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Relativistic solar proton dynamics during the 14 July, 2000 GLE. Modeling results

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Abstract. The primary relativistic solar proton parameters during the 14 July 2000 “Bastille day” GLE have been obtained by a modeling of the ground level enhancement (GLE) effect on the neutron monitor network and comparing it with observed values. The modeling comprised an optimization procedure as well as proton trajectory calculations in the Tsyganenko-89 geomagnetic field model. The spectrum, pitch-angle distribution and anisotropy of relativistic solar protons (RSP) obtained for 6 successive moments of time showed a certain dynamical changes of these parameters during the event. It was shown that during the 14 July 2000 GLE the increase effect on the ground was caused by imposing of two components of relativistic solar protons, fast and delayed one originated probably from various sources on the Sun.

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 was detected by many neutron monitor stations of the worldwide network (Belov at 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 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.

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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 where the online Apatity NM data were available in real time during the 14 July 2000 GLE.

In profiles of increase the two-maximum structure is well visible which is characteristic for two components of relativistic solar cosmic rays (Vashenyuk and Miroshnichenko, 1998). 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 and Miroshnichenko, 1998) what has revealed by the

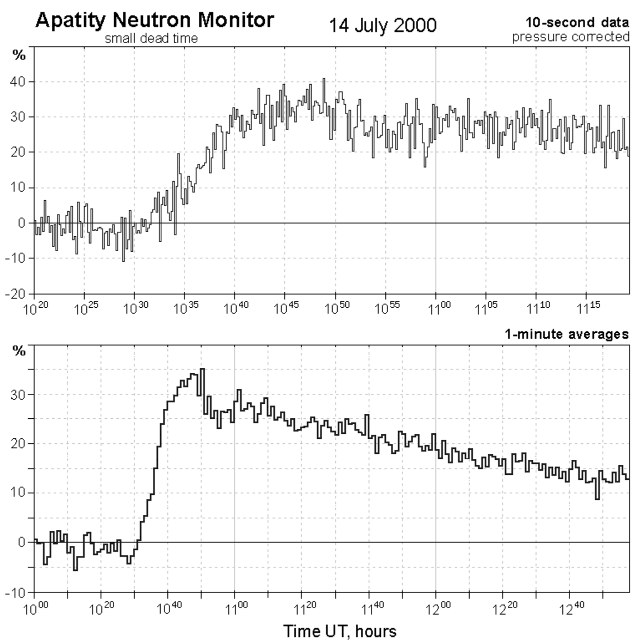

Fig.1. The GLE of 14 July 2000 as observed by the neutron monitor in Apatity, 10 s and 1 min data. The picture was obtained in real time from Internet.

carried out modeling. The detailed description of the event is done in a number of papers in this ussue, in particular, in (Belov et al., 2001).

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. The modeling itself included also calculation of the responses of NM stations. Determination of the anisotropic solar proton flux parameters outside magnetosphere was carried out by optimization methods based on comparison of computed 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):

$$(\Delta N/N)_j \approx K \int_{R_{Q\,j}}^{\infty} J_{//}(R)\ S(R)\ F(\theta_j(R))\ dR \ +$$

$$K\ \overline{F(\theta_j(R))} \int_{R_{C\,j}}^{R_{Q\,j}} J_{//}(R)\ S(R)\ dR \qquad (1)$$

where R is a rigidity, $J_{//}(R) = J_O R^{-\gamma}$ is a rigidity spectrum of RSP flux in the direction of anisotropy axis, j is a station index, $(\Delta N / N)_j$ is relative to galactic background increase effect at j_{th} station in percents, K is a 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 a pitch-angle (defines an angle between the anisotropy axis and a particle approach direction at a given rigidity), R_C is effective geomagnetic cutoff for a given station, R_Q is the main cone rigidity, $S(R)$ 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 $\leq$ 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 avarage of really observed PAD. The computation of $\overline{F(\theta_j(R))}$ was carried out employing the calculated PAD inside the penumbra rigidity domain. The details are in (Pchelkin and Vashenyuk, 2001).

The normalization of data to a standard barometrical pressure (1000 mb) was carried out by the two attenuation length metod (Mc Cracken, 1962; Kaminer, 1968). After the barometrical correction is done the system of constrained equations may be obtained (Dennis and Schnabel, 1988). Whith the Legendre principle (Shcigolev, 1969) the system of constrained equations is reduced to the nonlinear least square problem:

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

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 are determined by the described above optimization procedure.

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. A quality of the optimization results was estimated by a residual error defined by the formula:

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

Table 1. Modeling parameters of relativistic solar protons

UT	10^{40-45}	11^{05-10}	11^{25-30}	12^{00-05}	12^{30-35}	13^{00-05}
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

Fig. 2 shows the rigidity RSP spectra, obtained in the consecutive moments of time during the event. It can be seen a sharp difference between the form of a spectrum (1), obtained during the first increase maximun (Fig. 1) and spectra received later. The spectrum (1), as it was noted above, belongs to the prompt component of RSP. The spectra of prompt component are characterized by great rigidity and may have an exponential form (Vashenyuk et al., 2000). The spectra measured later a little differ on intensity in the range of small rigidities. In the large rigidity range the regular softening in course of the event is observed.

On Fig. 3 pitch-angle distributions of RSP are shown at the various moments of event. The sharp difference of a curve obtained during the first increase maximum (Fig.1) from others, obtained later is again observed. As is known (Vashenyuk and Miroshnichenko, 1998) the prompt component of RSP is characterised by a large unidirectional (from the Sun) anisotropy. Wide pitch-angle distribution for

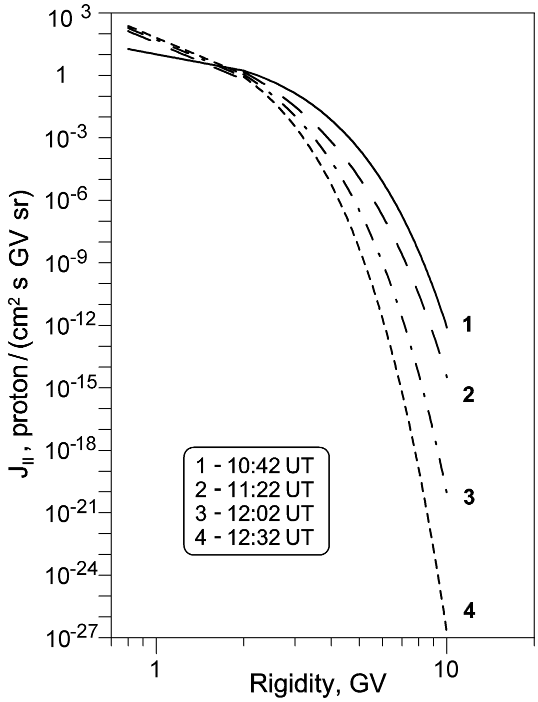

Fig.2. Derived rigidity spectra of relativistic solar protons for different phases of the 14 July 2000 GLE.

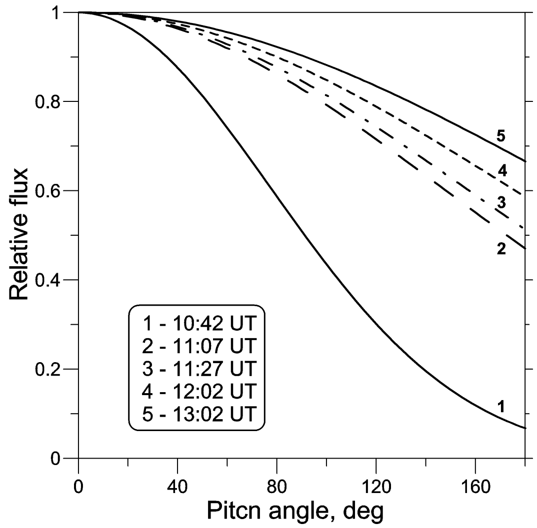

Fig.3. Pitch-angle distributions of relativistic solar protons for different moments of the 14 July 2000 GLE.

the delayed component can be connected with a significant flow from antisun direction.

Fig. 4 shows the computed 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 behaviour corresponds to an average observed value. The constant shift ~ 20^{o} is retained though through the event.

5 Summary

By methods of mathematical modeling the characteristics of relativistic solar protons in the GLE 14 July 2000 have been investigated. The modeling was carried out for 6 moments of time, that has allowed to study a dynamics of solar proton parameters during the event. Some neutron monitor stations during GLE registered two maxima which as shown in the paper were formed by two different populations of relativistic solar protons. The population which have formed the first maximum had a small duration, rather rigid spectrum and strong anisotropy directed from the Sun. The population of particles which have formed the more gradual second maximum, had a softer spectrum and wide pitch-angle distribution, which could be connected with 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, fast and delayed one originated probably from various sources on the Sun.

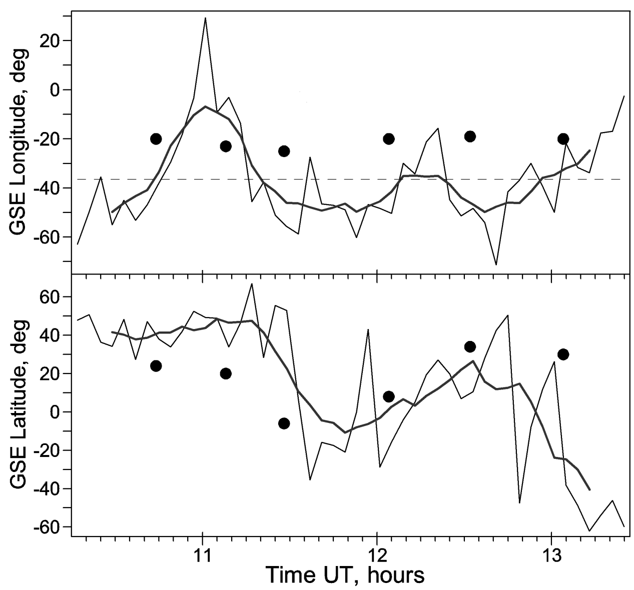

Fig.4. Derived longitudinal and latitudinal projection in GSE coordinates of the modeled anisotropy axis (points) and IMF data measured on the ACE spacecraft. Thin line is 4-min data and thick line is smoothed by running average with period of 30 min.

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