Characteristics of relativistic solar cosmic rays from GLE modeling studies

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***Abstract*. The modeling analysis of 32 large GLEs occurred in the period 1956-2006 on the data of the worldwide neutron monitors (NMs) has been performed. Characteristics of relativistic solar protons were derived from the ground based neutron monitor data with the least square procedure by comparison of the modeled NM responses to observed ones. In all studied cases two distinct RSP populations (components) were revealed: the early pulse-like intensity increase with exponential energy spectrum (prompt component, PC), and the late gradual increase with a softer energy spectrum of the power law form (delayed component, DC). The spectrum of DC has continuation into a range of lesser energies and well agrees with the TOM (Time of Maximum) spectrum obtained from direct solar proton measurements on spacecrafts and balloons. The exponential spectrum of PC has no continuation into lower energies. But it gives the significant contribution into the responses of neutron monitors resulting sometimes to huge increases up to ∼5000%, as was in GLEs of 23.02.1956 and 20.01.2005.**

***Keywords*: GLE, modeling, solar protons.**

I. Introduction

In this paper, based on the data of neutron monitors we consider regularities in characteristics of relativistic solar protons (RSP) in 32 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 solving a reciprocal task characteristic of relativistic solar proton (RSP) flux outside the magnetosphere of Earth can be obtained [1-4]. The paper briefly describes the technique of GLE modeling and basic regularities of RSP spectra obtained from the ground based neutron monitors data.

II. The GLE modeling technique

Our recent GLE 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 incident 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 modern magnetosphere models.
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.

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) [5] 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^o in eight equally spaced azimuths [4].

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:

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

where $(\Delta N/N)_j$ is a percentage increase in the count rate N_j at a given NM station j, a modified solar proton 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, 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 [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^o:

$$F(\theta(R)) \sim \exp(-\theta^2/C)(1 - a \cdot exp(-(\theta-\pi/2)^2/b)) \qquad (2)$$

where $a \leq 1,\ b > 0$. By using the 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^o are predicted by the theory of particle propagation in IMF [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.

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 spacecrafts.

Some of the GLEs considered in our paper have been already studied by modeling methods by different authors [1,2,8,9] and many others. Comparison of their results with our findings shows, almost in all cases, close similarity of spectra and other parameters of RSP.

III. Examples of modeling study: the GLE of January 20, 2005

The GLE 69 of 20 January 2005 was the greatest event since February 23, 1956. The parent solar flare 2B/X7.1 has heliocoordinates N14 W61. The type II radio onset (suggested moment of RSP generation [3,4]) was reported at 06:44 UT. Fig. 1a shows the character increase profiles in this GLE. A pulselike giant increase at McMurdo during the initial phase of the event is typical for the prompt component (PC) of relativistic solar protons (RSP). A gradual and long increase at Apatity characterizes the delayed component (DC). The derived from neutron monitor network data energetic spectra of RSP are shown in Fig. 1b,c [10]. The spectrum 1 is obtained at the moment when the prompt component dominated. It has an exponential dependence upon energy (a straight line in a semilogarithmic scale): J=2.5$\cdot10^6\cdot exp(-E/0.49)$. The spectrum 2 was obtained at the time when the PC already has finished and the only DC was present (Fig. 1a). As one can see the spectrum 2 has a power law form (a straight line in a double logarithmic scale): J=7.2$\cdot10^4 \cdot E^{-5.6}$. In Fig. 1b,c the data of direct measurements of solar protons in the adjacent energy interval (50-700 MeV) on GOES-11 spacecraft, (time of maximum intensities, TOM), black squares and balloons (black circles) [11] are shown. The good consent of a spectrum DC with the data of direct solar protons is seen. Moreover, TOM spectrum of solar protons in the range of moderate and lesser energies is a continuation of the DC spectrum. The spectrum of PC is bent to low energies and there is no continuation there. At the same time, intensity of particles of the PC is higher than the DC in the energy interval from 1 to 9 GeV (Fig. 1b,c). The specific

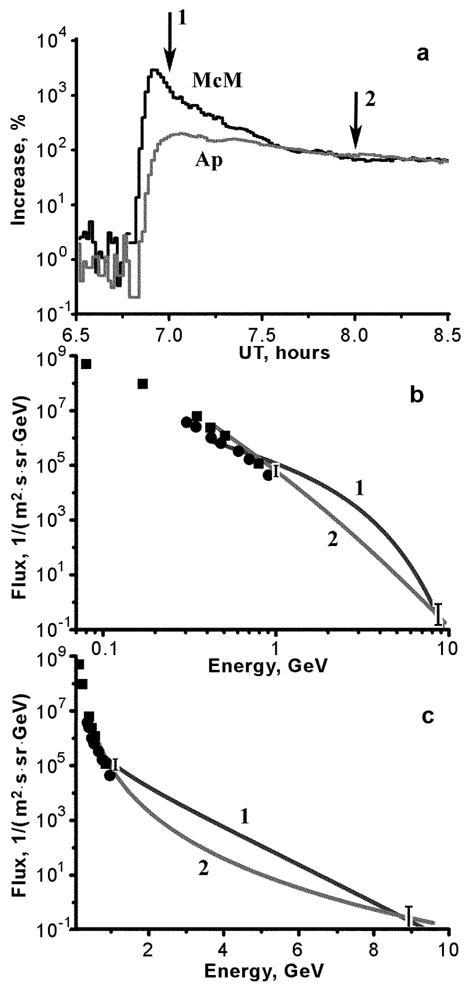

Fig. 1: (a). Increase profiles at NM stations McMurdo (McM) and Apatity (Ap) in the superevent of 20 January 2005. Numbered arrows mark the moments of time when the spectra of PC (1) and DC (2) of RSP were derived. Spectra of PC (1) and DC (2) in double logarithmic (b) and semi-logarithmic (c) scales are shown. Note an exponential form of the spectrum 1 of the prompt RSP component and the power law spectrum 2 related to the delayed component.

yield function of a neutron monitor has a maximum there [6]. Therefore a huge increase on a number of neutron monitors during the GLE 69 was caused by just the PC [12]. Owing to a strong anisotropy only a few southern neutron monitor stations could accept PC. These stations (including McMurdo, Fig. 1a) registered a giant pulselike increase. Other stations registered a quasiisotropic component with a power-law spectrum and showed a moderate increase [10], as it was observed at Apatity NM (Fig. 1a). On the late phase of the event already all stations accepted isotropic DC with the power law spectrum 2. They registered moderate increase, identical at all stations with equal R_C. The modeling analysis of the GLE 69 also was carried out in [8,9]. The results of our analysis are close to results of [8,9] in the part of delayed component. In [10,12] we

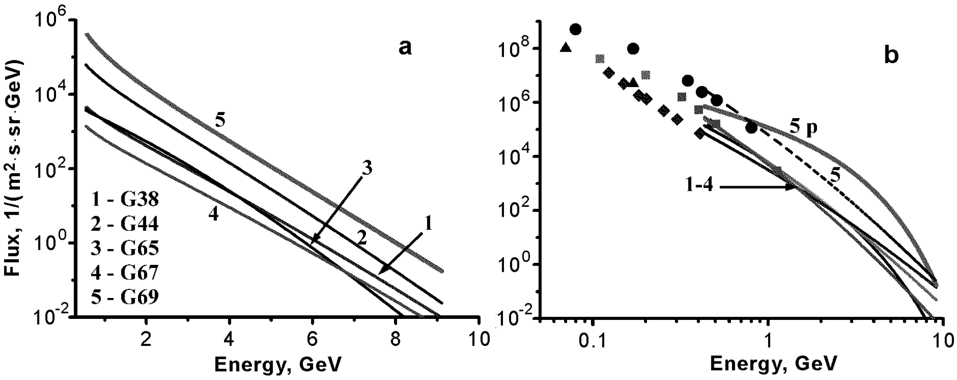

Fig. 2: Spectra of prompt (a) and delayed (b) solar proton components derived from neutron monitor data for a number of GLEs (Table 1). Spectra of the PC have exponential form, and spectra of DC power law one. Points in Fig. 2b are direct solar proton data from spacecrafts and balloons. The spectra numbered 5 belong to the superevent 20.01.2005. By dotted (5) and thick (5p) lines in Fig. 2b are shown spectra for the DC and PC, respectively. The PC spectrum (5p) causing the giant increase effect on neutron monitors has rather low intensity in the hundreds MeV energy region.

considered also the role of prompt RSP component in creating the huge increase on a number of NM stations. The described above example of the GLE 69 analysis is rather typical. We have carried out the modeling study of 32 large GLEs and almost in all of them have found out two components of RSP: prompt (PC) and delayed (DC) ones. A list of studied 32 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 is known as indication of a coronal shock forming. Besides this moment is close to the start of energy release at the null magnetic point at the low coronal level and is related to onset of eruptive coronal processes [13]. Therefore the type II onset was found to be a marker of the relativistic protons acceleration [14].

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 $J{=}J_O \cdot exp(-E/E_O)$ where E_O is characteristic proton energy. As to delayed component, its spectra may be fitted by the power-law forms $J{=}J_1 \cdot E^{-\gamma}$.

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 $[m^2\ s\ sr\ GeV]^{-1}$. Fig.2 shows spectra with parameters from the table for 5 events, respectively, for the PC (Fig. 2a) and DC (Fig. 2b). All the PC spectra have exponential form (Fig. 2a). By number 5 the PC spectrum of the GLE 69 superevent is marked. Four of 5 power law DC spectra (Fig. 2b) form a close family. Dashed line numbered 5 is the DC spectrum for the GLE 69. The PC spectrum of the super GLE 69 (5P) is shown in Fig. 2b for comparison. The good consent of modeled intensities of DC spectra with the data of direct measurements on balloons and spacecrafts can be seen. Exponential spectrum of PC as a rule has no extension into low energies. Perhaps it is because the intensity of PC in low energies lays below the threshold of spacecraft detectors. However at energies 2-6 GeV the intensity of PC is higher than DC (Fig. 2b). The giant increases in GLEs of 20.01.2005 and 23.05.1956 were caused just by the prompt component of relativistic solar protons [12].

IV. RESULTS

The modeling study of 32 GLE events occurred in the 50-year period 1956-2006 has been carried out. The analysis shows existence nearly in all the events two populations (components) of relativistic SCR particles: prompt and delayed ones. The prompt component (PC) is observed during initial phase of event, has an pulselike increase profile and the exponential energetic spectrum. The delayed component (DC) comes after PC (15-30 min), has a gradual increase profile and the power law energetic spectrum. The spectrum of DC has extension into lesser energies and well agrees with the TOM (Time of Maximum) spectrum of direct solar protons measured on spacecrafts and balloons. The exponential spectrum of PC has no extencion into lower energies. But it gives the significant contribution into the responses of neutron monitors resulting sometimes to huge increases up to ~5000%, as was in GLEs of 23.02.1956 and 20.01.2005. 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-α 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 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

TABLE I: Parameters of the exponential and power-law energetic spectra

No	GLE No	Date	Type II onset	Importance	Heliocoordinates	J_0 (PC)	E_0 (PC)	J_1 (DC)	$-\gamma$ (DC)
1	05	23.02.1956	03.36*	3	N23 W80	$7.4\cdot10^5$	1.37	$5.5\cdot10^1$	4.6
2	08	04.05.1960	10.17	3+	N13 W90	$2.7\cdot10^5$	0.65	$1.6\cdot10^3$	4.2*
3	10	12.11.1960	13.26	3+	N27 W04	-	-	$7.5\cdot10^3$	4.1**
4	11	15.11.1960	02.22	3	N25 W35	-	-	$1.0\cdot10^5$	5.3
5	13	18.07.1961	09.47	3+	S07 W59	$5.2\cdot10^3$	0.52	$3.6\cdot10^3$	6.0
6	16	28.01.1968	07.55	-	N22 W154	$1.4\cdot10^4$	0.58	$6.7\cdot10^3$	4.7
7	19	18.11.1968	10.26	1B	N21 W87	$1.2\cdot10^4$	0.58	$2.6\cdot10^3$	5.5
8	22	24.01.1971	23.16	3B	N19 W49	$3.4\cdot10^4$	0.45	$8.7\cdot10^3$	5.8
9	25	07.08.1972	15.19	3B	N14 W37	$6.6\cdot10^2$	1.23	$4.3\cdot10^2$	5.0
10	29	24.09.1977	05.55	-	N10 W120	$6.5\cdot10^2$	1.14	$9.3\cdot10^2$	3.2
11	30	22.11.1977	-	2B	N24 W40	$1.5\cdot10^4$	0.77	$1.1\cdot10^4$	4.7
12	31	07.05.1978	03.27	1B/2	N23 W82	$3.5\cdot10^4$	1.11	$1.3\cdot10^4$	4.0
13	32	23.09.1978	09.58	3B/X1	N35 W50	-	-	$7.0\cdot10^2$	4.7
14	38	07.12.1982	23.44	1B/X2.8	S19 W86	$5.7\cdot10^3$	0.65	$7.2\cdot10^3$	4.5
15	39	16.02.1984	09:00	-	- W132	-	-	$5.2\cdot10^4$	5.9
16	41	16.08.1989	01.06*	2N/X12.5	S15 W85	$6.8\cdot10^3$	0.56	$3.8\cdot10^3$	5.1
17	42	29.09.1982	11.33	-/X9.8	- W105	$1.5\cdot10^4$	1.74	$2.5\cdot10^4$	4.1
18	43	19.10.1989	12.49	3B/X13	S25 E09	$4.0\cdot10^4$	0.53	$3.0\cdot10^4$	4.8
19	44	22.10.1989	17.44	2B/X2.9	S27 W31	$7.5\cdot10^4$	0.91	$1.5\cdot10^4$	6.1
20	45	24.10.1989	18.00	2B/X5.7	S20 W57	$2.4\cdot10^4$	0.72	$1.1\cdot10^5$	4.9
21	47	21.05.1990	22.12	2B/X5.5	N35 W36	$6.3\cdot10^3$	1.13	$2.7\cdot10^3$	4.3
22	48	24.05.1990	21.00	1B/X9.3	N36 W76	$2.8\cdot10^4$	0.60	$9.1\cdot10^3$	4.3
23	51	11.06.1991	02.05	2B/X12.5	N32 W15	$2.6\cdot10^3$	0.83	$3.3\cdot10^3$	4.8
24	52	15.06.1991	08.14	3B/X12.5	N36 W70	-	-	$5.8\cdot10^3$	4.6
25	55	06.11.1997	11.53	2B/X9.4	S18 W63	$8.3\cdot10^3$	0.92	$8.2\cdot10^3$	4.6
26	59	14.07.2000	10.19	3B/X5.7	N22 W07	$3.3\cdot10^5$	0.50	$5.0\cdot10^4$	5.4
27	60	15.04.2001	13.48	2B/X14.4	S20 W85	$1.3\cdot10^5$	0.62	$3.5\cdot10^4$	5.3
28	61	18.04.2001	02.17	-	- W120	$2.5\cdot10^4$	0.52	$1.2\cdot10^3$	3.6
29	65	28.10.2003	11.02	4B/X17.2	S16 E08	$1.2\cdot10^4$	0.60	$1.5\cdot10^4$	4.4
30	67	02.11.2003	17.14	2B/X8.3	S14 W56	$4.6\cdot10^4$	0.51	$9.7\cdot10^3$	6.3
31	69	20.01.2005	06.44	2B/X7.1	N14 W61	$2.5\cdot10^6$	0.49	$7.2\cdot10^4$	5.6
32	70	13.12.2006	02:51	2/3.4	S06 W24	$3.5\cdot10^4$	0.59	$4.3\cdot10^4$	5.7

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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