The 3rd International Symposium on Cosmic Rays and Astrophysics
(ISCRA-2021)

Atmospheric effects of electron and muon components of cosmic rays: Sensitivity theory approach and data of operational satellite monitoring

Lagutin A.A. **Goncharov A.I.** **Raikin R.I.** **Reviakin A.I.**
Volkov N.V.

Institute of Digital Technology, Electronics and Physics
Radiophysical and Theoretical Physics Department
Altai State University, Barnaul, Russia

June 8-10, 2021

ISCRA-2021

Problem

Analysis shows that the spatial distributions of particles generated by a cascade process in the Earth's atmosphere is determined by the character of the height distribution of air density ρ, or (due to the relationship between density and temperature $\rho(t) \sim 1/T(t)$) by the distribution of temperature T over atmospheric depth t.

Variations in the atmospheric temperature profile change the spatial distribution of particles.

Main goal

Presentation of results of a complex approach to the study of sensitivity of spatial distributions of electron and muon components of extensive air showers (EAS), measured by scintillation detectors, to variations in the temperature profile of the atmosphere.

Solution to the problem

To study the effect of variations in the temperature profile $\Delta T(t)$ of the atmosphere on the characteristics of EAS, we divide the problem into two tasks.

Task I. Calculation of spatial distribution function (SDF) $\overline{N}_i(r, E, t; T(\cdot))$ of the shower particles at depth t, generated by a primary particle of type i with energy E, in unperturbed atmospheric state $T(t)$.

Task II. Determination of the sensitivity of this distribution $\Delta\overline{N}_i(r, E, t; T(\cdot) \to T(\cdot) + \Delta T(\cdot))$ to changes in temperature profile $T(t) \to T(t) + \Delta T(t)$.

Variable $T(\cdot)$ in the argument of these functions denotes the dependence of the corresponding functional value on the entire atmospheric temperature profile.

Variations in spatial distributions of the characteristics of EAS

For known functions $\overline{N}_i$ and $\Delta\overline{N}_i$, spatial characteristics of EAS at some temperature distribution $T(t) + \Delta T(t)$ (in the perturbed atmosphere) can be found using equation

$$\overline{N}_i(r, E, t; T(\cdot) + \Delta T(\cdot)) \quad \underbrace{= \overline{N}_i(r, E, t; T(\cdot)) +}_{\text{SDF in unperturbed atmospheric state } T(t)}$$
$$\underbrace{+\Delta\overline{N}_i(r, E, t; T(\cdot) \to T(\cdot) + \Delta T(\cdot)).}_{\text{Sensitivity of SDF to changes in temperature profile } T(t) \to T(t) + \Delta T(t)} \qquad (1)$$

Sensitivity of SDF

The sensitivity of SDF of shower particles to changes in the temperature profile at the atmosphere depth t_1 can be written as

$$\Delta\overline{N}_i(r,E,t;T(\cdot)\to T(\cdot)+\Delta T(\cdot))\approx$$
$$\approx\int\overline{N}_i^{(1)}(r,E,t;t_1,T(\cdot))\Delta T(t_1)dt_1\approx$$
$$\approx\int\frac{\delta\overline{N}_i(r,E,t;T(\cdot))}{\delta T(t_1)dt_1}\Delta T(t_1)dt_1. \quad (2)$$

Coefficient of differential sensitivity

$$\overline{N}_i^{(1)}(r,E,t;t_1,T(\cdot))=$$
$$=\frac{\delta\overline{N}_i(r,E,t;T(\cdot))}{\delta T(t_1)dt_1},$$

1st order variational derivative of SDF.

Calculating of the spatial characteristics of EAS

To calculate the spatial characteristics of EAS in the atmosphere whose temperature profile $T(t)$ varied by $\Delta T(t)$, it is sufficient to know the spatial characteristics of shower at some unperturbed temperature profile $\overline{N}_i(r, E, t; T(\cdot))$ and the coefficients of differential sensitivity

$$\overline{N}_i^{(1)}(r, E, t; t_1, T(\cdot)) = \delta \overline{N}_i(r, E, t; T(\cdot)) / \delta T(t_1) dt_1,$$

caused by variations in temperature of the atmosphere at different depths t_1, i.e.,

$$\overline{N}_i(r, E, t; T(\cdot) + \Delta T(\cdot)) = \underbrace{\overline{N}_i(r, E, t; T(\cdot))}_{\text{Task I}} +$$

$$+ \underbrace{\int \frac{\delta \overline{N}_i(r, E, t; T(\cdot))}{\delta T(t_1) dt_1} \Delta T(t_1) dt_1}_{\text{Task II}}.$$

Temperature effect of the electron component of EAS

To analyze the temperature effect of the electron component of EAS, we modified the Nishimura–Kamata–Greisen (NKG) modulus in CORSIKA code (v7.6400).

- To calculate the spatial distributin of electrons $\overline{N}_i$, we replaced the NKG formula with the scaling function (see ISCRA contribution ID 11).
- Calculations of $\overline{N}_i^{(1)}$ were performed using the database of temperature coefficients (variational derivatives) for the lateral distribution of electrons in electromagnetic cascades, which we obtained in [1,2] by solving adjoint equations for variational derivatives of the distributions of particles in electron-photon cascades. In CORSIKA code this temperature coefficients were interpolated according to parameters of EAS.

1. Lagutin, A.A. and Uchaikin, V.V. Adjoint Method in the Theory of Transport of High-Energy Cosmic Rays: Monograph. Barnaul: Altai. Univ., 2013 (in Russian).
2. Goncharov, A.I., Lagutin, A.A., and Melent'eva, V.V. Sensitivity of the Spatial Distribution of Electrons in Electron-Photon Cascades to Variations of the Atmospheric Temperature Profile, Barnaul: Altai. Univ., 2000 (in Russian).

Temperature effect of the electron component of EAS

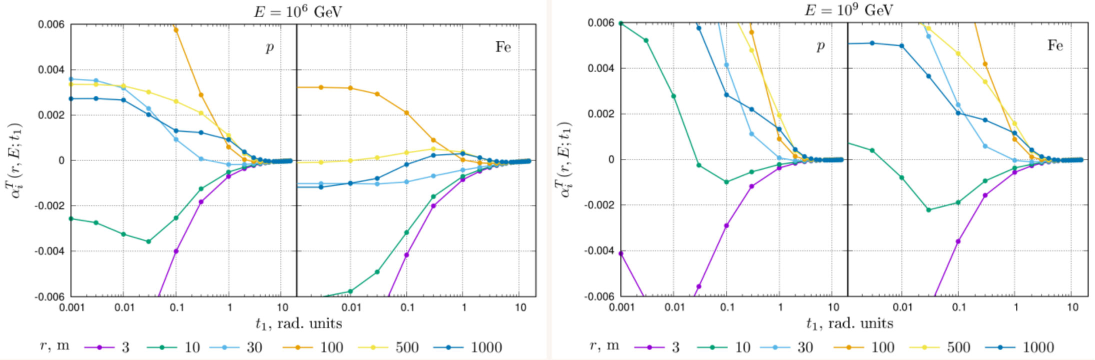
Calculations of both the differential temperature coefficients of the spatial distributions of electrons $\overline{N}_i^{(1)}(r, E, t; t_1, T(\cdot))$ and normalized temperature coefficients α_i^T,

$$\alpha_i^T(r, E, t; t_1) = \frac{\overline{N}_i^{(1)}(r, E, t; t_1, T(\cdot))}{\overline{N}_i(r, E, t; T(\cdot))},$$

were performed for an isothermal atmosphere
($T_0 = 293$ K, $\rho(0) = 1.22 \cdot 10^{-3}$ g/cm^3).

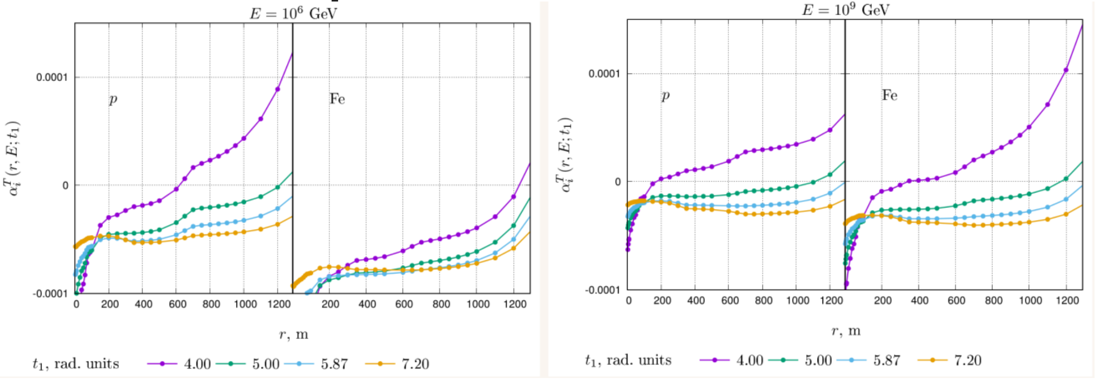
Variable t was counted from the level of observation, so it will be excluded from function variables below.

Normalized temperature coefficients



Dependencies of the temperature coefficients of the electron component of EAS from depth of perturbation t_1 for different distances from the shower axis at primary particle energies $E = 10^6$ GeV (left) and $E = 10^9$ GeV (right); EASs were initiated by primary protons ($i = p$) and iron nuclei ($i =$Fe).

Normalized temperature coefficients



Dependencies of the temperature coefficients of the electron component of EAS from distances from the shower axis r for different depth of perturbation t_1.

Normalized temperature coefficients

Results

- An one-degree change in temperature in a depth of one radiation unit leads to a change in SDF on $(0.2 - 0.6)\%$ under perturbations of the atmosphere in the surface layer $t_1 \approx (0 \div 0.03)$ rad. units and on 0.06% – for $t_1 \approx 4$ rad. units.
- An increase in the temperature of the atmosphere reduces the particle density in the range $r \le (10 - 20)$ m and raises it when $r > 40$ m. In the range $r \approx (20 - 40)$ m the temperature effect of the spatial distribution of electrons is minimal.

Method of adjusting SDF of electrons for the temperature effect

Integral temperature coefficient

In the linear approximation the change of SDF of electrons with a change in the temperature profile $T(t_1) \to T(t_1) + \Delta T(t_1)$ in the bottom troposphere $[0, t]$ for $t \approx 6 - 8$ rad. units. describes by the integral

$$\int_0^t \alpha_i^T(r, E; t_1)\, \Delta T(t_1) dt_1.$$

An analysis of the behavior of the temperature coefficients shows that this integral can be approximated by the expression (3)

$$\int_0^t \alpha_i^T(r, E; t_1)\, \Delta T(t_1) dt_1 \approx \overline{\alpha}_i^T(r, E; t)\, \Delta\overline{T}, \quad (3)$$

The integral temperature coefficient $\overline{\alpha}_i^T(r, E; t)$

The average temperature variation

$$\Delta\overline{T} = \frac{1}{t}\int_0^t dt_1 \Delta T(t_1).$$

SDF of EAS electrons

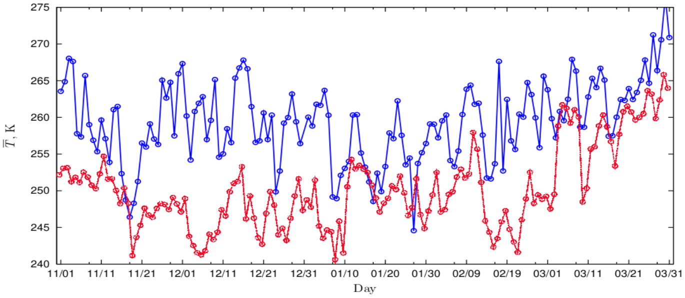
The SDF of electrons $f(r, E; T(\cdot) + \Delta T(\cdot))$ in the atmosphere with a temperature profile $T(t) + \Delta T(t)$ is expressed in terms of SDF in the basic isothermal atmosphere $f(r, E; T_0)$ as

$$f(r, E; T(\cdot) + \Delta T(\cdot)) = f(r, E; T_0)\left[1 + \overline{\alpha}_f(r, E; t)\,\Delta\overline{T}\right]. \qquad (4)$$

In particular, relative changes in the SDF of electrons at the distance $r = 600$ m from axis in a vertical EAS initiated by a proton with the energy $E = 10^6 - 10^8$ GeV is given by

$$\frac{\Delta f_p(600, E; T(\cdot) \to T(\cdot) + \Delta T(\cdot))}{f_p(600, E; T_0)} = (2 \div 4) \cdot 10^{-3} \Delta\overline{T}. \qquad (5)$$

Variations of the temperatures



Variations of the average temperatures in a layer of 300 hPa above the observation level from November to March at the location of the TAIGA observatory (blue) and the Yakutsk EAS array (red). AIRS/Aqua data

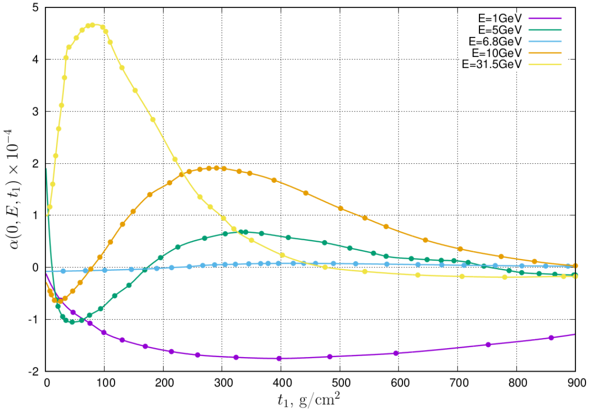
> Since variations $\Delta\overline{T}$ in a layer of $\sim 6-8$ rad. units in the areas of the Yakutsk EAS array and the TAIGA observatory can reach up to 30 K, the changes in the SDF of electrons can exceed $\sim 10\%$.

Temperature effect of the muon component of EAS

Temperature effect of the muons of EAS

An approach based on the numerical solution of adjoint equations and equations for the variational derivatives was used to calculate the partial temperature coefficients of the muon component [1].

1. Lagutin, A.A. and Uchaikin, V.V. Adjoint Method in the Theory of Transport of High-Energy Cosmic Rays: Monograph. Barnaul: Altai. Univ., 2013 (in Russian).



Partial temperature coefficients of the muon component of EAS.

Conclusion

- Coefficients of the differential sensitivity of SDF of the electron and muon components of EAS to variations in the atmosphere temperature profile were obtained for the first time. It was shown that variations in the spatial distributions are determined mainly by changes in the atmospheric temperature in a layer of 6-8 rad. units above the level of observation.
- Based on the obtained data, a method for correcting the EAS detectors readings in view of the temperature effect has been developed. It is shown that changes in the lateral distribution function of the EAS electromagnetic component due to variations in the atmospheric temperature profile in one annual cycle of operation can exceed 10%.
- To calculate the partial temperature coefficients of the muon component, an approach based on the numerical solution of adjoint equations and equations for the variational derivatives was proposed.

Thanks

Questions and Comments

lagutin@theory.asu.ru, volkov@theory.asu.ru

Template of this presentation `https://github.com/deuslirio/UFGTeX-Presentation`