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PRIMARY SOLAR COSMIC RAY PARAMETERS OBTAINED FROM GROUND BASED OBSERVATIONS BY MODELING TECHNIQUE

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Abstract. Almost the only source of data on the relativistic solar cosmic rays are observations of ground based neutron monitors. A neutron monitor registers not primary particles, but secondary neutrons created by cosmic ray primaries in nuclear cascades in the atmosphere. So before detection by a neutron monitor the primary proton should undergo declination in the magnetic field of Earth and interact with its atmosphere. Therefore determination of parameters of primary solar proton flux in interplanetary space on the data of neutron monitors is a rather complicated task. Thus the network of neutron monitors distributed on a globe is considered as a unit device. And the characteristics of the primary SCR flux (energetic spectrum, anisotropy and pitch-angle distribution) are defined by optimization methods by achieving the maximal consent of the observed and modeled neutron monitor responses. As an example of such technique the analysis of the well known relativistic solar proton event of 14 July, 2000 ("The Bastille day GLE") has been considered.

1 Introduction

The Ground-Level Enhancement (GLE) of 14 July 2000 was related with a solar flare 3B/X5.7 with heliocoordinates N22 W07. The start of type II radioburst designating the beginning of energetic phenomena in the flare and being close to the moment of relativistic proton acceleration (Cliver et al., 1982) was registered at 10:20 UT. The GLE occurred during Forbush effect caused by preceded solar activity. So one should expect a loopelike IMF structure leading to the bidirectional particle flow (Richardson et al., 2000). The increase effect on the ground was detected by many neutron monitor stations of the worldwide network (Vashenyuk et al., 2001). In our analisys we used data of 21 stations. This allowed us to carry out definition of parameters of primary relativistic solar protons (RSP) outside magnetosphere by optimization methods based on modeling the ground level increases and comparing them with observations. The modeling was carried out for 6 moments of time, that has allowed to obtain the parameters of solar protons: rigidity spectra, anisotropy and pitch-angle distribution as well as their dynamics reflecting the processes of RSP generation on the Sun and propagation them to the Earth.

2 Neutron monitor observations

Fig. 1 shows increase effect on the neutron monitor in Apatity, Russia (67.5N, 33.3E) on the 10 s and 1 min data. The plot is obtained from Internet (http://pgi.kolasc.net.ru/CosmicRay) where the online Apatity NM data were available in real time during the 14 July 2000 GLE.

In profiles of increase the two-peak structure is well seen which is characteristic for two components of relativistic solar cosmic rays: prompt and delayed one (Perez-Peraza et al., 1992). The initial short maximum with a fast rise corresponds to the prompt component and following gradual maximum to the delayed one. The prompt and delayed components differs significantly by their spectral and pitch-angle characteristics (Vashenyuk et al., 2000) what has been revealed by the carried out modeling.

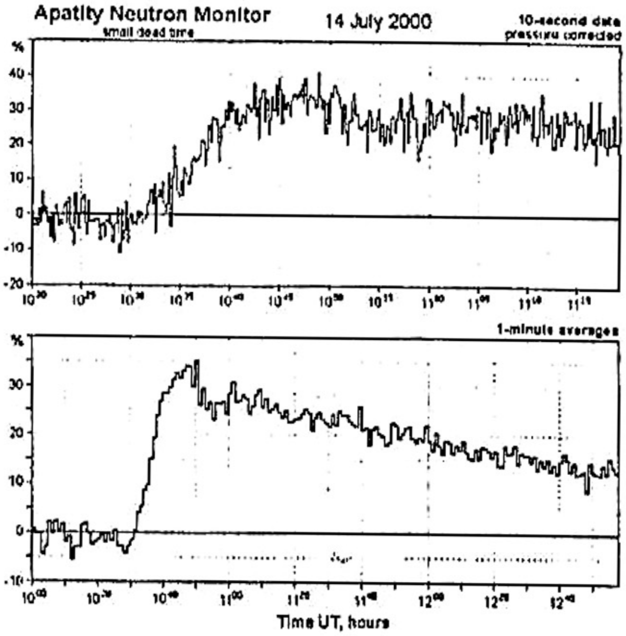

Fig.1. The GLE of 14 July 2000 as observed by the neutron monitor in Apatity, 10 s and 1 min data. The picture was obtained in real time from the Internet (http://pgi.kolasc.net.ru/CosmicRay)

3 Modeling technique

Our modeling technique of the neutron monitor response to an anisotropic solar proton flux (Pchelkin and Vashenyuk, 2001) included definition of asymptotic viewing cones of neutron monitor stations under study by the particle trajectory computations in a model magnetosphere. The magnetospheric model Tsyganeko 89 (Tsyganenko, 1989) was employed. Determination of the anisotropic solar proton flux parameters outside magnetosphere was carried out by optimization methods based on comparison of computed neutron monitor responses with observations.

We employed the following form of response function of a neutron monitor to anisotropic flux of solar protons (Pchelkin and Vashenyuk, 2001):

$$(\Delta N/N)_j = K \int_{R_{Qj}}^{\infty} J_{||}(R)\ S(R)\ F(\theta_j(R))\ dR\ +$$

$$K\ F(\theta_j(R)) \int_{R_{Cj}}^{R_{Qj}} J_{||}(R)\ S(R)\ dR \qquad (1)$$

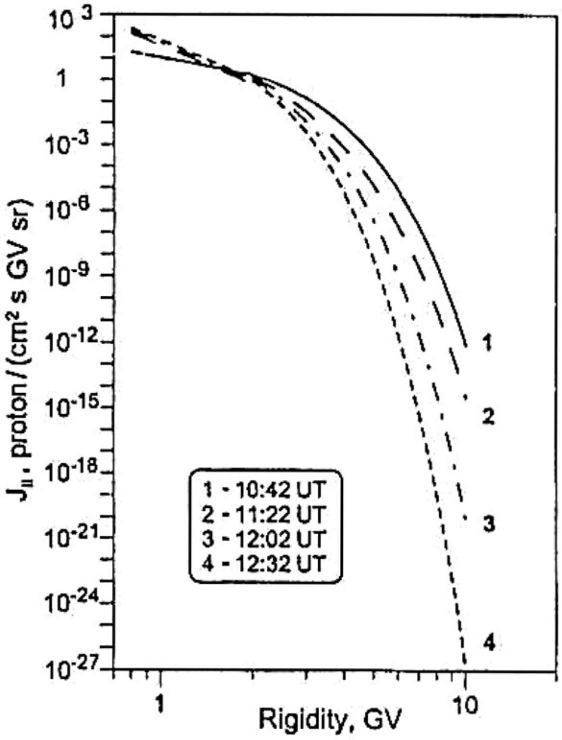

Fig.2. Derived rigidity spectra of relativistic solar protons for different phases of the 14 July 2000 GLE.

where R is a rigidity, $J_{||}(R) = J_0 R^{-\gamma}$ is a rigidity spectrum of RSP flux in the direction of anisotropy axis, γ monotonically increases in rigidity and $\Delta\gamma$ is an increase per 1 GV (Cramp et al, 1993), j is a station index, $(\Delta N/N)_j$ is relative to galactic background increase effect at j_{th} station in percents, K is coefficient of proportionality, and $F(\theta) \sim exp(-\theta^2/C)$ is a pitch-angle distribution (PAD) of primary protons in the IMF, where $\theta(R)$ is pitch-angle (defines an angle between the derived anisotropy axis and a particle approach direction at a given rigidity), R_{Cj} is effective geomagnetic cutoff for a given station, R_{Qj} is the main cone cutoff (Cook et al., 1991), $S(R)$ is specific yield function (Debrunner et al., 1984).

As can be seen the range of integration consists of two parts. The first of it includes the range of rigidities for the Stormer type trajectories, and inside of it the response function is determined by the standard methodics (Shea and Smart, 1982). The second term in (1) is a contribution to response of the penumbra rigidity range. As fine trajectory computations (step ≤ 0.001 GV) show, the asymptotic directions inside the penumbra region are randomly distributed inside a narrow latitude band around geomagnetic equator (Pchelkin and Vashenyuk, 2001). This permits to approximate the pitch-angle distribution inside the penumbra by a quantity which is close to an average of the modeled PAD. The computation of $F(\theta_j(R))$ was carried out employing the derived PAD inside the penumbra rigidity domain. The details are in (Pchelkin and Vashenyuk, 2001). Normalization of data to a standard barometrical pressure (1000 mb) was carried out by the two attenuation length method (Mc Cracken, 1962; Kaminer, 1968). With the corrected for pressure data and modeled neutron monitor responses a system of constrained equations may be arranged (Dennis and Schnabel, 1983). Whith the Legendre principle (Shcigolev, 1969) the system of constrained equations is reduced to the nonlinear least square problem:

$$SN = \sum_j \left((\Delta N/N)_{j\,\mathrm{calc}} - (\Delta N/N)_{j\,\mathrm{observ}} \right)^2 \rightarrow \min \qquad (2)$$

Inscriptions in the indexes in the relation (2) correspond to calculated and observed amplitudes of GLE. Unknown parameters of solar proton flux are six quantities: normalization constant of the spectrum J_0, direction of the anisotropy axis (a pair of coordinates, Φ and θ, in the GSE system), the exponent in the rigidity power spectrum γ and $\Delta\gamma$, and a constant of gaussian pitch-angle distribution $C=2\sigma^2$. These parameters were determined by the described above optimization procedure. A quality of the optimization results was estimated by a residual error defined by the formula:

$$\varepsilon = SN / \sum_j (\Delta N / N)^2_{j\,obser} \qquad (3)$$

4 Modeling results

Mentioned above 6 parameters of RSP for 6 moments of time were obtained as a result of optimization and are given in the Table 1.

Fig. 2 shows the rigidity RSP spectra, obtained in the consecutive moments of time during the event (Table 1). It can be seen a sharp difference between the form of a spectrum (1), obtained during the first increase peak

(Fig. 1) and spectra obtained later. The spectrum (1), as was noted above, belongs to the prompt component of RSP. Spectra of prompt component are characterized by great rigidity and may have an exponential form (Perez-Peraza et al., 1992, Vashenyuk et al., 2000, 2001b). The spectra measured later differ very little in the range of small rigidities. In the large rigidity range the regular softening in course of the event is observed.

Table 1. Modeling parameters of relativistic solar protons.

UT	$10^{40\text{-}45}$	$11^{05\text{-}10}$	$11^{25\text{-}30}$	$12^{00\text{-}05}$	$12^{30\text{-}35}$	$13^{00\text{-}05}$
J_0	10.4	53.2	82.6	64.2	50.8	36.2
γ	2.62	4.92	5.83	5.87	5.90	5.87
$\Delta\gamma$	1.31	1.63	1.32	2.00	2.82	1.62
C	3.66	13.1	14.8	18.5	19.2	24.3
θ, °	24	20	-6	8	34	30
Φ, °	-20	-23	-25	-20	-19	-20
ε, %	6.8	4.4	3.0	1.4	2.4	3.6

In Fig. 3 pitch-angle distributions of RSP are shown at the various moments of event. The sharp difference of a curve 1, obtained during the first increase maximum (Fig.1) from others, derived for later times is seen. As it is known (Vashenyuk et al., 1997) the prompt component of RSP is characterized by a large unidirectional anisotropy. Wide pitch-angle distribution for the delayed component may be related with a significant particle flow from antisun direction which was really observed in the event (Vashenyuk et al., 2001a).

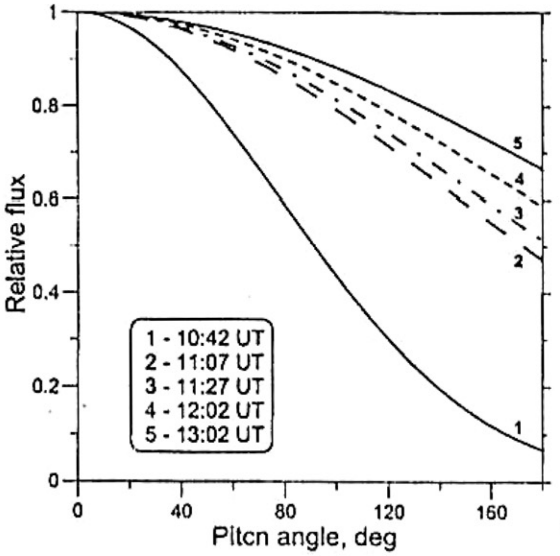

Fig.3. Pitch-angle distributions of relativistic solar protons for different moments of the 14 July 2000 GLE.

Fig. 4 shows the derived longitudinal and latitudinal GSE projections of the anisotropy direction (points) and IMF direction measured on the spacecraft ACE. The IMF data are shifted in time by 45 min (estimated travelling time of solar wind with a speed of 600 km/s from ACE to Earth). Thin lines are the 4-minute data of IMF and thick lines are the same data smoothed by running average with period of 30 min. It is seen rough correspondence of the smoothed values of latitude with modeled anisotropy values. As for the modeled longitudinal component, its behavior corresponds to an average observed value of IMF. The constant shift ~ 20° remains through the event and may be consequence of insufficient coverage of angular space by asymptotic cones.

5 Discussion

As a result of study of the GLE 14 July 2000 with methods of mathematical modeling the two populations of RSP connected, obviously, with various sources on the Sun. have been revealed. The two-peak structure of increase observed at some stations of neutron monitors (Fig. 1) can testify to existence of these two RSP components.

The characteristics of solar protons, formed these peaks, strongly differ. During the first maximum the rather rigid spectrum (Fig. 2, curve 1) and narrow pitch-angle distribution around the derived anisotropy axis (Fig.3, curve 1) is observed. The population of particles which have formed the second maximum is characterized by more steep spectrum (Fig. 2, curves 2-4), which is softened in time in the rigidity range higher 2 GV. In the range of low rigidities the practical constancy of a RSP flux within more than 1 hour is observed (Fig. 2), compare with behavior of spectrum of delayed RSP component in the GLE 29.09.1989 (Vashenyuk et al., 2001b).

The pitch-angle distribution measured for particles of second maximum (Fig. 3, curves 2-5) strikingly differs by width from that of the initial phase of event (Fig. 3, curve 1). Wide PAD for delayed population could be caused by a RSP flux from the antisun direction (Vashenyuk et al.,

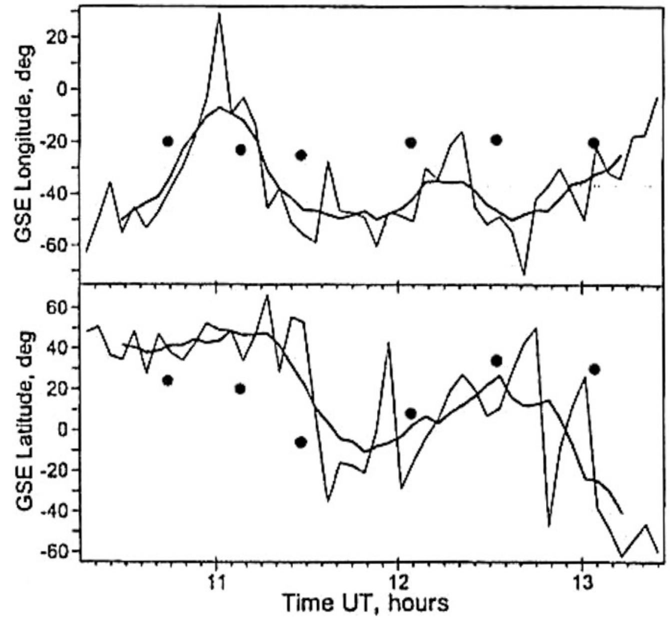

Fig.4. Derived longitudinal and latitudinal projection in GSE coordinates of the modeled anisotropy axis (points) and IMF data measured on the ACE spacecraft. Thin line is 4-min data and thick line is smoothed by running average with period of 30 min.

2001a).

The delayed component is ejected from the Sun as a rule ~20 min - 1 hr later than prompt one. It has a gradual intensity profile, rather soft energetic spectrum and a wide PAD.(Vashenyuk et al., 1997, 2001b). Its probably source could be the acceleration by a coronal shock (Ellison and Ramaty, 1985). Alternative generation mechanism for delayed component may be a stochastic acceleration by plasma turbulence in the flare volume or its vicinity (Miroshnichenko et al., 1996). Accelerated particles may be carried out in the upper corona by arising CME. Both generation mechanisms of delayed component should create a sources of RSP of large extension in the corona. Owing to Forbush effect, during which the GLE of 14 July 2000 has occurred, the configuration of IMF probably had a looplike structure (Richrdson et al., 2000). The injection of particles from an extended source (coronal shock, CME) in both ends of a loop rooted on the sun could create the observed bidirectional anisotropy (Vashenyuk et al., 1997)

6 Summary

By methods of mathematical modeling the characteristics of relativistic solar protons in the GLE 14 July 2000 have been obtained. The modeling was carried out for 6 moments of time that allowed us to study a dynamics of solar proton flux during the event. Two-peak structure was registered by some neutron monitor stations during the GLE which, as shown in the paper, was formed by two different populations of relativistic solar protons. The population forming the first maximum had a small duration, rather rigid spectrum and strong anisotropy directed from the Sun. The population of particles forming the gradual second maximum, had a softer spectrum and wide pitch-angle distribution, which could be attributed by a bidirectional anisotropy. Thus, during the 14 July 2000 GLE the increase effect on the ground was caused by imposing of two components of relativistic solar protons, prompt and delayed one originated probably from various sources on the Sun.

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