STUDY OF CHERENKOV LIGHT LATERAL DISTRIBUTION FUNCTION AROUND THE KNEE REGION IN EXTENSIVE AIR SHOWERS

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SUMMARY: The Cherenkov light lateral distribution function (LDF) was simulated with the CORSIKA code in the energy range ($10^{13} - 10^{16}$) eV. This simulation was performed for conditions and configurations of the Tunka EAS Cherenkov array for the two primary particles (p and Fe). Basing on the simulated results, many approximated functions are structured for two primary particles and different zenith angles. This allowed us to reconstruct the EAS events, which is, to determine the type and energy of the primary particles that produced showers from signal amplitudes of Cherenkov radiation measured by the Tunka Cherenkov array experiment. Comparison of the calculated LDF of Cherenkov radiation with that measured at the Tunka EAS array shows the ability to identify the primary particle that initiated the EAS cascades by determining its primary energy around the knee region of the cosmic ray spectrum.

Key words. cosmic rays – methods: numerical

1. INTRODUCTION

The accurate appreciation of the primary cosmic rays (PCRs) spectrum and mass composition in the range around the knee region is very important towards obtaining information about their origin and acceleration mechanisms (Phyllis et al. 1975, Berezinsky 2007). In the region of high and ultrahigh energies the only possible way of cosmic rays (CR) registration is indirect from extended air showers (EAS) produced in the atmosphere, precisely, by registration of atmospheric Cherenkov radiation. The investigation of CRs based on registration of

Cherenkov radiation of secondary particles produced in the cascade processes of EAS has intensively been developed in the last years (Fomin and Khristiansen 1986, Peter and Grieder 2010). The Monte Carlo method is one of the necessary tools in numerical simulation for investigation of EAS characteristics, and experimental data processing and analysis (determination of the primary particle energy and type and direction of the shower axis from the characteristics of Cherenkov radiation of secondary charged particles). Reconstruction of the characteristics of primary particles that initiate the atmospheric cascade from Cherenkov radiation of secondary particles calls for the creation of a library of shower patterns

that requires a substantial computation time (Heck and Peirog 2013).

The CORSIKA software package (Heck and Peirog 2013, Knapp et al. 2003) is one of the numerical methods that simulate the Cherenkov light LDF emitted by atmospheric cascades initiated by primary high-energy CR protons and nuclei. This simulation requires a long computation time for a single shower with energies 10^{17} eV for a processor with a frequency of a few GHz. Therefore, the development of fast modeling algorithms and the search for approximations of the results of numerical modeling are important practical problems.

Cherenkov light LDF as a function of distance from the shower axis in EAS was proposed (Alexandrov et al. 2001, Mishev and Stamenov 2005). This function was developed by approximating the results of numerical simulation of LDF of Cherenkov photons emitted by EAS initiated in the Earths atmosphere by the CR particle as a function of the primary energy and distance from the shower axis (Al-Rubaiee et al. 2005, Al-Rubaiee et al. 2014). Nerling et al. (2006) have used the shower simulation code CORSIKA to investigate the electron energy and angular distributions in high-energy showers. Based on the universality of both distributions, they have developed an analytical description of the Cherenkov light emission in extensive air showers, which provides the total number and angular distribution of photons. The parameterization can be used to calculate the contribution of direct and scattered Cherenkov light to shower profiles measured with the air fluorescence technique. On the other side, Rädel and Wiebusch (2012, 2013) have investigated and parameterized the amount and angular distribution of Cherenkov photons, which are generated by low-energy secondary particles (typically 500 MeV), which accompany a muon track in water or ice. These secondary particles originate from small energy loss processes.The authors have elaborated the contributions of the different energy loss processes as a function of the muon energy and the maximum transferred energy. For the calculation of the angular distribution they have developed a generic transformation method, which allows us to derive the angular distribution of Cherenkov photons for an arbitrary distribution of track directions and their velocities. Also, they have followed the same procedure of parameterization by electro-magnetic cascades in water or ice. They have simulated electromagnetic cascades with Geant4 for primary electrons, positrons and photons with energies ranging from 1 GeV to 10 TeV. Additionally, the total Cherenkov-light yield as a function of energy, the longitudinal evolution of the Cherenkov emission along the cascade-axis and the angular distribution of photons are parameterized. Furthermore, they have investigated the fluctuations of the total light yield, the fluctuations in azimuth and changes of the emission with increasing age of the cascade.

In the present work, we have used this parameterization to describe the results of numerical simulation of EAS by the CORSIKA code of Cherenkov light emitted by EAS measured with the Tunka EAS facility, which is constructed to study the energy

spectrum and the mass composition of CRs around the knee region (Gres et al. 1999, Chernov et al. 2005). The main advantage of this approach is to reconstruct the real events of Cherenkov radiation measured with Tunka EAS array (Budnev 2013). Comparison of the approximated Cherenkov light LDF with the reconstructed EAS events registered with the Tunka EAS Cherenkov array allows for primary particle identification and definition of its energy around the knee region.

2. CHERENKOV LIGHT PRODUCTION IN EAS

The phenomenon of Cherenkov light can be observed when charged particles pass through dielectric medium, such as air, faster than the phase speed of light in the medium ($v = c/n$) where v is the speed of charged particles, c is the speed of light in medium with refractive index n. The threshold energy of charged particles, which excite the Cherenkov radiation through the atmosphere, can be determined through the condition $\gamma = \gamma_{th}$ when $\gamma = E/mc^2$, where γ is the Lorenz factor of particles in the laboratory system. The Lorenz factor at the threshold energy (γ_{th}) is defined as:

$$\gamma_{\text{th}} = 1/\sqrt{1 - \beta^2} = 1/\sqrt{1 - (1/n(h))^2}. \quad (1)$$

The condition $\gamma > \gamma_{th}$ is equivalent to the condition ($v > c/n$), i.e. $n\beta > 1$, where $\beta = v/c$, which means that the speed of charged particle should exceed the speed of light c in the medium with refractive index n that depends on the shower height h:

$$n(h) = 1 + \zeta(h), \ \zeta(h) = \zeta_o \exp(-h/h_o), \quad (2)$$

where $\zeta_o \approx 3 \cdot 10^{-4}, h_o = 7.5$ km. The electron energy in the atmosphere is:

$$E_{\text{th}} = mc^2 \gamma_{th}. \quad (3)$$

Substituting Eq. (1) in Eq. (3) yields:

$$E_{\text{th}} = \frac{mc^2}{\sqrt{1 - (1/n(h))^2}} = mc^2 \frac{n(h)}{\sqrt{n^2(h) - 1}}. \quad (4)$$

Eqs (2) and (3) give the dependence of the electron threshold energy at height h in the atmosphere when:

$$E_{\text{th}} = mc^2 \frac{1 + \zeta}{\sqrt{2\zeta(1 + \zeta/2)}} \approx$$

$$\approx \frac{mc^2}{\sqrt{2\zeta(h)}} \approx \frac{mc^2}{\sqrt{2\zeta_o}} \exp(h/2h_o). \quad (5)$$

At the sea level, $n = 1 + \zeta_o$, and the Cherenkov radiation will be emitted by electrons that exceed the threshold energy E_{th} i.e. when $\gamma > \gamma_{\text{th}} = \frac{E_{th}}{mc^2} \approx 40.8$.

The threshold energy E_{th} for radiation of Cherenkov photons by electrons at height h in the atmosphere can be approximated by Eq. (5) at height $h_o = 7.5$ km (which means the development of shower at maximum $X_{\max} \approx 500$ g/cm^2, $E_{\text{th}} = 34.4$ MeV). Cherenkov light produced by very high energy particles ($\beta \sim 1$) slants under a small angle θ_r:

$$\cos \theta_r = \frac{1}{\beta n} \sim 1 \qquad (6)$$

where θ_r is the angle in which we can detect Cherenkov radiation (Kalmykov et al. 1983). Since $\beta \leq 1$, then $\cos \theta_r \leq 1$ and the relation holds when $n > 1$. From Eqs. (1)-(6) we find:

$$\sin^2 \theta_r = 1 - \frac{1}{(n\beta)^2} \approx 2\zeta(h)(1 - \frac{E_{\text{th}}^2(h)}{E^2}) =$$

$$= 2\zeta_o \exp\left(-h/h_o\right) \left(1 - \frac{E_{\text{th}}^2(h)}{E^2}\right), \quad (7)$$

and for $E >> E_{\text{th}}(h)$ at the sea level, we get:

$$\sin \theta_r \approx \theta_r \approx 1/\gamma_{\text{th}} \approx \sqrt{2\zeta_o} \exp\left(-h/2h_o\right) = \quad (8)$$

$$= 2.45 \cdot 10^{-2}$$

The number of Cherenkov photons per wavelength interval (λ_1, λ_2) may be obtained from the Tamm-Cherenkov relation under the assumption that the refractive index is independent of the wavelength (Nerlig et al. 2006):

$$\frac{dN_\gamma}{dx} = 2\pi\alpha \sin^2 \theta_r \int_{\lambda_1}^{\lambda_2} \frac{d\lambda}{\lambda^2} =$$

$$= 2\pi\alpha[\frac{1}{\lambda_1} - \frac{1}{\lambda_2}]\zeta_o(1 - \frac{E_{\text{th}}^2(h)}{E^2}) \exp\left(-h/h_o\right) \quad (9)$$

where $\alpha = 1/137$ and:

$$\frac{dN_\gamma}{dt} = \frac{dN_\gamma}{dx}\frac{dx}{dt} = x_o \exp(h/h_o)\frac{dN_\gamma}{dx}, \qquad (10)$$

where:

$$\frac{dx}{dt} = x_o \exp(h/h_o), \qquad (11)$$

where $x_o = t_o/\rho_o$ which is the distance of electrons at the sea level, $t_o \approx 37.1$ g/cm^2 and $\rho_o = 1.2 \cdot 10^{-2}$ g/cm^3 By neglecting the absorption of Cherenkov radiation in the atmosphere, the total number of Cherenkov photons N_γ radiated by electrons can be written as:

$$N_\gamma = 45 \cdot 10^{10} \frac{E_o}{10^{15}\text{eV}} . \qquad (12)$$

Estimations of the core position and age parameter are also made by using the total number of

Cherenkov photons in EAS, which is directly proportional to the primary energy E_o:

$$N_\gamma = 3.7 \cdot 10^3 \frac{E_o}{\beta_{\text{t}}}, \qquad (13)$$

where β_{t} is the critical energy at which it equals ionization losses at the t-unit: $\beta_{\text{t}} = \beta_{\text{ion}} \cdot t_o$. For electrons, $\beta_{\text{ion}} = 2.2$ MeV $\cdot$ (g.cm^{-2})$^{-1}$ and $\beta_{\text{t}} = 81.4$ MeV (Kalmykov et al. 1983).

Thus, the number of Cherenkov photons in the shower is directly proportional to the primary particle energy. It is difficult to measure this value experimentally; therefore, the Cherenkov radiation density, namely, the number of photons per unit area of the detector not model related (Mishev et al. 2001) to the primary particle energy:

$$Q(E, R) = \frac{\Delta N_\gamma(E, R)}{\Delta S} \qquad (14)$$

is used for experimental data processing. As demonstrated by direct measurements of Cherenkov light (Kalmykov et al. 1983), fluctuations in the form of the LDF for EAS are much less than fluctuations in the photon number N_γ.

3. RESULTS AND DISCUSSION

3.1. Simulation and parameterization of Cherenkov light LDF

A simulation of Cherenkov light LDF from EAS was performed using the CORSIKA (COsmic Ray SImulations for KAscade) software package (Heck and Peirog 2013) with using two models: QGSJET (the Quark Gluon String model with JETs) codes (Ostapchenko 2006) were used to model interactions of hadrons with energies exceeding 80 GeV and GHEISHA (Gamma Hadron Electron Interaction SHower) codes (Heck and Engel 2003) were used for lower energies. The CORSIKA code is the Monte Carlo program for simulating EAS to calculate the output hadrons, muons, electrons, and photons in the cascade. The program allows information on the type and energy of shower particles as well as on the angle and time of their arrival to the observation level to be obtained. The code supports the option of Cherenkov radiation generation by charged shower particles with the use of the Electron Gamma Shower (EGS4) system to simulate the electromagnetic component of EAS. The results of simulation by the CORSIKA software package are influenced by parameters such as the primary energy interval, distances passed by Cherenkov radiation, threshold energies of hadrons, electrons, muons and photons; and the factor taking into account a multiple Coulomb scattering of electrons. The Cherenkov light was simulated for the following values of input parameters of the Tunka EAS facility. The LDF of Cherenkov light was calculated for distances 2.5 to 400 m from the axis of showers initiated by protons, and iron nuclei

with energies $10^{13} - 10^{16}$ eV for different zenith angles 0^0, 10^0 and 20^0.
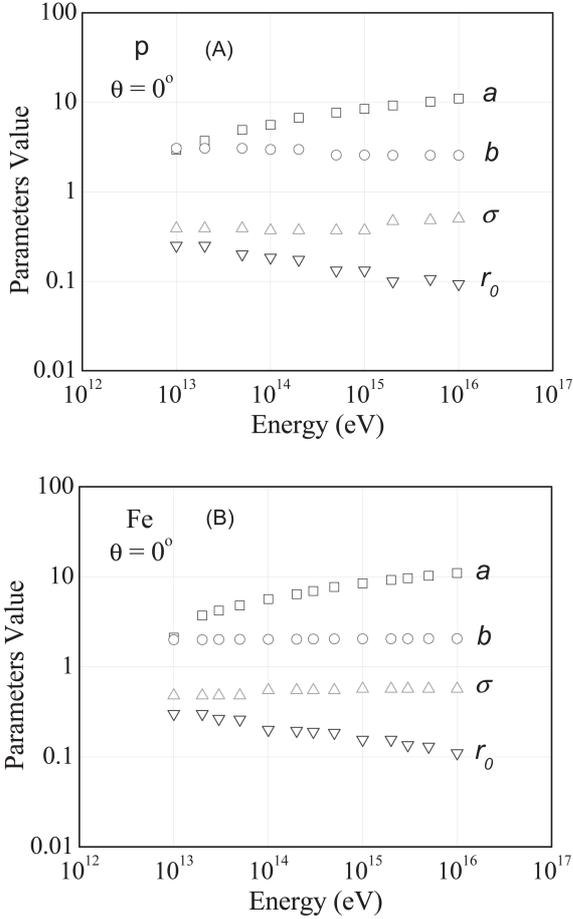
Fig. 1. *Value of parameters as function of primary energy (Eq. 16) for vertical showers initiated by: (A) primary proton, (B) iron nuclei in the energy range $10^{13} - 10^{16}$ eV.*

In order to parameterize the simulated Cherenkov light LDF, the function of four parameters a, b, σ and r_o suggested in (Alexandrov et al. 2001) was used. This function was normalized by introducing the coefficient $C = 10^3$ m^{-1} to provide the correct dimension of $Q[\text{m}^{-2}]$ and to be consistent with dimensions of the parameters from (Al-Rubaiee et al. 2005):

$$Q(E,R) = \frac{Cs \exp[a - G]}{b[\frac{R}{b}]^2 + [\frac{(R-r_o)}{b}]^2 + \frac{R\sigma^2}{b}}, \qquad (15)$$

where G is defined as:

$$G = \frac{R}{b} + \frac{(R - r_o)}{b} + [\frac{R}{b}]^2 + [\frac{(R - r_o)}{b}]^2,$$

where R is the distance from the shower axis and E is the primary particle energy. The values of parameters a, b, σ and r_o were determined by fitting the

function Eq. (15) to the values of the LDF calculated by the CORSIKA software package on a certain grid (R, E). The energy dependence of parameters a, b, σ and r_o was approximated by:

$$k(E) = c_0 + c_1 \log(E) + c_2 \log^2(E) + c_3 \log^3(E), \quad (16)$$

where the primary energy E in eV units and $k(E)$ $=\{a, \log(b), \log(\sigma), \log(r_o)\}$; c_0, c_1, c_2 and c_3 are coefficients obtained using the procedure of approximation for LDF parameters depending on the type of primary particles (p, Fe) and zenith angle as shown in Figs. 1 and 2.
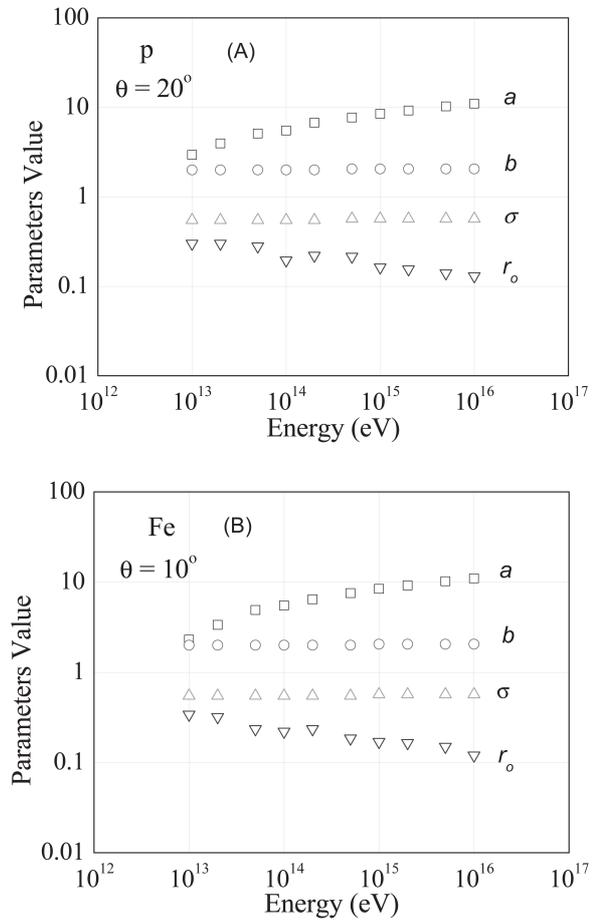
Fig. 2. *Value of parameters as function of primary energy (Eq. 16) for inclined showers initiated by: (A) primary proton at $\theta = 20^o$, (B) iron nuclei at $\theta = 10^o$ in the energy range $10^{13} - 10^{16}$ eV.*

3.2. Reconstruction of showers registered with Tunka EAS array

The total flux of photons from the charged particles of the EAS is proportional to the primary particle energy E_o. The signal amplitude from the

photodetector is proportional to the area of the photocathode and flux density of the Cherenkov light. The function of the LDF of the Cherenkov radiation describes the dependence of the Cherenkov light at distance from the shower axis, and can be expressed as (Budnev 2013):

$$N_i = (A_i - A_{i0})K_a K \qquad (17)$$

where N_i is the number of photons at the i-th detector, A_i (channel) is the amplitude, A_{i0} (channel) is the pedestal base and a is the range of additional charge-to-digital converter, K_a and K are calibration parameters of photodetectors (in ns/ch units). The time information for event reconstruction of the Tunka EAS array was measured through the following expression:

$$T_i = t_i K_i, \qquad (18)$$

where t_i is the front delay of the maximum amplitude (in ns unit). Recovered events determine the direction of arrival EAS (zenith θ and azimuth angle ϕ), position of the axis in the plane of detectors (coordinates X and Y):

$$X_s = \frac{\sum_{i=1}^{n_D} N_i X_i}{\sum_{i=1}^{n_D} N_i}, Y_s = \frac{\sum_{i=1}^{n_D} N_i Y_i}{\sum_{i=1}^{n_D} N_i} \qquad (19)$$

Here n_D is the number of detectors, X_s, Y_s (m) are the shower coordinates; X_i, Y_i (m) are the detector coordinates. The accuracy of core position by using Eq. (19) is about 10 m. The distance to the shower axis is defined by:

$$R_i = \sqrt{(X_i - X_s)^2 + (Y_i - Y_s)^2}. \qquad (20)$$

The density of Cherenkov radiation is defined as the number of photons per unit area of the detector S_D and is given by:

$$Q_i(E, R_i) = \sum_{i=1}^{n_D} N_i(E, R_i)/S_D. \qquad (21)$$

We shall now illustrate the potential of the presented approach in reconstruction of events based on time and amplitude characteristics of the signals recorded by the array Tunka (Gress et al. 1999, Chernov et al. 2005, Budnev et al. 2009, Budnev 2013). The angle of the shower axis (in the approximation of a plane front of Cherenkov radiation) is recovered by the time characteristics of the signal from the photodetector. Identification of the event was made on the basis of minimizing the function:

$$\Delta = \sum_i [Q^{calc}(E_o, R_i)/Q^{exp}(R_i) - 1]^2 \to \min. \qquad (22)$$

Trial results (excluding corrections for absorption of Cherenkov light and error estimations for determining the shower axis) of events reconstruction are shown in Figs. 3 and 4.
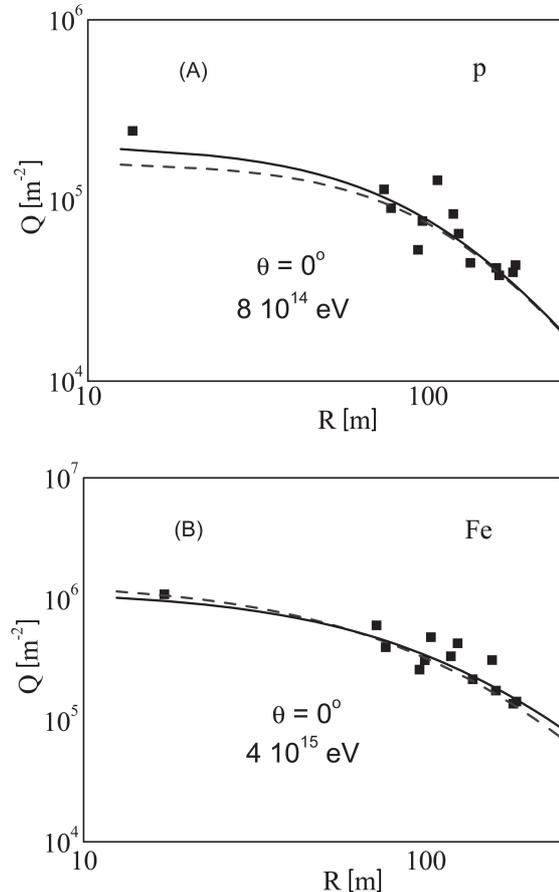
Fig. 3. *Reconstruction of vertical showers initiated by: (A) primary proton with energy $8 \cdot 10^{14}$ eV (solid line) and (B) iron nuclei with energy $4 \cdot 10^{15}$ eV (dashed line), in comparison with Tunka EAS array measurements (symbols).*

Fig. 3A demonstrates the comparison of the calculated Cherenkov light LDF with that measured by the Tunka EAS array at the distance 2.5 to 400 m from the shower core. The solid line shows the calculated LDF in vertical showers of primary protons at energy $8 \cdot 10^{14}$ eV: the hypothesis of a p-shower yields $\Delta_{min} = 0.7710$, while the hypothesis of a p-shower with the same energy but for inclined showers $\theta = 10^o$ (dashed curve) gives $\Delta_{min} = 0.8085$. On the other hand, at $\Delta_{min} = 0.6784$ for iron nuclei with energy $4 \cdot 10^{15}$ eV, and $\Delta_{min} = 0.7494$ for primary proton with energy $3 \cdot 10^{15}$eV, as seen in Fig. 3B, which means that this event (the shower axis inclined at angle $20°$ to the vertical) can be identified at about the same level of significance.

The solid line in Fig. 4A shows the calculated Cherenkov light LDF for inclined showers $\theta = 20°$

of the primary proton with energy 1 PeV, while symbols represent the Cherenkov light LDF as reconstructed from measurements of the Tunka array. From the Fig. 4A one can see that the p-shower hypothesis gives $\Delta_{\min} = 0.7828$ and Fe-shower gives $\Delta_{\min} = 0.9465$ at the primary energy 1 PeV (dashed curve), while in Fig. 4B, for inclined showers with $\theta = 10°$ initiated by iron nuclei yields $\Delta_{\min} = 0.7754$ at energy 5 PeV (solid curve) and $\Delta_{\min} = 0.7780$ for primary proton with energy of 1 PeV (dashed line). The accuracy of Cherenkov light LDF in EAS initiated by a primary proton for the 0° zenith angle was about 10-20% at the distance interval 80-180 m from the shower core, and about 5-20% for the 10° zenith angle at the same distance interval from the shower core. For iron nuclei the accuracy was found to be 5-15% for the 0° zenith angle at the distance interval 80-180 m and 5-20% for the 10° zenith angle at the same distance interval.
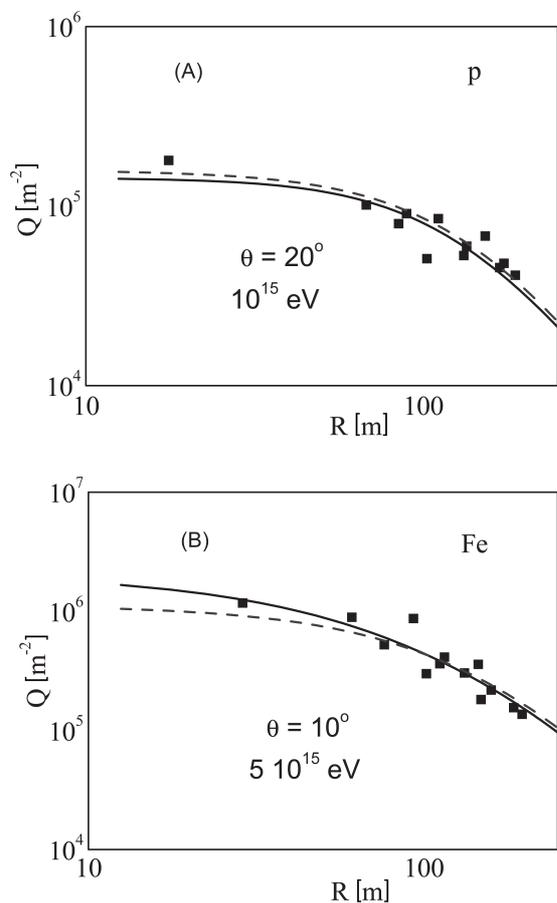
Fig. 4. *Reconstruction of inclined showers initiated by: (A) primary proton at energy 10^{15} eV for $\theta = 20°$ (solid line) and (B) iron nuclei with energy $5 \cdot 10^{15}$ eV for $\theta = 10°$ (dashed line), in comparison with Tunka EAS array measurements (symbols).*

4. CONCLUSION

The simulation of LDF of Cherenkov radiation in EAS that induced by two primary particles (protons and iron nuclei) was fulfilled using the CORSIKA code for configurations and conditions of the Tunka EAS Cherenkov array in the energy range $10^{13} - 10^{16}$ eV. On the basis of this simulation, the approximation of the Cherenkov light LDF was developed, which allowed to carry out a trial reconstruction of events. The main feature of the given model consists of the feasibility to make a library of Cherenkov light lateral distribution samples that may be used for analyzing the real EAS events detected by the Tunka EAS array, and to reconstruct the energy spectrum and chemical composition of primary cosmic radiations. The comparison of the calculated LDF of the Cherenkov radiation from experimental data of the EAS Cherenkov Tunka array has demonstrated the potential for the primary particle identification and definition of its energy around the knee region.

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ИСПИТИВАЊЕ ЛАТЕРАЛНЕ ФУНКЦИЈЕ РАСПОДЕЛЕ ЧЕРЕНКОВЉЕВОГ ЗРАЧЕЊА У ОБЛАСТИ КОЛЕНА КОД ШИРОКИХ АТМОСФЕРСКИХ ЛАВИНА

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У раду је симулирана функција латерална расподеле Черенковљевог зрачења коришћењем кода CORSIKA за примарно космичко зрачење у области колена енергија $10^{13} - 10^{16}$ eV. Симулације су прилагођене условима и конфигурацији Черенковљевог детектора екстензивних пљускова честица Тунка и рађене су за два типа примарних честица (протоне и језгра гвожђа). На основу резултата симулације изведене су апроксимативне функције расподеле за различите зенитске углове у случају обе примарне честице. Ово је омогућило да, помоћу амплитуде сигнала Черенковљевог зрачења мереног у експерименту Тунка, реконструишемо догађаје широких атмосферских лавина, односно да одредимо врсту и енергију честице која ју је изазвала. Поређење латералне функције расподеле са подацима добијеним детектором Тунка показује способност метода да утврди врсту примарне честице која изазива каскаду, као и њену енергију, уколико се налази у области колена у енергетском спектру космичког зрачења.