29th International Cosmic Ray Conference Pune (2005) **2**, 389-392

Variations of Intensity of Cosmic Ray Muons due to Thunderstorm Electric Fields

N.S. Khaerdinov and A.S. Lidvansky
Institute for Nuclear Research, Russian Academy of Sciences, 60th October Anniversary pr. 7a, Moscow, 117312 Russia
Presenter: A.S. Lidvansky (lidvansk@sci.lebedev.ru), rus-khaerdinov-N-abs1-sh35-oral

The effect of thunderstorm electric field on the muon intensity observed at the ground level is considered. It is demonstrated that both linear and quadratic effects are present in the intensity as a function of the near-earth electric field and the potential difference between the ground level and the altitudes of muon production. The resulting effect is predominantly negative (decrease of intensity) and its amplitude increases with decreasing threshold energy of muons, in accordance with the data of the Baksan experiment.

1. Introduction

In [1], correlations with the near-earth electric field during thunderstorms were studied for cosmic ray muons with different threshold energies. In all cases the regression curve "relative intensity versus field" was approximated by second-order polynomials. Both linear and quadratic coefficients of regression were shown to be negative and strongly increasing when the muon threshold energy decreased. This result is generally consistent with calculations [2] of the effect for muons in the electric field with three different profiles. However, the results of some calculations published later [3, 4, 5] turned out to be in contradiction with our results, quantitatively and even qualitatively. In this paper we consider the problem in some detail and discuss possible causes of this controversy, based on the Baksan experimental data.

2. Electric field during thunderstorms

Under fair weather conditions the potential difference between the ground surface and lower ionosphere is rather small (200-500 kV). During thunderstorms, electric charge in clouds is concentrated mainly in horizontal layers [6] so that the field vector has almost vertical direction. According to direct measurements of vertical profiles of thunderstorm electric fields [7, 8], they have several layers with oppositely directed strong field, but the net field between the ground and ionosphere is probably still rather small. Generally, the level of generation of muons is higher than the top of thunderclouds, therefore, a muon propagating through several regions of oppositely directed strong field has no considerable gain or loss of energy.

3. Propagation of muons through air during thunderstorms

Let us consider the one-dimensional problem for vertical muons moving in the electric field. Neglecting scattering of muons and energy dependence of their energy loss, the kinetic equation for the muon intensity J has the following form (for definiteness, positive muons are considered)

$$\frac{\partial J(z,\varepsilon)}{\partial z} - [\alpha - \beta(z)]\frac{\partial J(z,\varepsilon)}{\partial \varepsilon} + \frac{b}{z\left(\varepsilon^2 - (mc^2)^2\right)^{1/2}} J(z,\varepsilon) = U(z,\varepsilon), \qquad (1)$$

where z is the muon path length in g·cm^{-2} (z = 0 corresponds to the atmosphere boundary), α = 2 MeV/(g·cm^{-2}), ε is the total energy, b = 1 *GeV* is the decay constant, and $\beta(z)$ is the Lorentz force acting upon particles and normalized to the medium air density $\beta(z) = \frac{|e|D(z)}{\rho(z)}$ (positive field direction is from top to bottom). The solution to equation (1) for the level of detection x at the initial conditions $J(0, \varepsilon) = 0$ has the form

$$J(x,E) = \int_0^x \left\{ U(t,\varepsilon(t,E)) \cdot \exp\left[-b\int_t^x \frac{dt'}{t'\left(\varepsilon^2(t',E)-(mc^2)^2\right)^{1/2}} \right] \right\} dt . \qquad (2)$$

Here,

$$\varepsilon(t,E) = E + mc^2 + \alpha(x-t) - \int_t^x \beta(z)dz , \qquad (3)$$

and E is the kinetic energy of muons at the level of detection. Thus, variations of the muon intensity are formed throughout the entire depth of the atmosphere. In order to determine them, one needs to calculate the integral of the electric field vertical profile. Let us estimate the value of this integral using characteristic features of the electric field noticed above. Its maximum strength decreases with altitude being limited by $|\beta|_{\max} \approx \alpha$, while its sign is alternating. Let us introduce the characteristic altitude t^* starting from which the electric field strength is negligibly small. We assume

$$\beta(z) = \begin{cases} 0, & z < t^* \\ \beta(z), & t^* \le z \le x \end{cases} \qquad (4)$$

Usually the value of t^* corresponds to altitudes of order of 10 km [7]. The potential difference $\Phi(t^*, x)$ should be close to the potential difference between the ionosphere and ground surface, and its value in this approximation is limited: $\Phi(t^*,x) < 1\ MeV << mc^2$. On the strength of (3) the total energy of muons produced at some point t and reaching the observation level x looks like

$$\begin{cases} \varepsilon_\Phi(t,E) = E + mc^2 + \alpha(x-t) - \Phi(t^*,x)), & t \le t^* \\ \varepsilon(t,E) = E + mc^2 + \alpha(x-t) - \Phi(t^*,x)) + B(t^*,t) & t > t^* \end{cases} . \qquad (5)$$

Here, $B(t^*, t)$ is the potential difference between levels t^* и t. Making identical transformations, we reduce solution (2) to the following form

$$J(x,E) = J_0(x,E-\Phi)\cdot\exp\left[-b\int_{t^*}^{x}\left(\frac{1}{E^*(t')} - \frac{1}{E_\Phi{}^*(t')}\right)\frac{dt'}{t'}\right] +$$

$$+\int_{t^*}^{x}\left\{U(t,\varepsilon_\Phi)\exp\left(\int_t^x \frac{-b\,dt'}{t'E_\Phi{}^*(t')}\right)\left[\exp\left(\int_{t^*}^{t}\left(\frac{-b}{E^*(t')} - \frac{-b}{E_\Phi{}^*(t')}\right)\frac{dt'}{t'}\right) - \exp\int_t^x\left(\frac{-b}{E^*(t')} - \frac{-b}{E_\Phi{}^*(t')}\right)\frac{dt'}{t'}\right]\right\}dt +$$

$$+\int_{t^*}^{x}\left\{\left[U(t,\varepsilon(t,E)) - U(t,\varepsilon_\Phi(t,E))\right]\cdot\exp\left(\int_t^x \frac{-b\,dt'}{t'E^*(t')}\right)\right\}dt.$$

Here, $E^*(t') = \left[\varepsilon(t',E)^2 - (mc^2)^2\right]^{1/2}$, $E_\Phi{}^*(t') = \left[\varepsilon_\Phi(t',E)^2 - (mc^2)^2\right]^{1/2}$. Since a change of muon energy under the action of electric field is small in comparison with the energy loss of a muon we make further estimates using the following small parameter $\lambda = \frac{B(t^*,t)}{E + \alpha(x-t)} << 1$. After expansion of integrand into series in terms of powers of parameter λ we retain the terms of the first order and have the following expression

$$J(x,E) = J_0(x,E-\Phi)\times\left\{1+\left[b\int_{t^*}^{x}\frac{B(t^*,t)\varepsilon_\Phi(t',E)}{(E_\Phi{}^*(t'))^3}\frac{dt'}{t'}\right]\right\}. \qquad (6)$$

Let us expand the potential difference into a series at the point of detection x:

$$B(t^*,t) = \int_{t^*}^{t}\beta(z)dz = \Phi(t^*,x)-\beta(x)(x-t)+\frac{1}{2}\frac{d\beta}{dt}\bigg|_{t=Y}(x-t)^2, \qquad t^* < Y < x \qquad (7).$$

The last term determines the error of approximation. Observations show that the field varies slightly at small altitudes. At large altitudes the contribution of this error is reduced since the energy of particles is much higher. Neglecting the error, we have in the linear approximation after substituting (7) into (6) the following expression

$$J(x,E) = J_0(x,E-\Phi)\cdot\left[1+A_\Phi\cdot\Phi(t^*,x)-A_D\cdot D(x)\right], \qquad (8)$$

where the coefficients A_Φ and A_D have the following forms

$$A_\Phi = b\int_{t^*}^{x}\left(\frac{\varepsilon_\Phi(t',E)}{(E_\Phi{}^*(t'))^3}\right)\frac{dt'}{t'}, \quad A_D = \left(\frac{\rho_o/\rho(z)}{D_0}\right)\cdot b\int_{t^*}^{x}\frac{\alpha(x-t')\varepsilon_\Phi(t',E)}{(E_\Phi{}^*(t'))^3}\frac{dt'}{t'}.$$

Here, $D_0 = (\alpha/\alpha_m)D_C = 259$ *kV/m*, $\alpha_m = 1.67$ *MeV/(g cm^{-2})* is the minimum ionization losses for electron in air under standard conditions, $D_C = 216$ *kV/m* is the critical field strength, and ρ_0 is the air density under standard conditions at sea level. Formula (8) represents the final solution to the problem in the approximation specified above.

4. Results and discussion

The only term in (8) directly related to the local field has negative linear coefficient. In order to compare the above results with the experimental data, we calculated the linear coefficient at D taking the angular distribution of muons into account and setting the ratio $J_+/J_- = 1.25$ throughout the entire energy range. The results for median energy of each interval are given in Table 1.

Table 1. Experimental and calculated linear coefficients for muon intensity versus local field.

Muon energy range, *MeV*	Median energy, *MeV*	Linear coefficient *[%/(kV/m)]*, calculation	Linear coefficient *[%/(kV/m)]*, experiment
15 - 90	60	-0.0747	-0.0412 ± 0.0126
80 - 1000	550	-0.0200	-0.0141 ± 0.0007
> 1000	2400	-0.0032	-0.0028 ± 0.0003

Experimental coefficients in Table 1 are slightly different from those published in [1], since more data are included in the present case. One can see that there a qualitative agreement of calculated values with experiment (and even quantitative agreement at high energies).

When $\Phi = 0$ the transformation of the muon spectrum is reduced to a linear negative effect. At nonzero Φ the positive linear term in brackets can either partially compensate or intensify this negative effect depending on the sign of Φ. Quadratic effect is hidden in the original muon spectrum with shifted energy $J_0(x, E - \Phi)$. The sign of this effect is always the same and is determined by the form of the original spectrum of muons (this spectrum is convex due to decays of muons). According to (8), the negative quadratic effect takes place for potential Φ, while experimentally we detect the negative quadratic effect in the local field D. In order to explain our observations, we should assume (at least at some time intervals) sufficiently strong correlation between D and Φ. This correlation can introduce distortions into the linear dependence, and the discrepancy between the calculation and experiment at low energies can be explained precisely by this fact. Actually, it follows from (8) that there are several different effects related both to the near-earth field and to the potential difference between the ground and muon production levels. Combination of these effects produces a variety of phenomena observed in the muon intensity disturbances. However, the resulting effect is predominantly negative. As an illustration, we present one thunderstorm with especially strong and prolonged variations of the muon flux.

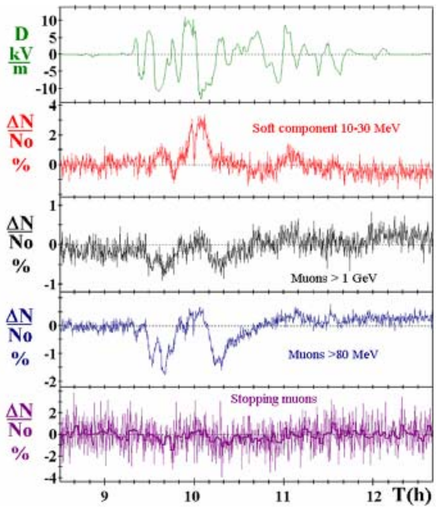

Figure 1. Thunderstorm on August 6, 2003 in Baksan Valley (North Caucasus). The top panel presents the near-earth electric field, all others give intensities of the soft component and muons of different energies averaged over 15 s intervals.

One should emphasize that previous calculations of the muon effects in the electric fields cannot describe our experimental data. In [3], where the differential sensitivity of muon component to the electric field was calculated, it has been found that the effect is larger for 1 GeV muons than for 0.2 GeV muons. One can readily see in Figure 1 that the energy dependence of the muon effect is opposite. In [4, 5] rather unphysical field distributions were assumed. The large-scale field of only one sign was considered, while there are no such fields under real conditions. Hence, not only too strong effects were obtained in [4, 5], but in some cases also the sign of the effect contradicts the experimental data.

In the context of the model considered by us the value of the muon effect is determined by the potential difference between the muon production level and the ground surface. Thus, studying these variations in detail, one can hope to understand the behavior of this potential difference during thunderstorms. In particular, it seems obvious in Figure 1 that this potential difference has a tendency to decrease when the process of generation of the soft component takes place.

5. Acknowledgements

The work is supported in part by the Russian Foundation for Basic Research, grant no. 03-02-16487, and by the RF State Program of Support of Leading Scientific Schools, grant NSh-1828.2003.02.

References

[1] N.S. Khaerdinov, A.S. Lidvansky, and V.B. Petkov, 28th ICRC, Tsukuba (2003) pp. 4173-4176.
[2] V.V. Alexeenko et al., 20th ICRC, Moscow (1987), 4, 272.
[3] L.I. Dorman, A.A. Lagutin, G.V. Chernyaev, 21st ICRC, Adelaide (1990) 7, 92.
[4] P.V. Mironychev, Geomagnetizm i Aeronomia, 43, no. 5, 702 (2003).
[5] Y. Muraki, W.I. Axford, Y, Matsubara, et al., Phys. Rev. D, 69, 123010 (2004).
[6] M. Stolzenburg, W. D. Rust, and T. C. Marshall, J. Geophys. Res., 103, 14,097 (1998).
[7] T.C. Marshall, W. Rison, W. D. Rust, M. Stolzenburg, J. C. Willett, and W. P. Winn, J. Geophys. Res., 100, 20,815 (1995).
[8] T.C. Marshall, M. P. McCarthy, and W. D. Rust, J. Geophys. Res., 100, 7097 (1995).