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SIMULATION OF THE TRANSPORT OF SOLAR PROTONS THROUGH THE ATMOSPHERE IN THE 13 DECEMBER 2006 GLE

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Abstract. Using the PLANETOCOSMICS simulation framework we simulated solar proton transport through the Earth's atmosphere and estimated angular and energy distributions of secondaries (protons, electrons, positrons, muons, photons and neutrons) at various atmospheric levels. As the source spectrum of solar protons at the boundary of atmosphere the spectrum obtained with the GLE modeling from the data of neutron monitor network in the event of 13 December, 2006 has been used. These Monte Carlo simulation results were compared with the solar cosmic ray neutron monitor and balloon measurements during 13 December, 2006 SPE. The calculated solar proton spectra are in good agreement with the balloon and neutron monitor observational data.

1 Introduction

The ground level enhancement (GLE) 13 December, 2006 was related to the parent flare X3.4/2B, heliocoordinates S06 W24. The flare was accompanied by halo type CME and radio emission of II and IV types. The type II onset was reported at 02.26 UT. By feature 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. At the same time the event of 13.12.2006 concerns to be large ones. It was registered by more than 30 neutron monitors of a worldwide network.
The modeling study of this GLE was carried out in [1, 2]. With usage of a modeling procedure [3] characteristics of a flux of primary solar protons outside the magnetosphere on the data of neutron monitors have been obtained and their dynamics during the event studied. The characteristics of primary solar protons obtained in the GLE model study have been used then as input parameters on the atmosphere boundary at simulation of a transport through the atmosphere of these particles.
Our recent modeling technique takes into account the contribution into the neutron monitor response not only vertical, but also oblique incident particles. This kind of analysis requires the data of no less than 25-30 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 incident on detector particles) of the NM stations under study by the particle trajectory computations in a model magnetosphere.
2. Calculation of the NM responses at variable 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.
For calculation of cascades of particles in the atmosphere in this paper the PLANETOCOSMICS 2.0 package [4] based on GEANT4 [5] has been used. For the initial geometry the "Plane" geometry has been taken (Flat Geometry), with gradient separation of layers, each of which contained 5 % from a whole column of air. For the representation of physical properties of the atmosphere the NRLMSISE-00 model is used. On boundary of the atmosphere (80 km) the source of primary protons with the given energy distribution (0,5 - 10 GeV, Fig.2) has been used. Lesser energies have not been used owing to restricted resources of a computer. For an evaluation of secondary particle fluxes by means of PLANETOCOSMICS have been given detecting layers at definite altitudes. Resulting fluxes for a model absorption profiles are obtained, as integral.

2 Experimental data

Figure 1 shows time profiles of NM count rate increase at several stations on 13 December, 2005.
The marked point on a profile of the Apatity station shows results of calculation of the ground based neutron monitor response to the neutron flux at the ground level. It is obtained as a result of simulation of transport of solar particles through the atmosphere.
This event gave an opportunity to estimate energy spectrum of solar protons in the wide energy range (from 10 MeV to 10 GeV) using satellite, balloon measurements and ground-based neutron monitors observations [1, 2]. A pair of modeled relativistic solar proton spectra are presented in Figure 2. They agree well with the direct solar proton data obtained at the GOES-11 spacecraft.

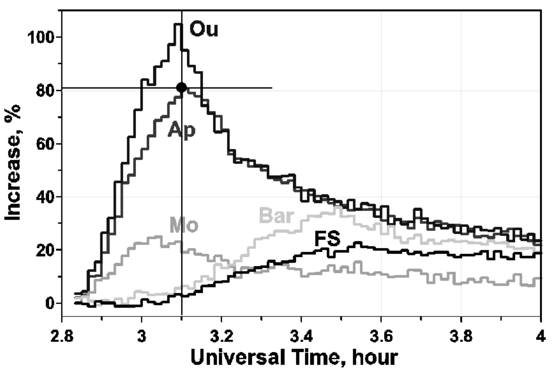

Fig. 1. Increase profiles during GLE 13.12.2006 at a number of neutron monitor stations: Ou-Oulu, Ap-Apatity, Mo-Moscow, Bar- Barentsburg, F.S- Fort Smith. The marked point on a profile of the Apatity station shows the calculated NM response using the results of simulations of solar particle transport through the atmosphere.

During the SPE 13.12.2006 balloon measurements of solar protons were carried out too. Determination of solar proton spectra on the measured by a balloon an absorption curve in the air. was carried out using a standard method [6]. The long-term balloon observations of ionizing particles in the atmosphere from the ground level up to 30 - 35 km are carried out by Lebedev Physical Institute (LPI) using light radio sounds since 1957 [7].

If the high energy proton fluxes are large enough to essentially enhance the nucleonic component of the atmospheric cascade at the Earth's surface the effect is recorded by the ground based neutron monitors. Recently we developed a new approach to the determination of solar proton spectra at the top of Earth's atmosphere based on Monte Carlo simulations of solar proton transport through the Earth's atmosphere [6]. These simulations allow us to estimate angular and energy distributions of secondaries (protons, electrons, positrons, muons, photons and neutrons) produced by the primary solar proton flux in the atmosphere. We present here results of simulations obtained for the SPE of 13 December, 2006.

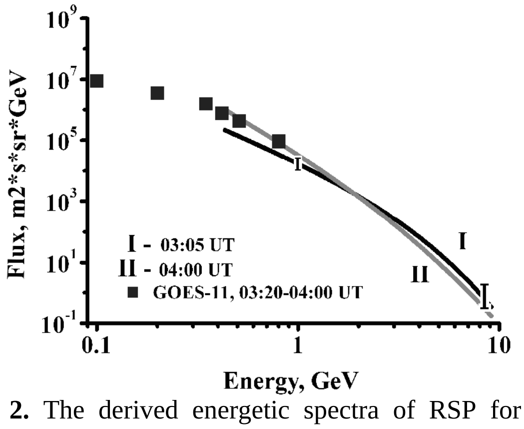

Fig. 2. The derived energetic spectra of RSP for 2 moments of time. The direct solar proton data are shown by filled squares (GOES-11).

3 Simulation results

By using the Monte Carlo PLANETOCOSMICS code based on GEANT4 [4, 5] we have computed interaction of different solar proton populations with the Earth's atmosphere. The code takes into account the following processes: bremsstrahlung, ionization, multiple scattering, pair production, Compton scattering, photoelectric effect, elastic and inelastic nuclear interaction, and the decay of particles. The solar proton populations are considered as isotropic at the top of the atmosphere. The proton energy spectrum in the energy range of Emin -Emax was defined by a power law (J(>E) = A¢E¡°) using a set of °, Emin and Emax. For each proton population (characterised by °, Emin and Emax), we calculated the total flux of secondary particles (e, photons, protons, and neutrons) at different atmospheric depth. We compared the calculated depth dependence of the total secondary particle flux with the data recorded in balloon experiment in the Earth's atmosphere during several SEP events [8]. In present analysis we used the solar proton energy spectrum (fig. 2) determined on 3.05 UT on December 13, 2006 as an input in the Monte Carlo simulations. The results of simulations are presented in Figures 3-6. Energy spectra of protons and neutrons at selected levels of the atmosphere are shown in Figure 3 and 4. Resulting absorption profiles of secondary particle flux in the atmosphere (protons, electrons, positrons and muons) are presented in Figure 5. We note that the recorded absorption profile of particles in the atmosphere (circles) and the calculated one as total flux J(x) = Jprotons + Jmuons + J(e¡+e+) + 0.01*Jphotons are in good agreement. This result is a validity check of the solar proton spectrum (Fig. 2) derived from the set of the satellite, balloon and ground-based NM measurements.

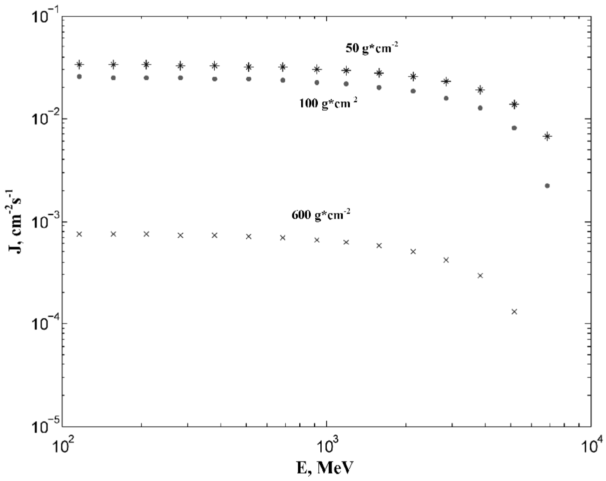

Fig. 3. The energy spectra of protons at various altitudes, obtained as a result of simulation of transport of primary solar protons through the atmosphere layers. Input data have been smoothed by means of approximating.

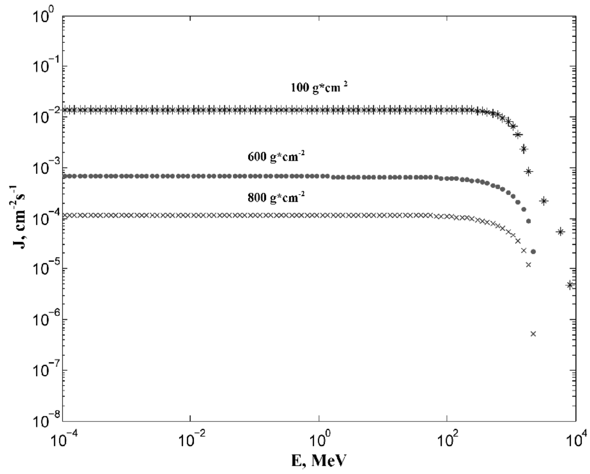

Fig. 4. The energy spectra of neutrons at various altitudes, obtained as a result of simulation of transport of primary solar protons through the atmosphere layers. Input data have been smoothed by means of approximating.

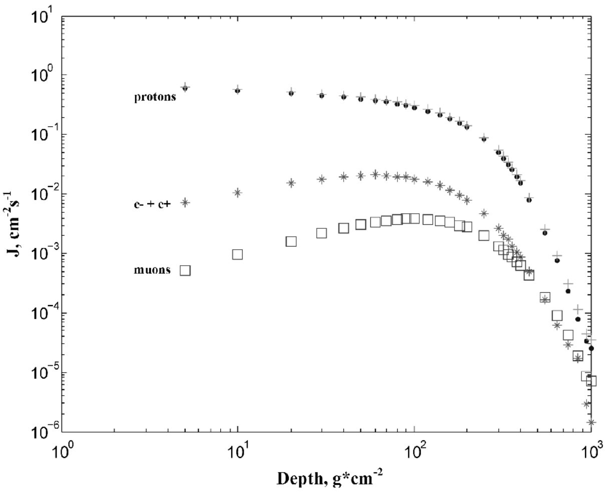

Fig. 5. Simulated absorption profiles of secondary particle fluxes in the atmosphere (protons, electrons and positrons, muons). ”Pluses” present the total flux.

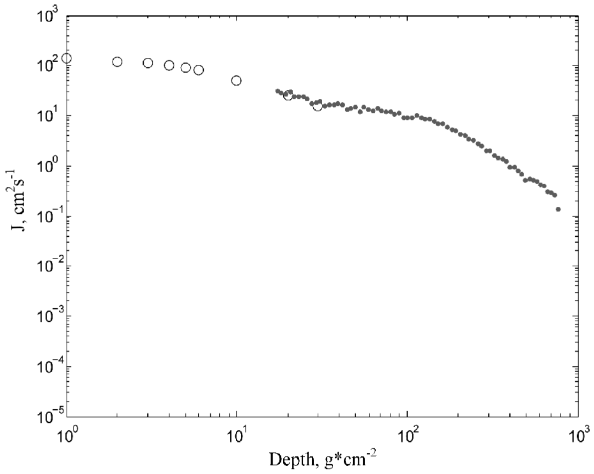

Fig. 6. “Circles” is simulated absorption profiles of secondary particle fluxes in the atmosphere (protons, electrons and positrons, muons) with GOES-11. spectrum as input parameter of model. Points are a balloon observation.

4 Comparison with observations

In fig. 6 the counting rate of the G-M counter (the charged component) presented depending on a rest pressure in flight of the balloons started at 10.00 UT in Apatity. Circles show results of simulation of the summary count rate due to simulated fluxes of charged particles: electrons, positrons, protons and muons. The good consent of simulation with observations is seen.

A response of NM to simulated neutron and proton fluxes at ground level has been calculated in a similar way. For calculation the response function of NM to neutrons has been used [9]. For calculation of response of NM to a flux of protons results of [10] were used. In fig. 7 a response function of a NM to neutrons , the simulated spectrum of secondary neutrons at the ground level and their product are shown. In fig. 8 analogous plots for protons are shown. Calculation of response of NM to the summary flux of neutrons and protons at the ground level was computed with the help of the formula:

$$j\,(t) = \int_{E_1}^{E_2} R(E)\cdot\Phi(E,t)dE$$

Where $j\,(t)$ it was computed separately for protons and neutrons. The response of NM was computed as total $j\,(t)_{\text{protons}} + j\,(t)_{\text{neutrons}}$. With usage of the spectrum 1 in fig. 2 for the moment of 3.05 UT the spectrum of secondary neutrons at the surface of the earth, presented in fig. 4 is obtained. For calculation of protons the same spectrum was used, and the results is shown in fig. 3. The summary response for neutrons and protons represented on fig. 1 as a marked point.

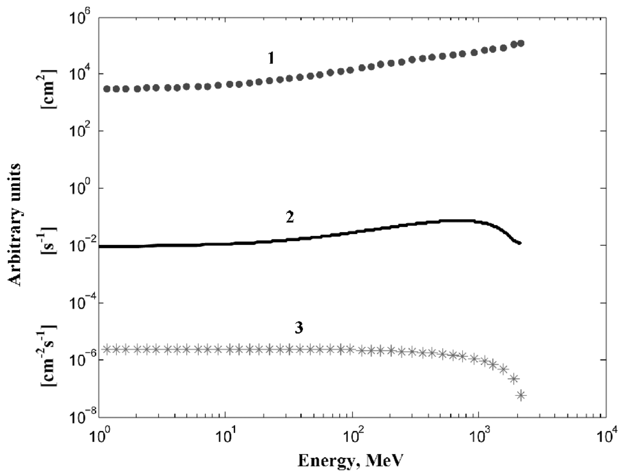

Fig. 7. On this picture a simulated NM response function on neutrons, a neutron ground level spectra and their product are numbered 1, 3 and 2 respectively.

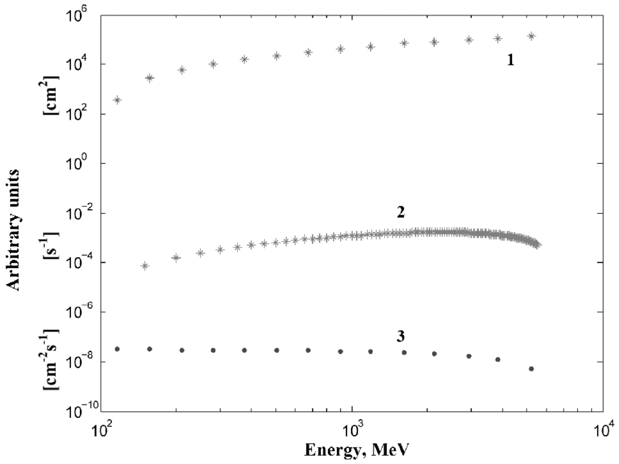

Fig. 8. On this picture a simulated NM response function on protons, a proton ground level spectra and their product are numbered 1, 3 and 2 respectively.

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