Geomagnetic Variations of Cosmic Ray Ionization in the Ionosphere for Different Latitudes

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The galactic cosmic rays create ionization in the D region of the lower ionosphere where the mesosphere and the lower thermosphere are disposed. This ionization - electron production rate profiles q(h), is characterized by strongly expressed latitudinal effect. The cosmic ray (CR) ionization has three types of variations: I class - meteorological variations (related to the atmosphere density changes), II class - geomagnetic variations (during the magnetic disturbances and storms) and III class - primary variations (related to CR spectra). These variations are most strongly expressed in the main phase of the magnetic storms when the magnetosphere is compressed. The geomagnetic field decrease leads to corresponding geomagnetic threshold Rc decrease and to ionization increase due to cosmic ray intensity growth. A physical model is created. The storm influence is described with the simple model of Obayashi and Hakura (1960), which gives the decrease of the geomagnetic cut-off rigidity Rc. The CR ionization variations are analyzed in altitude and in geomagnetic latitude for different concrete big geomagnetic storms in the last solar cycle, for example: 27 July 2004, 10 November 2004, and 21 January 2005. Some of them are connected to solar proton events or GLEs (Ground Level Enhancements) and also SPE (Solar Particle Events). The provided quantitative analysis can be used for modeling of the solar-terrestrial influences and for explanation of their physical mechanisms. The equations take into account the different levels of modulation of CR protons and CR hevier nuclei.

Introduction

The galactic cosmic rays (GCR) create ionization in the *D* - region of the lower ionosphere where the mesosphere and the lower thermosphere are disposed. This ionization - electron production rate profiles *q(h)*, is characterized by strongly expressed latitudinal effect. The cosmic ray (CR) ionization has three types of variations. A physical model is created. The storm influence is described with the simple model of [1] which gives the decrease of the geomagnetic cut-off rigidity R_c. In Table 1 and 2 are presented the results from our model calculations. The prompt and delayed solar cosmic rays (SCR) spectra from GLE05 and GLE69 events are shown on Fig. 1.

Variations of the electron production rate profiles

In the general expression for q at an altitude h (km) three factors may be changed in principle: atmospheric density $\rho(h)$ (g.cm^{-3}), geomagnetic cut-off rigidity R_c (BV) and differential spectrum $D(R)$. In order to find the relative q – variation, the following equation is obtained (Velinov, 1971):

$$\frac{\partial q(h)}{q(h)} = \frac{\partial \rho(h)}{\rho(h)} - \partial R_c W(R_c) + \int_{R_c}^{\infty} \frac{\delta D(R)}{D(R)} W(R)\,\mathrm{d}R \qquad \textbf{(1)}$$

where

$$W(R) = \frac{2\pi}{Q} \frac{D(R)(\mathrm{d}R/\mathrm{d}h)}{q(h)} \qquad \textbf{(2)}$$

is the coefficient relating the variation of $\delta q/q$ with δR_c and with $\int (\partial D / D)\mathrm{d}R$. After certain transformations it is obtained

$$W(R) \approx (\gamma\text{-}1)/R$$

where $\gamma \approx 2.6$ is the power of the differential spectrum $D(R)=K.R^{-\gamma}$.

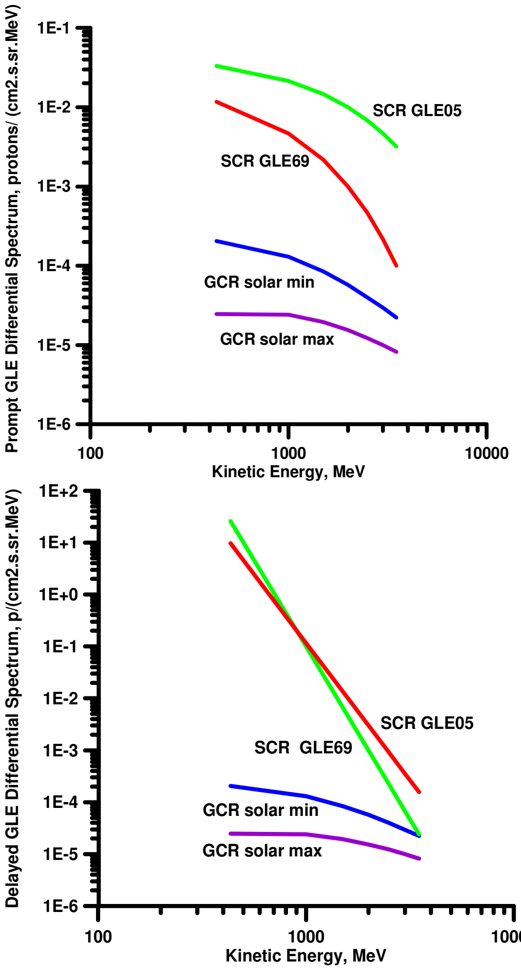

Fig. 1. Prompt and delayed SCR spectra from GLE05 (23 February 1956) and GLE69 (20 January 2005); GCR spectra for minimal and maximal solar activity

In accordance with equation (1) the electron production rate variations may be divided into three classes corresponding to the three classes of CR variations:

I. Class – variations of the atmospheric density

These variations are connected with change of air density and hence with the proportional variation of the ionization losses of the CR. There are several sub-classes of the variations $\delta\rho/\rho$.

II. Class – geomagnetic variations

They are connected with the change of the Earth magnetic field and its influence on the geomagnetic cut-off. This class of variations depends on the magnetic storm intensity as well as on the magnetic latitude. The class II variations show themselves mostly during the period of the main phase of the geomagnetic storm when under the influence of the solar corpuscular fluxes the magnetosphere shrinks. The geomagnetic field decrease leads to decrease of the geomagnetic cut-off and according the expression [2]

$$-\partial R_c\, W(R_c) = -(\gamma - 1)\frac{\partial R_c}{R_c} \qquad (3)$$

to the respective increase of the electron production rate as a result of the increase of the *CR* intensity. In one of the first theoretical models of the magnetic storm (Obayashi and Hakura, 1960) the following formula of the geomagnetic cut-off variation is obtained

$$\frac{\partial R_c}{R_c} = 1 - \text{const}\left(1 - \frac{r_0^3 \partial H}{2M}\right)^2 \qquad (4)$$

where r_0 is the Earth radius, $M = 8.1\times10^{25}$ G cm^3 is its magnetic moment and δH is the geomagnetic field variation. The percentage change in q as a function of the cut-off rigidity is represented in [1] for different values of the disturbance in geomagnetic field.

Symbols and abbreviations which are used in Tables 1 and 2

CR decrease – ratio of the cosmic rays (CR) decrease intensity to the quiet CR intensity, ΔH – variation of the geomagnetic field value during the geomagnetic storms, R_C - value of the cut-off rigidity at quiet conditions, R_c' , GV – decreased value of the cut-off rigidity at disturbed conditions, γ_0 - power of the CR differential spectrum at quiet conditions, γ - power of the CR differential spectrum at disturbed conditions, Cosmic rays Integral Spectrum (IS):

$$D(>R_C) = (K{*}R_C^{\ -\gamma+1})/(\gamma-1);$$

$D_1(>R_C)$ - IS at quiet conditions; $D_2(>R_C)$ - IS at disturbed conditions for the initial cut-off rigidity value R_C; $D_3(>R_C')$ - IS at disturbed conditions for the decreased cut-off rigidity value R_C' , caused by the geomagnetic storm;

$q_1(50)$ – electron production rate at altitude 50 km (base of the CR layer) at quiet conditions for the given R_C value,

$q_2(50)$ – electron production rate at altitude 50 km (base of the CR layer) at disturbed conditions for the given R_C value,

$q_2(\Delta H, 50)$ – electron production rate at altitude 50 km (base of the CR layer) at disturbed conditions for the decreased R_C value.

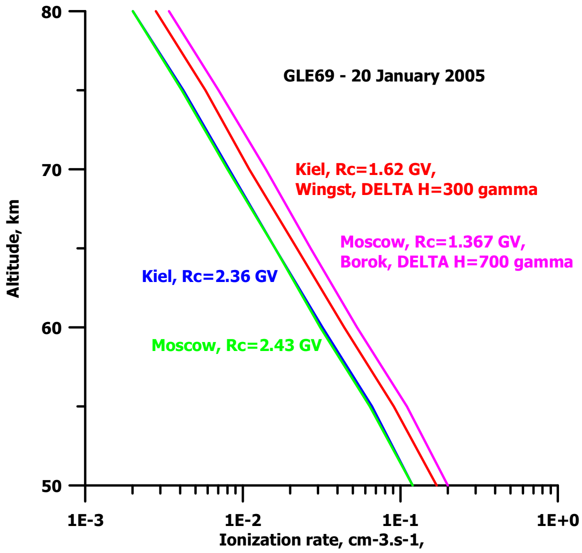

Fig.2. Electron production rate profiles increase due to geomagnetic storm during the GLE69 event for the CR observatories at Moscow and Kiel

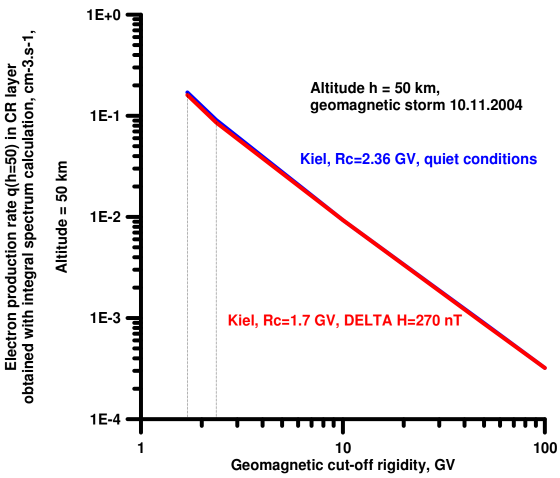

Fig. 3. Electron production rate at altitude h=50 km for the geomagnetic storm on 10 November 2004, obtained with integral spectrum calculation

III. Class – variations of the primary CR

This is the biggest and most important class of variations which are of extraterrestrial origin [3, 4, 5]. They are connected with the change of the energetic spectrum far from the Earth. The most important sub-classes are the modulation and generation processes connected with the solar activity. The more important types of variations III. Class are the following: a) 11 yr variations, Forbush effects, 27 day variations; b) Solar cosmic rays – process of particle generation in the solar atmosphere

Some experimental results and their explanation

In Table 1 are given the calculations of the Forbush decrease effects of the SSCs on 27 July 2004, on 10 November 2004 and of the GLE69 on 20 January 2005. It can be seen that the modulation of the GCR spectrum causes smaller decrease of the electron production rate in its absolute value than the electron production rate increase due to the cut-off rigidity decreases [5] caused by the geomagnetic storms (Figs. 2-3). Greater geomagnetic storms cause greater decrease of the cut-off rigidity. It follows from the the respective geomagnetic storms and the characteristic Forbush decreases (see Table 1). This is the reason for the corresponding higher value of the electron production rate (Table 1, Fig.1-3). It corresponds to the model in [1].

The solar cosmic rays on 20 January 2005 cause a respective increase of the electron production rate profiles [6, 7]. These results are presented on Figs. 1, 4, 5. [8].

The SCR effect on the electron production rate is observed in the middle atmosphere at lower altitudes where is situated the stratospheric ozone maximum. The impact of SCR on it is calculated and statistically evaluated [9]. A Monte Carlo model is applied there (the CORSIKA programme) because of the nuclear interactions which dominate under the altitude of 35 km [11]. An analytical - numerical model is applied above this altitude [5, 6, 7].

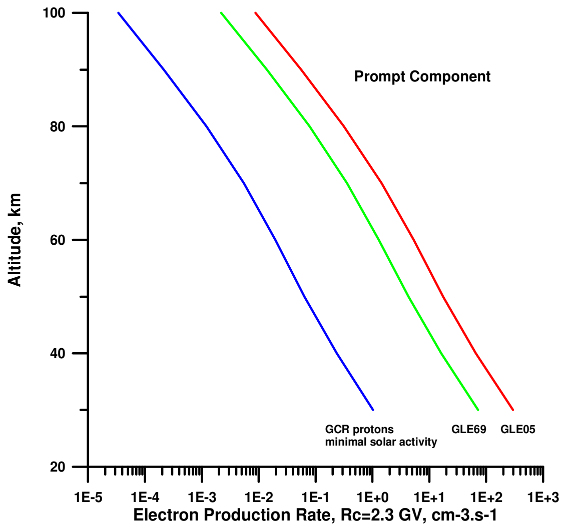

Fig.4.Electron production rate profiles – prompt component, for GLE69 and GLE05 with analytical– numerical model, Moscow region, compared with GCR minimal solar activity ionization

Induced ionization by SCR and geomagnetic storms

An improved analytical and numerical model of the electron production rate q ($cm^{-3}s^{-1}$) from solar cosmic rays with charge Z in the Earth atmosphere and ionosphere is created. A two energy interval approximation of the ionization losses function (*dE/dh*) is introduced. It performs better approximation of the measurements and experimental data in comparison with previous results. An intermediate transition region between the intervals is used for their coupling on the traveling substance path during the cosmic ray (CR) penetration in the middle atmosphere. The ionization profiles are calculated on the PC with application of the Romberg extrapolation method. They are in accordance with experimental data [10]. Different groups of CR nuclei are considered: protons p, α - particles (He nuclei), medium (M nuclei) etc. A new third energy interval for charge decrease in lower energies is taken into account. The atmospheric cut-offs and the geomagnetic cut-off rigidities are included and computed. The energy transformation of CR in the middle atmosphere is calculated.

This model is applied for calculation of *q(h)* profiles by galactic (GCR) and solar cosmic rays in the middle atmosphere. The ionization rates are obtained for different cases following given solar CR spectrum (Fig.1). Two major solar proton events (20 January 2005, 23 February 1956) and their effects on the Earth environment are studied (Fig.2) .

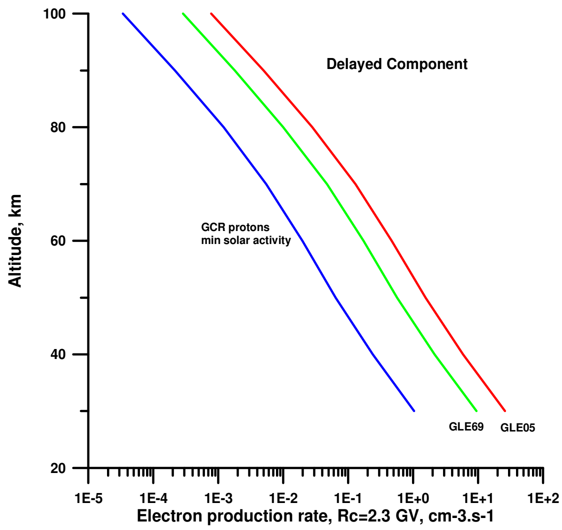

Fig.5. Electron production rate profiles – delayed component, for GLE69 and GLE05 with analytical – numerical model, Moscow region, compared with GCR minimal solar activity ionization

Simulations with the recent nuclear physics model for evaluation of solar cosmic ray induced ionization in the atmosphere

Our computations carried out with CORSIKA 6.52 code using FLUKA 2006 and QGSJET II hadronic interaction models, precisely the energy deposit of CR induced air showers, are used under the altitude of 35 km. The ionization yield function Y and the ion pair production *q(h)* in the atmosphere for the above mentioned solar proton events are calculated [9, 11].

Modeling of GCR and SCR Spectra.

The GCR spectra modeling is presented in [6]. The GCR spectra for maximal (ϕ=1200 MV for GLE05) and minimal (ϕ=400 MV for GLE69) solar activity [12] (Usoskin and Kovaltsov, 2006) are also included. The prompt and the delayed SCR spectra (Vashenyuk et al., http) are modeled with the following formulas:

$-D(E)=2.914\times10^{6}\exp(-0.767E)$[protons/($m^2$.s.GeV)], prompt component (PC) with exponential law spectrum for GLE05

$-D(E)=5.06\times10^{15}E^{-5.28}$ [protons/(cm^2.s.MeV)], delayed component (DC) with power law spectrum for GLE05

$-D(E)=1.363\times10^{6}\exp(-1.535E)$[protons/($m^2$.s.GeV)], prompt component with exponential law spectrum for GLE69

-D(E)=$5.4\times10^{19}E^{-6.645}$ [protons/(cm^2.s.MeV)], delayed component with power law spectrum for GLE69

This spectra modeling takes into account the SCR flux transformation during the GLE05 and the GLE69 events

Conclusions

The integral spectrum model for ionization rate calculation can be applied for evaluation of electron production rate profiles of the ionosphere CR layer under the influence of measured geomagnetic storms and the associated Forbush decreases of GCR for different latitudes. The obtained computational results are in accordance with experimental data [5].

The computed electron production rate profiles from SCR for the GLE05 and the GLE69 events show an ionization increase in the middle atmosphere which is important for the electrical and chemical state of the Earth's environment. This ionization increase influences the ozone content in the stratosphere. It corresponds to the CR spectra intensities and to the geomagnetic cut-off rigidities in the atmosphere. At lower altitudes, under 35 km, the nuclear interactions and the atmospheric cut-offs must be taken into account – with the Monte Carlo model and the programme CORSIKA [13]. That means, the analytical - numerical model can be applied above the altitude 35 km [5, 14, 15].

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TABLE 1.
Parameters of CRs (Forbush decreases), geomagnetic storms and their effects on the atmospheric ionization at 50 km during the strong SSC in 2004 and 2005, namely in January 2005 (associated with the GLE69 on 20 January 2005), on 10 November 2004 and on 27 July 2004

Parameters	Oulu, 21.01. 2005	Moscow, 21.01. 2005	Kiel, 21.01. 2005	Oulu, 10.11. 2004 (1)	Oulu, 10.11. 2004 (2)	Moscow, 10.11. 2004 (2)	Kiel, 10.11. 2004 (1)	Kiel, 10.11. 2004 (2)	Oulu, 27.07. 2004	Moscow 27.07. 2004	Kiel 27.07. 2004
CR decrease	0.14	0.27	0.31	0.054	0.057	0.055	0.058	0.069	0.11	0.13	0.121
ΔH, nT	970	700	300	1850	1070	1250	270	210	900	720	330
Rc , GV	0.5	2.43	2.36	0.5	0.5	2.43	2.36	2.36	0.5	2.43	2.36
Rc' , GV	0.188	1.367	1.62	0.062	0.125	1.14	1.7	1.77	0.156	1.29	1.593
$\gamma 0$	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
γ	2.57	2.52	2.49	2.59	2.59	2.57	2.58	2.58	2.57	2.56	2.56
D1	0.255	0.15	0.152	0.19	0.19	0.11	0.114	0.114	0.19	0.112	0.114
D2	0.218	0.11	0.1	0.18	0.18	0.1	0.107	0.106	0.17	0.097	0.1
D3	0.218	0.264	0.175	0.18	0.18	0.33	0.179	0.168	0.17	0.258	0.184
q1(50)	0.7	0.12	0.12	0.52	0.52	0.088	0.091	0.091	0.85	0.15	0.15
q2(50)	0.6	0.088	0.081	0.49	0.49	0.08	0.086	0.085	0.76	0.13	0.13
q2(ΔH,50)	2.7	0.26	0.16	13	4.3	0.36	0.16	0.15	4.7	0.43	0.27

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