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The GLE of December 13, 2006 according to the ground level and balloon observations

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Abstract: The analysis of the GLE on 13.12.2006 using the data of neutron monitors, balloons and modeling computations has been carried out. The event was connected to the flare: X3.4/2B, S06W24, and appeared rather unexpected, as it occurred during the ongoing phase of solar minimum. The characteristics of relativistic solar protons (RSP) were derived by modeling technique from the neutron monitor network data. The direct solar proton data obtained by balloons in Apatity and Mirny (Antarctica) allowed to extend the energetic spectra derived from ground based measurements from relativistic to moderate energies (hundreds MeV). Dynamics of solar proton spectra and pitch-angular distributions during the event is investigated. A good agreement of spectra obtained by modeling using data of the ground based observations with results of direct solar proton measurements on balloons and spacecrafts is shown.

1. Introduction

The ground level enhancement (GLE) on 13 December 2006 was related to the parent flare X3.4/2B with heliocoordinates S06 W24. The flare was accompanied by the halo type CME and radio emission of the II and IV types. The type II onset was reported at 02.26 UT. Peculiarity of the event was that it has occurred in conditions on the Sun and in interplanetary medium appropriate to a minimum of a solar cycle. The sudden growth of activity in the region AR10930 proceeded against the background of almost absence of solar spots. Nevertheless, the event 13.12.2006 refers to large ones. It was registered by more than 30 neutron monitors (NM) of the worldwide network. The paper studies dynamics of relativistic solar protons (RSP) which characteristic were derived by modeling technique from the worldwide NM network, as well as by direct solar proton measurements on balloons and spacecrafts. Our recent modeling technique [1], in general, is similar to that of [2,3]. This kind of analysis requires the data of no less than 20-25 ground-based cosmic ray stations, and consists of a few steps:

1. Definition of asymptotic viewing cones (taking into account not only vertical but also oblique arrival of incident on detector particles) of the NM stations under study. The particle trajectories are calculated using the magnetosphere model of Tsyganenko, 2001 [4].
2. Calculation of the NM responses at various primary solar proton flux parameters.
3. Application of a least square procedure for determining primary solar proton parameters (namely, energy spectrum, anisotropy axis direction, and pitch-angle distribution) outside the magnetosphere by comparison of computed ground based detector responses with observations. A modified power rigidity spectrum was taken with variable slope $J_\parallel(R) = J_0 R^{-\gamma^*}$, $\gamma^* = \gamma + \Delta\gamma \cdot (R-1)$ where J_0 is a normalization constant, γ is a power-law spectral exponent at $R = 1$ GV, $\Delta\gamma$ is a rate of γ increase per 1 GV. The other parameters are the coordinates Φ and Λ, defining anisotropy axis direction in the GSE system; and a parameter C, characterizing the pitch-angle distribution (PAD) in form of a Gaussian: $F(\theta(R)) \sim exp(-\theta^2/C)$. The derived from modeling parameters: $J_0, \gamma, \Delta\gamma, C, \Lambda, \Phi$ are considered in section 3.

2. Observations

The GLE 13.12.2006 in its initial phase showed a large anisotropy. In Fig. 1 characteristic intensity-time
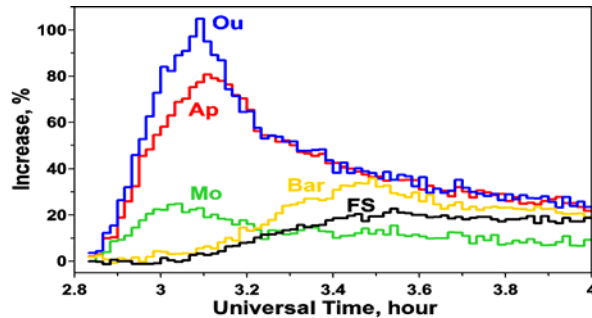

Fig. 1. Intensity-time profiles during the GLE 13.12.2006 at the neutron monitor stations: Ou-Oulu, Ap-Apatity, Mo-Moscow, Bar- Barentsburg, FS- Fort Smith.

profiles at selected NM stations are shown. The early onset, fast rise and maximal amplitude of increase were registered by the stations Oulu (104 %) and Apatity (81 %) according to 1-min data. The fast rise to a maximum has also registered the Moscow NM (Fig. 1), and other European mid-latitude stations [5]. At the NM in Barentsburg (Spitsbergen) the increase started 5 minutes later, than in Apatity. It had the slow growth and only 36 % maximal increase. In the majority of other stations of the worldwide network the increase was even smaller. So, the next to Barentsburg station Tule (Greenland) showed the increase of ~ 21 %. Nearly the same effect registered Southern polar stations McMurdo and SANAE.

3. Results of modeling analysis

The results of the modeling are presented in Table 1. As the NM data show (see below) during the initial phase of the event, the RSP flux arrived at the Earth as a collimated bunch from a direction close to an average IMF. In Fig. 2 the map of celestial sphere in solar-ecliptic (GSE) coordinates with asymptotic cones (for vertically incident particles) for a number of NM stations is shown. The cones are calculated in a range of rigidities from 1 to 20 GV. In Fig. 2 the name of stations is put at the 20 GV edge of an asymptotic cone. As illustration, the asymptotic directions of the 1 GV and 20 GV particles are indicated for the Barentsburg station. Lines of equal pitch angles relative to the calculated direction of the anisotropy axis at 3.00 UT are also shown here. It is seen, that the anisotropy axis

corresponds to an average direction of a Parker spiral (43° to the West of the Sun-Earth line) and almost coincides with the IMF direction (ACE spacecraft
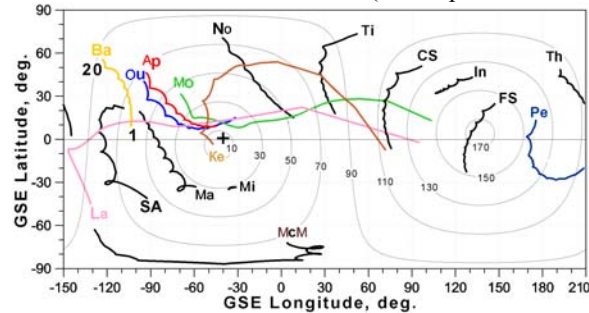
Fig. 2. The derived anisotropy axis and pitch angle grid lines for solar proton flux at 03.00 UT. IMF direction (ACE data) is indicated by cross. The asymptotic cones (1-20 GV), the title is placed at the 20 GV end, are shown for the following NM stations: Th-Thule, Bar-Barentsburg, McM-McMurdo, Sa-SANAE, Ma-Mawson, Ou-Oulu, Ap-Apatity, Mo-Moscow, Mi-Mirny, No-Norilsk, Ti-Tixie, CS-Cape Shmidt, In-Inuvik, FS-Fort Smith, Pe-Pewanuk, Th-Thule.

data). At the same time, an early increase was registered by only the stations with asymptotic cones within a limit of 50° relative to the calculated anisotropy axis. These are: Apatity, Oulu, Moscow, and some mid-latitude European stations where increase began at 02.50-02.52 UT. An asymptotic cone of the Fort Smith station was looking to the antisun direction (Fig. 2). Thus, the intensity-time profile at Fort Smith characterizes behavior of backward (to the Sun) flux of RSP. The increase at Fort Smith started at 3.05 UT, which is 15 minutes later than the onset of direct RSP flux (Apatity, 02.51 UT). The increase rate of backward flux was very slow. At Barentsburg station, which registered particles of the direct flux with large pitch angles (> 60°), the increase began slightly earlier, at 02.58 UT. However, the intensity rise was also very slow. Dynamics of the direct (from the Sun) and the backward (to the Sun) fluxes of RSPs can be traced by the evolution of pitch-angular distributions (PAD) of RSP derived at consecutive moments of time (Table 1, Fig. 3).

The PADs with numbers from 1 up to 3 (Fig.3) characterize a collimated bunch of particles from the Sun a PAD curve being close to a Gaussian. This collimated flux was registered from 02.56 to 3.05 UT. Since 3.10 UT an appreciable backward (to the Sun) flux of particles has appeared.

The profile 4 corresponds to the moment of time 03.20 UT. According to Fig. 3, the simultaneous intensity

**Table 1.** Modeled parameters of relativistic solar protons

№	UT	$|\gamma|$	$\Delta\gamma$	C rad^2	Λ deg	Φ deg	J_0
1	02:57	3.92	0.11	0.68	-13	-47	$1.3 \cdot 10^5$
2	03:00	4.25	0.11	0.44	-6	-45	$1.7 \cdot 10^5$
3	03:05	4.38	0.14	0.46	0	-43	$3.2 \cdot 10^5$
4	03:20	4.16	0.36	6.47	8	-52	$8.1 \cdot 10^5$
5	03:30	6.06	0.06	12.6	12	-59	$1.8 \cdot 10^6$
6	04:00	6.91	0.00	18.4	1	-47	$2.5 \cdot 10^6$
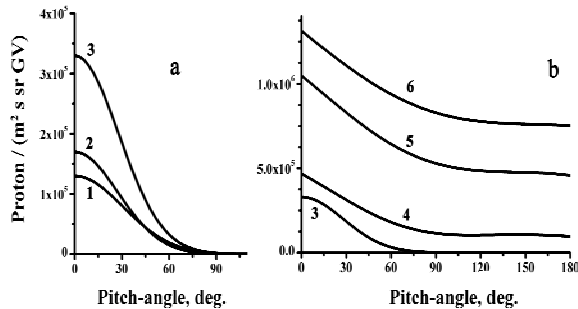
Fig.3. Dynamics of derived pitch-angle distributions. Numbers denote moments of time: 1- 02.57, 2-3.00, 3-3.05, 4-03.20, 5-03.30, 6-4.00 UT.

rise of derived flux of solar protons from both the Sun and the opposite directions continued up to 4.00 UT (profile 6), though the intensity-time profiles of NMs showed a decline (Fig. 1). The cause of discrepancy is that the PAD profiles in Fig. 3 are constructed for protons with rigidity 1 GV (430 MeV) that corresponds to the lower limit of a NM response. The main contribution to the NM response is given by solar cosmic rays in the rigidity range 2-10 GV. The growth in intensity of solar protons with energy up to 700 MeV up to 4 UT proves to be true by direct solar proton data on the GOES-11 spacecraft.

Fig.4 shows the energetic spectra dynamics from 3.05 to 4.00 UT. The spectrum derived at 3.05 UT belongs to the direct RSP flux and its form differs from a power law. On the contrary, the spectrum derived at 4.00 UT, during the event decline phase has a pure power law form. In Fig. 4 the data on direct solar protons in adjacent energy interval from 700 to 100 MeV obtained by GOES-11 spacecraft and by balloons (joint experiment LPI-PGI [6]) are given also. It is seen a good agreement between the spectra, derived from the ground based observations, and those of the directly measured solar proton fluxes. The balloon data shown in Fig.4 were obtained at about 10 UT. Differential intensities of protons in different energy

channels of the GOES 11 were taken at the times of a maximum in a given energy channel (TOM spectrum). This can explain their good consent with a spectrum of the maximal fluxes for moderate solar proton energies.
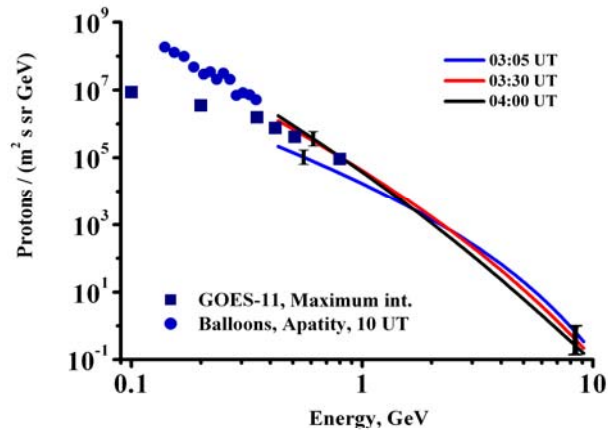
Fig.4. The derived energetic spectra of RSP at different moments of time. Direct solar proton data are shown by blacked circles (balloons) and filled squares (GOES-11).

4. References

[1] Vashenyuk E.V., Balabin Yu.V., Miroshnichenko L.I., J.Perez-Peraza, A. Gallegos-Cruz. Relativistic SCR events 1956-2006 from GLE modeling studies. This issue, paper ID 658

[2] M.A. Shea and D.F. Smart. Space Sci. Rev., 32. 251, (1982).

[3] J.L. Cramp et al., J. Geophys. Res. 102, 4919 (1997).

[4] Tsyganenko N.A. J. Geophys. Res., 107. No.A8, 1176, 2002. doi: 10.101029/2001JA000219, (2002).

[5] R. Buetikofer and E.O.Flueckiger. Neutron monitor data for Jungfraujoch and Bern during the Ground-Level solar cosmic ray event on 13 December 2006. preprint of Physicalisches Institut, University of Bern (2006).

[6] G.A.Bazilevskaya, A.K.Svirzhevskaya. Space Sci. Rev., 85, 431, (1998).