Proton energy spectrum and source parameters of the September 29, 1989 event

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Summary. — Ground Level Enhancement (GLE) of solar cosmic rays (SCR) widely observed on September 29, 1989 is studied. The event was remarkable for a number of unusual features. Among them were the double-peak increases observed at some neutron monitor (NM) stations and complicated behaviour of the proton energy spectrum and anisotropy at high rigidities ($R \geqslant 1$ GV). Two-component structure of the proton intensity-time profiles in the event has been demonstrated. The first (prompt) component (PC) had a short duration and very hard energy spectrum. The second (delayed) component (DC), being ejected from the Sun ~1-2 h later, was dominated by a particle population with the soft spectrum and gradual profiles. By fitting the observed proton spectrum to the calculated one in a computational model with a fast acceleration mechanism at the first, early stage of the event, we estimate parameters of the magnetic field and plasma in the source of the prompt component: $B = 91$ G; $n = 1.2 \times 10^7$ cm^{-3}; $L = 10^9$ cm (B, n and L are magnetic field intensity, plasma density at the acceleration site and length of the current sheet, respectively). Such values of B and n are characteristic for the trailing part of coronal transient (behind an eruptive filament) at the coronal heights of several tenths of solar radius, and the value of L is of the order of the filament length.

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1. – Introduction

The solar proton event (SPE) of September 29, 1989—the largest Ground Level Enhancement (GLE) of solar cosmic rays (SCR) for the last three solar cycles—was recorded by the worldwide network of neutron monitors (NM), surface and underground muon telescopes (MT), and has been extensively discussed (*e.g.*, [1-3] and references therein). As is widely accepted now, this rare GLE was due to the very powerful solar flare occurred behind the west limb of the Sun. The most remarkable

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feature of the event was the two-peak increase profile observed by a number of neutron monitor (NM) stations. This fact was interpreted by some authors as a two-fold ejection of accelerated particles from the Sun [4] or as a two-source acceleration [5-7]. Namely, the first ejection was impulsive, and this prompt component (PC) had a very hard energy spectrum (*e.g.*, [8, 9]) as evidenced by low-latitude NM data and even by underground muon detectors in Embudo (USA) [10] and Yakutsk (USSR) [11]. The second, delayed component (DC) was probably ejected from the Sun about 1-2 h later. It had a soft energy spectrum characteristic for stochastic acceleration mechanism [12, 13] and a bi-directional anisotropy [7, 14].

In spite of almost 10 years of intensive studies, no generally accepted scenario exists for this outstanding event, and many researchers are still fascinated by its challenging properties. This short paper demonstrates a two-component structure of the proton intensity-time profiles in the event of September 29, 1989 and reveals the nature of the first, prompt component. As shown below, a possible source of the PC is linked with the electric fields produced by the magnetic reconnection process at the trailing part of the eruptive prominence (filament).

2. – Data selection and analysis

In our analysis we used characteristic intensity-time profiles of SCRs observed on September 29, 1989 at the four NM stations (fig. 1) with different geomagnetic cutoff rigidities, R_c, namely: Thule, Greenland ($R_c = 0.00$ GV); Mawson, Antarctic ($R_c = 0.20$ GV); Deep River, Canada ($R_c = 1.14$ GV); and Bern, Switzerland ($R_c = 4.61$ GV). The two-peak structure of some profiles may imply the existence of two distinct (and shifted in time) ejections of relativistic protons from the Sun [5-7]. Namely, the pulse-like profile at the Bern NM suggests the first (hard and prompt) ejection in the event, while the delayed profile at the Mawson NM may correspond to the second (soft

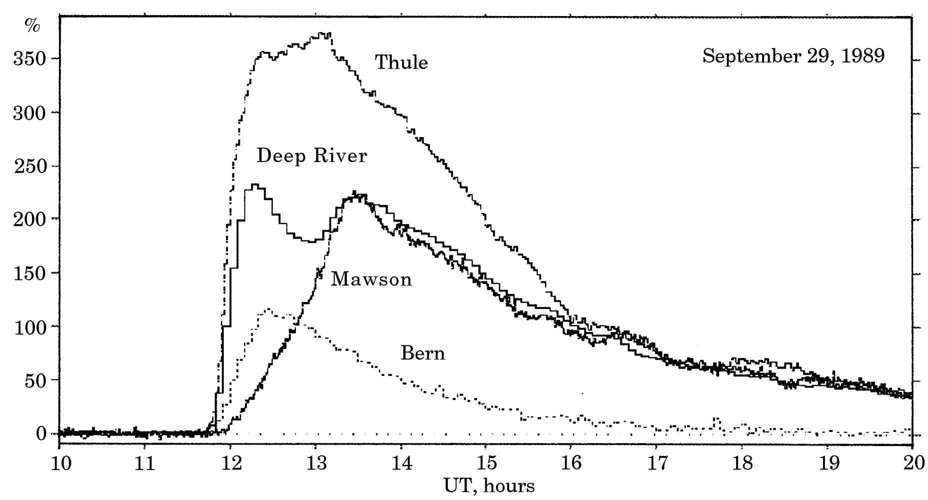

Fig. 1. – Intensity-time profiles at the four neutron monitors with different geographic locations and geomagnetic cutoff rigidities recorded during the September 29, 1989 GLE: Thule, Greenland ($R_c = 0.00$ GV); Deep River, Canada ($R_c = 1.14$ GV); Mawson, Antarctic ($R_c = 0.20$ GV); Bern, Switzerland ($R_c = 4.61$ GV).

and delayed) ejection. The Deep River NM reveals two peaks, one of which seems to be caused by the first ejection because it nearly coincides in time with the Bern NM profile. The second peak was probably formed by the second ejection because it coincides with the delayed profile at the Mawson station. The flat maximum of the Thule NM profile is possibly a result of the summation of decreasing prompt and increasing delayed profiles [14]. Notice that the profiles shown in fig. 1 are typical for the event under consideration; for example, the pulse-like profiles (PC only) also were observed at the NM Rome, Tbilisi, Alma-Ata, Tokyo, Darwin, and other stations at high geomagnetic cutoff rigidity; two peaks (PC+DC) were fixed at the NM Calgary, Hobart, Inuvik, Goose Bay and others; the delayed profile (DC only) was noted at the NM Mirny [1-3]. The pulse-like profiles have been recorded also at the surface and underground muon telescopes; a unique pulse-like increase in the counting rate was recorded by the "Carpet" detector—a central part of the Air Shower Array at the Baksan Neutrino Observatory (USSR) (for details see [2]).

Based on the same data, the existence of two proton components in the event of September 29, 1989 can also be displayed by the so-called vT_{m}-technique [15]. The total path, vT_{m}, traveled by the main bulk of solar particles constituting the intensity maximum at the Earth, may be presented as the sum of interplanetary, A_{m}, and coronal, $B_{\mathrm{m}} v$, parts of this path [15]:

$$vT_{\mathrm{m}} = A_{\mathrm{m}} + B_{\mathrm{m}} v \,, \tag{1}$$

where v is the velocity of particles; T_{m} is the time from the moment of generation to the maximum of intensity; A_{m} is the summary interplanetary path and B_{m} is the time delay of the particles in the corona. The vT_{m}-diagrams for the GLE of September 29, 1989 are shown in fig. 2. It is seen that the experimental points in fig. 2 form two linear dependencies of the type (1). One of them, with great inclination, unites data on non-relativistic solar protons measured by the GOES-7 sensors [16] and on relativistic particles recorded by the Deep River NM at the second peak. All these particles obviously belonged to the same population (DC) that was delayed in the corona and then released simultaneously through the same time $B_{\mathrm{m}} \approx 2$ h. Another possibility is a simultaneous acceleration of the DC particles at the post-eruption phase of the flare, as was suggested for the June 15, 1991 event [17].

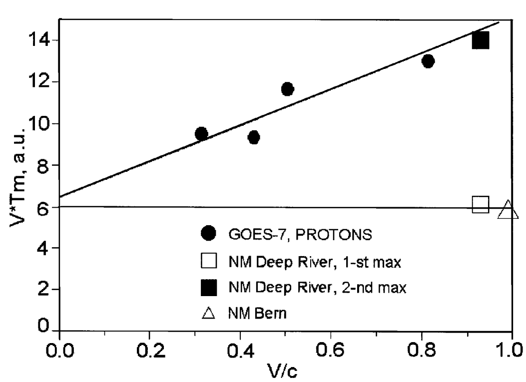

Fig. 2. – Results of the vT_{m}-analysis of the event of September 29, 1989 by the data of two neutron monitors (Deep River and Bern) and GOES-7 proton data in different energy channels. The diagrams show two particle populations in the event.

The second straight line nearly parallel to the horizontal axis ($B_m \approx 0$) is drawn through the points corresponding to the intensity maximum of the Bern NM profile and the first peak at the Deep River NM. So, the prompt component of the SCR escapes from the Sun without any delay, and is represented by the relativistic protons only [18]. This has been confirmed also by the quasi-exponential form of the proton energy spectrum depleted of low-energy particles (see sect. 3 below), this feature being characteristic for the mechanism of fast acceleration during processes of magnetic merging in the solar corona [19]. On the other hand, the rigidity spectrum of the delayed population in the event (second peak at the NM Deep River profile and the straight line with a great slope in fig. 2) corresponds more likely to the mechanism of slow stochastic acceleration [12].

3. – Source spectrum of relativistic protons

To describe the main features of this GLE, three possible scenarios have been postulated: 1) acceleration by a CME-driven coronal shock (*e.g.*, [20]); 2) post-eruption particle acceleration in the corona (*e.g.*, [21]); 3) a combined two-source acceleration (*e.g.*, [6]). Notice, however, that theoretical estimates of the source spectrum, up to now, were carried out in the framework of the two-source approach only. A very preliminary estimate of the DC spectrum has been obtained [12] under a rather conventional scenario. It was suggested that the bulk of energetic particles are generated in the flare volume or its vicinity, and the acceleration of the DC is due to magnetosonic turbulence, with initial particle energy around E_i and monoenergetic injection into the resonant stochastic process, the accelerated particles being trapped in an expanding magnetic bottle [22]. Because of the Rayleigh-Taylor instability, the bottle is destroyed at a height $\leqslant 0.9 r_s$, and energetic particles are released into the interplanetary space at a time of order 0.5–1.0 h after the flare. Assuming an injection energy $E_0 = 0.5$ MeV and a mean confinement time of particles in the acceleration region $\tau \approx 1$ s, the best fit was obtained at the acceleration efficiency $\alpha = 0.04\ \mathrm{s}^{-1}$. The calculated rigidity spectrum for the DC [12] and the observed spectrum for the second intensity peak at 1325 UT [8] are shown in fig. 3a by the solid line and the dots, respectively. The fitting [12] was carried out, however, with neglecting possible interplanetary modulation of the observed spectrum. Also, in fig. 3a we could not take into account a considerable difference between two estimates of the spectrum obtained in [8] and [23] for the same time 1325 UT.

Recently, the authors [24] have estimated the parameters of rigidity spectra for relativistic protons outside the magnetosphere at different stages of this GLE in the framework of two working hypothesis: 1) a unidirectional anisotropy during the first peak, and 2) a bi-directional anisotropy during the second peak. It was found, in particular, that early in the event (at 1225 UT) the spectrum near the Earth has been described by power law function $D_E(R) = D_0 R^{-\gamma}$, where $D_0 = 1.94$ particles $(\mathrm{cm}^2\,\mathrm{s\ sr\ GV})^{-1}$, and $\gamma = 1.08$ for $R < 2$ GV, the value of γ being increased by a quantity $\Delta\gamma = 0.13$ per 1 GV for $R > 2$ GV. Hence, the source rigidity spectrum for the prompt component, $D_{PC}(R)$, may be estimated by a simple empirical formula [25], under assumption of scatter-free interplanetary propagation:

$$D_{PC}(R) = D_E(R) \times (2\text{–}4)\,\Delta t \pi r_E^2, \tag{2}$$

where r_E is the radius of the terrestrial orbit and Δt is the recording time of the PC at the Earth. If one assumes the source to be instantaneous and highly anisotropic (zero

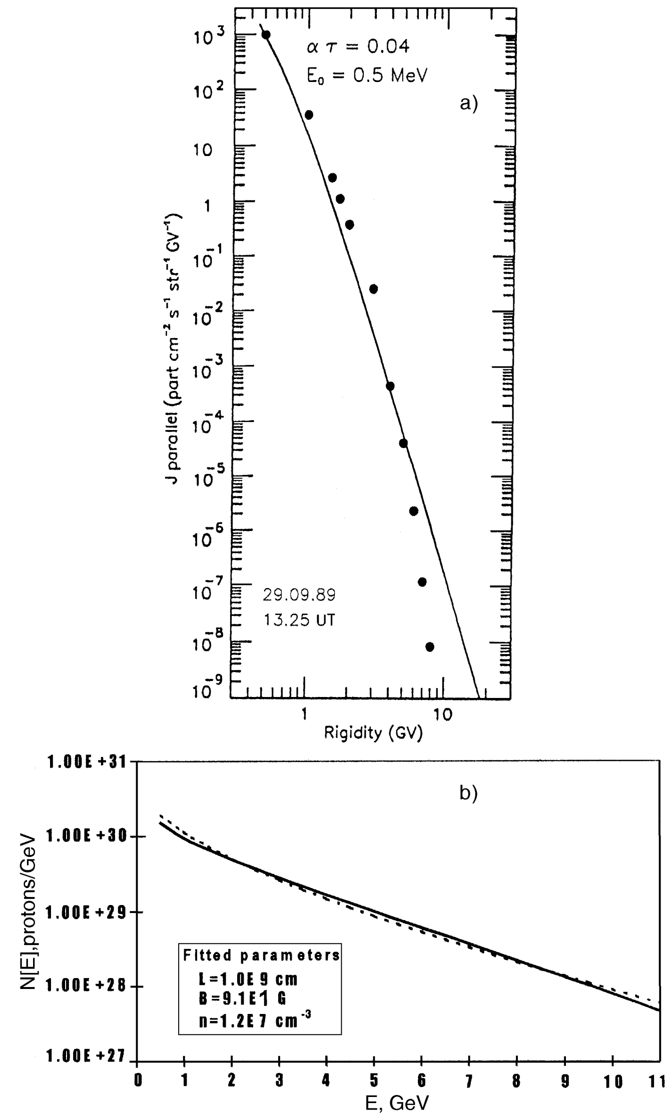

Fig. 3. – Source spectra of two relativistic components in the GLE of September 29, 1989: a) rigidity spectra of the delayed component derived from observational data [8] (dots) and calculated from stochastic acceleration model [12] (solid line); b) energy spectra of the prompt component derived from observational data [24] (dashed line) and calculated from the acceleration model [19] in the present work (solid line).

pitch angles of ejection), and scattering in the interplanetary medium to be negligibly small, then the particle distribution function at the Earth will be of the form $F_{\mathrm{PC}} \sim \delta(\tau)$ [26], where $\tau = t - (z - z_0)/v$. The coordinate z is figured along a line of force of the IMF, and z_0 is the coordinate of the source. This approximation corresponds to the case when all particles having velocity v arrive at the observation point in a time $t = (z - z_0)/v$. For relativistic particles $v \approx c$, the dispersion in the energies does not result in a dispersion in arrival times. If one takes into account the fact that under typical conditions in the interplanetary medium the length of a line of force, $z_E \approx 1.2$-1.3 AU (see also [27]), then we obtain $\Delta t \approx 600\ s = 10$ min. The spectrum (2) transformed from rigidity into energy scale is shown in fig. 3b by a dashed line.

As was demonstrated earlier [25], the source spectra derived from observational data at the early stage of a number of GLEs may be fitted to the PC ejection spectra within the framework of acceleration model [19] based on the magnetic reconnection in the extended coronal structures. In this particular case, we also used the relations [19] describing the source spectrum formation under the action of the electric field in the reconnecting current sheet

$$N(E) = N_0 (E/E_0)^{-0.25} \exp[-1.12 (E/E_0)^{-0.75}], \tag{3}$$

$$E_0 = 8.236 \cdot 10^{-3} (B^3 L/n)^{2/3}\ \text{MeV}, \qquad N_0 = 1.47 \cdot 10^7 (nL^2/BE_0)\ \text{proton/MeV},$$

where E_0 is the characteristic energy of the spectrum, and B, n and L are the magnetic field intensity, plasma density at the acceleration site and linear dimension of the current sheet, respectively. The results of our calculations of the PC source spectrum (3) are given in fig. 3b by the solid line. Fitting the spectrum calculated by (3) to that estimated from observational data (2), by the parameter optimization procedure, we obtained the following source parameters: $B = 91$ G; $n = 1.2 \cdot 10^7\ \text{cm}^{-3}$; $L = 10^9$ cm. Such values of B and n are characteristic for the trailing part of coronal transient (behind an eruptive filament) at the coronal heights of several tenths of solar radius, and the value of L is of the order of the filament length. As far as we know, the above theoretical determination of the source spectrum, calculated using the two-source model, gives the only numerical estimates of B, n, and L for the event of September 29, 1989 available in the literature. The other two models—CME-driven shock and post-eruption acceleration—do not yet have any similar estimates either for the source spectrum, or for the source parameters in this particular event.

4. – Conclusions

From these estimates we conclude that the acceleration of the hard prompt component of relativistic protons in the event of September 29, 1989 is similar to that described in the models [28-30]. An electric field appearing due to the reconnection process, at the typical plasma parameters, in the reconnecting current sheet (RCS) [29] is about $10\ \text{V cm}^{-1}$. On the other hand, the authors [30] found that the Priest-Forbes magnetic field configuration near the neutral current sheet (NCS) should produce most efficient proton and electron acceleration provided the B value is of 100 G. Such magnetic field produces inside the NCS a direct electric field of $10\ \text{V cm}^{-1}$, compatible with the observation, in particular, in erupting prominences [31]. We believe that, in our particular case, the particle acceleration proceeds in the electric field produced between reconnecting magnetic field lines in the trailing part of coronal transient behind the eruptive filament. At the same time, while gaining energy in the electric field, particles may accomplish an azimuthal drift in the NCS carrying them to the visible side of the Sun from a behind-the-limb flare. So, the prompt arrival of particles and gamma-ray emission [32] from this flare may be easily explained as well. However, a more detailed discussion of such intriguing consequences of the proposed scenario is out of the scope of this short paper (for more details see [3]).

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