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Numerical simulation of the cosmic rays transport through the Earth's atmosphere and detectors

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We carry out the study of the cosmic ray transport through the Earth's atmosphere and detectors using numerical modeling. We present some examples of models developed with the GEANT4 SDK. Also we publish the results in the form of response functions of the NaI (Tl) scintillation detector and the standard neutron monitor, as well as typical calculated maps of the ionization rate induced by the primary cosmic rays. These models and results can be used in a wide range of tasks: developing and calibrating detectors, solving inverse problems (primary cosmic rays spectra calculation), calculating cascades of secondary particles in the Earth atmosphere, obtaining atmospheric response functions to primary cosmic rays, radiation safety assessment, etc.

Keywords: Numerical modeling, cosmic rays, particle detectors

1 Introduction

Cosmic ray (CR) astrophysics is an extensive, interdisciplinary field of science that includes both fundamental and applied research aimed at studying particles (mainly protons, helium nuclei and a small fraction of nuclei with $Z > 2$, as well as electrons and positrons) that are detected in near-Earth space and come from various sources in space (Wefel, 2004). The discovery of CR starts with the work of V. Hess at the beginning of the 20th century, and to this day there are questions, related to their origin, acceleration mechanisms, interaction with interstellar medium, and even their effect on the Earth's atmosphere, which remain relevant. Of course, a wide variety of installations have been created (and are being created) to carry out such large-scale work. For example, space experiments such as SDO, GOES, PAMELA, AMS-02, Lomonosov, Coronas, and others can be highlighted (Pesnell, 2012; Picozza, 2007; Vagelli, 2023; Sadovnichii, 2017), which make it possible to enhance understanding of

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the parameters of primary CR fluxes, as well as the nature of their interaction with the Earth's magnetosphere. Special attention is paid to the modulation of CR in the heliosphere (Potgieter, 1998).

Both galactic and solar primary particles of CR (GCR and SCR), depending on their energy, can reach the Earth's atmosphere and create cascades of secondary particles in it, some of which (muons, photons and neutrons) can reach sea level. This process makes it possible to carry out research using ground-based detectors of various types (EAS registration equipment, balloon experiment, network of neutron monitor stations (Ivanov, 2022; Stozhkov, 2009)) in which information can be obtained about such important parameters as energy spectra, as well as the degree of anisotropy of the primary CR flux.

With the development of computing technologies, numerical calculations have been actively used to solve problems related to the cosmic ray transport in the Earth's magnetosphere and atmosphere. Such methods are also used to calculate the response functions of various elementary particle detectors. The GEANT4 SDK (software development kit) is designed for such calculations, which includes a large number of models describing the elementary particle interactions with matter and has a wide range of functionality for creating various types of geometry (Agostinelli, 2003). GEANT4 is based on the Monte Carlo method and is not a program, but a set of classes implemented in C++. The aim of this work is to show by the example of specific applications how numerical methods can be used to solve applied problems of the cosmic ray astrophysics. Of course, a very small part of this huge field of science is considered here, however, the presented results allow everyone to make conclusions about the possibilities and benefits of numerical modeling. First of all, the NaI (Tl) scintillation spectrometer was chosen for calculations in order to study the dependence of its response function on the geometric parameters of the crystal. This can be useful in normalizing the spectra obtained in measurements, as well as in constructing a relationship function between the detector counting characteristic and the primary particle flux. The standard neutron monitor (NM) was chosen as the second model. This detector has a very complex internal structure and has been reliably used in CR astrophysics for more than half a century as one of the main instruments for ground-based observations (Hatton, 1964). Calculating the particle interaction in it, for example, allows us to explain the nature of the particle flux incident on it, and the response function in convolution with the energy spectrum of secondary neutrons can provide a reliable coupling function. The third example is a model for calculating the cosmic ray transport through the Earth's atmosphere. It is also useful in solving many applied and fundamental problems. For example, to evaluate radiation safety during extreme solar proton events (Maurchev, 2024). It also allows one to get in detail the energy spectra, angular distributions, and absolute values of fluxes at different depths (heights) of the Earth's atmosphere (Maurchev, 2022), which is also valuable information for calculating the coupling function with primary CR. It should be noted that all the presented models are original, created and verified by the authors themselves.

2 Scintillation detector response function

A scintillation spectrometer is a gamma-ray detector, the sensitive volume of which is a NaI(Tl) crystal. The working principle is that it can generate optical photons in an amount proportional to the energy of the primary particle (this characteristic is called the specific light yield). In addition to the crystal, such a device also consists of an aluminum shield, a photomultiplier tube and a data acquisition system (Knoll, 2000). For modeling, we use a geometry with geometric crystal size (height $h = 7.5$ cm and diameter $\varnothing = 7.5$) and a sensitive volume, which work as a photomultiplier tube window. Figure 1 shows a visualization of the gamma-ray tracking model, while not showing the scintillation processes for a convenient presentation.

Detectors of this configuration are used, for example, in monitoring the count rate increase during precipitation (Balabin, 2024) as well as in spectral measurements and analysis (Balabin, 2023). As mentioned above, for a calculation we use the Monte Carlo method with the interaction cross sections to describe the photoelectric effect, the Compton scattering and the e^-e^+ pairs production (Biggs et al., 1988; Klein, 1929; Hubbell et al., 1980). It should be noted that scintillation processes are taken into account when visualization is not needed and the specific light yield is defined, as well as a table of refractive coefficients is set for the reflective surfaces. Thus, as mentioned earlier, an optical photon beam is formed in the crystal, which is detected by the sensitive volume, and a count of photons is directly proportional to the amount of energy deposited in the crystal. As a result of calculations of the transport of monoenergetic gamma-ray beams through the detector Fig. 2 shows the detection efficiency function (response function) as well as an example of restoring the measured spectrum (freely available on the https://cosmicray.pgia.ru/spectrum.html) using this response function.

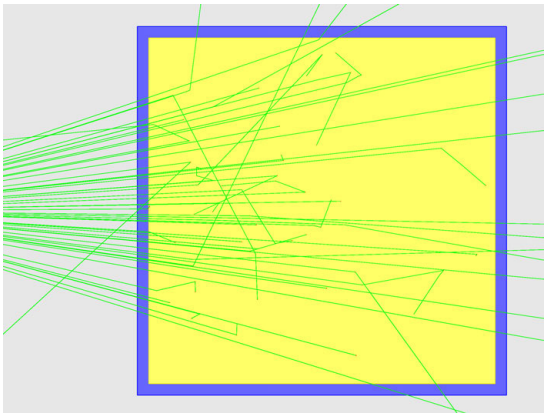


Figure 1 The scintillation detector model visualization. The blue volume is the aluminum body, yellow is the active volume (NaI(Tl) crystal), and the photomultiplier tube window set in invisible mode (plays the role of a sensitive volume in calculations). An example of tracking particles inside a crystal is also presented. The green lines show the trajectories of gamma rays from a point source, and Compton scattering processes are clearly visible. For convenient presentation the scintillation processes are disabled.

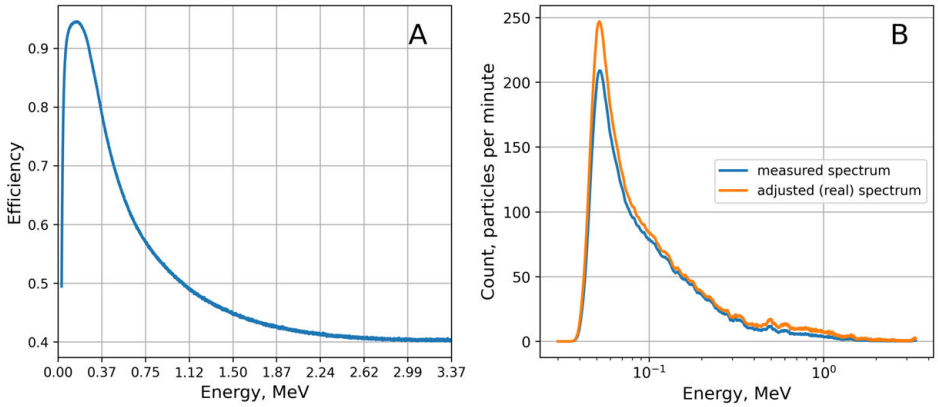


Figure 2 The response functions as the ratio of the number of detected particles to the number of particles in the primary beam, obtained as a result of modeling the transport of monoenergetic particles in models of cylindrical scintillation detectors with dimensions $h = 7.5$ cm, $\varnothing = 7.5$ cm (A) and example of restoring the measured spectrum using this response function.

3 Neutron monitor response function

The NM is a unique device operating on the principle of detecting secondary neutrons resulting from the primary CR interaction with the nuclei of the Earth's atmosphere. Since there is a strong relationship between the secondary neutrons flux and primary CR one, NM is very sensitive to changes in their intensity. This feature makes it possible to use such detectors to monitor the solar activity, study the propagation of CR in the heliosphere and the GCR variation (Bieber, 2004; Khamphakdee, 2025). It is important to note that for the NM observations, it is necessary to unite NM into a worldwide network at points with different geomagnetic cutoff rigidities in such a way as to cover as much of the primary CR arrival as possible. To do this, there is a project called the Neutron Monitor Database (www.nmdb.eu), which provides real-time information exchange between all observation stations and allows for comparative analysis. This approach makes it possible to quantify the SCR spatial variations and detect the ground level enhancement events (GLE). However, the NM data is important not only in the fundamental research, but can also be useful in solving applied tasks. For example, estimating the flux parameters and the differential energy spectra of primary CR during GLE can be used to ensure radiation safety on board both airliners and spacecraft. It is also important to use this data in space weather forecasting, which plays a huge role in ensuring the safety of space missions (Dorman, 2010). In addition, it should be noted that the long-term NM data series make it possible to study periodical variations in solar activity. The standard NM includes polyethylene moderator and reflector, a lead generator, as well as a neutron counter. Figure 3 shows the standard NM visualization obtained using our model.

The choice of interaction models is somewhat more complicated here than for a scintillation spectrometer. In addition to standard electromagnetic processes, cascade models are also used (Amelin et al., 1990; Heikkinen et al., 2003), and for neutrons

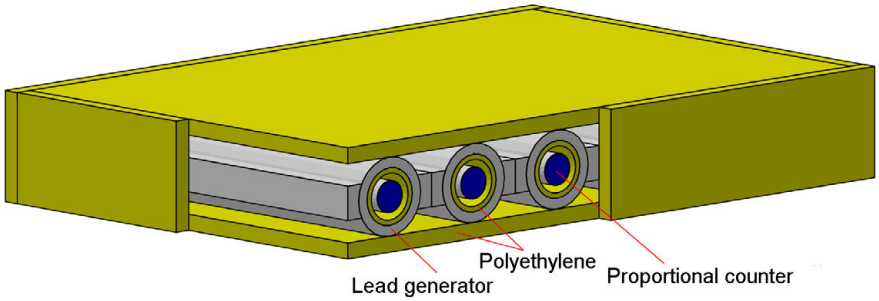


Figure 3 Visualization of the standard NM model. The polyethylene shell works as a reflector for albedo particles, a lead generator – to increase the number of neutrons into NM, and polyethylene pipes – to slow down the neutron energy to thermal, at which neutrons are recorded by a counter.

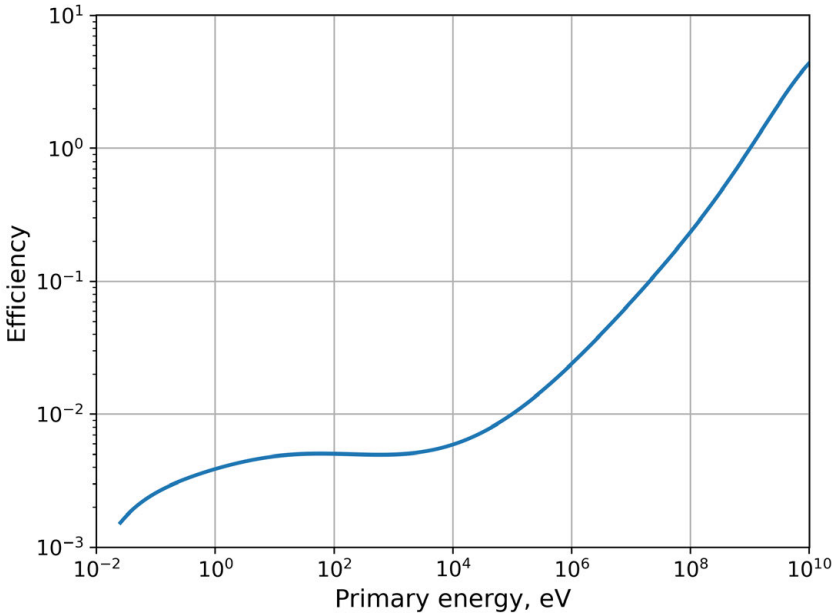


Figure 4 The standard NM response function obtained by modeling of the transport of the mono-energy neutron beams through a detector. It is calculated as the ratio of the registered particles to the number it in beam. The registration efficiency of more than 1 is due to the neutron multiplication by a lead generator.

with energies below 20 MeV to thermal, a calculation method using cross sections from the ENDF/B library is used (Chadwick et al., 2011). The NM response is modeled in several iterations, with a change in the energy value of the monoenergetic particle flux incident on the NM surface (in the range of 10^{-2} to 10^{10} eV) at each step. As a result of the calculation, Fig. 4 shows the response function of a standard NM. The energy dependence obtained characterizes the sensitivity of NM to neutrons and can be useful both in calibration tasks and for calculating the specific yield function.

4 CR transport through the Earth's atmosphere

Modeling of the CR propagation through the Earth's atmosphere is one of the most important tasks of modern astrophysics and space physics, which is carried out by leading scientific groups (Usoskin, 2024). Primary CR interact with atmospheric atoms, generate the secondary particle cascades – muons, neutrons, electrons and others, which reach the Earth's surface and even underground laboratories. An accurate understanding of these processes is necessary for interpreting data obtained using ground-based and underground detectors such as NM, muon telescopes, and other installations. Without correct modeling, it is impossible to unambiguously link the observed variations in secondary particle fluxes with changes in the external environment, for example, with solar activity or magnetic storms (Dorman, 2004). One of the important applied aspects is the assessment of radiation safety, which is based on the calculation of a dose equivalent at different depths of the Earth's atmosphere. Starting from the flight heights of civil airliners, the radiation dose increases significantly, especially during extreme solar events (Bazilevskaya, 2008; Maurchev, 2024). If we combine these results with the solar activity forecast models, we can greatly improve flight safety and the development of effective protective methods. Finally, calculations of the secondary CR particles in the Earth's atmosphere can be used together with experimental data to reconstruct the primary CR spectral characteristics (Makhmutov, 2023).

In our work, we use our own RUSCOMICS model (Maurchev, 2019), which is implemented on GEANT4 SDK. Firstly, the parameters of the atmosphere are determined. For most tasks, the so-called "flat" approximation is suitable, in which the atmosphere is represented as an air column with a conditional height limit (often $h = 100$ km) and a limit on the length of the edges (usually $l = 300$ km). Next, the atmosphere is divided into layers in which density, temperature, and chemical composition

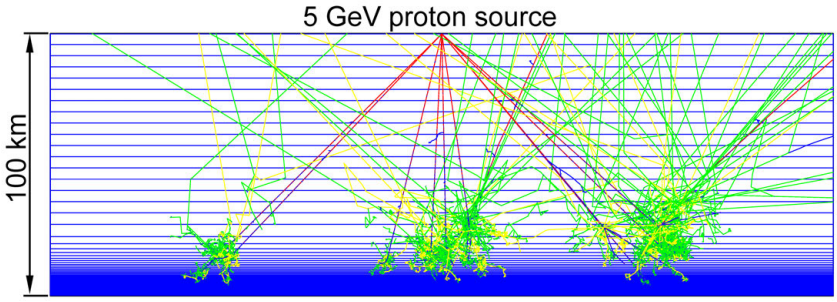


Figure 5 An example of modeling the propagation of primary and secondary CR particles through the Earth's atmosphere using the RUSCOSMICS model, only one projection of the atmospheric geometry is shown. The figure shows the geometry of the atmosphere in a "flat" approximation, the source of primary protons, defined as a point with an isotropic angular distribution, as well as the tracking of secondary particles. The atmosphere is divided into layers with the same percentage of air content and parameterized using the NRLMSISE-00 model. The red lines show positively charged particles, the blue lines show negatively charged particles, the green lines show neutrons, and the yellow lines show photons.

are parameterized using the NRLMSISE-00 model (Picone, 2002). To optimize the calculation, an algorithm is used in which the number of layers is reduced and set so that they contain the same amount of matter (the calculation speed using the Monte Carlo method depends very much on the number of "volumes"). For example, if 2% of the column weight is used, then there will be 50 layers, if 5%, then there will be 20 layers, etc. The more layers there are, the slower but more accurate the simulation will be. Therefore, this parameter is determined based on the needs of a specific task. An example of a geometry projection divided into 50 layers is shown in Fig. 5. At the necessary levels of the model, detection volumes are determined that allow the collection of information about the secondary CR integral flux, the energy spectrum of secondary CR, their angular distributions, as well as the ion production rate and the energy deposited (dose equivalent). Additionally, Fig. 5 shows particle tracking. In the task of modeling the CR propagation through the Earth's atmosphere, the particle source at the boundary of the atmosphere is defined as a point source with an isotropic angular distribution. It is also necessary to determine the energies that the primary particles will have (since more than 90% of CR consist of the protons, then we will consider only them further, modeling alpha particles and nuclei with $Z > 2$ is a separate task and goes beyond the scope of this work). To do this, you need to know the differential energy spectrum. For example such different spectra obtained using experimental data are shown in Fig. 6.

The main task in our work, of course, is to estimate the ionization rate for various geographical points (building global maps of ionization rates). To do this, it is necessary to set the lower limit of the energy spectrum at each node (set the value of the geomagnetic cutoff rigidities). To solve this problem, special programs are used based on calculating the trajectory of a particle in a magnetic field. After determining

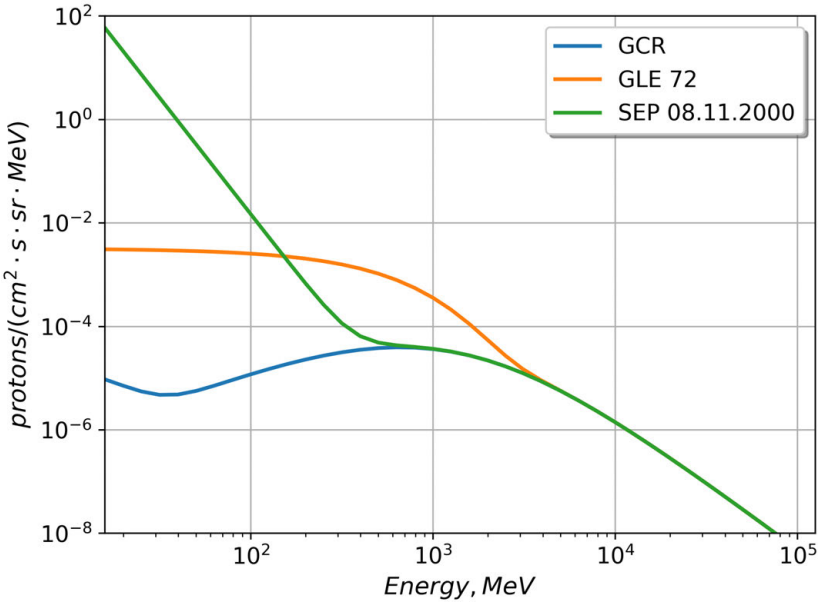


Figure 6 The primary CR protons differential energy spectra used in modeling.

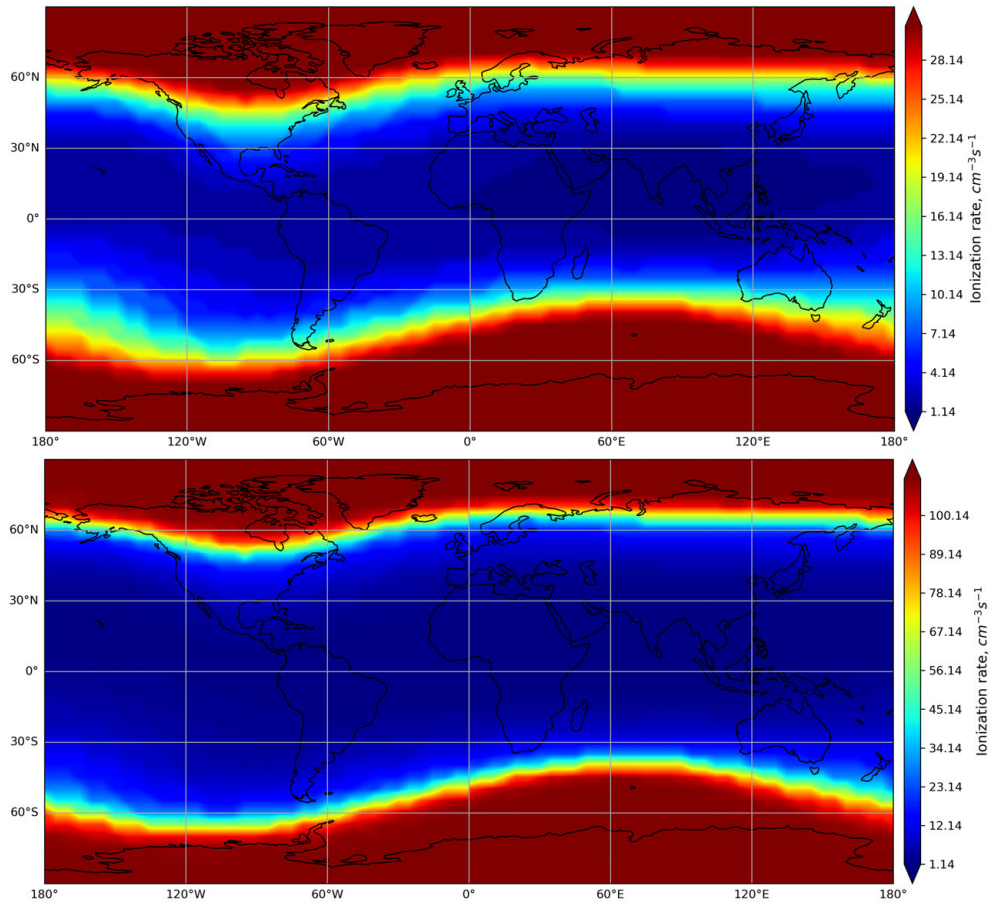


Figure 7 Typical maps of the ionization rate obtained as a result of modeling the transport of protons of primary CR through the Earth's atmosphere. The map received for GCR is at the top, and for the GLE 72 event is at the bottom.

the thresholds, a simulation is performed for all latitude and longitude (geographical) values in increments of 5 degrees. As a result, maps are obtained for different heights. For example, in Fig. 7 the ionization rate maps for 10 km and two solar activity states are presented.

5 Conclusions

In this work, we have shown the possibilities of using numerical modeling in relation to the problems of CR astrophysics. The results of calculations of the response function of a scintillation detector and the NM are presented. It also shows the solution of one of the most difficult tasks – calculating the propagation of CR particles through the Earth's atmosphere. Global maps of the ionization rate have been obtained for various initial energy spectra of protons of primary CR corresponding to different

states of solar activity. It should be noted that these results are not final, in the future, they are necessary for more comprehensive work. For example, the creation of a radiation safety assessment system in near-real time. The task of verifying the data obtained in the simulation using experimental installations remains also relevant for us (for example, verifying the counting rate of various detectors and correcting the model of the interaction of CR with the Earth's atmosphere). All this is necessary for a better understanding of the physics of CR particles in near-Earth space and the Earth's atmosphere, as well as for solving a range of applied tasks.

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