Ground level enhancements of solar cosmic rays (1956-2006): Study of solar and interplanetary aspects

L.I. Miroshnichenko*, **E.V. Vashenyuk**†, **Yu.V. Balabin**†, **J. Perez-Peraza**‡ **and B.B. Gvozdevsky**†

**N.V.Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation (IZMIRAN), Troitsk, Russia*
†*Polar Geophysical Institute, Apatity, Russia*
†*Instituto de Geofisica, Universidad Nacional Autonoma, de Mexico, Mexico*

***Abstract*. We discuss solar and interplanetary aspects concerning the observations and interpretation of two relativistic components of solar cosmic rays (SCRs). The modeling analysis of 30 large GLEs for the period of 1956-2006 by the data of the worldwide network of neutron monitors clearly revealed existence of two distinct SCR populations (components): 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 results of our analysis of available data and a number of theoretical arguments rule out an idea of interplanetary propagation as the origin for these two components. Most likely, they are formed in the multiple processes of particle acceleration in the solar atmosphere. We argue in favour of two-source model for PC and DC generation. The exponential spectrum for prompt component may be an evidence of acceleration by electric fields arising in the reconnecting current sheets in the corona. The possible source of delayed component is most likely stochastic acceleration at the MHD turbulence in expanding flare plasma.**

***Keywords*: solar protons, generation, propagation, GLE**

I. Introduction

As shown by the authors in the earlier works [14], 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) [2,7]. The delayed component can be considered theoretically (for example see [8]) 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 pulse-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 can not 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 [9].

II. Observational data on two RSP components

The GLE event of October 28, 2003 is a striking example of the existence of two components of relativistic solar energetic particles (Fig. 1). This event was related to a 4B/X17.2-class flare observed in the active region with heliocoordinates S16 E08. The onset of type-II radio-burst was reported at 11:02 UT and it is indicated by an arrow in Fig. 1a. Here also the enhancements detected with the Norilsk and Cape Shmidt neutron monitors (NMs) are shown. 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 modeling from the neutron monitor network data. It is seen that, within errors, the prompt component energy spectrum (1) is exponential, J=$1.2{\cdot}10^4 \cdot exp(-E/0.59)$, and the delayed component spectrum (2) is power-law: J=$1.5{\cdot}10^4 \cdot E^{-4.4}$.

The October 28, 2003 event is one of a number of GLEs for which the prompt and delayed RSP components were separately observed in the NM increase profiles. A strongly collimated prompt-component flux was actually

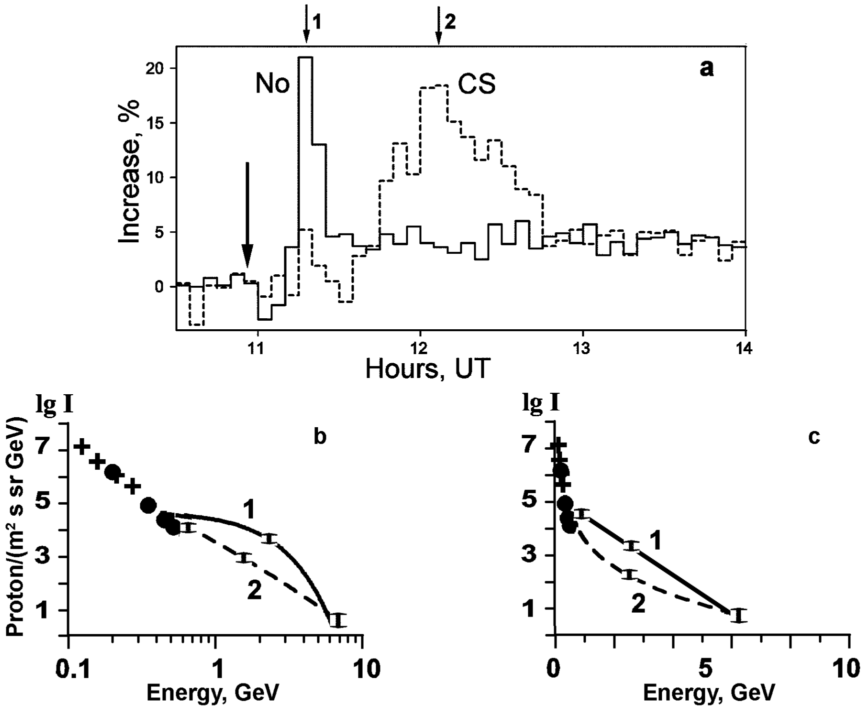

Fig. 1: The GLE event of October 28, 2003 (a). Prompt (1) and delayed (2) components of relativistic solar particles in the time profiles of enhancements detected with the Norilsk and Cape Shmidt neutron monitors. The vertical arrow marks the probable time of the SCR generation. The SCR spectra of the PC (1) and DC (2) in the double logarithmic (b) and semi-logarithmic scales (c) are shown. The direct solar proton data obtained by balloons (crosses) and GOES-11 (circles) are also shown.

deflected by a local irregularity (field-line bending) of the interplanetary magnetic field immediately before the Earth. The delayed component particles having the wide pitch-angle distribution passed through the irregularity relatively intact [9].

III. Interplanetary propagation effect

Theoretical modeling of high-energy solar particle propagation in the interplanetary magnetic field in the so-called focused diffusion regime [8,10,11] 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 a.u. 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 $\sim 50^o$ is an essential feature of particles in a supercoherent beam [8]. Accordingly, the mean velocity of ”supercoherent” peak particles transference is the halved total velocity ($V/2$).

It is known that in most cases, the enhancement detected by neutron monitors is delayed by $\sim$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 a.u. [13]. These so-called ”initial species” belong to the prompt component. Analyses of many events imply that these particles propagate as a collimated beam with extremely small pitch angles [3-5]. This was confirmed by direct 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.

IV. Energy spectrum

For a number of years authors carry out the modeling study of GLE events [3-7]. To the present time 32 events for the period 1956-2006 are studied [5]. Analysis of these 32 GLE events [17] shows that the prompt- and delayed-component spectra are exponential and power-law, respectively. It is difficult to explain such specific

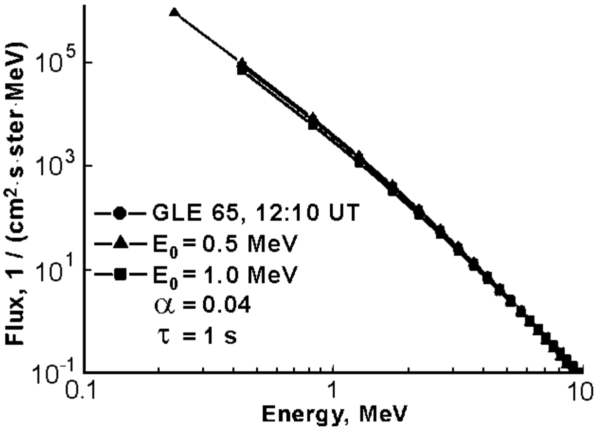

Fig. 2: Comparison of delayed-component spectra in October 28, 2003 event obtained from the experimental data (GLE65) and by calculations of proton acceleration in turbulent plasma at different initial energies E_0. α and τ are acceleration efficiency and time, respectively [18].

division in energies only by scattering and focusing in the interplanetary space. It is difficult to imagine that at middle lengths of interplanetary transport length from 0.1 to 1 a.u. [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 [1,6] that the most probable mechanism for the prompt component acceleration is the acceleration by the electric field in reconnecting coronal current sheets. This mechanism provides for an exponential energy spectrum similar to the observed prompt-component spectrum [16]. 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].
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.

V. Conclusions

The presence of two relativistic-SCR components with different parameters obviously requires an essential revisiting of the general concept of GLEs. Based on recent results on development of coronal mass ejections in solar-corona magnetic structures [19], we proposed a possible scenario for the generation of these two components [2,3,18]. 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. 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.
The physical conditions and mechanisms underlying the appearance of initial pulses 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.

VI. Acnowledgements

This work was supported by the Russian Foundation for Basic Research (projects no. 07-02-01405, 09-02-00076, 09-02-98511), the Council of the President of the Russian Federation for Support of Young Scientists and Leading Scientific Schools (grant no. NSh-4573.2008.2), and Consejo Nacional de Ciencia y Tecnologia (CONACYT) (grant no. 45822PERPJ10332).

References

[1] E.V. Vashenyuk, Yu.V. Balabin, G.A. Bazilevskaya, V.S. Makhmutov, Yu.I. Stozhkov, N.S. Svirzhevsky, *Solar particle event 20 January 2005 on stratosphere and ground level observations*, Proc. 29^{th} ICRC, Pune 1, 213-216, 2005.
[2] J. Perez-Peraza, A. Gallegos-Cruz, E.V. Vashenyuk, and L.I. Miroshnichenko, Geomagn. Aeron., V.32, N.2, P.2, 1992.
[3] L.I. Miroshnichenko, J. Perez-Peraza, E.V. Vashenyuk, et al., High Energy Solar Physics, AIP Conf. Proc., V.374, P.140, 1996.
[4] E.V. Vashenyuk, Yu.V. Balabin, J. Perez-Peraza, et al., Adv.Space Res., V.38, N.3, P.411, 2006.
[5] E.V. Vashenyuk, Yu.V. Balabin, L.I. Miroshnichenko, et al., Proc. 30^{th} ICRC, Merida, Mexico, V.1, P.253, 2007.
[6] E.V. Vashenyuk, Yu.V. Balabin, B.B. Gvozdevsky, *Characteristics of relativistic solar cosmic rays from GLE modeling studies*, Proc. 31 ICRC, paper 1304, Lodz, 2009.
[7] Yu.V. Balabin, E.V. Vashenyuk, O.V. Mingalev, et al., Astron.Zh., V.82, N.10, P.940, 2005.
[8] J. Perez-Peraza, A. Gallegos-Cruz, L.I. Miroshnichenko, and E.V. Vashenyuk, Proc. 30^{th} ICRC, Merida, Mexico, V.1, P.117, 2007.
[9] J.A. Earl, Astrophys.J., V.205, P.900, 1976.
[10] L.I. Miroshnichenko and J. Perez-Peraza, Int.J.Modern Phys., V.23, N.1, P.1, 2008.
[11] L.I. Miroshnichenko, K.-L. Klein, G. Trottet, et al., J. Geophys. Res., V.110, N.9, A09S08; doi: 1029/2004JA010936 (13 p.), 2005.
[12] I.N. Toptygin, *Cosmic Rays in Interplanetary Magnetic Fields*, Moscow: Nauka, 1983.

[13] G.A. Bazilevskaya and R.M. Golynskaya, Geomagn. Aeron.,V.29, N.2, P.204, 1989.
[14] J.W. Bieber, J.A. Earl, G. Green, et al., J.Geophys.Res. A, V.85, N.5, P.2313, 1980.
[15] E.W. Cliver, S.W. Kahler, M.A. Shea, and D.F. Smart, Astrophys.J., V.260, P.362, 1982.
[16] D.A. Timashkov, Yu.V. Balabin, V.V. Borog, et al., Proc. 30^{th} ICRC, Merida, Mexico, V.1, P.209, 2007.
[17] J.W. Bieber, W.H. Matthaeus, C.W. Smith, et al., Astrophys.J., V.420, P.294, 1994.
[18] L.I. Miroshnichenko, *Solar Cosmic Rays*, Berlin: Kluwer, 492 p., 2001.
[19] E.G. Berezhko and S.N. Taneev, Pis'ma Astron.Zh., V.29, N.8, P.601, 2003.
[20] J. Perez-Peraza, A. Gallegos-Cruz, E.V. Vashenyuk, et al., Adv.Space Res., V.38, N.3, P.418, 2006.
[21] P.K. Manoharan and M.R. Kundu, Astrophys.J., V.592, P.597, 2003.