Relativistic solar cosmic ray dynamics in large ground level events

Eduard V. Vashenyuk, Yury V. Balabin, and Boris B. Gvozdevsky

Abstract— **The neutron monitors (NMs) long since and down to the present time remain the basic means of relativistic solar cosmic rays study. These particles are observed in rather rare Ground Level Enhancement (GLE) events. The rate of GLEs occurrence is ~ 1 per year. For 66 years from the first GLE registered on 28 February, 1942, only 70 events occurred up to now. The worldwide network of neutron monitors can be considered as a multidirectional cosmic ray spectrometer. The author's GLE modeling technique employing the optimization methods and modern magnetosphere models allows obtaining characteristics of relativistic solar protons (RSP): rigidity (energy) spectrum, anisotropy axis and pitch angle distribution in the primary solar proton flux. Two distinct populations of RSP: the prompt and delayed ones probably having different origins on the Sun have been revealed. To the present time the authors analyzed by a GLE modeling 22 events, the brief items of information about which are considered.**

1. INTRODUCTION

In this paper, based on the data of neutron monitors we consider regularities of relativistic solar protons (RSP) generation and release from the Sun in the 22 large Ground Level Enhancements (GLE) events occurring in the period 1956-2006. The worldwide neutron monitor (NM) network may be considered as a united multidirectional solar proton spectrometer in the relativistic energy domain. With the modeling of the NM responses to an anisotropic solar proton flux and comparing them with observations the parameters of primary solar protons outside the magnetosphere can be obtained [1, 2]. In this study we have carried out the analysis of 22 solar cosmic ray (SCR) events at ground level. One of the basic results of this study was the detection of two distinct populations (components) of relativistic solar cosmic rays: prompt (PC) and delayed (DC) ones. The PC and DC have various spectra and anisotropy characteristics and, probably various sources on the Sun. Here we result also description of a GLE modeling study technique, which brief form was published in [3].

2. MODELING TECHNIQUE OF THE GROUND LEVEL DATA

The worldwide network of ground-based detectors may be considered as a united multidirectional solar proton spectrometer in the relativistic energy range. With the modeling of the NM responses to anisotropic solar proton flux and then comparing them with observations the parameters of primary solar protons outside the magnetosphere can be obtained [1,2]. Our recent modeling technique, in general, is similar to that of [2], as it takes into account the contribution in the neutron monitor response not only vertical, but also oblique falling particles. This kind of analysis requires the data of no less than 20-25 ground-based cosmic ray stations, and consists of a few steps:

1. Definition of asymptotic viewing cones (taking into account not only vertical but also oblique incident on detector particles) of the NM stations under study by the particle trajectory computations in a model magnetosphere.
2. Calculation of the NM responses at variable primary solar proton flux parameters.
3. Application of a least square procedure for determining primary solar proton parameters (namely, energy spectrum, anisotropy axis direction, and pitch-angle distribution) outside the magnetosphere by comparison of computed ground based detector responses with observations.

A. *Asymptotic cone calculations*

Determination of asymptotic viewing cones of NM stations under study was carried out by computations of the particle trajectories in the magnetosphere model (Tsyganenko, 2002) [4] with a step in rigidity of 0.001 GV. For each given value of rigidity we calculate nine trajectories of particles that are "launched" in vertical, as well as in inclined directions under an angle of 20° in eight equally spaced azimuths. Directivity diagram of a neutron monitor has a maximum at a zenith angle ~ 20° (Fig.1a). It is slightly different for GCR (λ_g =140 g/cm^2) and SCR (λ_f =140 g/cm^2), λ is attenuation length. Nearly the same direction has also a median of particle distribution on a zenith angle. It is shown as a circle at bottom of Fig.1. All angular diagram of a NM is divided into 8 equal sectors. To each sector one asymptotic direction is assigned. It is obtained by calculation of a trajectory of a particle launched from an average point, of particle distribution in a sector (Fig.1b).

Thus, test particles are launched at zenith angle 20° and 8 equally spaced azimuths (Fig.1b). Schematically this is shown in Fig.2, where starting directions at launching point forming

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Authors are with the Polar Geophysical Institute of Russian Academy of sciences, Apatity, Murmansk reg. Russia, 184209 (corresponding author is E.V. Vashenyuk to provide phone: +7-81555-79173; fax: 7-81555-74339; e-mail: vashenyuk@pgia.ru).

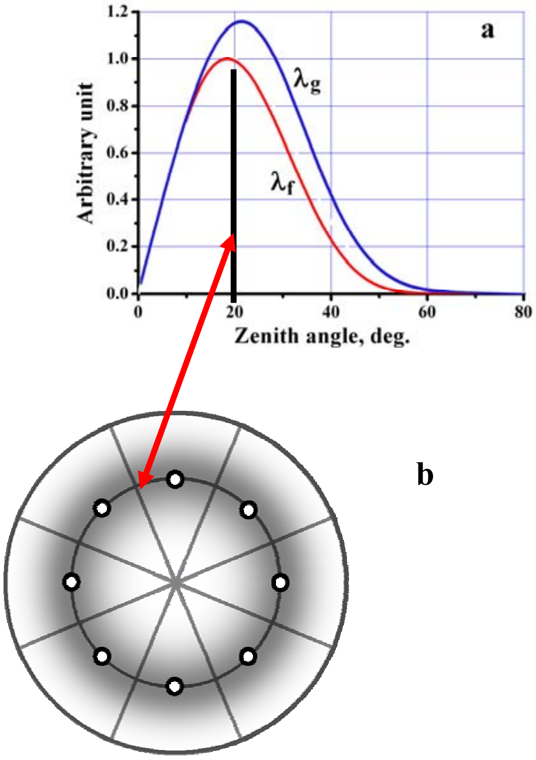

Fig.1. **a.** Directivity diagram on a zenith angle for GCR (λg) and SCR (λf); **b**. Launching directions of the 8 inclined trajectories.

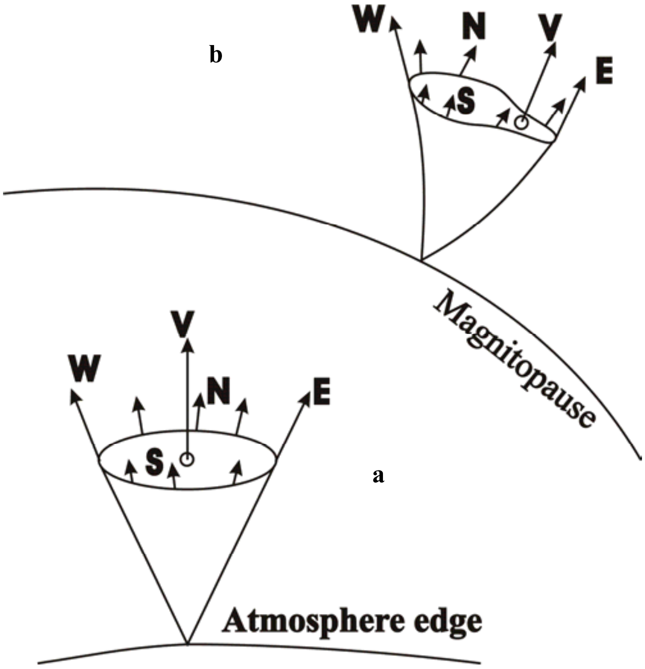

Fig.2. **a** Starting directions at a launching point; **b.** at the magnetopause

a

launching cone are shown. The launching point itself is at the altitude level 20 km, where transformation occurs of primary cosmic ray protons into secondary neutrons. The deformed cone of particle outlet at magnetopause is shown in upper part of Fig.2. Owing to Liuville's theorem particle fluxes through these two cones must coincide.

B. Calculation of primary solar proton parameters from the neutron monitor data

The response function of a given neutron monitor to anisotropic flux of solar protons with regard to the contribution of obliquely incident particles is given by the relation:

$$\left(\frac{\Delta N}{N}\right)_j = \frac{1}{8}\sum_{i=1}^{8}\left(\sum_{R=1}^{20} J_{||}(R)\,S(R)\,F(\theta_{j,i}(R))\,A(R)\,\Delta R\right)$$

where $(\Delta N/N)_j$ is a percentage increase in the count rate N_j at a given NM station j, a modified power rigidity spectrum with variable slope $J_{||}(R) = J_0 R^{-\gamma^*}$, $\gamma^* = \gamma + \Delta\gamma\cdot(R-1)$, J_0 is a normalization constant, γ is a power-law spectral exponent at $R = 1$ GV, $\Delta\gamma$ is a rate of γ increase per 1 GV. The other parameters are the coordinates Φ and Λ, defining anisotropy axis direction in the GSE system; and a parameter C, characterizing the pitch-angle distribution (PAD) in form of a Gaussian: $F(\theta(R)) \sim \exp(-\theta^2/C)$. $S(R)$ is specific yield function (Debrunner et al., 1984[5]). For muon telescopes we used instead of [7] the yield function of (Fujimoto, 1976 [6]). $\theta(R)$ is pitch angle for a given particle. A value $A(R) = 1$ for allowed and 0 for forbidden trajectories. So, 6 parameters are to be determined: J_0, γ, $\Delta\gamma$, C, Λ, Φ. There are however situations when a pitch angle distribution has more complicated form than a Gaussian. We suggest the following function taking into account features of a pitch angle distribution close to 90°:

$$F(\theta(R)) \sim \exp(-\theta^2/C)(1-a\,\exp(-(\theta-\pi/2)^2/b)), \quad 0\le|a|\le 1 \qquad (2)$$

By using of function (2) we add to 6 required parameters another two ones: a and b. It should be noted, that at a =0 the function (2) turns into the usual Gaussian. The features in PAD at 90° are predicted by the theory of particle propagation in IMF [Bieber et al., 1980 [7]). Besides, the function (2) has universality allowing to describe other complex cases of pitch-angular distributions. For the description of a bidirectional anisotropy we used the combination from functions of a kind (2), describing particle fluxes from opposite directions.

The control of accuracy of the derived solar proton parameters was carried out by summation of the measured responses of neutron monitors with a random quantity equal to a probable error of experimental data. The resulting dispersion of solar proton parameters calculated by the optimization procedure can serve a measure of an error of the given method. Such error estimation is given for all solar proton spectra under study. In our calculations we also use a quantitative criterion of adequacy of modeling. A residual should be no more than 5% from an average of increase over all NM stations at a given moment.

The validity criterion for the spectra obtained from the NM records may be also provided by comparison with the direct solar proton intensities measured in adjacent energy intervals by balloons and spacecraft.

Some of the GLEs considered in our paper have been already studied by modeling methods by different authors [1,2,8], and many others. Comparison of their results with our findings shows, almost in all cases, close similarity of spectra and other parameters of RSP.

3. Examples of Modeling Study: the GLE of February 23, 1956

On 23 February 1956 a number of ground-based detectors of cosmic rays (neutron monitors, muon telescopes and ionization chambers) have registered a ground level enhancement (GLE) of solar cosmic rays (SCR), the largest one for the entire 65-year history of SCR observations (since the first observed GLE of 28 February 1942, or GLE01 in current numeration). The GLE of 23 February 1956 (or GLE05) was caused by a giant solar flare (3+ or 3B) that occurred at 03:31 UT in the active region with heliographic coordinates 25°N, 85°W. The 3.3 GHz radio burst was registered at 03:34 UT. (ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_FLARES/HALPHA_FLARES/).

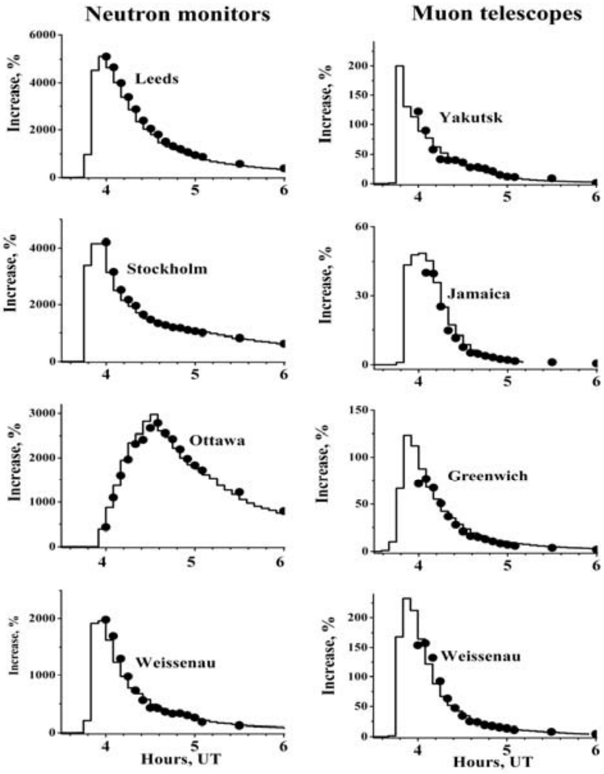

Fig.3. Increase profiles at number neutron monitors (left) and muon telescopes (right) during the GLE 23.02.1956. Points are modeled responses at consecutive 5-minute intervals.

Since the 50th of the last century up to now, many studies were devoted to the comprehensive study of this outstanding event (Miroshnichenko, 2000 [9], Belov et al,. 2004 [8], Vashenyuk et al., 2008 [10], and references therein). The most remarkable feature of this GLE was a narrow and extremely intensive beam of RSP arriving at the Earth at the beginning of the event. This unique beam, according to the estimates by [6] was not long and its width did not exceed 30-40°, and its contribution to solar particle density was not significant. In Figure 3 we present the dynamics of relativistic solar proton flux in the course of the GLE05 as it was derived by above modeling techniques in successive moments of time shown by arrows. Figure 3a shows a profile of a huge prompt increase at the European NM station Leeds in comparison with a gradual enhancement at the North American station Ottawa. Based on our previous results for a number of other GLEs [11] the authors incline to consider such behavior of the two profiles as a certain evidence of two-component structure of relativistic proton flux in the event of 23 February 1956. In other words, those two profiles seem to characterize the prompt component (Leeds) and delayed one (Ottawa). The pitch-angle distribution shown in Figure 3b is rather narrow at the early phase of the event and widens with time. From the derived rigidity spectra we also obtained the energy spectra for four consecutive moments of time (1-4).

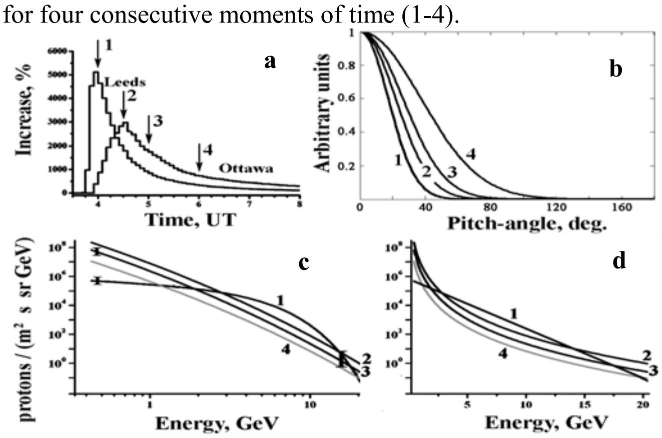

Fig.4. Dynamics of relativistic solar proton flux in the GLE05: (**a**) - intensity-time profiles on the Leeds and Ottawa neutron monitors demonstrating the prompt and delayed components of RSP; (**b**) - derived pitch angle distributions; (**c**) and (**d**) - energy spectra of RSP in the double-logarithmic and semi-logarithmic scales, respectively. Numbers near the curves correspond to the moments of time from Table 2 (UT): 1 - 04:00; 2 - 04:30; 3 - 05:00; 4 – 05:30; 5 – 06:00.

These spectra are presented in Figures 4c and 4d in double-logarithmic and semi-logarithmic scales, respectively. From comparison of Figures 4c and 4d, one can see that the spectrum 1 derived for the early phase of the event (04:00 UT) has an exponential dependence on energy. The spectra obtained for the later times are of the power-law form. We note that the PC spectrum (1), is exponential in energy $J = 1.4\times10^{6}\exp(-E/1.3)$, and the spectrum of DC (2) has a power-law form $J = 4.2\times10^{6}\,E^{-4.6}$.

4. RESULTS OF GLE MODELING STUDIES

A list of studied 22 large GLEs occurred during the period 1956-2006 is given in Table 1 where the event number, date, onset time of type II radio burst, importance and heliocoordinates of the flare are also indicated. The onset time of the type II radio emission corresponds to the start of energy release at the null magnetic point close to the low coronal level and related with its H-alpha eruption and start of CME [12]. The type II onset was also found to be a marker of relativistic proton acceleration [11]. In every event under study we tried to reveal the prompt (PC) and delayed (DC) components of relativistic solar protons judging on their spectral form. The best fits for the PC spectra are provided by exponential forms $J = J_O \exp(-E/E_O)$ where E_O is characteristic proton energy. As to delayed component, its spectra may be fitted by the power-law forms $J = J_1 E^{-\gamma}$.

The corresponding parameters of the PC and DC spectra are displayed in the last four columns of Table 1 where characteristic energies E_0 are given in GeV and proton intensities - in units of $m^{-2}s^{-1}sr^{-1}GeV^{-1}$.

Fig.5 shows a number of spectra with parameters from the table, respectively, for prompt (PC) and delayed (DC) components. The good consent of modeled intensities of DC with the data of direct measurements on balloons and spacecrafts is seen. The intensity of DC in low energies lays below the threshold of detectors on spacecrafts. However at energies 2-4 GeV the response of a neutron monitor is higher for PC, than for DC (Fig. 4 b) . The giant increases in GLEs of 23.05.1956 and 20.01.2005 are caused by the prompt component of relativistic solar protons [10].

One of important results is that the PC spectrum proved to have exponential form in energy, and this may be evidence of acceleration by electric fields arising in the reconnecting coronal sheets [10,14]. At impulsive magnetic reconnection in a current sheet an electric field arises which is directed along a null magnetic field line. The particles of surrounding plasma move along this electric field and gain energy, which is proportional to a path traveled in the electric field. At the same time, the number of particles traveled a given path in reconnecting area falls exponentially with increase of this path because of losses owing to a leaving of particles the acceleration volume due to drifts. So, the spectrum of particles accelerated by an electric field inside a volume, where reconnection proceeds should have exponential dependence on energy. The described here qualitative picture proves to be true by modeling computations, in which the structure of magnetic and electric fields in a reconnecting current sheet was reproduced [10,14]. The trajectories of particles of plasma accelerated in an electric field were computed and their energy was fixed at leaving the acceleration volume. The resulting spectrum of the accelerated particles had expressed exponential dependence on energy, that confirms a hypothesis about a magnetic reconnection as a source of prompt component of RSP.

Considering the timing of generation and release of two RSP components from the solar corona, the following scenario may be suggested. The prompt component of RSP is produced during initial energy release in a low-coronal magnetic null point. This process is linked with the H-alpha eruption, onset of CME and type II radio emission. The accelerated particles of PC leave the corona along open field lines with diverging geometry that results in strong focusing of a bunch. Particles of DC originally are trapped in magnetic

TABLE I

PARAMETERS OF THE EXPONENTIAL AND POWER LAW ENERGETIC SPECTRA

No	GLE No	Date	Type II onset	Impor-tance	Heliocoordinates	PC		DC	
						J_0	E_0	J_0	E_0
1	05	23.02.1956	03.36*	3	N23W80	$7.4\cdot10^5$	1.37	$5.5\cdot10^5$	4.6
2	08	4.05.1960	10.17	3+	N13 W90	$2.7\ 10^5$	0.65	$1.6\ 10^3$	4.2^{*}
3	10	12.11.1960	13.26	3+	N27 W04	-	-	$7.5\ 10^3$	4.1^{**}
4	11	15.11.1960	02.22	3	N25 W35	-	-	$1.0\ 10^5$	5.3
5	13	18.07.1961	09.47	3+	S07 W59	$5.2\ 10^3$	0.52	$3.6\ 10^3$	6.0
6	16	28.01.1968	-	-	N22 W154	$1.4\ 10^4$	0.58	$6.7\ 10^3$	4.7
7	19	18.11.1968	10.26	1B	N21 W87	$1.2\ 10^4$	0.58	$2.6\ 10^3$	5.5
8	31	07.05.1978	03.27	1B/X2	N23W82	$3.5\cdot10^4$	1.11	$1.3\cdot10^4$	4.0
9	38	07.12.1982	23.44	1B/X2.8	S19W86	$5.7\cdot10^3$	0.65	$7.2\cdot10^3$	4.5
10	39	16.02.1984	09:00	-	- W132	-	-	$5.2\cdot10^4$	5.9
11	41	16.08.1989	01.06*	2N/X12.	S15 W85	$6.8\ 10^3$	0.56	$3.8\ 10^3$	5.1
12	42	29.09.1982	11.33	- /X9.8	- W105	$1.5\ 10^4$	1.74	$2.5\ 10^4$	4.1
13	43	19.10.1989	12.49	3B/X13	S25 E09	$4.0\ 10^4$	0.53	$3.0\ 10^4$	4.8
14	44	22.10.1989	17.44	2B/X2.9	S27W31	$7.5\ 10^4$	0.91	$1.5\cdot10^4$	6.1
15	47	21.05.1990	22.12	2B/X5.5	N35W36	$6.3\cdot10^3$	1.13	$2.7\cdot10^3$	4.3
16	55	06.11.1997	11.53	2B/X9.4	S18W63	$8.3\ 10^3$	0.92	$8.2\ 10^3$	4.6
17	59	14.07.2000	10.19	3B/X5.7	N22W07	$3.3\cdot10^5$	0.50	$5.0\cdot10^4$	5.4
18	60	15.04.2001	13.48	2B/X14.4	S20W85	$1.3\cdot10^5$	0.62	$3.5\cdot10^4$	5.3
19	65	28.10.2003	11.02	4B/X17.2	S16E08	$1.2\cdot10^4$	0.60	$1.5\cdot10^4$	4.4
20	67	2.11.2003	17.14	2B/X8.3	S14W56	$4.6\cdot10^4$	0.51	$9.7\cdot10^3$	6.3
21	69	20.01.2005	06.44	2B/X7.1	N14W61	$2.5\cdot10^6$	0.49	$7.2\cdot10^4$	5.6
22	70	13.12.2006	02:51	2B/X3.4	S06W24	$3.5\cdot10^4$	0.59	$4.3\cdot10^4$	5.7

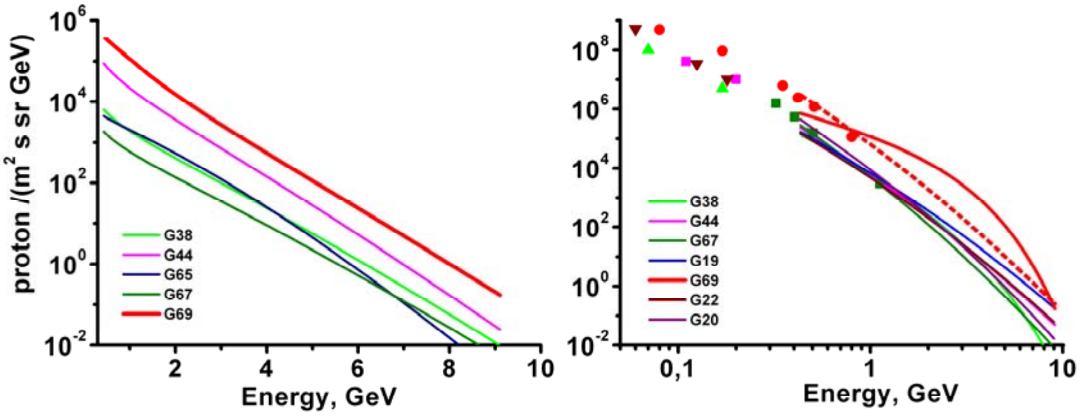

Fig.5. Spectra of prompt (a) and delayed (b) solar proton components derived from neutron monitor data for a number of GLEs (Table 1). Spectra of the PC have exponential form, and spectra of DC power law one. Points are direct solar proton data from spacecrafts and balloons. By dotted (DC) and thick red (PC) lines are shown spectra for the 20.01.2005 GLE. At energies > 1 GeV intensity of PC is higher than DC.

arches in the low corona and accelerated by a stochastic mechanism at the MHD turbulence in expanding flare plasma [12,13]. Accelerated particles of DC can be then carried out to the outer corona by an expanding CME. They are released into interplanetary space after the magnetic trap is destroyed giving rise to the source of accelerated particles that is extended in time and azimuth.

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