

The Parameterization Of Lateral Distribution Function Of Cherenkov Radiation For Tunka-133 And Yakutsk EAS Arrays

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Abstract

The CORSIKA program was used to model the lateral distribution function of the Cherenkov radiation (LDF) in the Extensive Air Showers (EAS) at $5 \cdot 10^{15}$ eV for the Tunka-133 and Yakutsk arrays. Based on this simulation, sets of estimated functions for primary proton and iron nuclei at zenith angles of 0° , 15° , and 25° were generated. By comparing the predicted LDF of the Cherenkov radiation with all data acquired with the Tunka-133 and Yakutsk arrays, the ability to identify the main particles and energy around the "knee" region has been established.

Keywords: CORSIKA, Cherenkov radiation, Tunka-133, Yakutsk.

Introduction

High-energy particles known as cosmic rays (CRs) come from space and penetrate the Earth's atmosphere. When they enter the atmosphere, ultra-high energy CRs particles may eventually smash into an atmospheric nucleus. This contact starts the EAS [1, 2] atmospheric cascade process, in which Cherenkov radiation LDF determines the density of the air shower. The registration of atmospheric Cherenkov radiation is the sole practical method for CR registration in the high and ultrahigh energy ranges. It is an indirect method based on EAS created in the atmosphere. In recent years, there has been a noticeable rise in the research of CRs based on the observation of secondary particle Cherenkov radiation produced in EAS cascade events [3, 4]. One of the essential tools for numerical simulation is the Monte Carlo approach, it is used for evaluating experimental data and researching EAS characteristics [5,6,7]. For the Tunka-133 and Yakutsk EAS array configurations [8, 9], the Cherenkov radiation LDF was modeled using the CORSIKA code at high energy of $5 \cdot 10^{15}$ eV for primary particles (iron nuclei and primary protons) and varied zenith angles (0° , 15° , and 25°). The simulated Cherenkov radiation density was approximated using a Lorentz fit based on Breit-Wigner functions.

The simulation and parameterization of LD

The lateral distribution function LDF was simulated using the QGSJET (Quark-Gluon String model with JETs) program [10], which was used to describe hadron interactions at energies greater than 80 GeV, and GHEISHA (Gamma Hadron Electron Interaction SHower) [11]. A thorough Monte Carlo simulation called CORSIKA was utilized to research the characteristics and development of EAS in the atmosphere [12].

The simulation of Cherenkov radiation LDF using CORSIKA code was used configurations and conditions of Tunka-133 and Yakutsk EAS array with the energy $5 \cdot 10^{15}$ eV for two main particles (p and Fe) at varied zenith angles (0° , 15° and 25°).

The Tamm and Cherenkov formula may be used to calculate the number of Cherenkov photons per wavelength interval (λ_1 , λ_2) [13]:

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

$$= 2\pi\alpha \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right) \zeta_0 \left(1 - \frac{E_{th}^2(h)}{E^2} \right) \exp(-h/h_0), \quad (1)$$

where $\alpha = 1/137$ is the constant of the fine structure; $\zeta_0 \approx 3 \cdot 10^{-4}$, $h_0 = 7.5$ Km; $E_{th} = mc^2\gamma_{th}$, where is the electron's atmospheric threshold energy at height h ; γ_{th} is the threshold energy's Lorenz factor, which may be calculated as:

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

At sea level $n = 1 + \zeta_0$, as well as electrons that are heavier than E_{th} may release Cherenkov radiation, i.e. when $\gamma > \gamma_{th} = \frac{E_{th}}{mc^2} \approx 40.8$.

To parameterize the findings of the simulated Cherenkov radiation LDF, we employed the function described in Ref. [3], which is dependent on 4 parameters a , b , δ and r_0 . The coefficient $C=10^3 \text{ m}^{-1}$ was used to standardize this function [14]:

$$Q(\theta, R) = \frac{C\sigma \exp[a-G]}{b [(R/b)^2 + (R-r_0)^2/b^2 + R\sigma^2/b]} \quad (3)$$

Where θ is the zenith angle; R is the distance from the shower axis and G is defined as:

$$G = R/b + (R - r_0)/b + (R/b)^2 + (R - r_0)^2/b^2 \quad (4)$$

Cherenkov radiation density was estimated around the knee region with an energy of $5 \cdot 10^{15}$ eV at several zenith angles and for primary particles (p and Fe). Because the parameters η , α , δ and ζ_c are distance dependent, we can compute the Cherenkov radiation LDF for any distance and fit it to the LDF simulated by the CORSIKA code. The relationship was used to estimate the distance dependence of the Cherenkov radiation LDF parameters:

$$Q(R) = \eta + \frac{2\alpha}{\pi} \frac{\delta}{4(R-\zeta_c)^2 + \delta^2} \quad (5)$$

Where: η , α , δ and ζ_c are the obtained Cherenkov radiation LDF coefficients (see Tables 1 and 2).

Table 1. The Lorentz function coefficients (Eq. 5) at the energy $5 \cdot 10^{15}$ eV and different zenith angles for Tunka-133 Cherenkov EAS array

Primary Proton					
Zenith angle (deg.)	Values of coefficients				R_i^2
	η	ζ_c	δ	α	
0	-3.8302×10^4	-96.72	64.36	1.662×10^9	0.9794
15	-1.3518×10^4	-83.74	47.83	1.612×10^9	0.9753
25	-8.3786×10^4	-127.71	318.43	5.790×10^8	0.9776
Iron					
0	-1.0514×10^4	-59.10	29.02	1.507×10^9	0.98235
15	-8.966×10^3	-67.61	34.33	1.320×10^9	0.97749
25	-9.547×10^3	-107.84	67.01	9.804×10^8	0.97229

Where R_i^2 is the determination coefficient.

Table 2. The Lorentz function coefficients (Eq. 5) at the energy $5 \cdot 10^{15}$ eV and different zenith angles for Yakutsk Cherenkov EAS array.

Primary Proton					
Zenith angle (deg.)	Values of coefficients				R_i^2
	η	ζ_c	δ	α	
0	3.1175×10^4	-39.352	18.054	4.352×10^9	0.98695
15	-2.1866×10^4	-67.689	36.556	2.955×10^9	0.98233
25	-2.5974×10^4	-77.572	43.965	2.502×10^9	0.97742
Iron					
0	3.5599×10^7	306.45276	3592.41824	-2.006×10^{11}	0.99359
15	3.6714×10^7	301.94334	3583.22942	-2.064×10^{11}	0.98183
25	2.3822×10^7	316.37733	3575.74148	-1.335×10^{11}	0.98044

Figure (1) shows the results of the simulated Cherenkov radiation LDF (solid lines) and that calculated with Eq. (5) (dashed) for Tunka-133 at the energy $5 \cdot 10^{15}$ eV for primary proton (a) $\theta = 0^\circ$; (b) $\theta = 15^\circ$; (c) $\theta = 25^\circ$; and for iron nuclei (d) $\theta = 0^\circ$; (e) $\theta = 15^\circ$; (f) $\theta = 25^\circ$. The Cherenkov radiation LDF approximation for $\theta = 0^\circ$ has an accuracy of better than 14% for p and close to 10% for fe at distances of 85-165 m from the shower axis. The remaining distances have an accuracy of at least 8%. The highest match of the fitted LDF with that estimated by the CORSIKA code may be obtained for the distance R of 150-375 m.

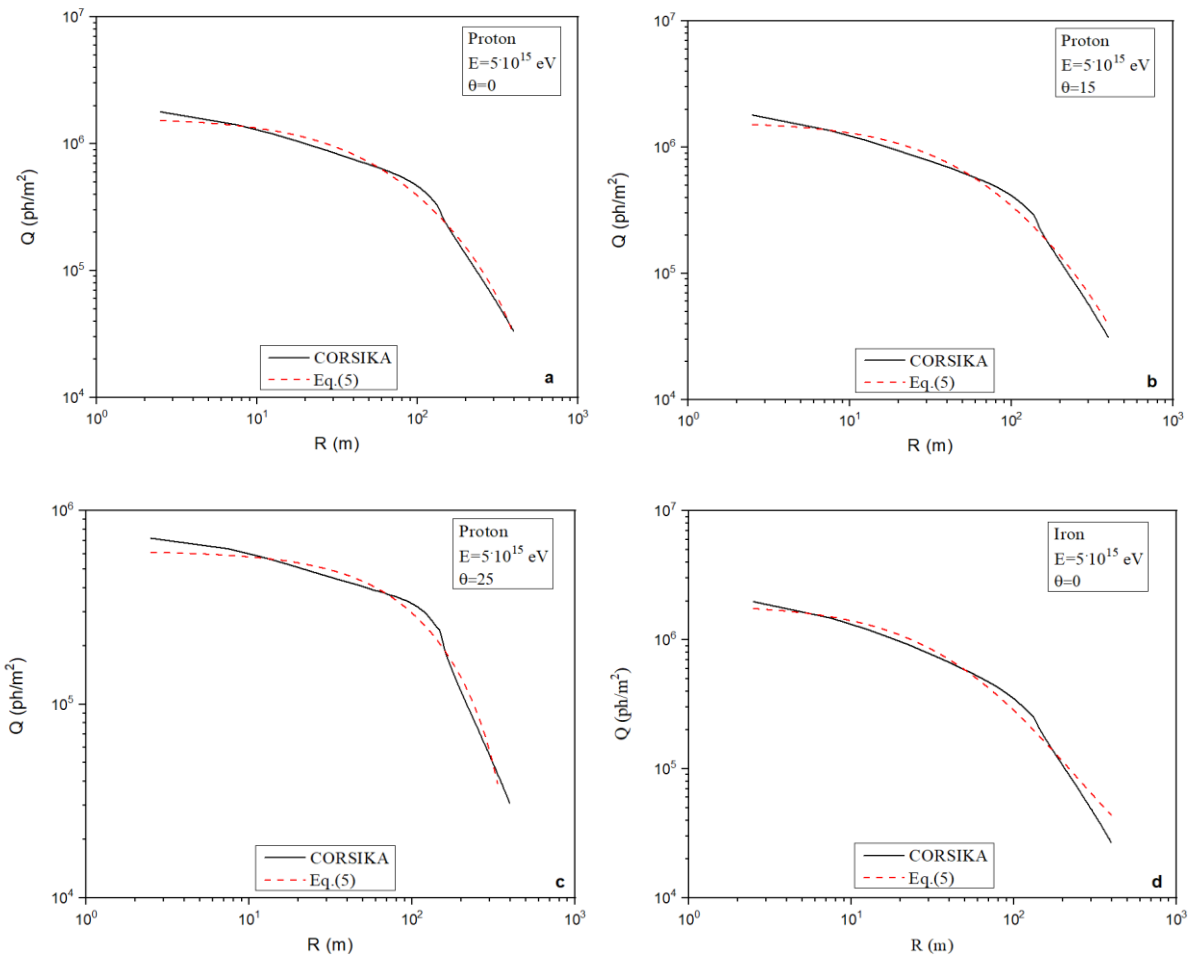
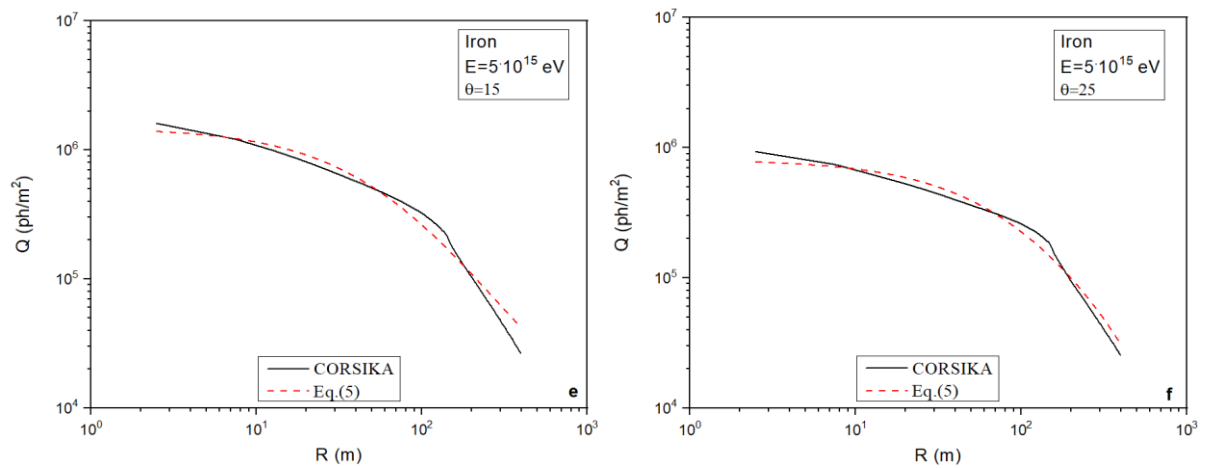


Fig. 1: The LDF of the radiation of Cherenkov for Tunka-133 array.



Complete Fig. 1

Figure (2) shows the results of the simulated Cherenkov radiation LDF (solid lines) and that calculated with Eq. (5) (dashed) for Yakutsk at the energy $5 \cdot 10^{15}$ eV for primary proton (a) $\theta = 0^\circ$; (b) $\theta = 15^\circ$; (c) $\theta = 25^\circ$; and for iron nuclei (d) $\theta = 0^\circ$; (e) $\theta = 15^\circ$; (f) $\theta = 25^\circ$. The Cherenkov radiation LDF approximation for equal to $\theta = 15^\circ$ at distances of 80-170 m from the shower axis has an accuracy of better than 13% for p and close to 19% for fe. The remaining distances are accurate to within 8%. The highest match between the fitted LDF and that estimated by the CORSIKA code may be obtained for the distance R of 120-360 m.

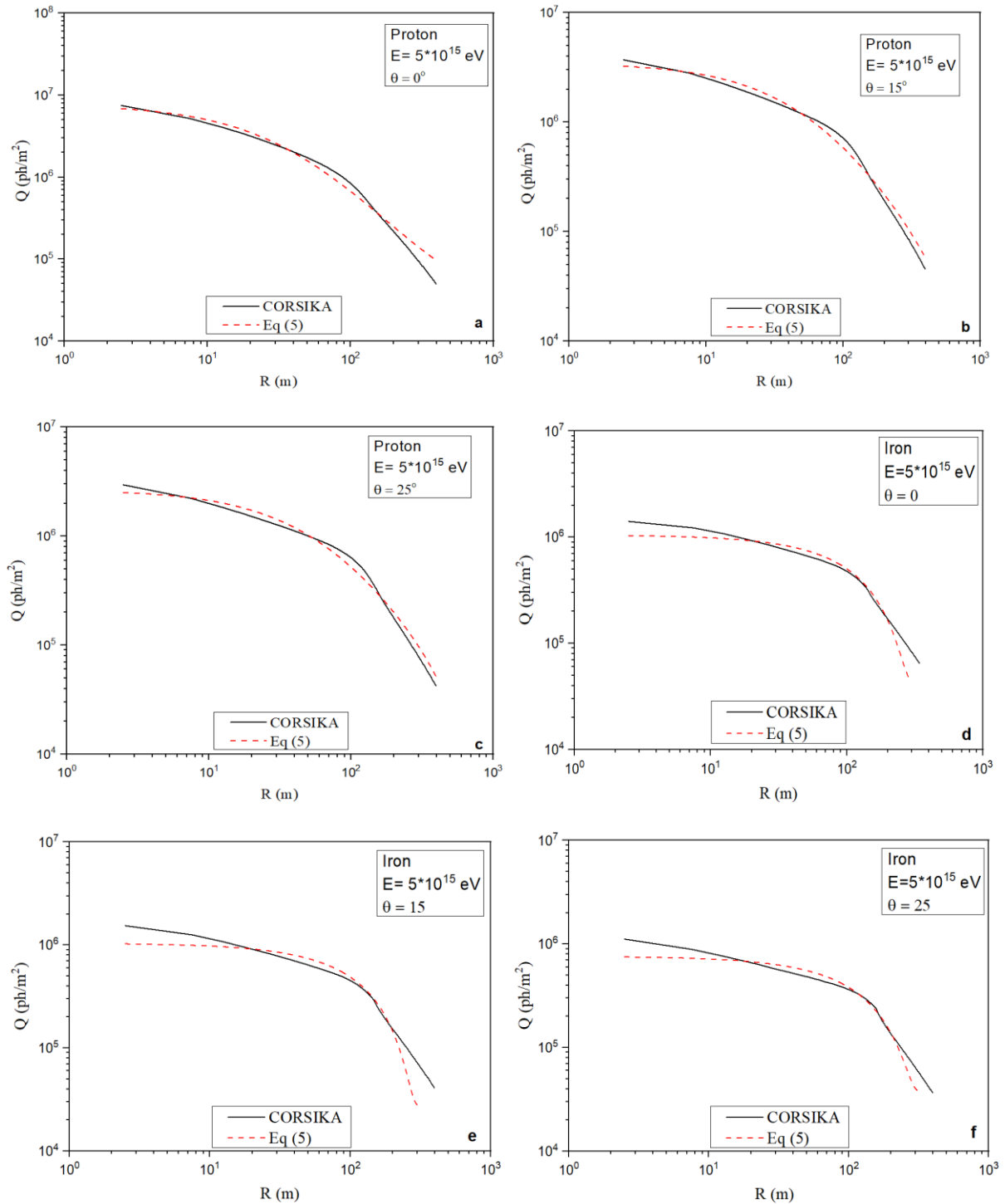


Fig. 2: The LDF of the radiation of Cherenkov for Yakutsk array.

The comparison with the Tunka-133 and Yakutsk measurement

The Tunka-133 and Yakutsk Cherenkov arrays are wide-angle Cherenkov arrays that were developed to investigate the energy spectrum and mass composition of CRs in the knee region. The basic parameters of EAS measurements are the zenith angles, shower core location, single LDF slope parameter R_0 , and Cherenkov radiation density Q . The recorded Cherenkov radiation LDF with the Tunka-133 and Yakutsk arrays will be fairly sensitive to EAS at distances of 15 - 160 m from the shower axis, according to EAS longitudinal development R_0 [15].

1- The comparison with the Tunka-133

A proposed function was used as a function of the shower's axis for parameterization of simulated Cherenkov radiation LDF [16, 17]:

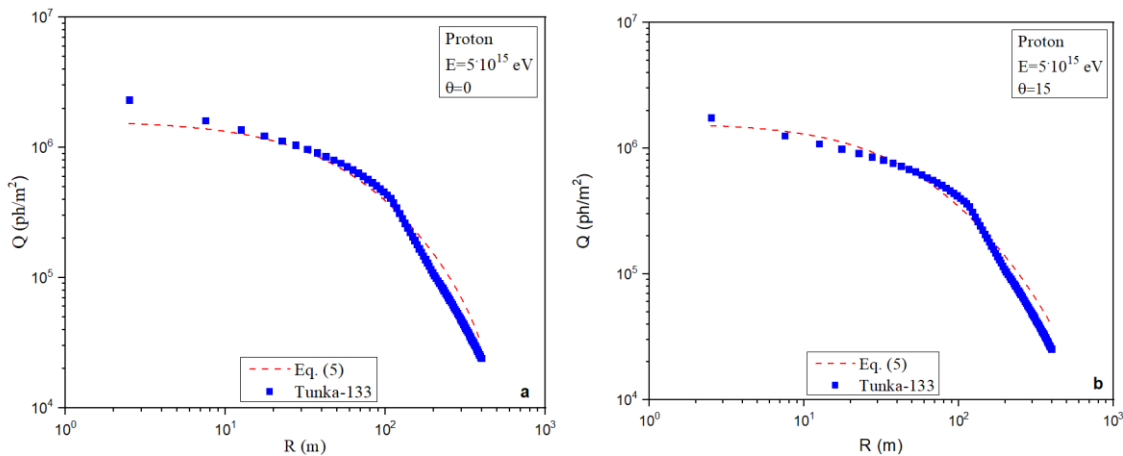
$$Q(R) = \begin{cases} Q_{kn} \cdot \exp((R_{kn} - R) \cdot (1 + 3/R)/R_0), & \text{for } R < R_{kn} \\ Q_{kn} \cdot (R_{kn}/R)^{2.2}, & \text{for } R \geq R_{kn} \end{cases} \quad (6)$$

$$R_0 = 10^{2.83-0.2 \cdot P}, \text{ m}$$

$$R_{kn} = 199 - 21.5 \cdot P, \text{ m}$$

Where R is the core distance (in meters), R_0 is a parameter of the first branch of LDF, R_{kn} is the distance of the first change of LDF, Q_{kn} is the radiation flux at the distance R_{kn} [18].

Figure 3 shows a good agreement between the parameterized Cherenkov radiation LDF calculated using Eq. (5) and that measured with the Tunka-133 array for p and fe at $5 \cdot 10^{15}$ eV and several zenith angles within 15 - 390 m of the shower axis. This figure represents the possibility of rebuilding the kind of EAS major particles.



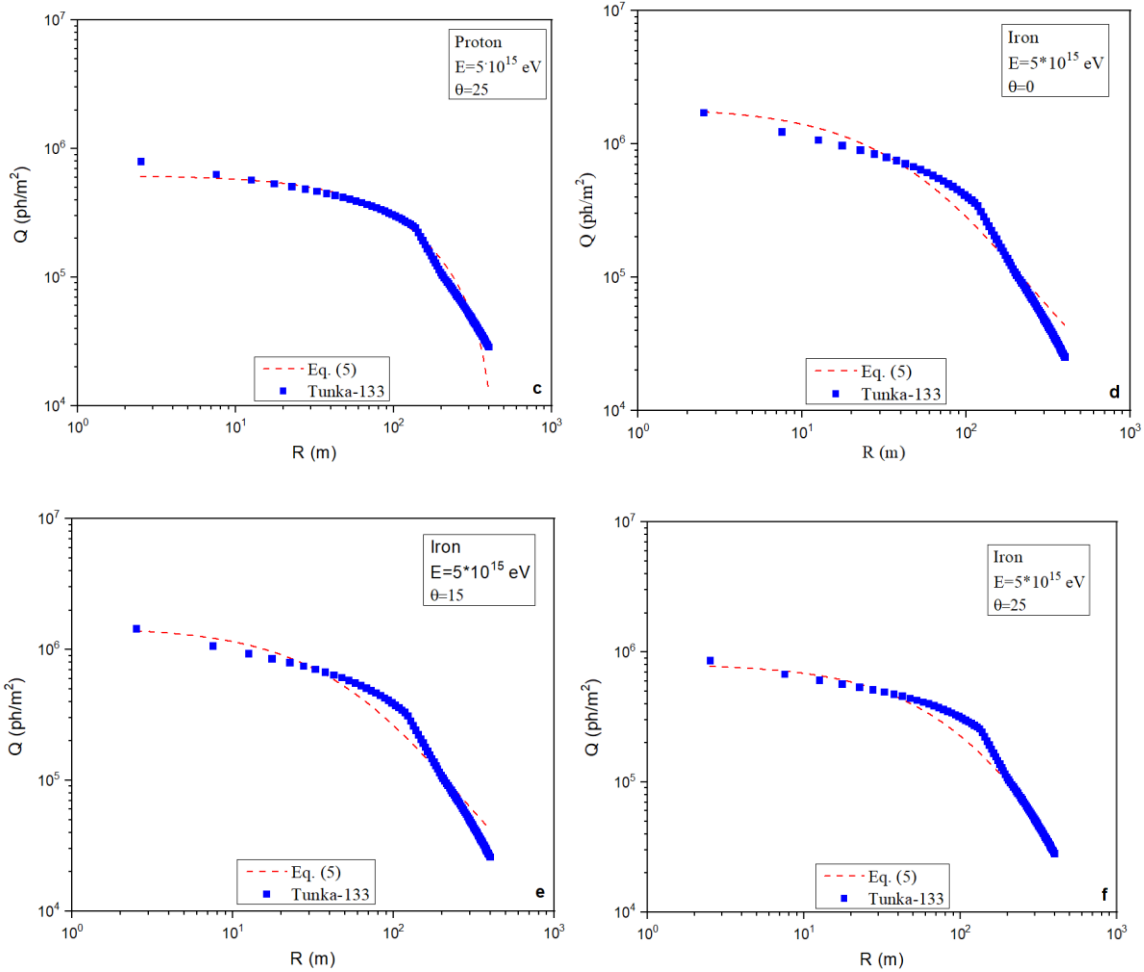


Fig.3: The comparison of the calculated radiation of Cherenkov LDF (Eq. (5)) with the data obtained by the Tunka-133 (symbols).

The parameterized Cherenkov radiation LDF in Figure 3 varies from the LDF detected with the Tunka-133 by around 10-17% for primary proton and iron nuclei with energies of $5 \cdot 10^{15}$ eV and $\theta=25^\circ$ and about 3-10% for distances of 15-260 m.

2- The comparison with the Yakutsk

Figure 4 summarizes our lateral distribution function (LDF) observations of Cherenkov radiation density. The results of both subarrays ($E=5 \cdot 10^{15}$ eV) are parameterized by the radiation density at 150 m from the shower core, Q_{150} , the only core distance present in the changing range of observations as the primary energy rises from $\sim 10^{15}$ to 10^{19} eV [19]. The observations are compatible with prior Yakutsk array results concerning the Cherenkov radiation and may be represented by the appropriate EAS model simulation. determines the parameters of the lateral distribution function of Cherenkov radiation [20].

$$Q(R) = Q_{150} \frac{(R_1 + 150)(R_2 + R)^{1-b}}{(R_1 + R)(R_2 + 150)^{1-b}} \quad (7)$$

Where:

$$R_1 = 60 \text{ m} ; R_2 = 200 \text{ m} ; b = (1.14 \pm 0.06) + (0.30 \pm 0.02) \times \log Q_{150}$$

Figure 4 presents a good agreement between both the parameterized Cherenkov radiation LDF calculated using Eq. (5) and that observed with the Yakutsk array for p and fe at the energy $5 \cdot 10^{15}$ eV and several zenith angles within 15-390 m of the shower axis. This figure depicts the possibility of reconstructed EAS main particles.

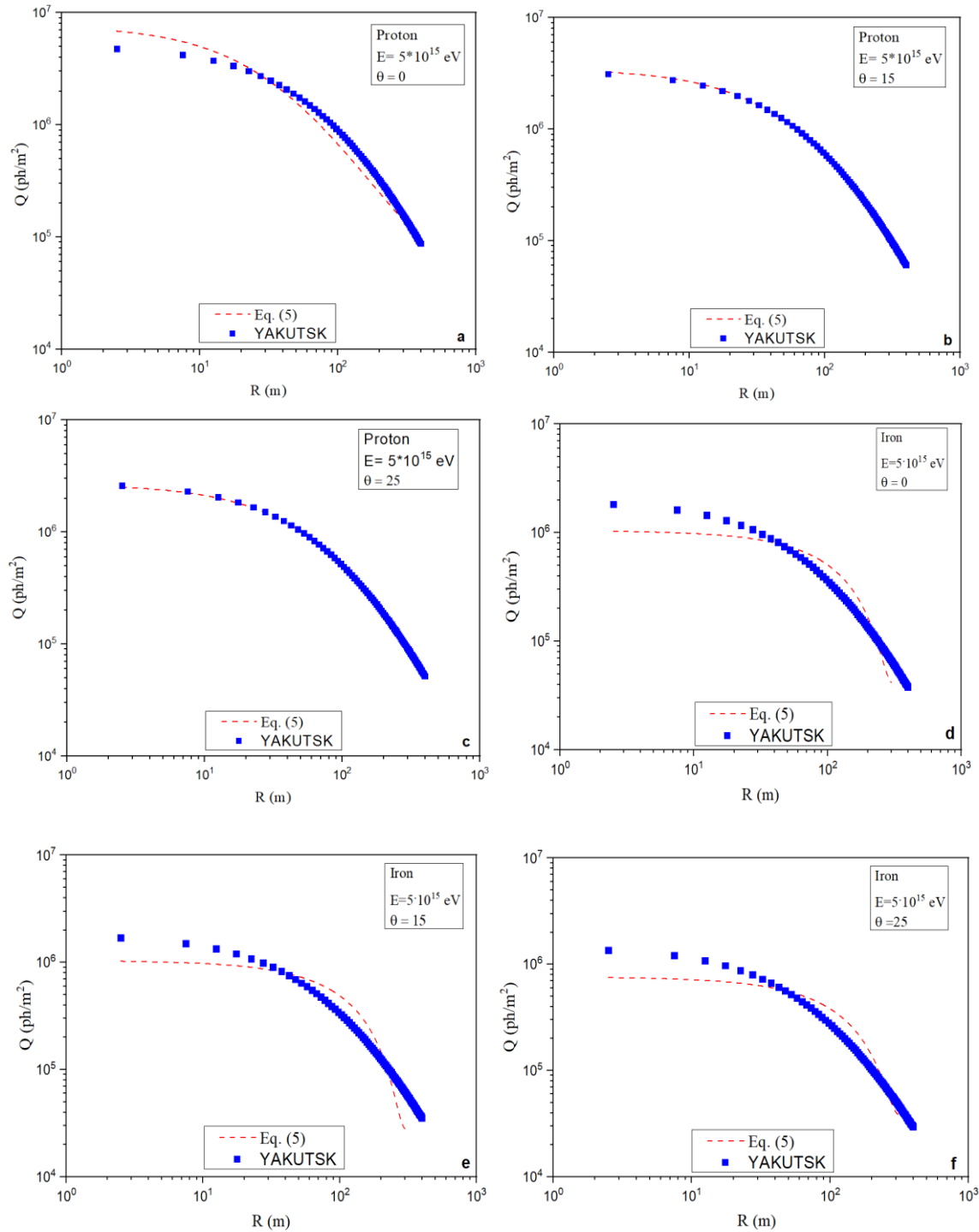


Fig. 4: The comparison of the calculated radiation of Cherenkov LDF (Eq. (5)) with the data obtained by the Yakutsk (symbols).

The parameterized Cherenkov radiation LDF in Figure 4 varies from the LDF observed with the Yakutsk; the difference was around 12-19% for p and fe with the energy of $5 \cdot 10^{15}$ eV and $\theta=15^\circ$ and approximately 2-8% for distances of 10-200 m.

Conclusion

This study calculated the LDF of Cherenkov radiation in EAS produced by primary protons and iron nuclei at an energy of $5 \cdot 10^{15}$ eV. The CORSIKA simulation of the Tunka-133 and Yakutsk EAS array configurations of the Cherenkov radiation LDF is finished. We determined the LDF parameters as a function of distance for two primary particles and several zenith angles using the simulation data. It is feasible to recognize primary particles and ascertain the energy around the knee region, as shown by a comparison of the calculated Cherenkov radiation LDF with that obtained using the Tunka-133 and Yakutsk arrays. The key advantage of the suggested approach is the potential for building a library of LDF samples that can be utilized for the analysis of actual events detected by the EAS array and the reconstruction of the energy spectrum and mass composition of primary cosmic rays.

Reference

- [1] P. S. Freier and C. J. Waddington, The cascading of cosmic-ray nuclei in various media, *Astrophys. Spac. Sci.* 38 (1975) 419–436.
- [2] J. V. Jelly, Cherenkov radiation and its applications, London: Pergamon Press, 1958.
- [3] Yu. A. Fomin and G. B. Khristiansen, Study of the longitudinal development of individual EAS inferred from the Cherenkov light pulse shape: method and results, *Nucl. Instrum. Meth. Phys. Res. A248* (1986) 227–233.
- [4] Peter K.F. Grieder, Extensive Air Showers: High Energy Phenomena and Astrophysical Aspects - A Tutorial, Reference Manual and Data Book high energy, 1200 p., Springer-Verlag Berlin Heidelberg, 2010,.
- [5] V.M. Grigoriev, S.P. Knurenko, M.I. Pravdin, A.V. Saburov, I.Ye. Sleptsov, Testing calculation results of Cherenkov radiation flux from extensive air showers using CORSIKA, *Phys. Part. Nucl. Lett.* 9 (2012) 567-570.
- [6] Ahmed Al-Rubaiee, Muhammed Ali Abid Kadhum, Omer Ahmed M., Simulation of lateral distribution function of Cherenkov light in extensive air showers for Yakutsk array, *Journal of the College of Basic Education*, 74 (2012) 1-6.
- [7] A.A. Al-Rubaiee, Uda Hashim and Y. Al-Douri, Investigating the Cherenkov Light Lateral Distribution Function for Primary Proton and Iron Nuclei in Extensive Air Showers, *Phys. Part. Nucl. Lett.*, 12 (2015) 751–756.
- [8] J. Knapp, D. Heck, S.J. Sciutto, M.T. Dova, and M. Risse, Extensive air shower simulations at the highest energies, *Astropart. Phys.*, 19 (2003) 77-99.
- [9] A. A. Ivanov, S. P. Knurenko and I. Y. Sleptsov, Measuring extensive air showers with Cherenkov light detectors of the Yakutsk array: the energy spectrum of cosmic rays, *New Jour. Phys.* 11 (2009) 30 p.
- [10] S. Ostapchenko, QGSJET-II: towards reliable description of very high energy hadronic interactions, *Nucl. Phys. B: Proceed. Suppl.* 151 (2006) 143–146.
- [11] D. Heck and R. Engel, Influence of low-energy hadronic interaction programs on air shower simulations with CORSIKA, *Proc. 29th ICRC, Japan*, (2003) 279–282.
- [12] D. Heck and T. Pierog, Extensive Air Shower Simulation with CORSIKA, May 1, 2021.
- [13] Tamm E. Radiation emitted by uniformly moving electrons. *Jour. of Phys. (USSR)*. 1939;1:439.
- [14] A.A. Al-Rubaiee, Extension of Cherenkov light LDF parametrization for Tunka and Yakutsk EAS array, *J. Astrophys. Astr.* 35 (2014) 631-638.
- [15] A.A. Al-Rubaiee, O.A. Gress, A.A. Kochanov, K.S. Lokhtin, Y.V. Parfenov and S.I. Sinigovsky, Parameterization for Cherenkov light lateral distribution function in Extensive Air Showers, *Proc. 29th ICRC, Pune*, (2005) 249–252.
- [16] L. Alexandrov, S.Cht. Mavrodiev, A. Mishev, *Proc. 27 ICRC, Hamburg*, 7-15 Aug 2001. P. 257- 260.
- [17] Marwah M. Abdulsttar, A. A. Al-Rubaiee, *Journal of Applied Physical Science International*, Vol. 7, Issue 2, 2016, UK.
- [18] EAS-TOP Collaboration and Korosteleva E. E., Kuzmichev L. A., Prosin V. V. “Lateral distribution function of EAS Cherenkov light: experiment QUEST and CORSIKA simulation,” *Proc. 28th ICRC, Tsukuba, Japan*, vol. 1, 2003, pp. 89-91.
- [19] M. N. Dyakonov et al., *Cosmic Rays of Extremely High Energy*, Nauka, Novosibirsk, 1991.
- [20] A.A. Ivanov, S.P. Knurenko, and I.Ye. Sleptsov, The energy spectrum of cosmic rays above 1015 eV as derived from air Cherenkov light measurements in Yakutsk, *astro-ph/0305053 v1* 5 May 2003.