MODELING OF THE EARTH ATMOSPHERE IONIZATION BY THE GALACTIC COSMIC RAYS AND THE SOLAR COSMIC RAYS

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ABSTRACT

An important task of cosmic ray physics is to estimate the radiation safety during solar flares, which are accompanied by the ground level enhancement (GLE, count rate increasing on neutron monitors). This phenomenon can be explained by the fact that the number of particles in the energy range from 1 GeV to 10 GeV increases in the flow of primary protons, which can lose their energy both for ionization and penetrate deeply into the atmosphere, causing cascade processes. The Polar Geophysical Institute has developed the RUSCOSMICS software package, the main of which is the ability to obtain the ionization altitude profiles for a given region of the atmosphere, using the spectra of primary protons of cosmic rays, both solar and galactic, as input. At the same time, the methodology for calculating spectra, as well as reception cones and pitch-angle distributions, has also been developed at the Polar Geophysical Institute. An important feature used in this work is that when modeling the interaction of particles, parallel computations are used (based on a computing center with an installed Intel Xeon Phi 5110 coprocessor and an Intel Core i7 main processor), which makes it possible to expand the applicability of the model from the local region to the global geometry atmosphere of the Earth. This work presents the results obtained for both galactic and solar cosmic rays in the form of ionograms at heights from 1 km to 80 km with a step of 1 km for all values of latitude and longitude with a step of 5 degrees. Previously, we also verified the model using the data obtained during the launch of the balloon-probes. Today this part of the study continues, including the development of our own system for measuring the fluxes of charged particles.

INTRODUCTION

During the interaction process of cosmic rays (CR) with the Earth's atmosphere, both galactic CR (GCR) and solar CR (SCR), secondary particle cascades are occured, while it able of transferring energy to the surrounding matter both through ionization processes and through inelastic, nuclear reactions [1]. One of the important tasks of the nuclear-physical, cosmo physical and applied aspects of CR physics is the study of the elementary particle transport in the Earth's atmosphere, their influence on the surrounding matter and various systems through successive interaction processes. So, for many years, the evaluation task of the ionization count rate induced by CR has not lost its relevance [2, 3, 4]. Since the progress in computing technology has stepped far forward, these studies are carried out not only by traditional experimental methods, but also with the numerical simulations. For these purposes, at the Neutron monitor (NM) Apatity station, in addition to the existing monitoring system, the RUSCOSMICS software package was developed based on the GEANT4 software development toolkit [5, 6, 7]. The development of such a technique is justified by the need to assess the radiation dose at different altitudes in the Earth's atmosphere using standard, inexpensive and continuous measurements obtained from NM ground stations. This will ensure radiation safety during flights on passenger liners, especially during long and intense transatlantic flights. Within the framework of the presented work, by modeling the proton transport through the Earth's atmosphere, the interaction of this type of particles of both GCR and SCR is studied. With these calculations, not only the numerical characteristics of the flux intensity of various components of secondary CRs (muons, protons, neutrons, electrons, gamma quanta) were obtained, but also the calculation of the ionization rate for a set of values of the geomagnetic cutoff rigidity was performed. The model was verified by comparing the count rate altitude profiles obtained during the launch of balloons and airbus flights with similar data calculated by simulating the passage of GCR protons through the Earth's atmosphere. The urgency of the problem of assessing radiation safety during GLE events (Ground level enhancement - the effect of increasing the count rate on a NM due to the SCR interaction with the Earth's atmosphere) is due to the fact that the absolute value of the primary proton flux can increase by several orders of magnitude, an example of comparing spectra for GLE No. 42 and GLE No. 44 [8] is shown in fig. 1.

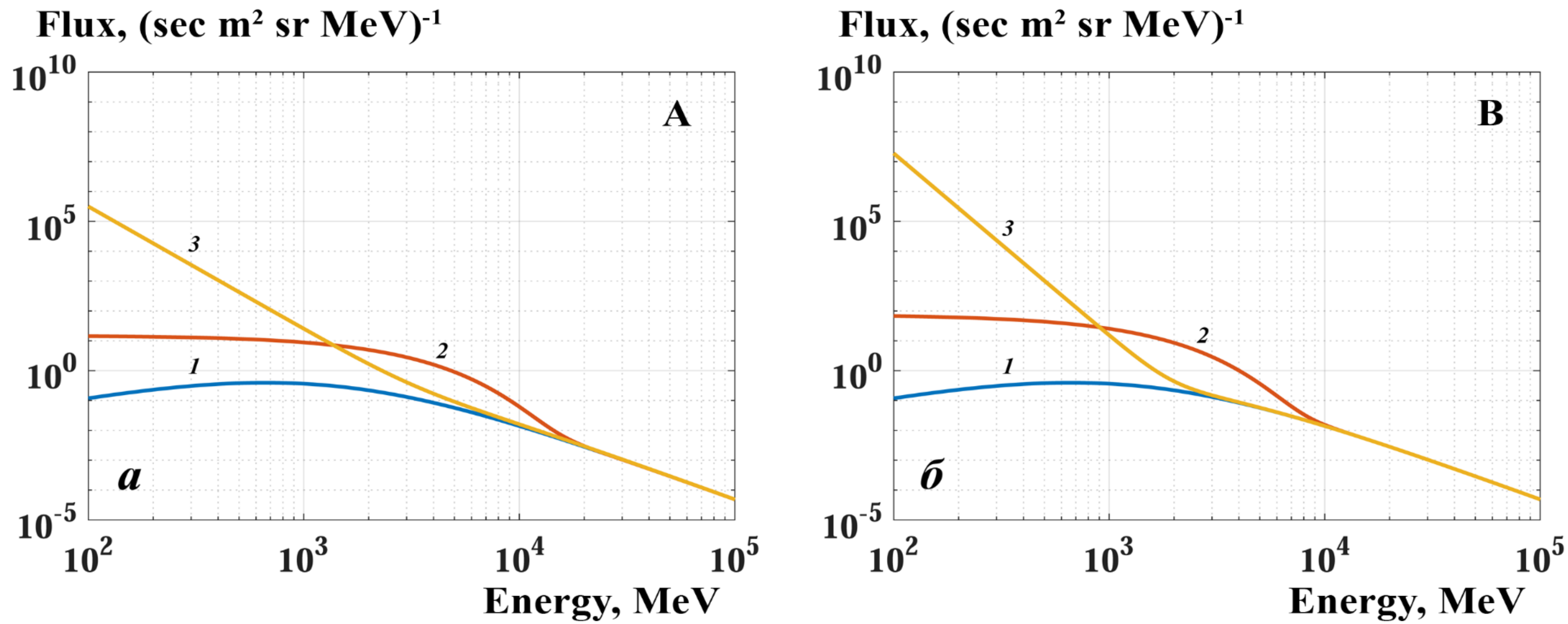

Fig. 1. Examples of the primary SCR proton spectra for events GLE N 42 (A) and GLE N 44 (B) in comparison with the primary GCR proton spectra. 1- GCR, 2 – PC, 3 – DC.

Table 1. The primary protons energy spectra parameters for GLE N 42 and GLE N 44

GLE N	Date	Primary energy spectra parameters			
		J_0	E_0	J_1	ϒ
42	29.09.1989	$1.5\cdot10^4$	1.74	$2.5\cdot10^4$	4.1
44	22.10.1989	$7.5\cdot10^4$	0.91	$1.5\cdot10^4$	6.1

RESEARCH METHODS AND MATERIALS

Firstly, it is necessary to determine the model geometry for which the calculations will be performed. This is done using parameterization in such a way that the resulting configuration is not only as close as possible to the real values of the physical parameters of the substance of the Earth's atmosphere, but is also optimized for calculations. The method is based on the concept of "flat" geometry, when the air column is divided into N layers, for which the value of mass, density, temperature, as well as the percentage of chemical elements is determined through the NRLMSISE-00 model [9] with their subsequent averaging. In practice, it was found that for a satisfactory final result, diverging from the data for verification within 15%, the optimal value is N = 20 (or 5% of the total depth of the column).

Secondly, a model proton source is determined. Its main parameters are the position in space and the probability density of generated particles, which corresponds to the differential energy spectrum. Based on the analysis of the results of the previous calculations, it was decided to use a point implementation of the generator, which consists in the fact that the source of primary particles is determined at the upper boundary of the atmospheric column in the central part without assigning a spatial distribution to it. This approach provides good statistical accuracy when collecting information on the intensity of secondary CR particles. To set the energy characteristics of GCR protons, the following formula was used [10]:

$$F(E) = \frac{D \cdot E^{\alpha}}{\left(10^{-2} \cdot E + B\right)^{4}} + C \cdot \exp\left(-\frac{E}{10}\right) \quad , \ s^{-1} m^{-2} sr^{-1} MeV^{-1}$$

where D, B, C, α are parameters depending on the phase of the 11-year cycle (in the presented work D = 5.2, B = 6.2, α = 1.4, C = 2, these coefficients correspond to the minimum solar activity). The SCR proton spectrum is described using the model developed at the PGI in Apatity [8, 11], according to which the spectrum contains two components

- prompt (PC) and delayed (DC), their energy dependences can be expressed through formulas:

$$J_{PC} = J_0 exp\ (-E/E_0),\ s^{-1}m^{-2}sr^{-1}GeV^{-1} \qquad J_{DC} = J_1 E^{-\gamma},\ s^{-1}m^{-2}sr^{-1}GeV^{-1}$$

where J_0, E_0, J_1, γ are coefficients that differ depending on the number of the GLE event. For example, for the GLEs N 42 and N 44, the parameters presented in table 1. The corresponding differential spectra are shown in fig. 1, from which it can be seen that the values for GCR and SCR differ up to several orders of magnitude for energies up to 5 GeV, but starting from 10 GeV the fluxes decrease and the total spectra become absolutely identical.

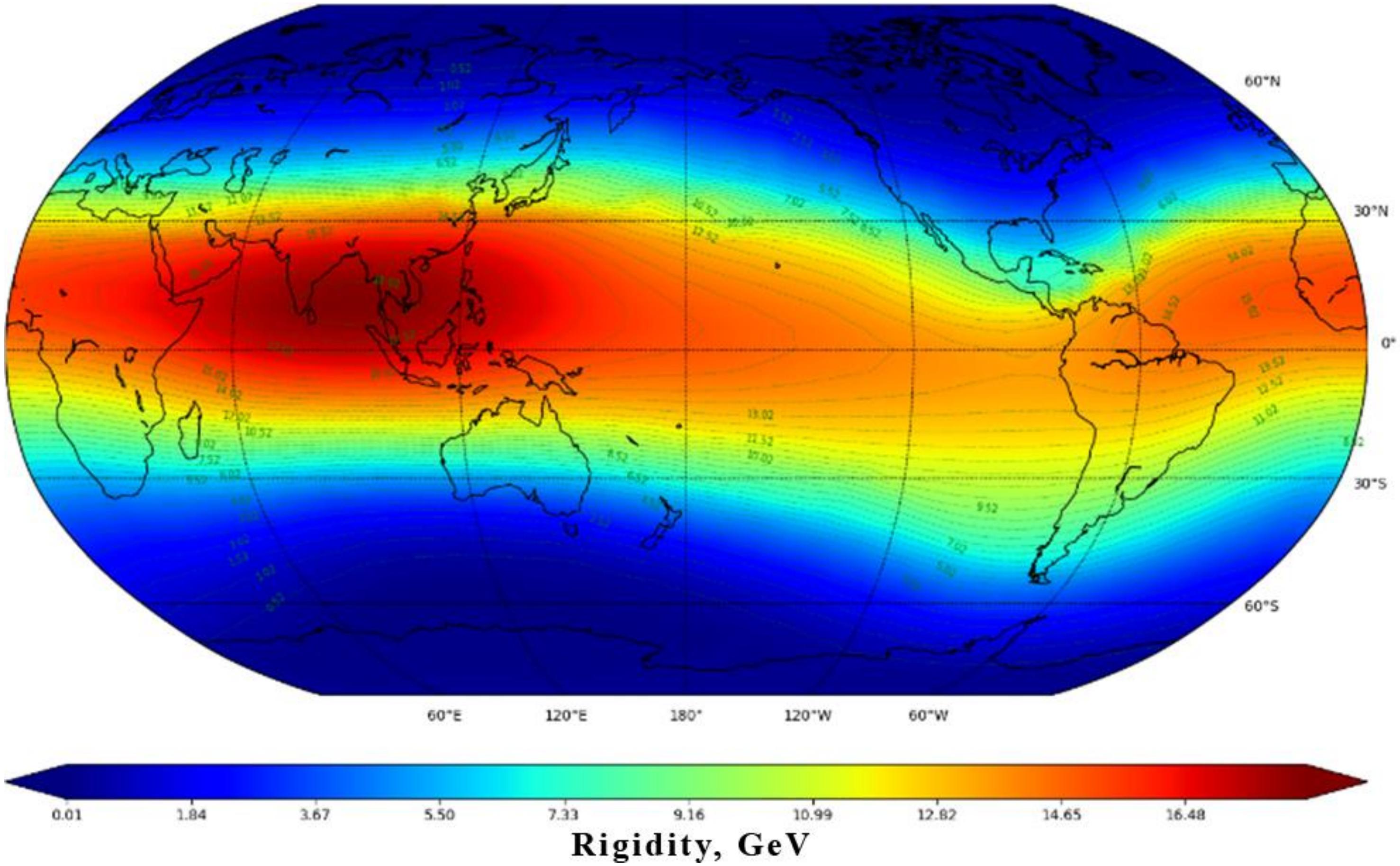

Fig. 2. Also, for each point, the value of the geomagnetic cutoff rigidities obtained by modeling is determined and set [12]. In fig. 2.15 shows the grid used to obtain the results of this work. Grid of geomagnetic cutoff rigidities values with a step of 5 degrees, used to calculate the passage of primary CR protons through the Earth's atmosphere in the case of using the global geometry model.

To calculate particle interactions, a standard list of models is used, which includes standard electromagnetic processes, Bertini cascades for nucleons with energies below 9.9 GeV [13], above 10 GeV - the quark-gluon string model [14], special sets of cross sections for calculating neutron interactions at low energies 0.025 eV - 20 MeV [15]. For the subsequent processing of information about the secondary CR fluxes, we wrote a program code that implements the data binned scorer and integrated as a method of detecting volumes located at specified heights. The result is output in the form of histograms.

RESULTS

The main module of the software package described here is designed to simulate the CR particles transport through the Earth's atmosphere and is able to calculate the parameters of the flux intensity and ionization rate for all geographic coordinates. Fig. 3 shows a typical illustration of the results obtained in the case of using the GCR proton spectrum and the values of the geomagnetic cutoff rigidities as input parameters, the grid step is 5 degrees. Other possibilities of the tool developed by us can be viewed on the project website www.ruscosmics.ru.

As a result of modeling the SCR protons transport through the Earth's atmosphere, their interaction with the surrounding matter, and the subsequent development of cascades, the corresponding curves of the ionization rate depending on the altitude were obtained for the geographical coordinates 65.57 N, 33.39 E (Apatity) and the value of the geomagnetic cutoff rigidity Rcutoff = 0.65 GV. The positions of the maximum of the ionization profile of the high-latitude atmosphere are revealed depending on the shape of the spectrum of the primary protons of solar cosmic rays.

Thus, it has been shown that the PC, the fast component, is characterized by the appearance of particles with energies above 1 GeV with almost the same probability as below 1 GeV. In the DC, the slow component, the situation is completely different; the spectrum exhibits fluxes that are several orders of magnitude higher in energy below 1 GeV than those above 1 GeV. Therefore, PC is characterized by an almost proportional increase in the value of ion production relative to the GCR, with only a slight shift in the profile maximum in height (the maximum increase in the flux at an altitude of 10 - 15 km by two orders of magnitude). For DC, the situation is different, since a huge number of low-energy primary particles that do not experience nuclear interactions cause a proportionally large increase in ionization with an upward shift of the maximum (an increase in flux by four orders of magnitude with a shift of the maximum to an altitude of 20 - 25 km). These results are shown graphically in Fig. 4.

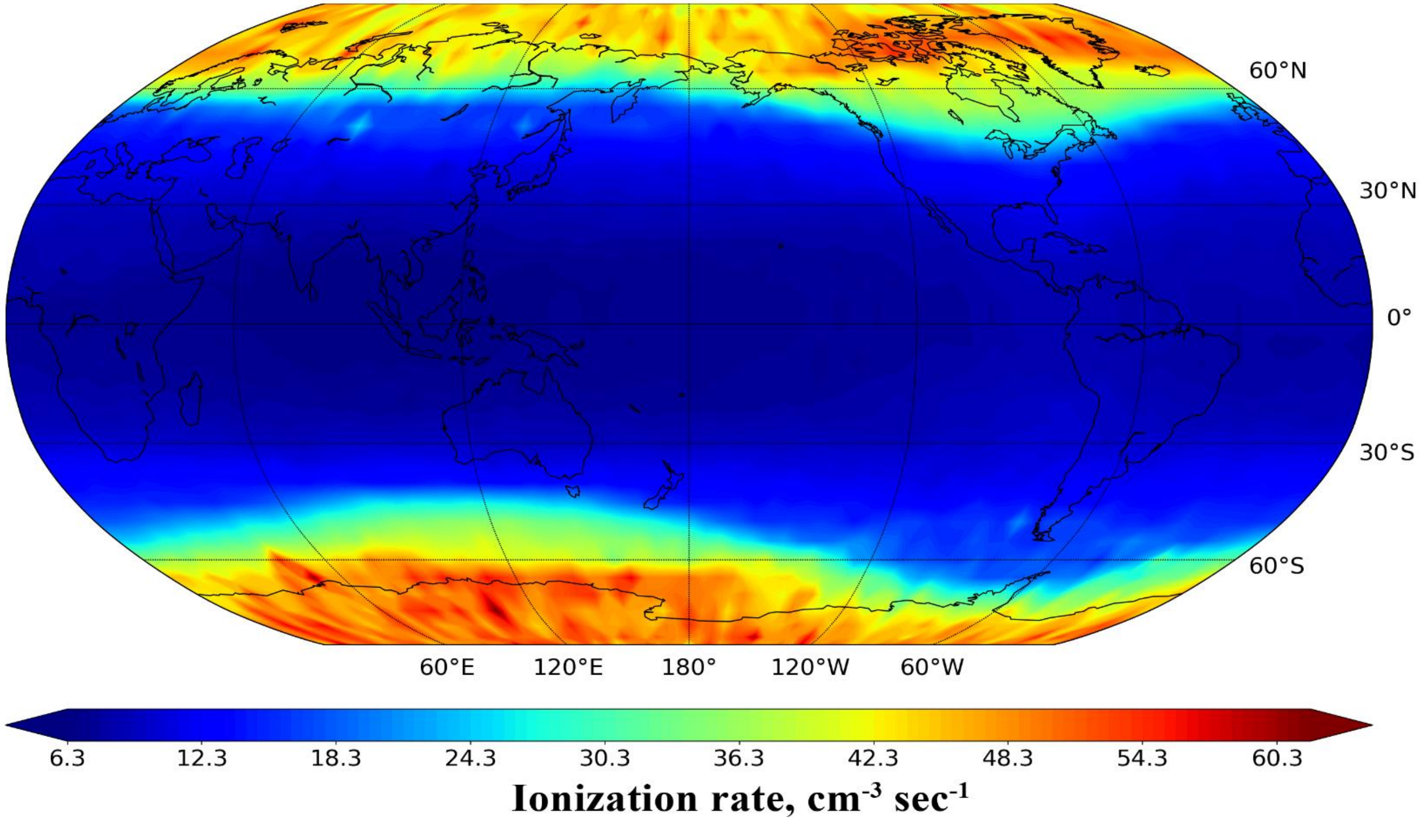

Fig. 3. Ionogram corresponding to heights of 12 km above sea level. The result was obtained using the global model and for the source of primary protons having the energy spectrum of primary GCRs during the solar minimum

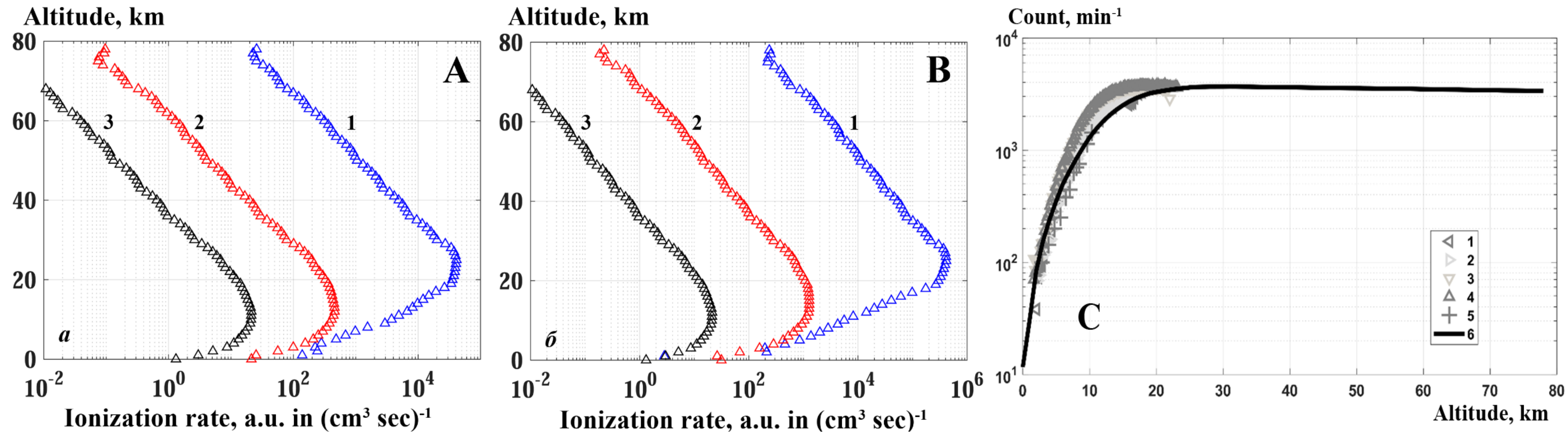

Fig. 4. Altitude profiles of the Earth's atmosphere ionization rate by CR particles during the event GLE N 42 (A) and GLE N 44 (B) in the case of PC and DC components. The data were obtained by modeling processes using the RUSCOSMICS software package. 1 - PC, 2 - DC, 3 - GCR. On C - comparison of the count rate altitude profiles obtained during the launch of the balloons for different periods of time and measurements on the plane with the results of modeling the passage of GCR protons. Left triangle - probe measurements (01/04/2010), right triangle - probe measurements (01/11/2010), down triangle - probe measurements (01/18/2010), up triangle - probe measurements (01/20/2010), crosses - Airbus measurements in 2018 (67.95 N, 32.8 E, climb), solid line - calculation data.

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