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Two-Component Concept for Ground Level Enhancements of Solar Cosmic Rays: Solar and Interplanetary Aspects

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Abstract—We discuss solar and interplanetary aspects concerning the observations and interpretation of two relativistic components of solar cosmic rays (SCRs), namely, impulsive (prompt) and slow (delayed) components (PC and DC, respectively). The prompt component is characterized by the strong anisotropy and exponential energy spectrum. The delayed component is essentially isotropy and has a power-law energy spectrum. Our analysis of observational data and theoretical arguments rules out the interplanetary propagation as the origin for these two components. Most likely, they are formed in the SCR generation on the Sun within the framework of two-source model with multiple acceleration processes in the solar atmosphere.

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INTRODUCTION

As shown by the authors in the earlier works [1–4], a number of solar cosmic ray (SCR) events on the surface of the Earth (the so-called ground-level enhancements, GLEs) definitely demonstrate a well-pronounced two-component structure in the form of impulsive (prompt) component (PC) and delayed (slow) component (DC). These components differ from each other by the intensity time profiles (impulsive vs. gradual), pitch-angle distributions (strong anisotropy vs. essential isotropy), energy spectra (hard exponential vs. soft power-law). In particular, the prompt component is strongly anisotropic at the beginning of a GLE event. The PC particles are presumably accelerated in the processes of magnetic reconnection in the lower coronal layers at a time close to the explosive phase of a flare and the beginning of a type-II radio burst [1, 5]. On the other hand, the DC particles can be accelerated by the stochastic mechanism in closed magnetic structures low in the corona and then are escape into the outer corona by the expanding coronal mass ejection (CME) [2, 6].

The delayed component can be considered theoretically (for example see [7]) as the result of transformation of a particle beam ejected from the Sun (prompt component) in the process of its interplanetary propagation (scattering of PC particles by interplanetary magnetic-field irregularities). However, a detailed physical picture of the processes leading to the initial impulse-like peak and, generally, double-peak structure observed in some events is not yet clear. Based on experimental and model results [3, 4], we conclude that the hypothesis of “interplanetary source” of the two components cannot solve all the problems related to relativistic GLE events. On the contrary, there are solid evidences in favor of the model of the SCR generation by two sources on the Sun within the framework of the concept of multiple SCR acceleration in the solar atmosphere [8].

OBSERVATION DATA ON TWO GLE COMPONENTS

The GLE event of October 28, 2003 is a striking example of the existence of two components of relativistic solar energetic particles. This event was related to a 4Ç/ï17.2-class flare observed in the area with heliocoordinates S16E08. The beginning of type-II radio-burst at 11: 02 UT is indicated. Figure 1a shows the enhancements detected with the Norilsk and Shmidt Cape neutron monitors (NMs). The data demonstrate typical prompt- and delayed component time profiles. A small initial peak in the Norilsk time profile corresponds to the prompt component; the subsequent smooth enhancement, to the delayed component. Figures 1b and 1c accordingly show the double- and semilogarithmic spectra obtained by optimizing the neutron-monitor. It is seen that, within errors, the prompt-component energy spectrum (*1*) is exponential, $\{J = 1.2 \times 10^4 \exp(-E/0.59)\}$ and the delayed-component spectrum (*2*) is power-law, $\{J = 1.5 \times 10^4 E^{-4.4}\}$.

The October 28, 2003 event is one of a number of GLEs for which the prompt and delayed components were observed. A strongly collimated prompt-component flux was actually deflected by a local irregularity (field-line bending) of the interplanetary magnetic field immediately before the Earth. The delayed- component

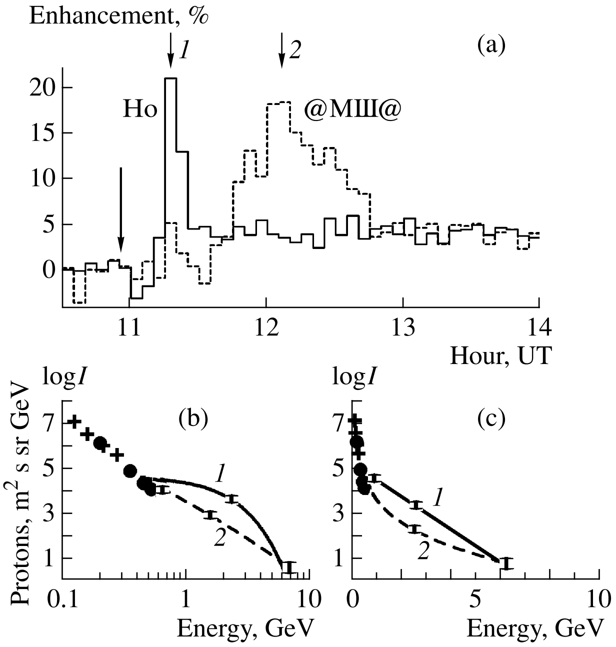

Fig.1. The GLE event of October 28, 2003 (a). Prompt (*1*) and delayed (*2*) components of relativistic solar particles in the time profiles of enhancements detected with the Norilsk and Shmidt Cape neutron monitors (NMs). The vertical arrow marks the probable time of the SCR generation. The GLE spectra of the prompt (*1*) and delayed (*2*) components plotted according to the ground-based data in the double logarithmic (b) and semi-logarithmic scales (c). The data of direct balloon-borne (crosses) and *GOES-11* (circles) measurements of the solar protons are also shown.

particles having the wide pitch-angle distribution passed through the irregularity relatively intact [9].

INTERPLANETARY PROPAGATION EFFECT

Theoretical modeling of high-energy solar particle propagation in the interplanetary magnetic field in the so-called focused diffusion regime [7, 10, 11] leads to a two-peak SCR structure similar to the time profiles shown in Fig.1. The scattering and adiabatic focusing in the diverging interplanetary magnetic field can balance each other for some group of particles under certain conditions. These particles move as a clustered bunch in front of bulk particles (diffusion cloud) propagating diffusively in the interplanetary space. An example of such "supercoherent" SCR propagation in the energy range >5 MeV observed by *Helios* spacecraft at a distance of 0.3 AU from the Sun is described in [12]. In the case of relativistic solar protons with the large transport path, the supercoherent mode can in principle be observable near the Earth. Meanwhile, a mean pitch angle of ~50° is an essential feature of particles in a supercoherent beam [7]. Accordingly, the mean velocity of "supercoherent" peak particles transference is the halved total velocity ($\upsilon/2$).

It is known that in most cases, the enhancement detected by neutron monitors is delayed by ~11 min with respect to the eruptive phase of a flare. The delay agrees with the time of direct flight of (zero-pitch-angle) relativistic solar protons from the Sun to the Earth along the medium field line of the interplanetary magnetic field by a distance of 1.2 AU [13]. These so-called "initial species" belong to the prompt component. An analyses of many events imply that these particles propagate as a collimated beam with extremely small pitch angles [3, 4]. This was confirmed by direct

Parameters of the exponential $J = J_0\exp(-E/E_0)$ and power-law $J = J_1E^{-\gamma}$ spectra for the GLE events observed in 1956–2006

No.	No. GLE	Date of the event	Beginning of type-II radio burst	Flare class	Heliocoordinates	Prompt component		Delayed component	
						J_0	E_0	J_1	$-\gamma$
1	05	Feb. 23, 1956	03:31*	3B	N23W80	7.4×10^5	1.37	5.5×10^5	4.6
2	31	May 07, 1978	03:27	1B/ї2	N23W82	3.5×10^4	1.11	1.3×10^4	4.0
3	38	Dec. 07, 1982	23:44	1B/X2.8	S19W86	5.7×10^3	0.65	7.2×10^3	4.5
4	39	Feb. 16, 1984	09:00	–	– W132	–	–	5.2×10^4	5.9
5	42	Sept. 29, 1989	11:33	–/X9.8	– W105	1.5×10^4	1.74	2.5×10^4	4.1
6	44	Oct. 22, 1989	17:44	2B/X2.9	S27W31	7.5×10^4	0.91	1.5×10^4	6.1
7	47	May 21, 1990	22:12	2B/X5.5	N35W36	6.3×10^3	1.13	2.7×10^3	4.3
8	55	Nov. 06, 1997	11:53	2B/X9.4	S18W63	8.3×10^3	0.92	8.2×10^3	4.6
9	59	July 14, 2000	10:19	3B/X5.7	N22W07	3.3×10^5	0.50	5.0×10^4	5.4
10	60	Apr. 15, 2001	13:48	2B/X14.4	S20W85	1.3×10^5	0.62	3.5×10^4	5.3
11	65	Oct. 28, 2003	11:02	4B/X17.2	S16E08	1.2×10^4	0.60	1.5×10^4	4.4
12	67	Nov. 02, 2003	17:14	2B/X8.3	S14W56	4.6×10^4	0.51	9.7×10^3	6.3
13	69	Jan. 20, 2005	06:44	2B/X7.1	N14W61	2.5×10^6	0.49	7.2×10^4	5.6
14	70	Dec. 13, 2006	02:51	2B/X3.4	S06W24	3.5×10^4	0.59**	4.3×10^4	5.7

[d] Beginning of radio burst at a frequency of 3m3 GHz;

1 [e] The spectrum in the initial phase of the GLE70 event has variable slope and does not exactly correspond to exponential dependencem. The prompt-component spectral parameters correspond to the best exponential fit for a spectrum in optimization process

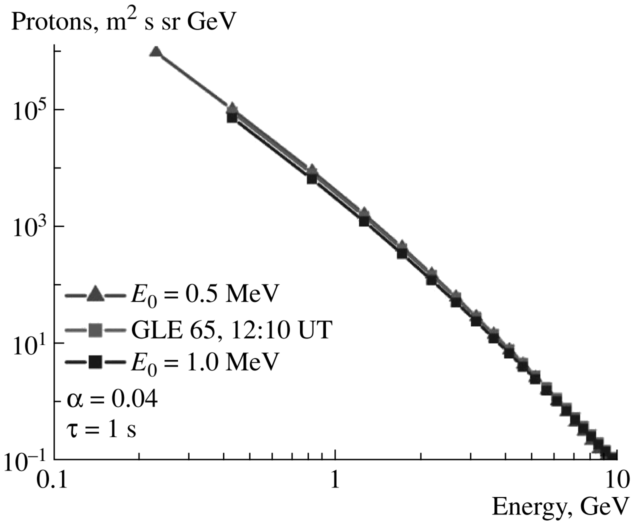

Fig.2. Comparison of delayed-component spectra in October 28, 2003 event obtained from the experimental data (GLE65) and by calculations of proton acceleration in turbulent plasma at different initial energies E_0 [18].

measurements with the “Uragan” muon hodoscope by the Moscow Engineering Physics Institute [14] in which a collimated flux of prompt-component particles was observed for the event of December, 13, 2006. Thus, the propagation of prompt-component particles essentially differs from “supercoherent” mode. As far as the collimation of prompt-component particles is concerned, it presumably takes place near the Sun and not affected by the weak interplanetary scattering along the path to the Earth.

ENERGY SPECTRUM

Analysis of a number of GLE events (see the table) [1–6] shows that the prompt-and delayed-component spectra are exponential and power-law, respectively. It is difficult to explain such specific division in energies only by scattering and focusing in the interplanetary space. It is difficult to imagine that at middle lengths of interplanetary transport race from 0.1 to 1 a.e. [15, 16] relativistic solar protons could essentially change the energy on the way from the Sun to the Earth. The assumption on the different sources of accelerated particles on the Sun seems to be more reasonable. The data on the development of active processes and accompanying radiation on the Sun evidences for a plethora of the possible high-energy particle generation. All the known mechanisms for particle acceleration can be classified into the three basic types [16]: electric-field acceleration, acceleration by shock waves in the solar atmosphere, and stochastic acceleration by plasma magnetohydrodynamic turbulence. It is shown in [1, 5] that the most probable mechanism for the promprt-component acceleration is the acceleration by the electric field in a reconnecting coronal current sheets. This mechanism provides for an exponential energy spectrum similar to the observed prompt-component spectrum [1–5]. The most probable mechanisms for the delayed-component generation are the shock acceleration near the Sun [17] and the acceleration by plasma magnetohydrodynamic turbulence in flare ejecta [18]. 2

The validity of the mechanism outlined in [18] was examined for a number of events. Figure 2 compares the delayed-component spectrum obtained from the experimental data of the October, 28, 2003 event (Fig.1b) with the spectrum calculated according to the stochastic-acceleration model [18]. It is seen that the observed and calculated spectra are in agreement for the model parameters corresponding to real conditions.

CONCLUSIONS

The presence of two relativistic-SCR components with different parameters obviously requires an essential revisiting of the general concept of GLEs. Based on the results [19] concerning the development of coronal mass ejections in solar-corona magnetic structures, we proposed a possible scenario for the generation of these two components [2, 3, 18]. The physical conditions and mechanisms underlying the appearance of initial impulses and double-peak GLE structure are still not adequately explored. Along with this, a detailed analysis of observational and theoretical arguments shows that these components are most likely formed not due to the interplanetary propagation, but directly in two sources of the SCR generation on the Sun within the framework of the multiple acceleration of particles in the solar atmosphere.

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SPELL: 1. dependencem, 2. ejecta, 3. ACKNOWLEDGEMENTS