Solar cosmic ray spectra in the 20 January 2005 GLE: comparison of simulations with balloon and neutron monitor observations

V.S. Makhmutov*, **G.A. Bazilevskaya***, **B.B. Gvozdevsky**†, **E.V. Vashenyuk**† **and Yu.V. Balabin**†

*Lebedev Physical Institute, Moscow, Russia
†Polar Geophysical Institute, Apatity, Russia

***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.**

***Keywords*: solar protons, simulation, GEANT4**

I. 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-11 spacecraft 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 at locations with geomagnetic cutoff rigidities $R_C \sim 0.5$-14.1 GV [1-4]. Figure 1 shows time profiles of solar proton fluxes recorded onboard GOES-11 and neutron monitor count rate increases on 20 January 2005 [2]. 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 [1-4]. Some examples of estimated solar proton spectra are presented in Figure 2. We used standard methods to determine these spectra from balloon observations [5]. Recently 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 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.

II. 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 [7]. The particle detector consists of two Geiger counter tubes with 0.05 g·cm^{-2} steel walls arranged as a vertical telescope with 2 g·cm^{-2} Al interlayer. An omnidirectional counter can record protons with energy E > 5 MeV, electrons (positrons) with energy >0.2 MeV, muons with energy >1.5 MeV (with efficiency of ~100%), and >0.02 MeV photons (efficiency of ~1%). A telescope is sensitive to >30 MeV protons, >5 MeV electrons and >15 MeV muons. The geometrical factors for isotropic particle flux are 15.1 cm^2 for a counter and 18 cm^2·sr for a telescope.

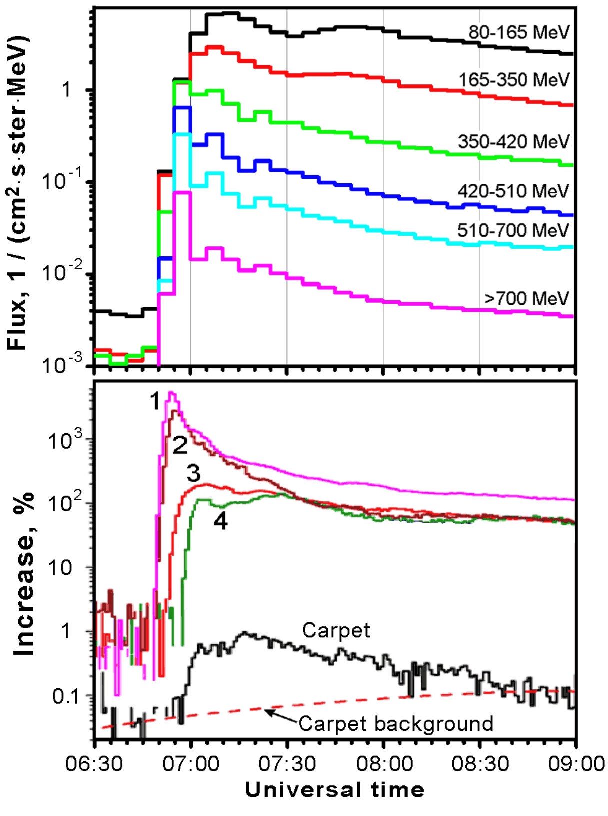

Fig. 1: *Top*: GOES-11 time profiles of solar proton flux in the different energy channels. *Bottom*: Count rate increases at neutron monitors: 1-South Pole, 2-McMurdo, 3-Apatity, 4-Barentsburg and Carpet EAS array (Baksan neutrino observatory).

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

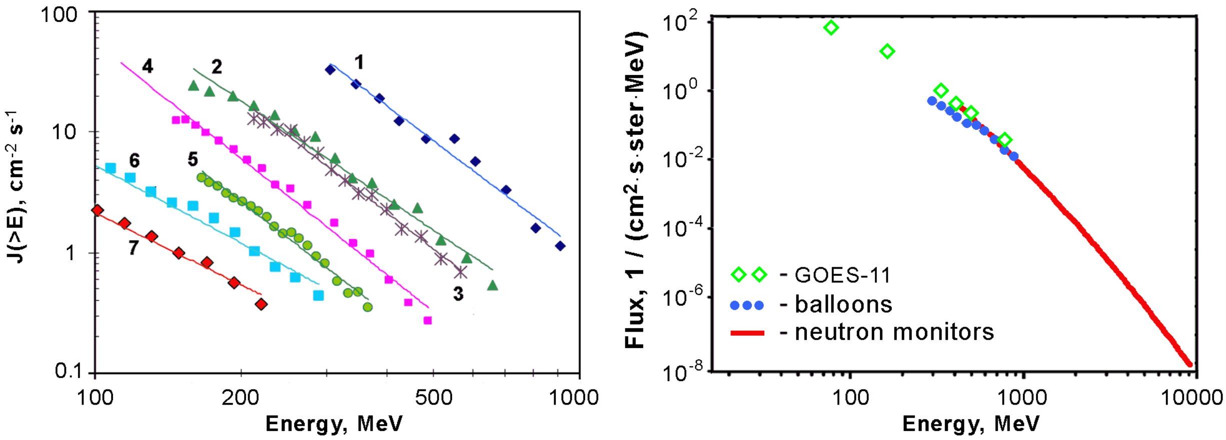

Fig. 2: *Left*:Energy spectra of solar protons evaluated from balloon measurements on 20 January: 1 - 07:32-08:38 UT, 2 - 09:57-10:38 UT, 3 - 12:19-13:03 UT, 4 - 16:40-17:43 UT, 5 - 19:47-20:56 UT, 6 - 22:43-23:22 UT and 21 January: 7 - 08:43-09:13 UT. *Right*: Solar proton spectrum evaluated from GOES,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

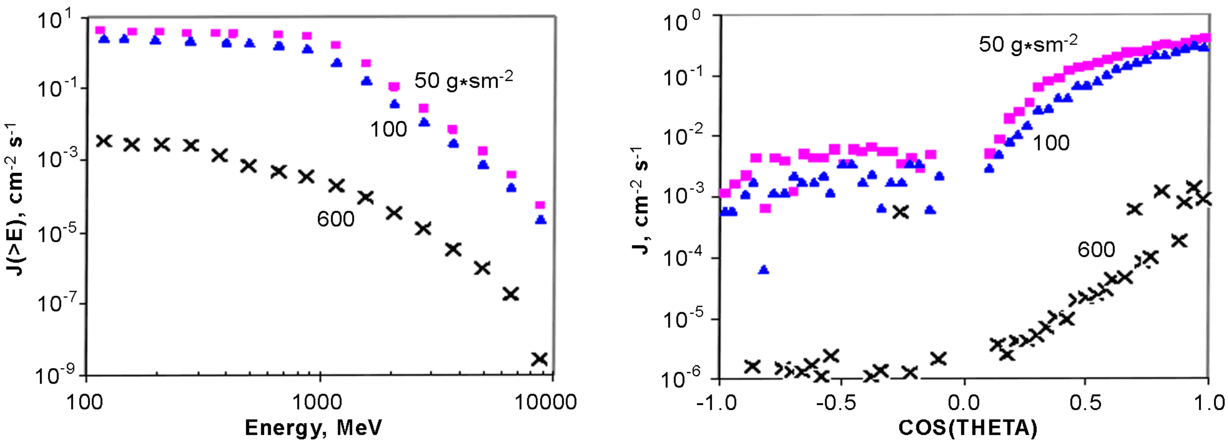

Fig. 3: Results on Monte Carlo simulations: Energy spectra (*Left*) and angular distributions (*Right*) of solar protons at atmospheric depth levels X = 50, 100 and 600 g*cm^{-2}.

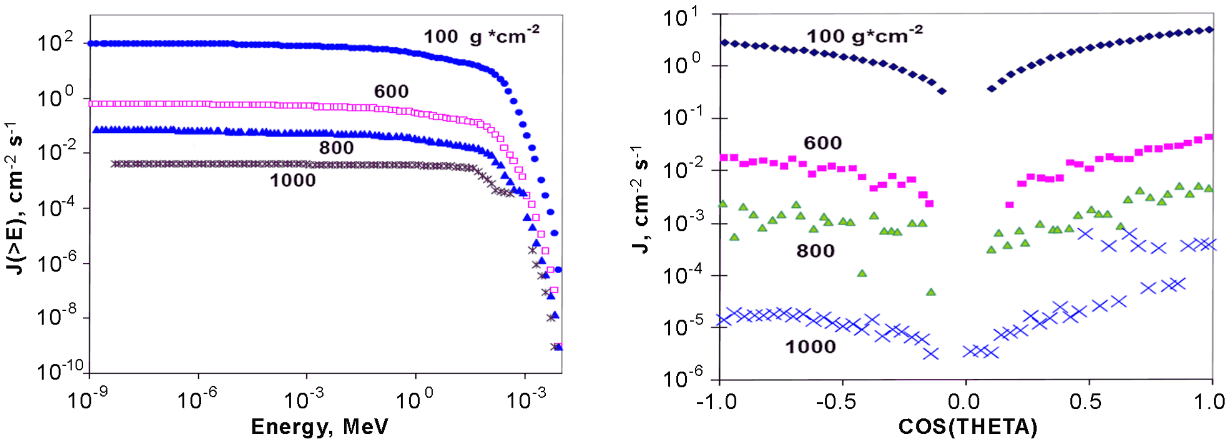

Fig. 4: Results on Monte Carlo simulations: Energy spectra (*Left*) and angular distributions (*Right*) of secondary neutrons at atmospheric depth levels X = 100, 600, 800 and 1000 g*cm^{-2}.

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 <500 MeV lose their energy mainly through ionization, reducing the primary flux number. More energetic protons (E > 500 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 cased 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 MeV) during a SEP event using a standard method [5]. 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 ∼0.5 GeV by the modeling technique [8,9]. This kind of analysis requires the data of no less than 20-25 ground-based neutron monitor 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, pitch-angle distribution) outside the magnetosphere by comparison of computed ground based detector responses with observations.

The spectrum in Fig. 2 (right panel) was derived from the data of 36 neutron monitors at the decline phase of the event (08.00 UT) [2]. Points are direct solar proton data measured at the GOES-11 spacecraft and during the balloon flight at ∼8 UT in Apatity [2].

III. Method

By using the Monte Carlo PLANETOCOSMICS code based on GEANT4 [10,11] 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 γ in the energy range of 10 MeV — E_{max}. For each proton population (characterised by γ and E_{max}), we obtained the integrated flux of secondary particles (e^-, e^+, gammas, protons, μ^-, μ^+ 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 ∼07:30-08:30 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 Figures 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 (circles) in the atmosphere (Apatity, 20 January 2005, ∼07:30-08:30 UT) and the calculated one ($J(x) = J_{protons} + J_{muons} + J_{(e-+e+)} + 0.01\cdot J_{photons}$, crosses) are in good agreement.

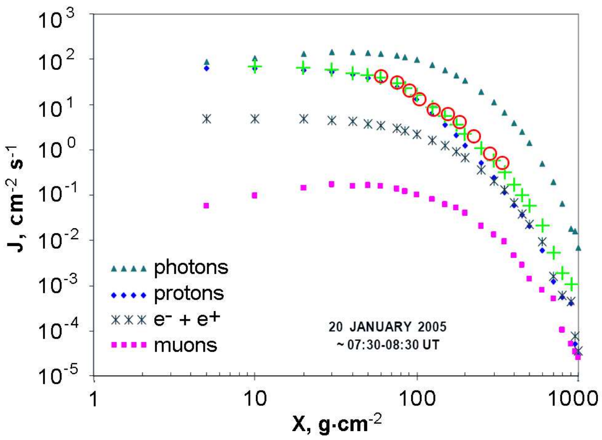

Fig. 5: Simulated absorption profiles of secondary particle fluxes in the atmosphere (photons, protons, electrons and positrons, muons). Crosses present the total flux of protons + muons + (e^- + e^+) + 0.01.photons. Circles show the observed absorption profile of particles in the atmosphere. The good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

IV. Acnowledgements

We thank all our colleagues from the neutron monitor stations for contributing GLE data. Neutron monitors of the Bartol Research Institute are supported by NSFATM-0527878.

GOES 11 data were obtained from the Space Physics Interactive Data Resource, http://spidr.ngdc.noaa.gov.

This study was partially supported by the Russian Foundation for Basic Research (grants 07-02-01019a, 07-02-10018k, 07-02-01405, 09-02-00076) and the Program of Presidium RAS "Neutrino physics".

REFERENCES

[1] E.V. Vashenyuk, Yu.V. Balabin, G.A. Bazilevskaya, V.S. Makhmutov, Yu.I. Stozhkov, N.S. Svirzhevsky, *Solar particle event 20 January, 2005 on stratosphere and ground level observations*, Proc. 29^{th} ICRC, Pune 1, 213-216, 2005.

[2] E.V. Vashenyuk, Yu.V. Balabin, B.B. Gvozdevsky, S.N. Karpov, *Relativistic solar protons in the event of 20 January, 2005. Modeling study*, Geomagnetism and Aeronomia, V.46(4), P.1-7, 2006.

[3] C. Plainaki, A. Belov, E. Eroshenko, H. Mavromichalaki, V. Yanke, *Modeling ground level enhancements: Event of 20 January 2005*, J.Geophys.Res., V.112, A04102, doi: 10.1029/2006JA011926, 2007.

[4] D. J. Bombardieri, M. L. Duldig, J. E. Humble, K. J. Michael, *An improved model for relativistic solar proton acceleration applied to the 2005 January 20 and earlier events*, Ap.J., V.682, P.1315-1327, 2008.

[5] G.A. Bazilevskaya, M.B. Krajnev, V.S. Makhmutov, A.K Svirzhevskaya, N.S. Svirzhevsky, Yu.I Stozhkov, E.V. Vashenyuk, *Solar proton events on observations in the stratospheric experiment of FIAN*, Geomagnetism and aeronomy, V.43, N.4, P.442-452, 2003.

[6] V.S. Makhmutov, G.A. Bazilevskaya, et al., *Evaluation of solar proton spectra using balloon cosmic ray observations and Monte Carlo simulation results*, JASR, V.39, N.8, P.1460-1463, 2007.

[7] A.N. Charakhchyan, *Study of cosmic ray intensity fluctuations in stratosphere caused by processes on the Sun*, Uspehi Physicheskih Nauk (in Russian), V.83(1), P.35-62, 1964.

[8] E.V. Vashenyuk, Yu.V. Balabin, J. Perez-Peraza, A. Gallegos-Cruz, L.I. Miroshnichenko, *Some features of relativisti particles at the Sun in the solar cycles 21-23*, Adv. Space Res. V.38, Issue 3, P.411-417, 2006.

[9] E.V. Vashenyuk, Yu.V. Balabin, B.B. Gvozdevsky, L.I. Miroshnichenko, *Characteristics of relativistic SCR in large ground level events of 1956-2005*, Izvestiya RAS, Ser.Phys. (in Russian), V.71(7), P.968-971, 2007.

[10] Agostinelli et al., *Geant4 a simulation toolkit, Nuclear Instruments and Methods in Physics Research*, Section A. 506, P.250-303, 2003.

[11] L. Desorgher, *PLANETOCOSMICS Software User Manual*, Univ. of Bern, 2005.