

# Ionisation state of the Earth's stratosphere during powerful solar proton events

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**Abstract.** Results on energy deposition and ionisation rate in the Earth's atmosphere during solar proton events (SPEs) are presented. The estimations for the most powerful solar proton events recorded in the Earth environment during 1956-2005 (23.02.1956, 4.08.1972, 29.09.1989, 19.10.1989, 23.03.1991, and 20.01.2005) are given. The solar proton measurements in the near-Earth space, in the atmosphere and by the ground-based neutron monitors are used to obtain energy spectra during the maximum phase of each event. The Monte Carlo simulation of the solar proton transport in the atmosphere based on GEANT4 enable us to determine spatial and energy distributions of secondary particles at the different atmospheric levels. The energy deposition and ion production rate in the stratosphere during powerful solar proton events are presented.

**Keywords:** solar protons, atmosphere, energy deposition, ionisation

## I. INTRODUCTION

The interest in the study of the ionisation process induced by charged particles of different origin in the Earth's atmosphere has grown during last decades. This is because ions might be involved in various atmospheric processes and could affect the global cloud cover, ion-induced nucleation, aerosol formation, atmospheric transparency, global electric circuit, etc. [1-6].

Galactic and solar cosmic rays, precipitating particles from magnetosphere are the most important sources of ionisation of the Earth's atmosphere above 2-3 km [7-11].

In this paper we present results obtained in two ways: (a) for the dose estimations from direct balloon cosmic ray measurements, and (b) for the GEANT4 Monte Carlo numerical derivation of energy deposition and ion production rate induced by galactic and solar cosmic rays in the atmosphere.

## II. ABSORBED DOSE ESTIMATION FROM BALLOON COSMIC RAY MEASUREMENTS

The long-term balloon observations of ionising particles in the atmosphere from the ground level up to 30 - 35 km have been carried out by Lebedev Physical Institute (LPI) using light radiosondes since 1957 [12]. The particle detector consists of two Geiger counters with 0.05 g·cm<sup>-2</sup> steel walls arranged as a vertical telescope with 2 g·cm<sup>-2</sup> Al absorber. 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  $\leq 1\%$ ). A telescope is sensitive to  $> 30$  MeV protons,  $> 5$  MeV electrons and  $> 15$  MeV muons. 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.

We note that balloon cosmic ray measurement gives a possibility of direct estimations of the absorbed dose from galactic cosmic rays and solar cosmic rays (SCRs) at different locations and altitudes in the atmosphere.

### A. Galactic cosmic rays

The main contribution to dose  $D$  in the atmosphere is from primary protons, helium nuclei, and secondary particles, i.e.  $D = D_p + D_{He} + D_{sec}$  [13]. The dose rates  $dD_p/dt$  and  $dD_{He}/dt$ , were calculated using equation [14]:

$$dD/dt = 2\pi Z^2 \int_{E_i}^{E_f} (dJ/dE) \cdot (\Delta E/\Delta x) dE \quad (1)$$

where  $dJ/dE$  is the differential energy spectrum of nuclei with a charge  $Z$ ,  $\Delta E/\Delta x$  are the ionization losses of nuclei ( $\Delta x$  in g·cm<sup>-2</sup>); and  $E_i$  and  $E_f$  are the initial and final energies, which are different for GCRs and SCRs. The estimations of dose from GCRs were performed for the altitude above 12 km. The fluxes of primary protons and helium nuclei at the atmospheric boundary for the solar activity minimum were taken from [15]. The proton and helium fluxes decrease due to nuclear interaction in the atmosphere were estimated using the mean free path  $\lambda_0=100$  g·cm<sup>-2</sup> for protons and  $\lambda_0=33$  g·cm<sup>-2</sup> for helium nuclei. We calculated the decrease in the number of primary particles and the contribution to the dose due to ionisation process. The absorbed dose rate from secondary particles was determined using an expression  $dD_{sec}(x)/dt = 1.8 MeV \cdot n_{sec}(x)$ , where  $n_{sec}(x)$  is the flux of secondary particles at the atmospheric depth  $x$ , taken from the LPI observations.

We choose balloon cosmic ray data obtained at polar region (Murmansk station, geomagnetic cutoff  $R_c=0.6$  GV) and at middle latitude (Moscow,  $R_c=2.36$  GV) during solar activity minimum January-May 1987. To calculate altitude dependence of absorbed dose  $D$  at these latitudes we used energy limits in expression (1) for

protons as  $E_i=0.175$  GeV (Murmansk) and 1.600 GeV (Moscow) and for helium nuclei  $E_i=0.047$  GeV/nucleon (Murmansk) and 0.565 GeV/nucleon (Moscow). The upper energy limit is  $E_f=100$  GeV for both stations. The obtained altitude dependences of the absorbed dose rate  $dD(x)/dt$  induced by GCRs at both latitudes are shown in Fig. 1 (curve 1 and 2; compilation from [13]).

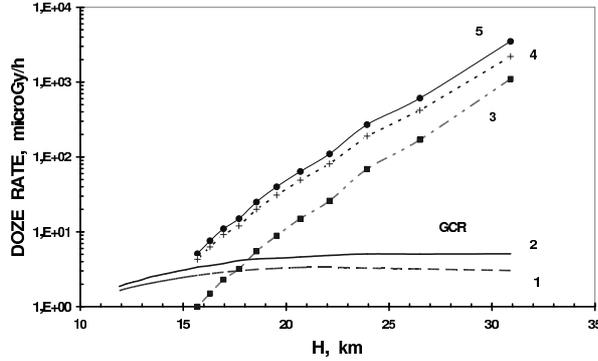


Fig. 1. The absorbed dose for GCRs in the atmosphere derived from the balloon CR measurements during solar activity minimum at middle ( $R_c=2.35$  GV; curve 1) and polar latitude ( $R_c=0.56$  GV; curve 2). The curves 3, 4 and 5 show the dose distribution in the atmosphere during solar proton events on 20.10.1989 (at 2306-2405 UT), 20.01.2005 (0957-1038 UT) and 14.07.2000 (1517-1608 UT), respectively.

### B. Solar protons

We selected the balloon measurements during solar proton events on 20 October 1989, 14 July 2000 and 20 January 2005. The energy spectrum of 100-500 MeV solar protons at the top of the atmosphere is determined for each radiosonde measurement using standard technique reported in [16]. The dose rate in the atmosphere was estimated on the assumption that the SCR flux consists of protons. The absorbed dose rate was calculated from formula (1) where we have taken energy parameters  $E_i=30$  MeV at Mirny and 100 MeV at Murmask station, respectively, while upper limit  $E_f=1000$  MeV for both stations. The curves 3, 4 and 5 show the derived dose distribution in the atmosphere over selected time intervals on 20 October 1989, 14 July 2000 and 20 January 2005. We point out that at altitudes of 12-18 km, the dose rate from SCRs is comparable with that from GCRs. At altitudes above 30 km, the dose rate from solar protons significantly exceeds that from GCRs. Also we note that dose rate at the atmospheric boundary on 15 July 2000 at 00-03 UT derived from our experiment as much as  $D=0.036$  Gy/h is in good agreement with that determined for the same time interval beyond the shield of  $1 \text{ g}\cdot\text{cm}^{-2}$  in [17].

### III. RESULTS OF MONTE CARLO SIMULATIONS: COSMIC RAY ENERGY DEPOSITION AND ION PRODUCTION IN THE ATMOSPHERE.

To calculate energy deposition and ion production rate in the atmosphere induced by GCRs and solar protons we used the Monte Carlo Planetocosmics code based on GEANT4 [18, 19]. The code takes into account the bremsstrahlung, ionization, multiple scattering, pair production processes, Compton scattering, photoelectric effect, elastic and inelastic nuclear interaction, and the decay of particles. To verify previous results we calcu-

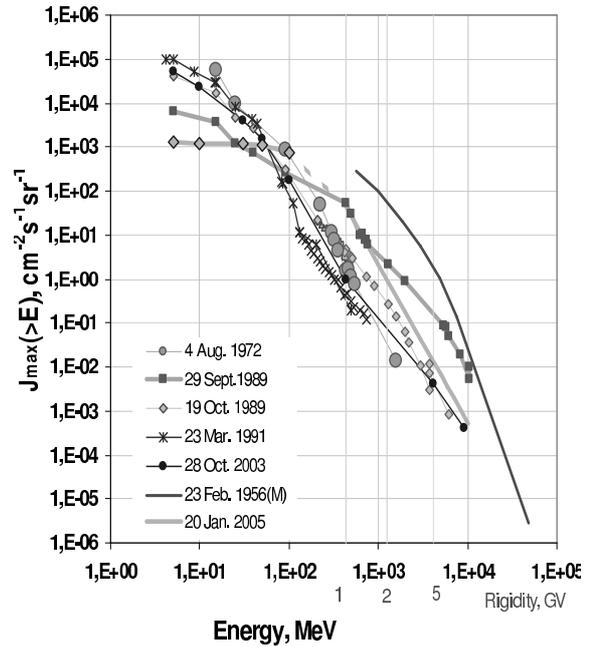


Fig. 2. Time-of-Maximum proton spectra derived from satellite, balloon and ground based neutron monitors measurements during powerful solar proton events 1956-2005.

lated absorbed dose distribution in the atmosphere using the solar proton spectra mentioned in previous subsection B. As a result we point out that both techniques, i.e. direct and based on the Planetocosmics code, are in a satisfactory agreement. It means that previous dose estimations for the solar protons ( $E \leq 500$  MeV) are correct [13].

To derive upper limit of the dose level from GCRs we used the GCR spectrum estimated during solar activity minimum 1976 [15] as an input into the code. The CGRs fluxes are maximum during this solar cycle epoch. The incident particles population is considered as isotropic at the top of the atmosphere.

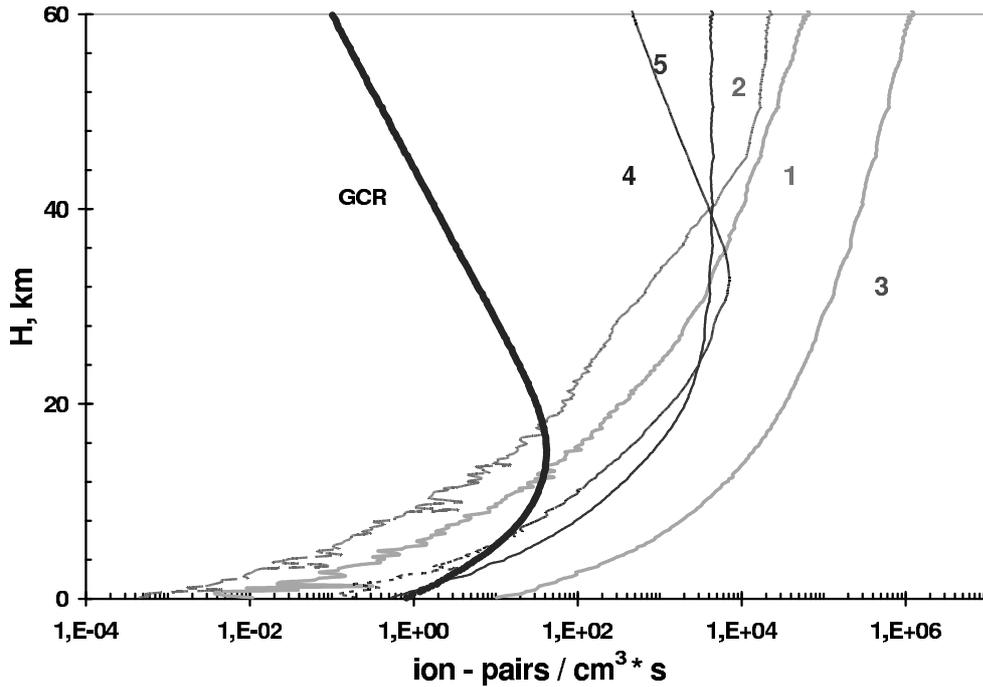


Fig. 3. Result of simulation: ion production rate in the atmosphere (upper limit) during solar proton events on 4.08.1972 (curve 1), 23.03.1991 (2), 23.02.1956 (3), 20.01.2005 (4) and 29.09.1989 (5). Solid line (left) shows an effect induced by GCRs in the atmosphere during solar activity minimum.

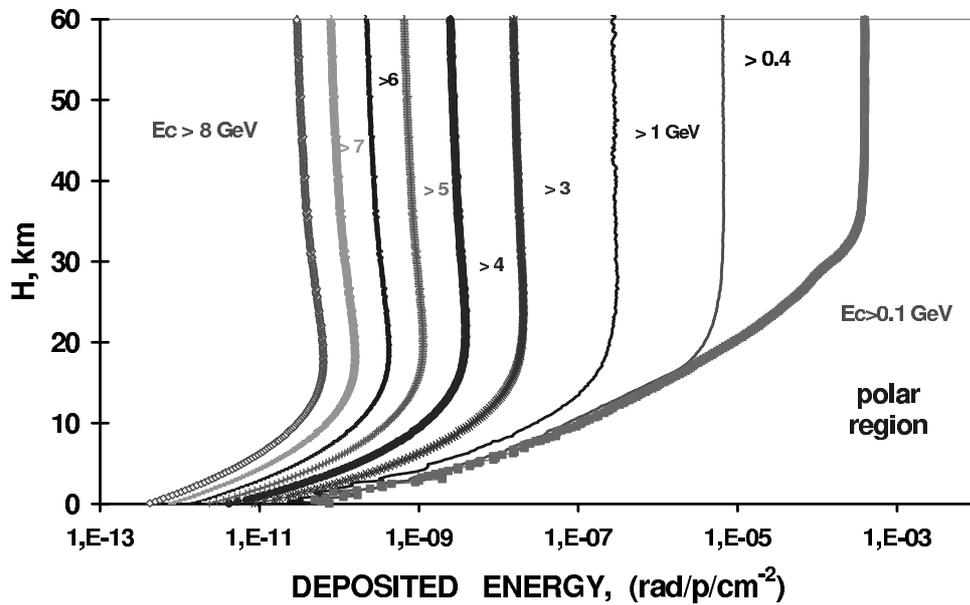


Fig. 4. The altitude dependence of energy deposition in the atmosphere at several geomagnetic locations as determined for solar proton event on 20 January 2005. The geomagnetic cutoff energy ( $E_c$ ) of the location denoted by numbers in the figure. 1 rad [rd]=  $10^4$  microgray [ $\mu$ Gy].

In order to determine maximum ionisation induced by solar protons in the atmosphere we composed the proton

energy spectra using available sets of experimental data obtained during strong solar proton events. We used peak

flux values of the solar protons flux in different energy domain recorded onboard satellites, in the atmosphere and by ground based neutron monitor network. As a result we derived so called Time-of-Maximum spectra [20] for the powerful solar proton events recorded during 1956-2005: 23.02.1956, 4.08.1972, 29.09.1989, 19.10.1989, 23.03.1991, 28.10.2003, and 20.01.2005 (Fig. 2). These evaluated proton energy spectra were used as an input into the Geant4 Monte Carlo simulations. We have computed interaction of proton populations with the Earth's atmosphere and derived energy deposition and ion production rate induced by galactic cosmic rays and solar protons. Obtained results are shown in Fig. 3.

Finally we estimated a possible latitude effect of the energy deposition in the atmosphere on 20 January 2005 event. In this case, we also used in the calculations a Time-of-Maximum proton energy spectrum shown in Fig. 2. Fig. 4 shows energy deposition in the atmosphere at several geomagnetic locations from low latitude up to polar region estimated for this event.

#### IV. SUMMARY

The results of the regular measurements of charged-particle fluxes in the Earth's atmosphere, performed at the Lebedev Physical Institute, Russian Academy of Sciences were used to determine the absorbed dose rate in the atmosphere from galactic cosmic rays in the period of minimum solar activity and from solar protons during solar proton events.

The GEANT4/Planetocosmics Monte Carlo simulations were used to estimate energy deposition and ion production rate in the atmosphere induced by galactic cosmic rays and solar protons during powerful solar flares.

Both approaches to the dose estimation give the consistent results.

#### V. ACKNOWLEDGMENTS

This study was partially supported by the Russian Foundation for Basic Research (grants 07-02-01019a, 07-02-10018k, 07-02-01405, 08-02-00054, 08-02-91006 and 09-02-10018) and the Program of Presidium of RAS "Neutrino physics".

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