

## SOLAR PROTON SPECTRA IN THE 20 JANUARY 2005 GLE: COMPARISON OF SIMULATIONS WITH BALLOON AND NEUTRON MONITOR OBSERVATIONS

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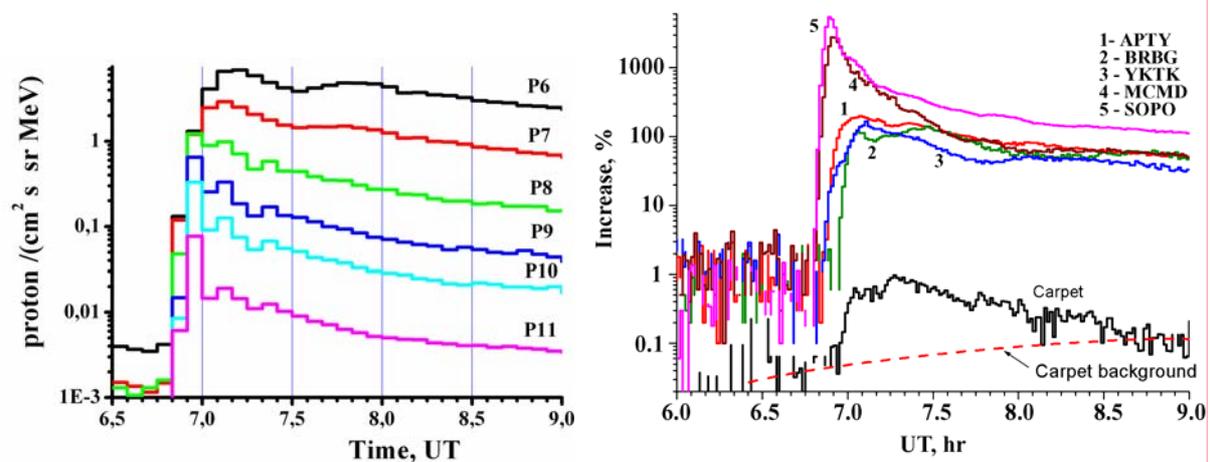
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### Abstract

Using the GEANT4 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. These Monte Carlo simulation results were compared with the results of cosmic ray balloon and neutron monitor measurements during 20 January 2005 solar proton event. The calculated solar proton spectra are in good agreement with the balloon and neutron monitor observational data.

### Introduction

The X7.1/2B class flare on January 20, 2005 (onset ~ 06:36 UT) produced the most powerful solar proton event for the last 50 years. Neutron monitor at Apatity station showed an increase of ~ 200 %, while the South Pole station 5000 %. The >100 MeV proton flux observed by GOES also was very high. The significant solar proton increase was observed in the stratosphere and a Ground Level Enhancement (GLE) was observed by neutron monitor stations (NM) at locations with geomagnetic cutoff rigidities  $R_c \sim 0.5$ -14.1 GV [1-3]. Figure 1 shows time profiles of solar proton fluxes recorded onboard GOES-11 and neutron monitor count rate increases on 20 January 2005. This event gave an opportunity to estimate energy spectrum of solar protons in the wide energy range (~10 MeV - 10 GeV) using satellite, balloon measurements and ground-based neutron monitors observations [1, 2]. Some



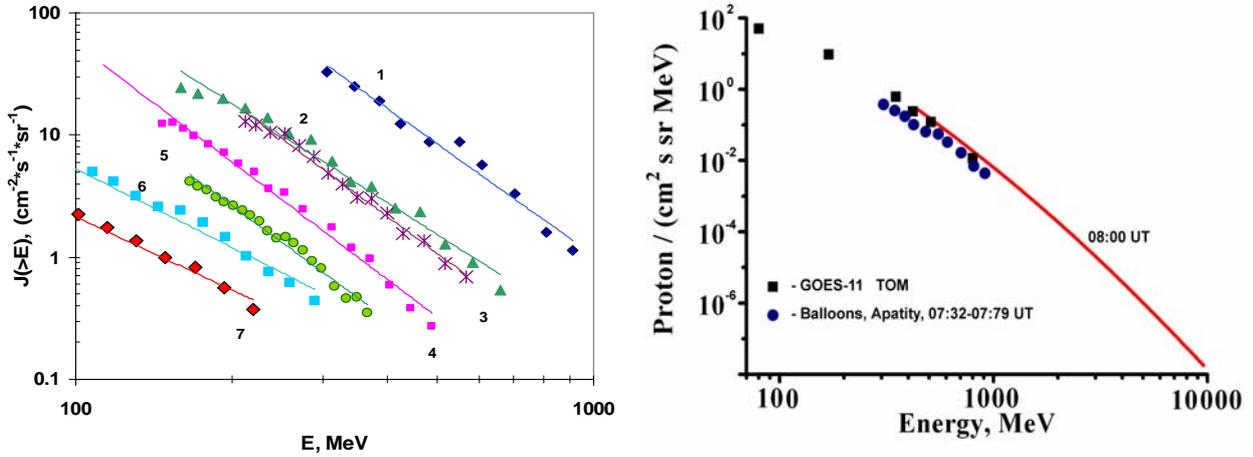
**Figure 1.** Left: GOES-11 time profiles of solar proton flux in the different energy channels: P6 (80 - 165 MeV), P7 (165-500 MeV), P8 (350-420 MeV), P9 (420 - 510 MeV), P10 (510-700 MeV) and P11 (> 700 MeV). Right: Count rate increases on 20 January 2005 at neutron monitors: 1- Apatity, 2-Barentsburg, 3-Yakutsk, 4- McMurdo, 5- South Pole and Carpet EAS array (Baksan neutrino observatory).

examples of estimated solar proton spectra are presented in Figure 2. We used a standard method to determine these spectra [4]. During last years we developed a new approach in 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 [5]. These simulations allow to estimate angular and energy distributions of secondaries (protons, electrons, positrons, muons, photons and neutrons) produced by primary solar proton flux in the atmosphere. We present results obtained for the solar proton event of 20 January 2005.

### Experiment

The long-term balloon observations of ionising particles in the atmosphere from the ground up to 30 - 35 km are

carried out by Lebedev Physical Institute (LPI) using light radio sounds since 1957 [6]. The particle detector consists of two Geiger counters with  $0.05 \text{ g}\cdot\text{cm}^{-2}$  steel walls arranged as a vertical telescope with  $2 \text{ g}\cdot\text{cm}^{-2}$  Al interlayer. An omnidirectional counter can record protons with energy  $E > 5 \text{ MeV}$ , electrons (positrons) with energy  $> 0.2 \text{ MeV}$ , muons with energy  $> 1.5 \text{ MeV}$  (with efficiency of  $\sim 100\%$ ), and  $> 0.02 \text{ MeV}$  photons (efficiency of  $\sim 1\%$ ). A telescope is sensitive to  $> 30 \text{ MeV}$  protons,  $> 5 \text{ MeV}$  electrons and  $> 15 \text{ MeV}$  muons. The geometrical factors for isotropic particle flux are  $15.1 \text{ cm}^2$  for a counter and  $18 \text{ cm}^2\cdot\text{sr}$  for a telescope.



**Figure 2.** *Left:* Energy spectra of solar protons evaluated from balloon measurements on 20 January (1- 07:32-08:38 UT, 2-09:57-10:38 UT, 3- 12:19 -13:03 UT, 4- 16:40-17:43 UT, 5-19:47-20:56 UT, 6- 22:43-23:22 UT) and 21 January (7- 08:43-09:13 UT). *Right:* solar proton spectrum evaluated from GOES, balloon and neutron monitor data.

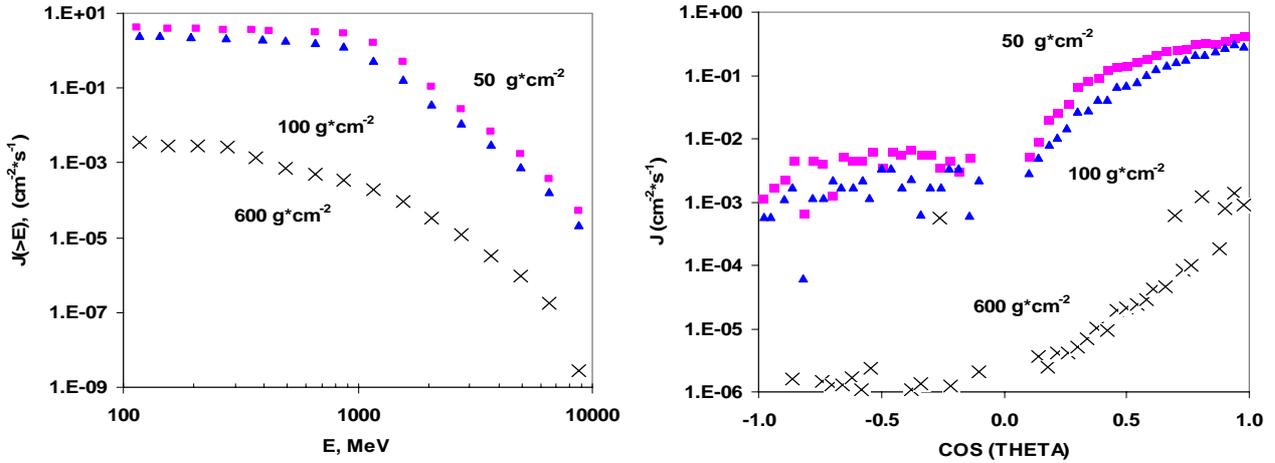
During each balloon flight the counter and telescope count rates versus atmospheric depth (or altitude) represent the cosmic rays transition curves, which are due to galactic cosmic rays (GCR) cascade processes in the atmosphere. Solar flare particles with energy above geomagnetic cutoff can penetrate into the atmosphere where they lose energy in interactions with the air nuclei. Protons with energy less than  $500 \text{ MeV}$  lose their energy mainly through ionization, reducing the primary flux number. More energetic protons ( $E > 500 \text{ MeV}$ ) lose their energy also in interactions with the air nuclei producing secondary particles. Higher energy solar particles produce nuclear and electromagnetic cascades, which lead to significant multiplication of particles. As a result, solar energetic particles incursion into the atmosphere changes the shape of the transition curve. Subtracting a background caused by GCR as measured on the pre-flare days solar energetic particles effect in the atmosphere can be estimated, e.g. a particle absorption profile in the atmosphere (particle flux number versus atmospheric depth or altitude) can be experimentally determined. Then it is possible to estimate solar proton energy spectra on the atmospheric boundary ( $E > 100 \text{ MeV}$ ) during a SEP event using a standard method [4]. 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. The data of the neutron monitor network allow to deduce the energy spectrum in the range above  $\sim 1 \text{ GeV}$  [7,8].

## Method

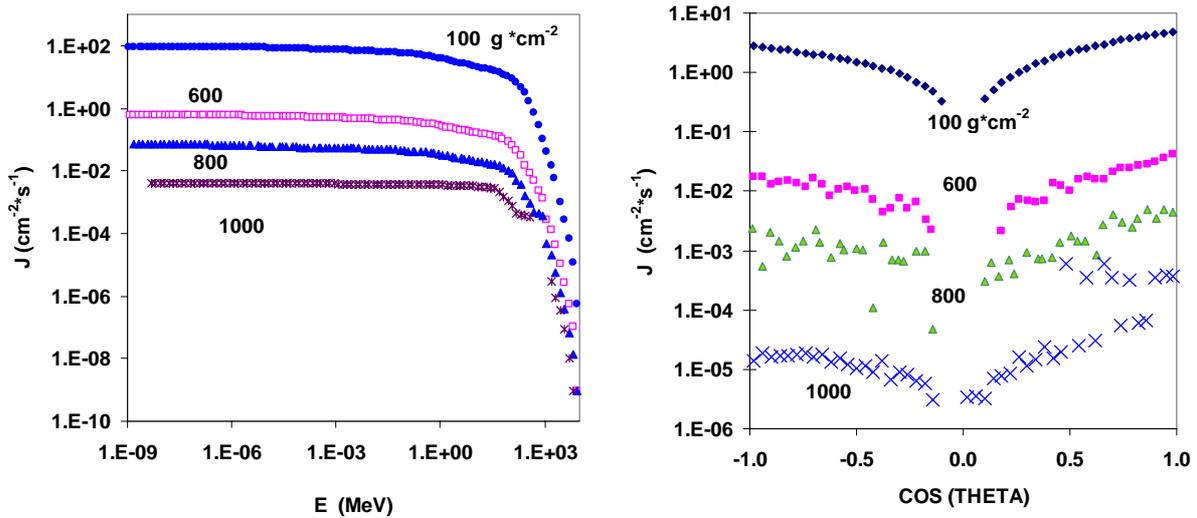
By using the Monte Carlo PLANETOCOSMICS code based on GEANT4 [9,10] we have computed interaction of different solar proton populations with the Earth's atmosphere. The code takes into account the following processes: bremsstrahlung, ionization, multiple scattering, pair production, Compton scattering, 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 energy spectra was described by a power law ( $J(>E) = A \cdot E^{-\gamma}$ ) with different power law indexes  $\gamma$  in the energy range of  $10 \text{ MeV} - E_{\text{max}}$ . For each proton population (characterised by  $\gamma$  and  $E_{\text{max}}$ ), we obtained the integrated flux of secondary particles ( $e^-$ ,  $e^+$ , gammas, protons,  $\mu^-$ ,  $\mu^+$  and neutrons) at different atmospheric depth. We compared the calculated depth dependence of the total secondary particle flux with the data obtained in balloon experiment in the Earth's atmosphere.

For analysis we selected satellite, balloon and neutron monitor observations on 20 January 2005  $\sim 07:30-08:30 \text{ UT}$ . These observations allow estimation of energy spectrum of solar protons using standard methods (see Figure 2, right panel). This proton energy spectrum obtained was used as an input in the Monte Carlo simulations. Results of simulations are presented in Figures 3-5. Energy spectra of protons and neutrons as well as their angular distributions (particle flux vs. cosine of zenith direction) are shown in Figure 3 and 4. Absorption profiles of

secondary particle flux in the atmosphere (photons, protons, electrons and positrons, muons) are presented in Figure 5. It is seen that the recorded absorption profile of particles (red circles) in the atmosphere (Apatity, 20 January 2005, ~ 07:30-08:30 UT) and the calculated one ( $J(x)=J_{\text{protons}}+J_{\text{muons}}+J_{(e+e+)}+0.01\cdot J_{\text{photons}}$ , pluses) are in good agreement.

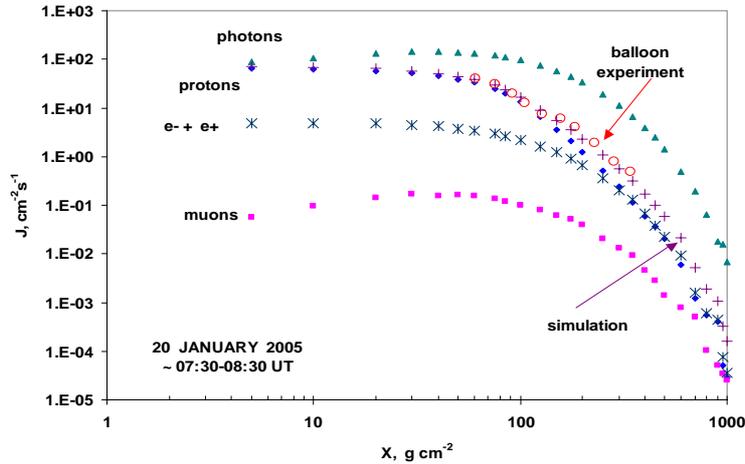


**Figure 3.** Results on Monte Carlo simulations: Left - Energy spectra of solar protons at atmospheric depth levels  $X=50, 100$  and  $600 \text{ g}\cdot\text{cm}^{-2}$ ; Right - angular distributions of solar protons at atmospheric depth levels  $X=50, 100$  and  $600 \text{ g}\cdot\text{cm}^{-2}$ .



**Figure 4.** Results on Monte Carlo simulations: Left - Energy spectra of secondary neutrons at atmospheric depth levels  $X=100, 600, 800$  and  $1000 \text{ g}\cdot\text{cm}^{-2}$ ; Right - angular distributions of secondary neutrons at atmospheric depth levels  $X=100, 600, 800$  and  $1000 \text{ g}\cdot\text{cm}^{-2}$ .

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**Figure 5** Simulated absorption profiles of secondary particle fluxes in the atmosphere (photons, protons, electrons and positrons, muons). “Pluses” present the total flux of protons + muons + ( $e^-+e^+$ ) + 0.01-photons. Circles show the observed absorption profile of particles in the atmosphere. The good agreement between “Pluses” and circles is noticeable.

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