observational manifestations [6, 7]. Induction electrical field caused by the rapid change of the magnetic field during the instability accelerates electrons up to energy order of 1 Mev. This electron are accelerated along the field lines and hit the photosphere, producing beam X-ray. Plasma acceleration upward along the current sheet causes the coronal mass ejection. The sources of hard X-rays emission are located at intersection of the magnetic lines from the current sheet with the solar surface. The X-ray emission is a result of the interaction of electrons accelerated in the field-aligned currents with lower dense layers of the solar atmosphere. The field-aligned currents are created in the current sheet as a result of Hall effect due to electron acceleration along the current sheet by $jB_n$ force (product of the current density in the current sheet on the component of the magnetic field which is perpendicular to the sheet).

### 3. Solar cosmic rays

The most important information about solar cosmic ray ejected from flares has been obtained from the worldwide network of neutron monitors. About 50 monitors are situated on the Earth surface. The trajectory of the protons that come to each monitor are defined by the magnetic field of the Earth. Each monitor detects the protons in a certain energy range, which came to the magnetosphere at certain angles. Typical results of the flow measurement of protons by two different monitors are shown in figure 2a. The monitor network works as a single multi-directional spectrometer for the cosmic rays. Processing of measurement results allows to determine the spectra of protons, which come at different times. To determine the spectra of the relativistic solar cosmic protons and anisotropy of the distribution of their pitch angles in the interplanetary magnetic field from the observed responses of the neutron monitors, the method for solving the inverse problem is developed [8, 9]. The energy and the asymptotic direction for the arrival of the proton, creating neutrons in the atmosphere above each station, are determined by calculating the trajectory of particle in the magnetosphere model. Figure 2a shows the typical measurements of the two monitors for proton flux from the flare registered in the western limb. The proton flux appeared in 15 minutes after the flare. It came to the register from flare with particle velocity along the spiral magnetic field. Such delay time of the proton flux is typical for western flares. Its definition became the first evidence of generation of solar cosmic rays during the solar flare. Analysis of the obtained data using the measurements of all the monitors showed that the proton flux has an exponential spectrum with energies up to 20 GeV.
This prompt component of accelerated protons is anisotropic one. It brings direct information about processes which take place during the explosive energy release. One of the most important parameters which describe this flare process is plasma inflow velocity in the sheet $V_{\text{in}}$ (or reconnection velocity, see figure 3). For example shown in figure 2a this prompt component is measured by the Leeds neutron monitor during several ten minutes after the flare, and later the delayed component is arrived. But the Ottawa monitor registers only the delayed solar cosmic rays component which appears about 1 hour after the flare. This delayed component consists of protons which are accelerated during the flare and then apparently scattered on magnetic field inhomogeneities in the interplanetary space. The protons distribution of the delayed component is isotropic and has the power spectrum.

The protons arrived from the eastern flares, consists only with the delayed component, which can arrive only due to their transfer by the flow of the solar wind or due to their transfer by diffusion across the magnetic field.

![Proton acceleration in the current sheet.](image)

From RHESSI: \( \langle \text{ME} \rangle = 5 \times 10^{49} \text{ cm}^{-3} \).
\[ T = 3.1 \text{ keV} \quad n = 10^{11} \text{ cm}^{-3} \]
\[ B^2/8\pi = n_k T \quad B = 110 \text{G} \]
\[ M = N m_p \sim 10^{15} \text{g} \quad \text{--- CME} \]

At \( V_{\text{in}} = 2 \times 10^7 \text{ cm/s} \) and \( L = 10^9 \text{ cm} \).

**Proton acceleration along the X-type**

\( B = 0 \) **magnetic line by the electric field** \( \mathbf{E} = -V \times \mathbf{B}/c \).
\[ E = 20 \text{V/cm} \]
\[ W = 2 \times 10^{10} \text{eV} \]

Conditions favorable for the generation of relativistic solar cosmic-ray particles appear at current sheet decay. When a current sheet is transferred in the unstable state its magnetic field is dissipates and magnetic energy is transferred in heat at the particle kinetic energy. The current sheet decays due to magnetic reconnection. Plasma with frozen in the magnetic field inflows in the current sheet from both sides, and reconnection of opposed directed magnetic field takes place. The plasma inflow velocity (the velocity of magnetic reconnection) during a flare can be estimated as \( 2 \times 10^7 \text{ cm/s} \), later it has been found by comparing of measured and calculated spectra of solar cosmic rays. At the typical current sheet magnetic field \( \sim 100 \text{G} \), the Lorenz Electric field \(-V \times \mathbf{B}/c\) along the current sheet axis is order of \( 20 \text{V/cm} \). At the current sheet length \( 10^9 \text{ cm} \) the proton moving along the current neutral line can be accelerating to \( 20 \text{ GeV} \) (figure 3). This energy received by particles that do not deflect by magnetic field. The spectrum of accelerated particles is formed because not all particles gain this maximal energy. Some of them have such initial positions that they are deviated by normal to the current sheet magnetic field component and escape from the acceleration regime before they pass all the current sheet length. This scenario of particle acceleration is numerically simulated by considering the proton motion in the magnetic and electric field obtained in the current sheet at numerical MHD simulation.
for a real flare. The simulation [10, 11] shows the exponential spectrum of protons. The calculated at the reconnection velocity $2 \times 10^7$ cm/s spectrum coincides with spectrum of prompt protons of flares appeared on the West side of the sola disk (figure 3).

4. Conclusion
Solar flare appears due to fast release of energy, which was accumulated in the magnetic field of the current sheet in the solar corona above the active region. Solar cosmic rays are generated due to particle acceleration by electric field in the current sheet. Measurements with the worldwide network of neutron monitors show the exponential spectrum of prompt component which consists from accelerated protons reached the Earth propagating along spiral interplanetary magnetic field without collisions. This prompt component brings information about explosive process in the corona. The spectrum obtained by calculation of proton trajectories in the electric and magnetic field of the current sheet is the exponential one. The fields of the current sheet are obtained by MHD simulation above the real active region. The calculated spectrum coincides with the spectrum of prompt component measured by neutron monitors for reconnection velocity in the current sheet $V_{in}=2 \times 10^7$.

The problem of possible analogy of origins of solar cosmic rays and traditional cosmic rays now remains to be open.

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