ISSN 0016-7932, Geomagnetism and Aeronomy, 2008, Vol. 48, No. 2, pp. 149–153. © Pleiades Publishing, Ltd., 2008.
Original Russian Text © E.V. Vashenyuk, Yu.V. Balabin, B.B. Gvozdevsky, L.I. Shchur, 2008, published in Geomagnetizm i Aeronomiya, 2008, Vol. 48, No. 2, pp. 157–161.

Characteristics of Relativistic Solar Cosmic Rays during the Event of December 13, 2006

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Received January 31, 2007; in final form, August 28, 2007

Abstract—The characteristics of relativistic solar protons have been obtained using the methods of optimization based on the data of ground detectors of cosmic rays during the event of December 13, 2006, which occurred under the conditions of solar activity minimum. The dynamics of relativistic solar protons during the event has been studied. It has been indicated that two populations (components) of particles exist: prompt and delayed (slow). The prompt component with a hard energy spectrum and strong anisotropy manifested itself as a pulse-shaped enhancement at Apatity and Oulu stations, which received particles with small pitch-angles. The delayed component had a wider pitch-angle distribution, as a result of which an enhancement was moderate at Barentsburg station and at most neutron monitors of the worldwide network. The energy spectra obtained from the ground-based observations are in good agreement with the direct measurements of solar protons on balloons and spacecraft.

PACS numbers: 94.20.Wq

DOI: 10.1134/S0016793208020035

1. INTRODUCTION

The solar cosmic ray (SCR) event of December 13, 2006, (GLE no. 70) occurred at the ground level during the decline phase of solar cycle 23. This event was related to an X3.4/2B flare with S06 W24 heliocoordinates. A flare was accompanied by radio bursts of types II and IV and by a halo coronal mass ejection (CME) (www.izmiran.rssi.ru/space/solar/forecast). Radio emission of type II (the probable instant of generation of relativistic SCRs [Cliver et al., 1982]) began at 0226 UT.

This event occurred when the conditions on the Sun and in the interplanetary medium corresponded to a solar cycle minimum. An abrupt intensification in the active region (AR) 10930 occurred against a background of an almost complete absence of sunspots. Nevertheless, the event of January 13, 2006, is among large events and was registered by more than 30 neutron monitors of the worldwide network. The present work analyzes the dynamics of relativistic solar protons (RSPs), the characteristics of which were obtained using the optimization methods based on the data from the worldwide network of neutron monitors.

The determination of the primary RSP parameters includes several stages. (1) The determination of asymptotic cones of acceptance for the studied neutron monitors by calculating the trajectories of particles with different rigidity in the [Tsyganenko, 2002] magnetospheric model. The calculations are performed from 1 to 20 GV at a rigidity interval of 0.001 GV. In contrast to the previous works (e.g. [Vashenyuk et al., 2006], where only the trajectories of particles launched vertically upward were calculated, nine particle trajectories for each value of rigidity were calculated in the present study. One of these trajectories was directed vertically upward, and remaining particles were launched at a zenith angle of 20° from eight equidistant radial directions. Thus, we determine the asymptotic cone of particles that fall on a neutron monitor not only from the vertical but also from the oblique directions. (2) The calculation of neutron monitor responses to an anisotropic flux of solar protons with specified parameters. (3) The determination of the parameters of relativistic proton fluxes outside the Earth's magnetosphere with the help of the least-squares technique (optimization) by comparing the calculated neutron monitor responses with observations.

The expression for the function of the neutron monitor response to an anisotropic flux of solar protons has the following form with regard to the contribution of obliquely incident particles:

$$\frac{\Delta N_j}{N_g} = \frac{1}{8} \times \sum_{(\theta,\varphi)=1}^{8} \frac{\sum_{R=1}^{R\max} A(R)J(R)S(R)F(\theta(R))dR}{N_g}, \quad (1)$$

where $(\Delta N_j/N_g)$ is the percentage excess of the count rate (N_j) at a neutron monitor station j over the galactic

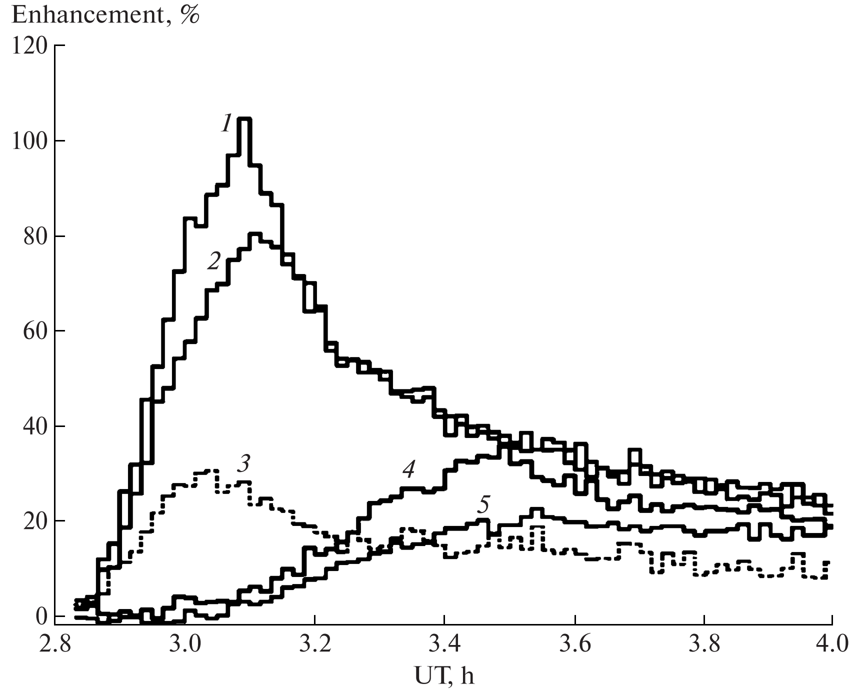

Fig. 1. Profiles of enhancements on December 13, 2006, at Oulu (*1*), Apatity (*2*), Moscow (*3*), Barentsburg (*4*), and Fort Smith (*5*) neutron monitor stations.

background (N_g); $J_{||}(R) = J_0 R^{-\gamma*}$ is the differential spectrum with respect to rigidity from the direction of a source with variable inclination; $\gamma^* = \gamma + \Delta\gamma \times (R - 1)$, where γ is the power spectrum exponent at $R = 1$ GV, $\Delta\gamma$ is the rate of 1-GV γ increment, and J_0 is the normalization constant. Other parameters in (1) are as follows: $S(R)$ is the specific yield function; $\theta(R)$ is the pitch-angle at a given rigidity (more exactly, the angle between the asymptotic direction for a given rigidity and the calculated axis of anisotropy, specified by coordinates Φ and Λ, in the solar–ecliptic coordinate system, GSE); $A(R) = 1$ and 0 for allowed and forbidden trajectories, respectively; and $F(\theta(R)) \sim \exp(-\theta^2/C)$ is the pitch-angle RSP distribution close to the Gaussian function with the characteristic parameter C. Thus, six parameters of the anisotropic flux of solar protons outside the Earth's magnetosphere (Φ, Λ, J_0, γ, $\Delta\gamma$, and C) should be determined, using the optimization methods, by comparing the calculated responses of ground detectors with the observations.

The observed pitch-angle distribution not always can be described by the function close to Gaussian. One also not always manages to describe this distribution by the combination of two such fluxes from opposite directions, which is observed in the cases of the so-called bidirectional anisotropy. In the present work, we used the expression for the pitch-angle distribution, which makes it possible to reach good convergence of the optimization process,

$$F(\theta(R)) \sim \exp(-\theta^2/C)(1 - a\exp(-(\theta - \pi/2)^2)/b). \quad (2)$$

Such a function has a singularity at pitch angles close to $\pi/2$ and, in principle, can take into account singularities in pitch-angle distributions predicted by a theory of particle propagation in IMF (see, e.g. [Toptygin, 1983; Bazilevskaya and Golynskaya, 1989]). According to its properties, expression (2) is close to the function used by Cramp et al. [1997] to describe complex cases of pitch-angle distribution. When function (2) is used, two more parameters (a and b) are added to six RSP flux parameters listed above. Expression (2) changes into a usual Gaussian function at zero values of these parameters.

2. OBSERVATIONS

The event of December 13, 2006, was characterized by a high anisotropy during the initial phase. Figure 1 shows the series of characteristic enhancement profiles at neutron monitors. An early beginning, comparatively rapid growth, and maximal enhancement amplitude were registered at Oulu (104%) and Apatity (81%) stations in 1-min data. A rapid growth to the maximum was also registered with the Moscow neutron monitor (Fig. 1) and at several other European midlatitude stations. The neutron monitor in Barentsburg (Spitsbergen) registered an enhancement 5 min later than at Apatity station, and this enhancement was prolonged and reached only 36% at a maximum. At most other stations of the worldwide network, an enhancement had even smaller amplitude. Thus, an enhancement was ~20% even at Thule station (Greenland), which is the adjacent station to Barentsburg.

RSP flux parameters

UT	γ	$\Delta\gamma$	C	Φ, deg	Λ, deg	a	b	J, $(m^2\ s\ sr\ GV)^{-1}$
0256	3.85	0.18	0.48	–13	–43	0	0	1.3E+05
0257	3.92	0.11	0.68	–13	–47	0	0	1.3E+05
0258	4.27	0.12	0.43	–9	–43	0	0	2.0E+05
0259	4.91	0.06	0.42	–8	–42	0	0	3.51E+05
0300	4.73	0.14	0.38	–10	–36	0	0	4.8E+05
0305	3.59	0.35	0.29	0	–44	0.47	0.35	2.1E+05
0320	4.16	0.36	6.47	8	–52	0.79	4.09	8.1E+05
0335	6.06	0.06	12.66	12	–59	0.64	6.01	1.8E+06
0345	6.68	0.00	13.65	0	–43	0.44	2.96	1.6E+06
0400	6.91	0.00	18.42	1	–47	0.62	9.63	2.5E+06

McMurdo and SANAE south polar stations registered approximately the same amplitude of the effect.

3. RESULTS OF MODEL STUDY

Results of analyzing the neutron monitor data using the optimization methods (solution of the inverse problem) are presented in table. An analysis of the data from the network of ground-based cosmic ray detectors indicated (see below) that, during the initial phase of the event, the flux of relativistic protons approached the Earth as a collimated beam from the direction close to the mean IMF direction at 0200–0300 UT. Figure 2 shows the map of the coelosphere in solar–ecliptic coordinates with asymptotic cones of several neutron monitor stations. The presented cones were calculated for vertically incident particles in the 1–20 GV range of rigidity. In Fig. 2 the station names are presented near the hard (20 GV) edge of the asymptotic cone. Rigidity values of 1 and 20 GV are presented for the Barentsburg asymptotic cone as an illustration. The lines of equal pitch angles are also shown on the map relative to the calculated direction of the anisotropy axis at 0300 UT. It is evident that this direction corresponds to the mean direction of the Parker spiral (43° westward of the Sun–Earth line) and almost coincides with the IMF direction (the ACE spacecraft data are marked by a cross) at that time.

Figure 2 indicates that, during the initial phase of the event, enhancements were registered only at the

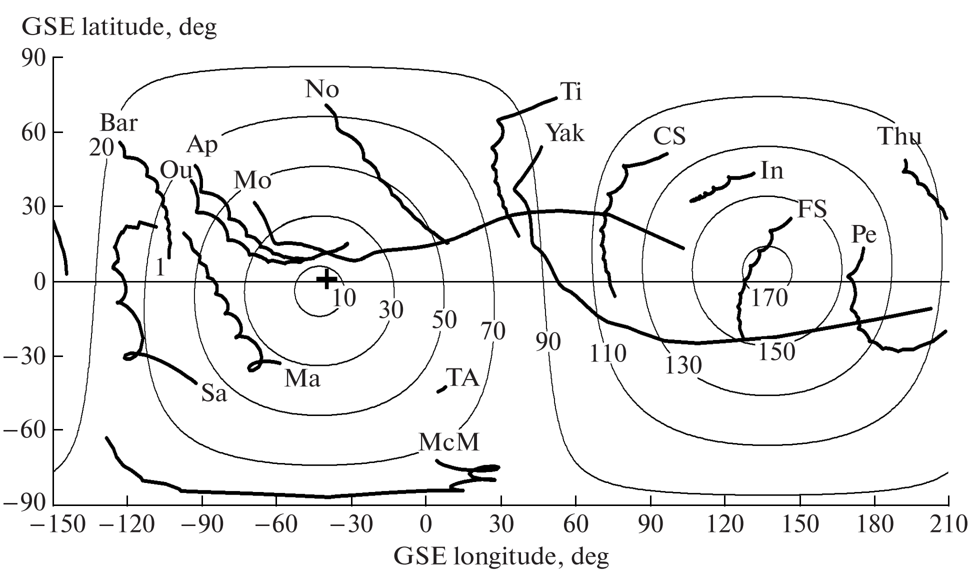

Fig. 2. Asymptotic communication cones for vertically incident particles in solar–ecliptic coordinates for Barentsburg (Bar), SANAE (Sa), Mawson (Ma), McMurdo (McM), Oulu (Ou), Apatity (Ap), Moscow (Mo), Norilsk (No), Terre Adeli (TA), Tixie Bay (Ti), Yakutsk (Yak), Cape Schmidt (CS), Inuvik (In), Fort Smith (FS), Peawanuck (Pe), and Thule (Thu) neutron monitor stations. Lines of equal pitch angles are indicated relative to the calculated anisotropy axis. The IMF direction at 0300 UT is shown by a cross (ACE data).

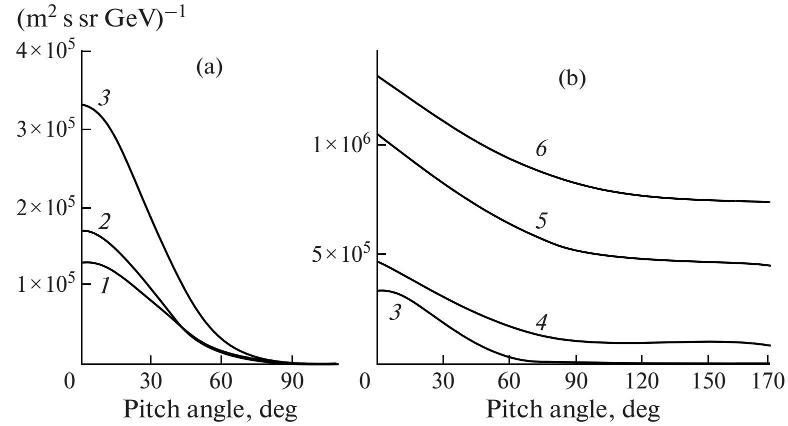

Fig. 3. The dynamics of the pitch-angle distributions of solar protons for (a) fast and (b) delayed components. Numerals correspond to the following UT instants: 0257 (*1*), 0300 (*2*), 0305 (*3*), 0320 (*4*), 0330 (*5*), and 0400 (*6*).

stations with asymptotic cones oriented within 50° relative to the calculated axis of anisotropy, namely: Apatity, Oulu, Moscow, and several midlatitude European stations. An asymptotic cone of Fort Smith station is turned from the Sun (Fig. 2), and the enhancement profile at this station characterizes the behavior of the inverse (sunward) RSP flux. At Fort Smith an enhancement began at 0305 UT and lags behind the direct flux by 15 min (Apatity, 0250 UT). The intensity increased very slowly at this station. At Barentsburg station, which registered direct flux particles with large pitch angles (>60°), an enhancement began slightly earlier (at 0258 UT); however, intensification was also prolonged. The dynamics of the direct and inverse (toward the Sun) RSP fluxes make it possible to trace the RSP pitch-angle distributions at successive instants, obtained as a result of optimization (table, Fig. 3). The curves with numerals from *1* to *3* characterize a narrowly directed particle flux from the Sun

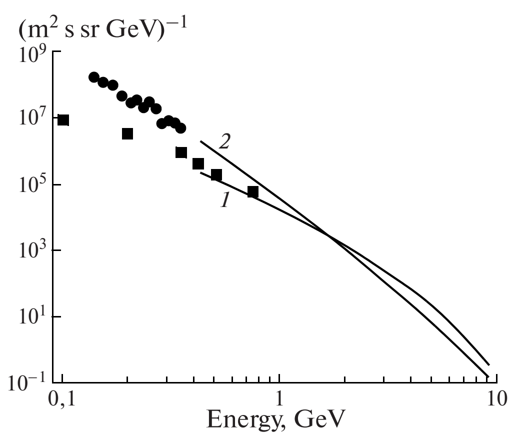

Fig. 4. Energy spectra of RSPs for 0305 (*1*) and 0400 (*2*) UT. The data of direct measurements of solar protons on balloons (filled circles) and GOES-11 spacecraft (squares) are demonstrated.

with the pitch-angle distribution close to Gaussian, which was registered from 0258 to 0305 UT. Beginning from 0310 UT, the antisunward particle flux became pronounced. Profile *4* corresponds to 0320 UT. The intensities of solar protons from the direct and inverse fluxes continued simultaneously increasing until 0400 UT, although a decrease is observed on the enhancement profiles of neutron monitors (Fig. 1). The intensity of 1-GV protons, which corresponds to the lower limit of neutron monitor sensitivity, is plotted on the vertical axis of Fig. 3. Harder particles mainly contribute to the neutron monitor count. Intensification of solar protons with energies of about 700 MeV until 0400 UT is confirmed by the direct measurements of the solar proton flux on GOES-11 spacecraft (http://sec.noaa.gov/ftpmenu/lists/pchan.html).

Figure 4 demonstrates the dynamics of the solar proton energy spectra obtained using the optimization methods. Numeral *1* marks the direct flux spectrum at the instant close to the spectral maximum (0305 UT). Numeral *2* denotes the spectrum obtained at 0400 UT during the phase of decreasing enhancement. The spectra obtained at intermediate instants between 0305 and 0400 UT are between spectra *1* and *2*. Figure 4 also presents the data of direct measurements of solar protons on GOES-11 spacecraft and balloons at Apatity station (FIAN–PGI joint experiment [Bazilevskaya and Svirzhevskaya, 1998]) in the adjacent energy interval (430–100 MeV). We should note that the data obtained as a result of the ground measurements of RSP spectra are in good agreement with the direct measurements of solar protons. The spectrum differs from a power spectrum at the beginning of the event but becomes purely power spectrum at the end of the event. In spite of an intensification of the inverse flux after 0330 UT (Fig. 3), a general decrease in the enhancement value at neutron monitor stations is also related to the fact that this intensification occurred due to the region of energies below 3 GeV, where the neutron monitor response function has a maximum.

4. DISCUSSION AND CONCLUSIONS

The structure of the RSP flux during the event of December 13, 2006, obtained using the optimization methods, included two populations (components) of particles: fast and delayed [Vashenyuk and Miroshnichenko, 1998]. The prompt component with a hard energy spectrum and strong anisotropy manifested itself as a pulse-shaped enhancement at Apatity and Oulu, several European midlatitude stations (Moscow, Lomnicki Peak, Jungfrauioh), and Mawson and Kerguelen south polar stations. The pitch-angle distribution of the prompt component is described by the Gaussian function with a characteristic width of $\sigma = 27°$. The spectrum of the prompt component was close to the power spectrum with an exponent of 4–5.

The delayed component was first registered from the antisunward direction (Fort Smith, Fig. 1) at 0305 UT, This component had a large isotropic constituent (Fig. 3b). The spectrum of the delayed component was steeper ($\gamma = 6–7$).

A considerable difference between the characteristics of the fast and slow components (fluxes *1* and *2*) could hardly result only from the effects of interplanetary propagation. This difference most probably indicates that the fast and slow RSP components had different sources on the Sun. The nature of the inverse flux could be related to the possible loop-shaped IMF structure. In this case the direct and inverse fluxes had to be initiated by the sources located at the base of the large-scale loop structure on the Sun, as was observed, e.g., during the event of October 28, 2003 [Miroshnichenko et al., 2005]. The existence of two components with different properties during the events with relativistic SCRs agrees with the general regularity obtained when 11 SCR events at the ground level were analyzed [Vashenyuk et al., 2006]. The possible scenario of generation of two relativistic SCR components was proposed based on the results of studying the development of CME in the solar corona magnetic structures [Manoharan and Kundu, 2003]. The fast RSP component is generated during the initial energy release at zero point of the magnetic field related to magnetic reconnection. Prompt component particles accelerated during magnetic reconnection leave the solar corona, moving along open field lines escaping from the vicinity of zero point. Since the structure of open field lines has a divergent configuration, a bunch of prompt component particles becomes strongly focused. Particles of the delayed component, initially captured in low-coronal magnetic arcs, are accelerated by the stochastic mechanism, interacting with MHD turbulence of the flare plasma. Accelerated particles of the slow component are subsequently carried into the outer corona within expanding CME. These particles leave a trap during its disintegration as a result of instabilities and form a particle source extensive in time and along heliolongitude.

ACKNOWLEDGMENTS

We are grateful to all researchers at the neutron monitor stations, who rapidly presented the data on the event of December 13, 2006.

This work was supported by the Russian Foundation for Basic Research (project nos. 05-02-17143 and 07-02-01405) and by the Presidium of the Russian Academy of Sciences (program 6 “Neutrino Physics”).

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