

REGULARITIES IN THE RELATIVISTIC SOLAR PROTON SPECTRA FORMATION

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Abstract. Based on the data of neutron monitors, balloons and spacecraft as well as EAS arrays and muon detectors, the regularities of relativistic solar proton (RSP) generation and release from the Sun in the events of 21-23 solar cycles have been studied. In total, 11 Ground Level Enhancements (GLE) of solar cosmic rays (SCR) were analyzed. The two-peak structure of solar proton intensity profiles gives certain evidence of two distinct particle populations (components). One is related to early impulse-like intensity increase with a hard exponential energy spectrum (the prompt component, PC) and the other refers to the late gradual increase with a soft power-law spectrum (the delayed component, DC). The exponential form of the PC energy spectrum may be an evidence of the acceleration by electric fields arising in the reconnection current sheets in the corona. The DC energy spectrum may be fitted with a power-law function that suggests a stochastic acceleration in the disturbed flare plasma. Considering the timing of generation and release of the two RSP components from the solar corona, a possible scenario of large particle event on the sun has been proposed.

1. Introduction

In this paper, based on the data of neutron monitors, balloons and spacecraft, we consider the regularities of relativistic solar proton (RSP) generation and release from the Sun in the events of solar cycles 21-23. In all, eleven Ground Level Enhancements (GLE) of solar cosmic rays (SCR) were analyzed from the data of ground based neutron monitors (NM). The worldwide NM network may be considered as a united multidirectional solar proton spectrometer in the relativistic energy range. By modeling the ground based detector responses to an anisotropic solar proton flux and comparing them with observations, the parameters of primary solar protons outside the magnetosphere can be obtained by the least square technique (e.g., Vashenyuk et al., 2003a). This kind of analysis requires the data of more than 25 NM stations, and it includes a few steps: 1) Determination of asymptotic viewing cones of the NM stations under study by particle trajectory computations in a model magnetosphere (with a step in rigidity of 0.001 GV). The magnetosphere model by Tsyganenko (2002a, b) was employed. 2) Calculation of the NM responses at variable primary solar proton flux parameters. 3) Application of a least square procedure (optimization) for determination of primary solar proton parameters (energy spectrum, anisotropy axis direction, pitch-angle distribution) outside the magnetosphere by comparison of computed ground based detector responses with observations. In this paper we will concentrate on the energy spectra of solar protons. The control of accuracy of the spectra obtained was performed by summation of the measured responses of neutron monitors with a random quantity equal to a probable error of the data. The resulting dispersion of solar proton parameters calculated by the optimization procedure can serve as a measure of the error of the given method. Such error estimation is given for all solar proton spectra under study. The validity criterion for the spectra obtained from NMs and EAS records may be provided by comparison with the direct solar proton intensities measured in adjacent energy ranges by balloons and spacecraft. Some of the GLEs considered in our paper have already been studied by modeling methods by different authors. A comparison of their results with ours shows, almost in all cases, a close similarity of the spectra, anisotropy axes and other parameters. At the same time, based on our analysis we suggest a new interpretation of the considered events in terms of two SCR populations (components) in the relativistic energy range. These components can be presumably connected to various sources (mechanisms) of particle acceleration at/near the Sun.

2. Observations

A list of eleven GLEs of solar cycles 21-23 that we are analyzing 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 type II radio emission corresponds to starting of energy release at the null magnetic point close to the low coronal level and related to its H-alpha eruption and start of CME (Manoharan and Kundu, 2003). The type II onset was also found to be a marker of relativistic proton acceleration (Cliver et al., 1982). In each event under study we tried to reveal the prompt (PC) and delayed (DC) components of relativistic solar protons based on their spectral form. The best fits for the PC spectra are provided by exponential functions $J = J_0 \exp(-E/E_0)$, where E_0 is the characteristic proton energy.

As for the 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 the characteristic energies E_0 are given in GeV and proton intensities in $m^{-2}s^{-1}sr^{-1}GeV^{-1}$. Figures 1-2 demonstrate some results of our analysis for events 9 and 11 from Table 1 (GLEs Nos. 65, 69). The two-peak structure of solar proton intensity profiles as well as different character of energy spectra show the presence of two distinct particle populations (components): the prompt (PC) and delayed (DC) ones.

Table 1. Parameters of energetic spectra of relativistic solar protons

No	No of GLE	Date	Type II Radio onset	Flare importance	Heliocoordinates	PC spectrum (exponential)		DC spectrum (power-law)	
						J_0	E_0	J_1	Γ
1	31	07.05.1978	03.27	1B/X2	N23W82	$1.4 \cdot 10^4$	1.65	-	-
2	38	07.12.1982	23.44	1B/X2.8	S19W86	$1.5 \cdot 10^5$	0.35	$2 \cdot 10^3$	3.2
3	39	16.02.1984	08.58	-	-W132	-	-	$1.6 \cdot 10^4$	6.2
4	42	29.09.1989	11.33	-/X9.8	-W105	$1.6 \cdot 10^4$	1.85	$2 \cdot 10^3$	4.2
5	43	19.10.1989	12.58	4B/X13	S27E10	$7 \cdot 10^3$	0.65	$4 \cdot 10^4$	4.5
6	44	22.10.1989	18.05	2B/X2.9	S27W31	$1 \cdot 10^5$	0.62	$5 \cdot 10^3$	4.2
7	59	14.07.2000	10.20	3B/X5.7	N22W07	$1.1 \cdot 10^4$	0.68	$2 \cdot 10^4$	5.6
8	60	15.04.2001	13.19	2B/X14.4	S20W85	$2 \cdot 10^5$	0.48	$2 \cdot 10^3$	5.1
9	65	28.10.2003	11.02	4B/X17.2	S16E08	$1.5 \cdot 10^5$	0.49	$3.5 \cdot 10^3$	3.5
10	67	2.11.2003	17.03	2B/X8.3	S14W56	$1.5 \cdot 10^3$	0.78	$8 \cdot 10^3$	6.0
11	69	20.01.2005	06.44	2B/X7.1	2B/X7.1	$1.5 \cdot 10^5$	0.72	$7.5 \cdot 10^4$	6.2

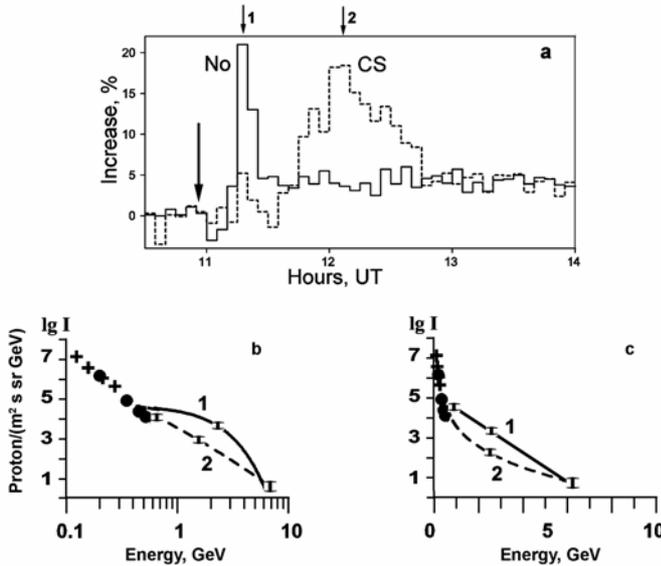


Fig.1. Prompt and delayed RSP components in the GLE of 28 October 2003: (a) intensity profiles at the NM stations Norilsk (No) and Cape Schmidt (CS); (b, c) derived energy spectra of PC (1, solid line) and DC (2, dashed line). Direct solar proton data are shown with crosses (balloons) and blackened dots (GOES-10 spacecraft)

GLE 65 of 28 October 2003 was related to the flare 4B/X17.2, heliocoordinates S16, E08, type II radio onset at 11:02 UT. In Fig. 1a, the increases in the profiles at Norilsk and Cape Schmidt stations are shown. The prompt component of RSP (1) manifests by the impulse-like increase at Norilsk neutron monitor and by the less pronounced first of the two peaks at Cape Schmidt station. The delayed component (2) was distinctly registered only by Cape Schmidt neutron monitor. The vertical arrow indicates the onset time of II type radio emission, shifted back by 8 min. (the supposed moment of relativistic particle generation on the Sun. The numbered arrows correspond to the times when in the RSP flux the prompt component (1) and delayed one (2) dominate. Figures 1b-1c show the spectra of PC (1) and DC (2), obtained from modeling, in double logarithmic and semi-logarithmic scale, respectively. In Fig. 1b-1c, are also shown direct solar proton data from GOES spacecraft and balloons launched in Apatity (joint Lebedev Physical Institute (LPI) and Polar Geophysical Institute (PGI) balloon experiment; for details see Bazilevskaya and Svirzhevskaya, 1998). In

Figures 1b-1c the derived spectra of prompt (1) and delayed (2) components are shown. We note that the PC spectrum (1), as well as in the previous case, is exponential in energy $J = 1.5 \times 10^5 \exp(-E/0.49)$, while the spectrum of DC (2) has a power-law form $J = 3.5 \times 10^3 E^{-3.5}$.

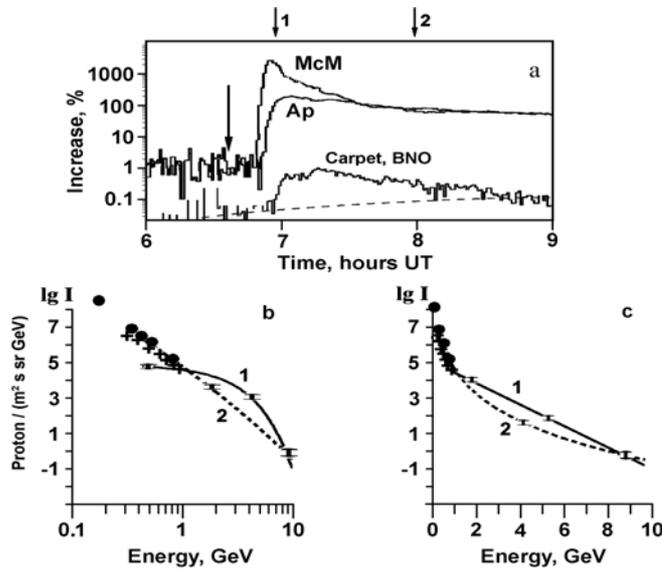


Fig. 2. Prompt and delayed components of relativistic protons in the GLE of 20 January 2005: (a) intensity-time profiles at the NM stations McMurdo (McM), Apatity (Ap); and EAS array “Carpet”. (b, c) derived energy spectra of PC (1, solid line) and DC (2, dashed line). Direct solar proton data are crosses (balloons) and blackened dots (GOES-11 spacecraft)

be produced by the mechanism of stochastic acceleration due to the interaction between Alfvén MHD mode turbulence and the particles trapped in the low coronal magnetic arches. The extrapolated intensity of the prompt component (spectrum 1) at energy 100 MeV, however, is about 3 orders of magnitude lower than that for DC (spectrum 2), so it turns out to be at the level of the background, being inaccessible to direct measurements.

3. Discussion and conclusions

The results of modeling study of 11 large GLEs of 21-23 solar cycles clearly show the existence of two distinct populations of relativistic solar protons: the prompt (PC) and delayed (DC) components. Because of large transport path and its weak dependence on rigidity (Bieber et al., 1994), the formation of PC and DC can hardly be attributed only to the interplanetary propagation effects, considering strongly different spectra.

One of the important results is that the PC spectrum proves to have exponential form in energy, and this may be an evidence of acceleration by electric fields arising in the coronal sheets (e.g., Balabin et al., 2005, Perez-Peraza et al., 1992; Vashenyuk et al., 2003). At impulsive magnetic reconnection, an electric field arises in the current sheet, 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 the path they travel in the electric field. At the same time, the number of particles traveling along a given path in the reconnection area subsides exponentially with this path increasing because of the losses associated with particle drifts. Consequently, the spectrum of the particles accelerated by the electric field inside the volume, where the reconnection proceeds, should have exponential dependence on energy. This qualitative picture has been verified by modeling computations, in which the structure of magnetic and electric fields in a reconnection current sheet was reproduced (Vashenyuk et al., 2003b). The trajectories of particles of the plasma accelerated in the electric field were computed, with their energy being fixed at leaving the acceleration volume. The resulting spectrum of the accelerated particles appeared to exhibit an exponential dependence on energy, which is consistent with the view that the magnetic reconnection is a source of the prompt RSP component. The interplanetary propagation must not appreciably deform the spectrum of RSP, at least for the prompt component (PC). A rapid intensity increase and strong anisotropy, typical for the particles of the PC, testify the propagation in the IMF with minimum scattering. Thus, the time of direct travel along an IMF line with the characteristic length of

The GLE of 20 January, 2005

Super GLE 69 occurred on 20 January 2005, being the greatest event since 23 February 1956. The parent solar flare 2B/X7.1 had heliocoordinates N14, W61. The type II radio onset was reported at 06.44 UT. The GLE was extremely anisotropic. Figure 2a shows the intensity-time profiles, as registered by the neutron monitors at Mc Murdo (McM) and Apatity (AP) stations. The increase at McMurdo was about 2300 % that exceeded 20 times the appropriate effect on the NM in Apatity, which, in turn, was significant (~100 %). As well as in the previous cases we can see the presence of the prompt (1) and delayed (2) components. The corresponding spectra of the PC (1) and DC (2) are shown in Figs 2 b,c. The spectrum of the PC is exponential in energy: $J = 1.5 \times 10^5 \exp(-E/0.72)$, and the spectrum of the DC has a power-law form: $J = 7.5 \times 10^4 E^{-6.2}$. As in the previous cases, one can see a good consistence between the derived spectra and the data of direct solar proton measurements.

The DC spectrum can be extended with keeping the slope into the range of moderate energies of solar protons measured in the balloon and spacecraft experiments. As demonstrated by Perez-Peraza et al. (2003), the DC spectrum could

1.2 AU, makes 13.2 and 10 minutes for the particles with the energy about 0.5 GeV and 10 GeV, respectively. We note that corresponding ratio v/c is, respectively, 0.76 and 0.996, where v is the particle velocity and c is the speed of light. Hence, relativistic solar protons in the energy range of 0.5-10 GeV come to the Earth within 3-minute interval. In the modeling technique applied (Vashenyuk et al., 2003), 5-minute averaged NM data are used, therefore, the obtained solar proton spectrum is suggested to have the form which is close to that of generation spectrum on the Sun, in case the particles were released simultaneously. The best fit for DC spectrum is a power-law form in energy with a rather steep slope ($\gamma \sim 5-6$). As a source of the DC, it would be possible to suggest a coronal shock wave (Kahler, 1994). The acceleration on a shock wave also gives a power-law spectrum, but in the non-relativistic energy range (Ellison and Ramaty, 1985). Taking into account our previous results, we are more apt to consider acceleration by MHD turbulence as a probable mechanism for DC formation during explosive energy release in a flare (Miroshnichenko et al., 1996). The proton spectrum in this case has a variable slope and should be described by a curve of the Bessel function type in rigidity in general case, and by the power law in the high-energy limit (Gallegos-Cruz and Perez-Peraza, 1995). Our experimentally obtained spectra of the DC of relativistic solar protons obviously correspond to this theoretical result. Therefore, considering the timing of generation and release of two relativistic proton components (PC and DC) 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 associated with the H-alpha eruption, onset of CME and type II radio emission. The accelerated particles of the PC leave the corona along open field lines with diverging geometry that results in high anisotropy due to strong focusing of a particle bunch. The DC particles are trapped originally in magnetic arches in the low corona. As the disturbance grows, DC particles are accelerated by a stochastic mechanism at the MHD turbulence in expanding flare plasma. Accelerated particles can be then carried to the outer corona by an expanding (lifting) CME. They are released into interplanetary space after the magnetic trap is destroyed, giving rise to an extended in time and azimuth particle source.

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