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Features of relativistic solar proton spectra derived from ground level enhancement events (GLE) modeling

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Abstract. With the developed by the authors of a ground level enhancements events (GLE) modeling technique, the modeling study of 35 large GLEs for the period 1956 – 2006 has been carried out. The basic characteristics of relativistic solar protons (RSP) are obtained: a rigidity (energetic) spectrum, anisotropy axis direction, and pitch angle distributions for each event. It is shown that in nearly all events there existed two components (population) of relativistic solar particles: prompt and delayed. The prompt component (PC) prevails in the beginning of the event. It is characterized by an impulsive profile, strong anisotropy and exponential energetic spectrum. The delayed component (DC) dominates during maximum and decline phases of the events. It has a gradual intensity profile, moderate anisotropy and a power law energetic spectrum. The analysis of the large number GLE shows the value of a characteristic energy in the exponential spectrum of PC has rather stable meaning ~ 0.5 GeV and well agrees with the spectrum of protons accelerated in an electric field arising during the magnetic reconnection in the solar corona. The value of a spectral exponent of the power law spectrum of DC is distributed from 4 up to 6 with most at 5. This is close to the simulated spectrum arising in the process of stochastic acceleration in turbulent solar plasma.

1 Introduction

The study of 35 large ground level enhancements (GLEs) during the period of 1956 – 2006 has been carried out with the GLE modeling technique developed by the authors (Vashenyuk et al., 2009). The GLE modeling technique allows derivation of the basic characteristics of the relativistic solar protons (RSP) from the data of the worldwide network of neutron monitors. These are: rigidity (energy) spectrum, direction of anisotropy axis, and pitch angle distributions.

Dynamics of these parameters in each event were studied. It is shown that in nearly all events there existed two components (populations) of relativistic solar particles: prompt and delayed ones.

The prompt component (PC) prevails in the beginning of the event. It is characterized by an impulsive profile, a strong anisotropy and an exponential energetic spectrum. The delayed component (DC) dominates during maximum and decline phases of the events. It has a gradual intensity profile, a moderate anisotropy and a power law energy spectrum. The averaged parameters of the PC and DC spectra and their possible connection to probable mechanisms of acceleration on the Sun were studied. The acceleration by electric field in the region of magnetic reconnection for the PC and the stochastic acceleration in the turbulent plasma for the DC are considered the most probable of these mechanisms.

2 GLE modeling technique

Parameters of the primary solar protons outside the magnetosphere can be obtained by modeling the responses of the neutron monitors (NM) to an anisotropic solar proton flux and comparing them with the NM observations (e.g. Smart et al., 1971; Shea and Smart, 1982; Cramp et al., 1997; Vashenyuk et al., 2006b, 2009). This kind of analysis requires data of no less than 25 – 30 NM stations, and it consists of a few steps:

1. Definition of asymptotic viewing cones of the NM stations under study by the particle trajectory computations in a model magnetosphere (with a step in rigidity of 0.001 GV). The magnetosphere model of Tsyganenko (2002) was employed.

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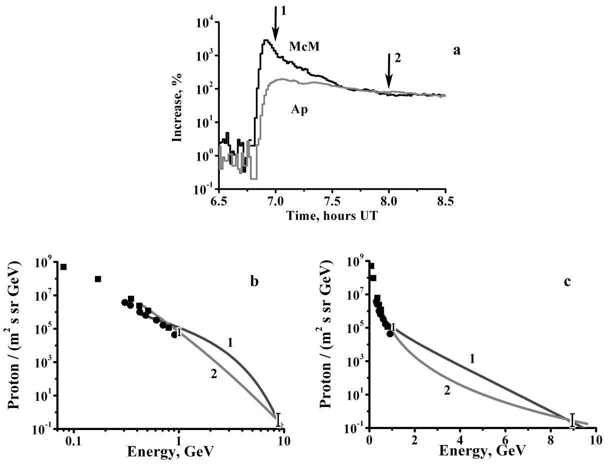

Fig. 1. **(a)** Increase profiles on the neutron monitor stations McMurdo (McM) and Apatity (Ap) during the GLE on 20 January 2005. Arrows mark times when the prompt component (PC) (1) and delayed component (DC) (2) is dominated. **(b),(c)** the derived energetic spectra of RSP: 1 is the spectrum of PC and 2 is the spectrum of DC. Points indicate the direct solar proton data from balloons launched in Apatity (filled circles) and GOES-11 (squares)

2. Calculation of the NM responses with variable primary solar proton flux parameters.

3. Application of the least square procedure (optimization) for determining primary solar proton parameters (energy spectrum, anisotropy axis direction, pitch-angle distribution) outside the magnetosphere by comparison of computed NM responses with observations.

In this paper we will concentrate on the energy spectra of solar protons. The details of our GLE modeling technique can be found in Vashenyuk et al. (2009). As an example of GLE modeling analysis application, we consider an event of 20 January 2005.

3 The GLE No 69 of 20 January 2005

The event was connected to a solar flare 2B/X7.1, heliocoordinates N14 W61, which occurred at 06:44 UTC (type II radio onset). An onset of pion-decay gamma-ray emission > 100 MeV signaling on appearance of protons with Ep ~ 300 MeV was detected at 06:45:34 $\pm$ 4 s by the SONG instrument at the CORONAS-F spacecraft (Kurt et al., 2010). It agrees with the arrival time 06:49 UTC of the first particles, taking into account an approximate propagation time ~ 11 min of the prompt component protons.

The GLE No 69 was the largest RSP event in intensity since the famous GLE No 5 of 23 February 1956. Figure 1**(a)** shows the intensity profiles of the two ground based neutron monitor (NM) stations: McMurdo (Antarctica) and Apatity.

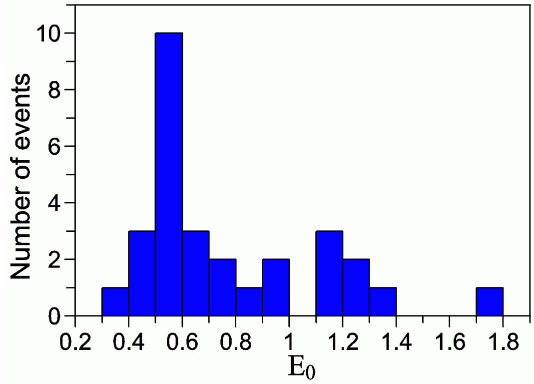

Fig. 2. Statistical distribution of parameter E0 of the PC exponential spectrum

One can see a short-lived and very intense peak in the profile of the McMurdo NM, which is caused by the so-called prompt component of relativistic solar protons. The smooth profile of the Apatity station belongs to the so-called delayed component (Vashenyuk et al., 2006a,b). Parameters of RSP were obtained with the modeling technique from the data of 36 NM stations of the worldwide network (Vashenyuk et al., 2006b). Energetic spectra of RSP derived for moments 1 and 2 are shown in Fig. 1**(b)** and **(c)**. The spectrum of PC (I) obtained during a short-lived intense peak has exponential dependence on energy (a straight line in the semi-log scale in Fig. 1**(c)**):

$$J = J_0 \exp(-E/E_0). \quad (1)$$

The spectrum of DC (2) obtained at the decline phase of the event has a power-law form (a straight line in a log-log scale in Fig. 1**(b)**):

$$J = J_1 E^{-\gamma} \quad (2)$$

where E, E_0 are measured in GeV and J_0, J_1 in $(\mathrm{m}^2\,\mathrm{s\,st\,Gev})^{-1}$. Accordingly, the parameters of the exponential PC spectrum (1) for the GLE of 20 January 2005 (No 69) are $J_0 = 2.5 \cdot 10^6\,(\mathrm{m}^2\,\mathrm{s\,st\,Gev})^{-1}$ and $E_0 = 0.49$ GeV. Parameters of the power law spectrum (2) for this event: $J_1 = 7.2 \cdot 10^4\,(\mathrm{m}^2\,\mathrm{s\,st\,Gev})^{-1}$ and $\gamma = 5.7$. There is a good agreement between the DC of the relativistic solar proton spectra derived from ground level observations and the direct solar proton measurements on balloons and spacecraft (Fig. 1**(b)** and **(c)**).

4 Results of GLE modeling study

By now, we have analyzed 35 GLEs of the total 50 that occurred in the period 1956 – 2006. Nearly all of them were sufficiently large events where no less than $25-30$ NM stations showed an increase, consistent with the condition of applicability of the GLE modeling technique (Vashenyuk et

Table 1. Parameters of energetic spectra of relativistic solar protons in the GLEs 1956 – 2006.

No	GLE No	Date	Type II onset	Flare Importance	Heliocoordinates	Energetic spectra parameters			
						Prompt component		Delayed component	
						J_0	E_0	J_1	γ
1	05	23.02.1956	03:36*	3	N23 W80	$7.4 \cdot 10^5$	1.37	$5.5 \cdot 10^1$	4.6
2	08	04.05.1960	10:17	3+	N13 W90	$2.7 \cdot 10^5$	0.65	$1.6 \cdot 10^3$	4.2
3	10	12.11.1960	13:26	3+	N27 W04	-	-	$7.5 \cdot 10^3$	4.1
4	11	15.11.1960	02:22	3	N25 W35	-	-	$1.0 \cdot 10^5$	5.3
5	13	18.07.1961	09:47	3+	S07 W59	$5.2 \cdot 10^3$	0.52	$3.6 \cdot 10^3$	6.0
6	16	28.01.1968	07:55	-	N22 W154	$1.4 \cdot 10^4$	0.58	$6.7 \cdot 10^3$	4.7
7	19	18.11.1968	10:26	1B	N21 W87	$1.2 \cdot 10^4$	0.58	$2.6 \cdot 10^3$	5.5
8	20	25.02.1969	09:12*	2B	N13 W37	$7.7 \cdot 10^4$	0.38	$4.7 \cdot 10^3$	5.0
9	22	24.01.1971	23:16	3B	N19 W49	$3.4 \cdot 10^4$	0.45	$.7 \cdot 10^3$	5.8
10	23	01.09.1971	19:34	-	S11 W120	-	-	$4.7 \cdot 10^3$	5.4
11	25	07.08.1972	15:19	3B	N14 W37	$6.6 \cdot 10^2$	1.23	$4.3 \cdot 10^2$	5.0
12	29	24.09.1977	05:55	-	N10 W120	$6.5 \cdot 10^2$	1.14	$9.3 \cdot 10^2$	3.2
13	30	22.11.1977	-	2B	N24 W40	$1.5 \cdot 10^4$	0.77	$1.1 \cdot 10^4$	4.7
14	31	07.05.1978	03:27	1B/X2	N23 W82	$3.5 \cdot 10^4$	1.11	$1.3 \cdot 10^4$	4.0
15	32	23.09.1978	09:58	3B/X1	N35 W50	-	-	$7.0 \cdot 10^2$	
16	36	12.10.1981	06:24*	2B/X3	S18 E31	$1.7 \cdot 10^3$	1.21	-	-
17	38	07.12.1982	23:44	1B/X2.8	S19 W86	$5.7 \cdot 10^3$	0.65	$7.2 \cdot 10^3$	4.5
18	39	16.02.1984	09:00	-	-W132	-	-	$5.2 \cdot 10^4$	5.9
19	41	16.08.1989	01:06*	2N/X12.5	S15 W85	$6.8 \cdot 10^3$	0.56	$3.8 \cdot 10^3$	5.1
20	42	29.09.1989	11:33	-/X9.8	-W105	$1.5 \cdot 10^4$	1.74	$2.5 \cdot 10^4$	4.1
21	43	19.10.1989	12:49	3B/X13	S25 E09	$4.0 \cdot 10^4$	0.53	$3.0 \cdot 10^4$	4.8
22	44	22.10.1989	17:44	2B/X2.9	S27 W31	$7.5 \cdot 10^4$	0.91	$1.5 \cdot 10^4$	6.1
23	45	24.10.1989	18:00	2B/X5.7	S20 W57	$2.4 \cdot 10^4$	0.72	$1.1 \cdot 10^5$	4.9
24	47	21.05.1990	22:12	2B/X5.5	N35 W36	$6.3 \cdot 10^3$	1.13	$2.7 \cdot 10^3$	4.3
25	48	24.05.1990	21:00	1B/X9.3	N36 W76	$2.8 \cdot 10^4$	0.60	$9.1 \cdot 10^3$	4.3
26	51	11.06.1991	02:05	2B/X12.5	N32 W15	$2.6 \cdot 10^3$	0.83	$3.3 \cdot 10^3$	4.8
27	52	15.06.1991	08:14	3B/X12.5	N36 W70	-	-	$5.8 \cdot 10^3$	4.6
28	55	06.11.1997	11:53	2B/X9.4	S18 W63	$8.3 \cdot 10^3$	0.92	$8.2 \cdot 10^3$	4.6
29	59	14.07.2000	10:19	3B/X5.7	N22 W07	$3.3 \cdot 10^5$	0.50	$5.0 \cdot 10^4$	5.4
30	60	15.04.2001	13:48	2B/X14.4	S20 W85	$1.3 \cdot 10^5$	0.62	$3.5 \cdot 10^4$	5.3
31	61	18.04.2001	02:17	-	-W120	$2.5 \cdot 10^4$	0.52	$1.2 \cdot 10^3$	3.6
32	65	28.10.2003	11:02	4B/X17.2	S16 E08	$1.2 \cdot 10^4$	0.60	$1.5 \cdot 10^4$	4.4
33	67	02.11.2003	17:14	2B/X8.3	S14 W56	$4.6 \cdot 10^4$	0.51	$9.7 \cdot 10^3$	6.3
34	69	20.01.2005	06:44	2B/X7.1	N14 W61	$2.5 \cdot 10^6$	0.49	$7.2 \cdot 10^4$	5.6
35	70	13.12.2006	02:51	2B/X3.4	S06 W24	$3.5 \cdot 10^4$	0.59	$4.3 \cdot 10^4$	5.7

*Type II was not observed; type IV or microwave radio emission onset is indicated.

al., 2009). In almost all of 35 events considered, we discovered two RSP components, i.e. the prompt component and the delayed component. Table 1 shows the results of the GLE modeling for 35 events under study.

The Table presents in consecutive columns: GLE No, date of event, and type II radio emission onset (probable time of relativistic solar proton generation). When the data on type II onset were not available, the onset of the type IV or microwave radio burst was indicated. These cases are marked by an asterisk. The flare importance in the H-alpha and in the soft X-rays, as well as the flare heliocoordinates, are listed in the next columns. In the last columns the parameters of derived energetic spectra in accordance with relations (1) for the PC and (2) for the DC are given.

5 Regularities in the spectra of prompt and delayed solar proton components

Figure 2 shows the statistical distribution of E_0, which is a characteristic energy of the exponential energetic spectrum of the RSP prompt component. It has a pronounced peak at $E0 \sim 0.5$ GeV, which means that the majority of events have such a PC spectrum. However, there are also several events with $E_0 \geq 1$. In Fig. 3 the statistical distribution of the spectral parameter γ is shown. Here, the majority of the events have the value of γ around 5 (from 4 to 6).

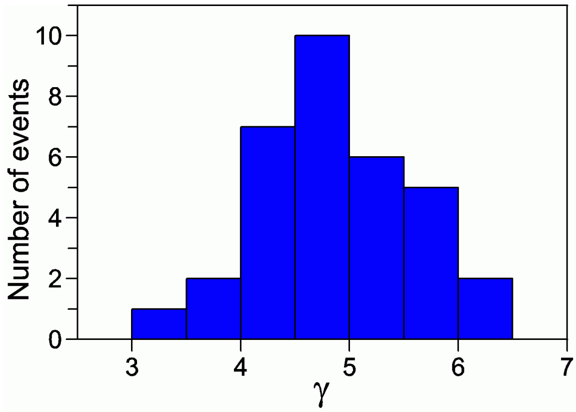

Fig. 3. Statistical distribution of parameter γ of the DC power law spectrum

6 Discussion

It can be shown that the interplanetary propagation cannot significantly influence the spectral form of the relativistic solar protons (Vashenyuk et al., 2006a). Thus, we consider the regularities of the spectral parameters in the Figs. 2 and 3 as the evidence of a specific mechanism of particle acceleration during flare-related phenomena of the Sun. In our previous papers, the prompt component was associated with acceleration by an electric field, originating in a region of magnetic reconnection in the solar corona. Such reconnections may arise at the border of magnetic polarities near the photosphere (Manoharan and Kundu, 2003) or in the trailing part of a rising Coronal Mass Ejections (CME) (Aschwanden, 2011). In an area of magnetic reconnection, an electric field arises that accelerates particles of surrounding plasma. The spectrum of protons obtained by simulation in the configuration of magnetic and electric fields typical for the reconnection site has a form close to exponential (Vashenyuk et al., 2006a,b, 2008; Perez-Peraza et al., 2009). Podgorny et al. (2010) performed simulation of the proton energy distributions in the actual magnetic and electric fields configuration in the area of the "Bastille Day" flare on 14 July 2000. The obtained proton spectrum has an exponential form with $E_0 \sim 0.5$ GeV. The spectrum obtained from experimental data with the GLE modeling has the same magnitude of E_0 (Table 1).

Bazilevskaya (2009) and Aschwanden (2011) found that the first relativistic particles leave the Sun at the moment close to the maximum of the hard X-rays. Nearly simultaneously with the hard X-rays the high energy gamma-rays are observed, testifying to an acceleration of protons (Kuznetsov et al., 2006).

This is another evidence for the connection of PC particles with a flare rather than with any other phenomena. Gopalswamy et al. (2010) consider CME and connected coronal shock as the main source of RSP. We, in turn, suppose that CME and the connected coronal shock can be related to the DC of relativistic solar protons. The DC appear $10-30$ min after the PC (Vashenyuk et al., 2006a,b) and have the power-law energetic spectrum, which is typical for shock wave acceleration (Ellison and Ramaty, 1985). At the same time, we consider a stochastic acceleration by the magneto hydrodynamic (MHD) turbulence in disturbed coronal plasma as a most appropriate generation mechanism for the DC of relativistic solar protons (Gallegos-Cruz and Perez-Peraza, 1995; Perez-Peraza et al., 2006, 2008, 2009). This mechanism may also be connected to a CME. Particles that are trapped in closed magnetic loops interact with MHD turbulences inside an expanding CME. Energy losses due to adiabatic deceleration are small compared to the effect of acceleration (Perez-Peraza et al., 2009). In this paper the spectra of DC obtained with the GLE modeling for the events No 42, 59, 65, and 69 were fitted by the theoretical spectra calculated at reasonable parameters of magnetic turbulence and a CME expansion speed. A good consistency between the experimental DC spectra obtained with the GLE modeling and the ones calculated within the theory of a stochastic acceleration (Gallegos and Perez-Peraza, 1995) was shown.

This enables one to consider the stochastic acceleration as the basic mechanism of DC generation. In the present paper we have not considered in detail the effect of acceleration at the shock wave on our results. But, according to estimations of Perez-Peraza et al., (2009), the diffusive shock wave acceleration is more effective in the subrelativistic energy domain.

Any large disturbance event on the Sun has two important components: a flare and a CME. Based on the properties of the prompt and delayed components of RSP considered above, a more probable source of PC is the flare (connection with hard X-rays and gamma radiations). The source of DC (plasma turbulence) is likely connected to the CME.

Tylka and Dietrich (2009) tried to perform the comprehensive analysis of rigidity spectra of relativistic solar protons during GLEs. Based on the simplified procedure, they obtained the "event-integrated spectra" in the power law form and showed the good consent of these spectra with the direct solar proton data of moderate rigidities. In our procedure we obtain spectra through every 5 min and only such time resolution allows us to separate the prompt and delayed components. We also show the good consent of DC spectra with direct measurements of solar protons of moderate energies. For PC such consent it is not observed (Vashenyuk et al., 2006a, 2009). Procedure of (Tylka and Dietrich, 2009) deriving "event-integrated spectra" (EIS) does not allow the separation of PC and DC. Their event-integrated spectra in the main present DC as the PC occupies only a small initial part of the event. Therefore, the consent is observed by EIS with direct solar proton data in moderate energies. At the same time, the definition of a power law spectrum on a basis of event-integrated spectra comprises an error associated with a superposition of spectra of PC and DC.

7 Conclusions

The study of 35 large GLEs during the period 1956 – 2006 has been carried out with the GLE modeling technique developed by the authors. The basic characteristics of relativistic solar protons (RSP), such as a rigidity (energy) spectrum, direction of anisotropy axis, and pitch angle distributions are obtained, and their dynamics are studied for each of the events. It is shown that in almost all events, there exist two components (populations) of relativistic solar particles: the prompt component and the delayed one. The prompt component (PC) prevails in the beginning of the event. The mark of the PC in the solar corona can be an onset of hard gamma rays. The PC is characterized by an impulsive profile, a strong anisotropy and an exponential energy spectrum: $J(E) = J_0 \exp(-E/E_0)$. The delayed component (DC) dominates during the maximum and the decline phases of the events. The DC has a gradual intensity profile, a moderate anisotropy and a power law energy spectrum: $J(E) = J_1 E^{-\gamma}$. The analysis of the large number of GLEs shows that E0 in the exponential spectrum of PC has a rather stable mean of ~ 0.5 GeV in the majority of the events. The value of the spectral exponent γ is distributed from 4 up to 6 with most at $\gamma = 5$. The exponential spectrum of PC with $E_0 \sim 0.5$ GeV agrees well with the spectrum obtained in simulating proton acceleration in the electric field arising during magnetic reconnection in the solar corona. The power law spectrum of DC with a spectral exponent $\gamma = 5$ is close to the model spectrum resulting in the process of stochastic acceleration in a turbulent solar plasma.

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