Transport of solar protons through the atmosphere during 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 spectra obtained with the GLE modeling from the data of neutron monitor network in a number of events have been used. These Monte Carlo simulation results were compared with the available solar cosmic ray neutron monitor and balloon measurements. The calculated solar proton spectra are in good agreement with the balloon and neutron monitor observational data.

1. Introduction
At present day in researches of the cosmic ray physics a various applications based on the methods of numerical simulation are widely used. One of the most modern tools is a Geant4 modeling toolkit [1]. With this package including all physics of electromagnetic and hadronic interactions it is possible to study particular cases of elementary particle interactions with matter in more details.

In such problems as determining the atmosphere matter ionization rate it is necessary to know the energy distribution of particles of various kinds as a function of the given atmosphere altitude. For study of radiation transport processes and nuclear cascade formation in the atmosphere at present day also there are different programs, such as FLUKA, MCNP [2], etc. The most advanced among them is based on Geant4 simulation framework PLANETOCOSMICS [3].

In this work we modeled solar cosmic rays transportation through the atmosphere with PLANETOCOSMICS simulation framework. As in previous work on modeling of cosmic rays transportation through the atmosphere, PLANETOCOSMICS used Geant 4.9.4 which contains more modern interaction cross-sections and therefore has better calculation precision. As a result of simulation we obtained energy distributions of secondary cosmic radiation (electrons, positrons, muons, protons, neutrons, photons) at various altitudes of the atmosphere.

2. Methods
In this work we use PLANETOCOSMICS simulation framework which has its own built-in methods of specifying the geometry and the choice of modeling parameters. The so-called "plane geometry" [4] has been selected to create an atmosphere geometric model. In this case the atmosphere is represented as a column of air with gradient distribution of layers with user-defined thickness (we
have selected 5% from a total mass. At selected altitudes the detecting layers were installed, allowing to obtain and display information about the particle fluxes in the atmosphere.

Physical properties of layers are given according to the NRLMSISE-00 atmosphere model [5]. The altitude of air column has been selected 80 km.

Particular attention should be given to modeling the source of the particles. According to [6] nearly in all events GLE two components of relativistic solar protons existed: prompt and delayed. Moreover, the energy spectrum of the prompt component has an exponential dependence:

\[ J = J_0 \exp\left(-\frac{E}{E_0}\right), \quad (1) \]

and the energy spectrum of the delayed component has the shape of the power law:

\[ J = J_1 E^{-\gamma}, \quad (2) \]

where \( E \), \( E_0 \) are measured in GeV and \( J_0 \), \( J_1 \) in \( \text{m}^2 \text{s} \text{sr GeV})^{-1} \).

In this paper we selected events No 65 and 67. For example, spectra of solar relativistic protons, which were used in GLE modeling are shown in Fig. 1.

Physical processes of different particle interactions with matter are included in Geant4 as ready models and presented by physics list classes. In this work physics list QGSP_BERT_HP was used to simulate hadronic interactions. It includes processes of high-energy particle interactions (QGSP), inelastic scattering of protons, neutrons, pi-mesons and k-mesons at energies lower than 10 GeV (BERTINI cascades), and also processes of elastic and inelastic interacting of neutrons with energy lower than 20 MeV (HP, the model is based on the ENDF cross-sections database [7]). For electromagnetic physics the Geant4 standard and the Geant4 low energy models are available.

![Figure 1](image.png)

**Figure 1.** The spectra obtained with the data of neutron monitors [6] used in the simulation. (A) represents the spectrum for GLE No 67 (02.11.2003) and (B) for GLE No 65 (28.10.2003)

3. Results

Main results of this work are energy spectra of secondary cosmic radiation particles at various altitudes of the atmosphere. These data can be applied in such tasks as an evaluation of ionization rate and also as the primary spectra of particle sources in simulation of the different effects arising in lower atmosphere layers. For verification of evaluations the modeled data were compared to experimental data obtained in flights of balloons. In Fig. 2 comparison of a measured with balloons altitude profile and the calculated profile of the total count rate of charged particles obtained as shown in the formula:
where $I(h)_{\text{protons}}$, $I(h)_{e^{-}e^{+}}$, $I(h)_{\text{muons}}$ and $I(h)_{\text{photons}}$ are values of the total flux of corresponding particles at altitude $h$. From figures it is seen, that this simulations and the observation data are in good agreement. It should be noted, that calculation errors are determined by internal methods of Geant4 [8], as well as a precision of an estimation of interaction crossection [7] and cannot be evaluated by the user directly.

Figure 2. Comparison of experimental count rate profile obtained in balloon observations (28.10.2003) with profile, obtained as a result of simulation of solar cosmic ray proton transportation through the Earth's atmosphere.

References
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