Monte Carlo Simulation Using the CORSIKA Code for Cherenkov Photon Flux

Kadhom F. Fadhel

Directorate General of Education in Diyala, Ministry of Education, Baghdad, Iraq

Corresponding author; E-mail: kadhumfakhry@uomustansiriyah.edu.iq

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Abstract:

This study seeks to determine the lateral distribution of atmospheric Cherenkov photon flux in extended air showers (EAS) generated by various primary particles across a broad energy spectrum. The Cherenkov photon flux in EAS initiated by primary protons and iron nuclei in the energy range of 10^{14}–10^{17} eV at the Moussala array observation level (700 g/cm^2) is modeled using the CORSIKA 5.62 code. An estimate of the Cherenkov photon flux lateral distribution in showers as a function of the EAS shower primary energy. This makes it possible to differentiate between proton and iron primaries while accounting for the characteristics of the suggested approach and model. Additionally, parameters for shower axis location estimate are proposed, and the accuracy of shower axis determination is examined. The approximations and the statistics (Gauss Amp) function approximation derived using an alternative technique are contrasted. At the same time, studies are conducted at the Moussala observation level on angled showers up to a zenith angle of 30 degrees. The vertical showers model and the previously obtained approximation are contrasted with the obtained lateral distributions of vertical showers. This makes it possible to modify the reconstruction plan and examine the behavior of the model parameters.

Key words*: Cosmic Rays; Extensive Air Shower; Cherenkov photon flux; CORSIKA code.*

1. INTRODUCTION

Investigating the traits of EAS produced by Cosmic Rays (CRs) with extremely high energies is essential. Moreover, the chain reaction EAS showers generated in the Earth's atmosphere have been used to detect high-energy cosmic rays. Because primary particles are not directly observable [1], they must be studied indirectly through the measured air showers. Due to their incredibly low fluxes, the Ultra High Energy Cosmic Rays (UHECR) that reach the Earth cannot be directly observed in space [2]. These particles interact with atomic nuclei as they enter the atmosphere, causing secondary particles known as EAS. There are millions of collisions and secondary particle decays in the EAS [3]. These showers can be seen with detectors, which can track energy depositions as they grow along the atmosphere, or surface detectors, which track depositions as the particles hit the ground [4]. The local density of charged particles is one of the primary EAS characteristics that huge ground-based air shower arrays can detect with remarkable accuracy at various distances from the shower core [5]. As a result, precise theoretical forecasts of the lateral distribution function (LDF) of the fundamental EAS elements at a variety of distances from the shower are essential for both interpreting previous experimental results and studying the design of future experiments in CR research [6,7]. Given the reported index change of the power spectrum of the primary cosmic radiation spectra about 3 PeV, known as the "knee" region, it is particularly interesting to examine the mass composition and energy spectrum of primary CR in the energy range between 10^{13} and 10^{17} eV [8,9]. Relativistic cosmic rays in the EAS emit Cherenkov radiation, which offers vital information about the shower's growth and PCR particles [10]. The Cherenkov light LDF depends on the energy and primary particle type, observation level, first impact height, and shower axis direction [11]. One of the most important numerical simulation tools for processing and analyzing experimental data as well as for investigating EAS characteristics is the Monte Carlo method, which can be used to determine the primary particle energy type and shower axis from the characteristics of Cherenkov photon flux of secondary charged particles. It has provided comprehensive explanations of the simulation, experimental setup, and Cherenkov light detection method in EAS [12,13]. As G. R. Farrar and H.-J. Drescher, the Cherenkov photon flux LDF generated throughout the shower growth phase was measured using electrons with energy ranging from 8 to 200 GeV [14]. The Cherenkov photon flux profiles and Monte Carlo simulation results are compared. The Tunka-133 LDF EAS array was established by Mavrodiev et al. [15]. This array allows for a systematic analysis of the mass composition and energy spectrum of CR in the energy range of 10^{16}–10^{18} eV [16]. The depth of the EAS shower maximum Xmax might be determined by analyzing the LDF and time structure of the EAS Cherenkov photon flux [17]. In this work, LDF is simulated for conditions as well configurations of the Moussala EAS array using the CORSIKA code model for hadronic process simulation, which is QGSJET for EAS simulation. [18]. On the basis of statistics (Gauss Amp) function, a method for describing the distribution of the showers, the results of the numerical simulation of LDF density were approximated, and its potential for use in reconstructing the events recorded in Moussala was examined [19]. The primary benefit of this strategy is the ability to recapture LDF events that were observed using the Moussala array. Located 500 meters apart, the four 34 m^2 water-Cherenkov detectors (A1–A4) make up the core portion of the Moussala array [20]. The simulations were performed for two elementary particles, the proton and the iron nucleus, in the 10^{14}–10^{17} eV energy range, with zenith angles that are vertical and inclined. Using the statistics (Gauss Amp) function, the LDF of the Cherenkov light was computed and compared to Cherenkov array experiments. The simulations and the experimental data showed good agreement. Comparing the estimated LDF with the reconstructed showers recorded with 875 $g.cm^{-2}$ Yakutsk , 700 $g.cm^{-2}$ Moussala, and 536 $g.cm^{-2}$ Chacaltaya field observation levels has shown a good chance for primary particle identification and the characterization of its energy around the knee areas.

2. METHODOLOGY

In this work, the QGSJET model for interactions of hadrons in the energy from 10^{14} to 10^{17} eV is used to simulate the evolution of the atmospheric cascade and the LDF of Cherenkov photon flux in EAS. The CORSIKA code simulates the interactions and decay of various nuclei, photons, and hadrons in the atmosphere [21]. The particles are monitored as they move through the atmosphere until they encounter an air nucleus or, in the case of unstable secondary particles, until they decay. The simulation results contain information on the type, position, momentum, energy, and arrival time of the generated secondary particles at a selected elevation above sea level [22]. For hadronic cascades with energy in the "knee" region, the atmosphere was predicted to be near the shower maximum in the simulation at this observation level. The simulations are able to provide flatter distributions of the different shower components, particularly the flux of atmospheric Cherenkov photons, because the changes in shower development are less noticeable than at lower observation levels. Protons as well as iron nuclei act as the primary nuclei that start the simulation of LDF flux densities in EAS. The acquisition of Cherenkov photon flux densities in EAS with less uncertainty leads to a significant reduction of statistical fluctuations. The LDF in EAS produced by through two primaries iron nuclei and primary protons with two zenith angles and an energy range of 10^{14}–10^{17} eV is shown in Figures 1 and 2 using simulation software CORSIKA. The measured lateral distributions of atmospheric LDF caused by different CR nuclei around the "knee" region Figures 1 and 2 show the simulated lateral distributions of Cherenkov photon flux for different primary nuclei in the knee region. Where the axis shows 'R' the distance from the shower axis, while the vertical axis 'Q' represents the number of particles resulting from the interaction of CR particles with the atmospheric particles. As the incident particle's energy increases, we observe that the simulation curves start to rise. This indicates that as the energy of the incident particle grows, so does the number of secondary particles generated by the contact.

The shower's development-related variations predominate in the high-energy range over 10^{15} eV. Through the figures, we conclude that the simulation curves begin to decrease as the azimuth angle of the incident body increases. This means that when a particle incident vertically, it travels a longer path to produce secondary particles than the particle that occurs at a certain angle, and the path of the particle decreases as the angle of incidence increases. Table 1 shows the input data for the simulations performed using the CORSIKA software. The Yakutsk array has been measuring Cherenkov light for almost 35 years. since 1993, with a 530 cm^2 reception area. A 4-level air shower generation method is employed in the project. Experimental results at medium and great distances from the axis show a good agreement. Calculations show that the measured flux of Cherenkov light is less than one for distances less than 80 meters. This disparity may be explained by differing zenith angles due to various mass compositions. The CORSIKA 5.62 program was used to derive the parameters of the cosmic background EAS, namely the flux of Cherenkov light and hadrons with energy larger than 10^{14} eV, for the observational level of Chakaltaya 536 $g.cm^{-2}$. The high mountain observatories have been used for environmental monitoring and research over the years. These locations have the benefit of having little human impact, which makes it possible to keep an eye on pollution and cross-border transportation. At 2925 meters above sea level, the highest peak in the Balkan Peninsula is home to the Basic Environmental Observatory Moussala (42°10' 45" N; 23° 35'07" E). This is a special location for these kinds of research. This is among the most suitable locations in the Balkan region. It has very little human influence. It provides a great opportunity for environmental monitoring.

Table 1. CORSIKA input card Used.

Number of run/ events	00500
Number of first shower event	100400
Primary particle code	402/ 1608
QGSJet-II.04	T 0
Cherenkov detector grid	10 8 1200 1500 80 50
Cherenkov wavelength band	320-400 nm
Thinning	10^{-6}
Observation level	700 $g.cm^{-2}$
Energy range of primary	10^{14}–10^{17} eV
Range zenith angle	angles ≤ 30°

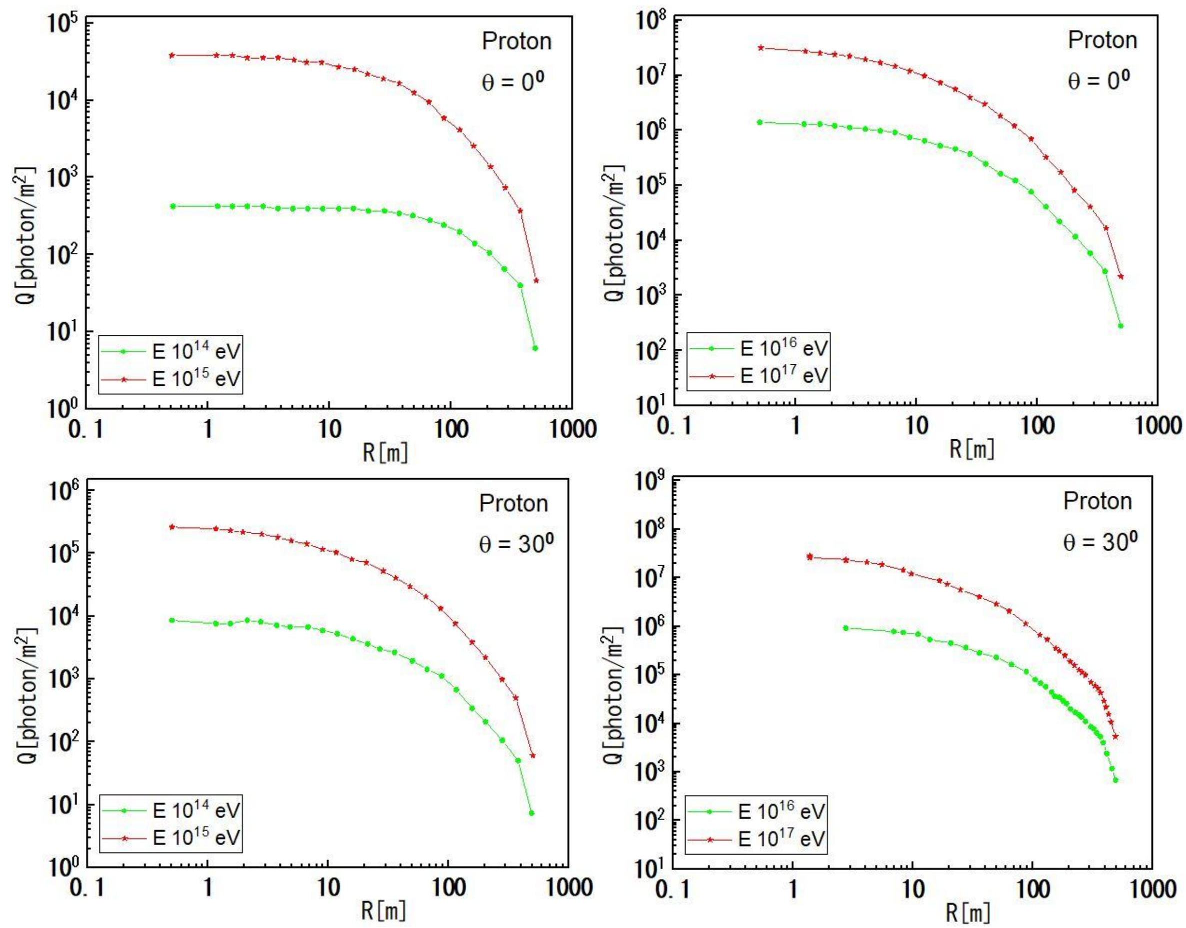

Figure 1. The primary energy effect of LDF Cherenkov photon flux by primary proton using the CORSIKA code with vertical and inclined zenith angles.

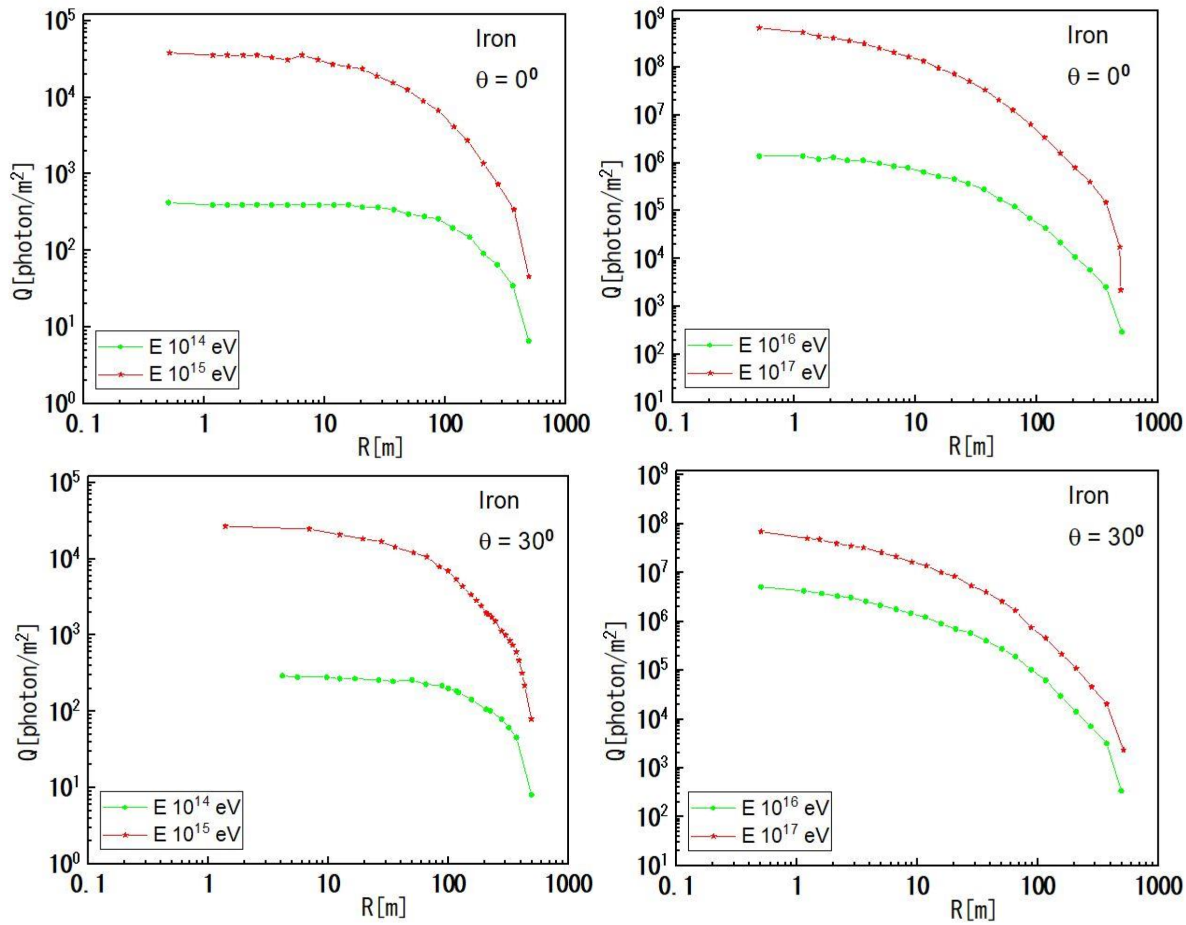

Figure 2. The primary energy effect of LDF Cherenkov photon flux by primary iron nuclei using the CORSIKA code with vertical and inclined zenith angles.

3. Results and discussion

3. 1 Parameterization of the Lateral Distribution of Cherenkov flux

The flux of Cherenkov photon in order to learn more about primary particles, event reconstruction often uses the LDF function to describe how photon of Cherenkov flux varies laterally with core distance. The shower density, or overall number of particles, is obtained by integrating throughout the entire range of the LDF core distance. The value is also estimated using the total photon Cherenkov flux (N_γ) emitted by electrons in the EAS, which is directly proportional to the primary energy for the shower E_0 [23]:

$$N_\gamma(E_0) \approx 3.7 \times 10^3 \frac{E_0}{\xi_e} \approx 4.5 \times 10^{10} \frac{E_0}{10^{15} eV} \quad (1)$$

where ξe is equal to 81.4MeV, critical energy for electrons. Since it is challenging to determine this magnitude experimentally, Cherenkov photon flux density, or the number of photons ($\Delta N\ \gamma$) per unit detector area (ΔS), which varies with distance from the shower axis and energy, can be used [24]:

$$Q(R) = \frac{\Delta N_\gamma(R)}{\Delta S} \quad (2)$$

where R is the shower axis's radius. In EAS, the change in LDF is basically smaller than the total quantity of photons direct measurements of Cherenkov light indicate $N\gamma$ [25]. The High Energy Cosmic Ray Experiment HECRE proposed parameterization [26].

$$Q(R) = \frac{\sigma e^{\alpha}\, e^{-[(\frac{R}{\gamma})+(R-r_0/\gamma)+(R/\gamma)^2+\frac{(R-r_0)^2}{\gamma^2}]}}{\gamma[(R/\gamma)^2-\frac{(R-r_0)^2}{\gamma^2}+\frac{R\sigma^2}{\gamma}]} \quad (3)$$

where the model parameters are $\alpha,\ \sigma,\ \gamma$ and r_0 and R is the distance from the shower axis. According to the model, the energy of the incident source particle is equal to the total number of Cherenkov photons at the selected observation level multiplied by a parameter.

$$\beta = (R/\gamma)^2 + \frac{(R-r_0)^2}{b^2} \tag{4}$$

$$S = \gamma[(R/\gamma)^2 - \frac{(R-r_0)^2}{\gamma^2} + \frac{R\sigma^2}{\gamma}] \tag{5}$$

Substituting equation (4) and equation (5) into (3), we get.

$$Q(R) = \frac{\sigma e^{\alpha}\ e^{-[(\frac{R}{\gamma})+(R-r_0/\gamma)+\beta]}}{S} \tag{6}$$

From equation statistics (Gauss Amp) for CORSIKA data.

$$Q_{(E)}{=}\sigma{+}\gamma e^{-0.5(\frac{R-\varphi}{\omega})^2} \tag{7}$$

We utilized the proposed function for the Cherenkov photon flux LDF, which depends on several sets of shower simulations using different parameters $\gamma, \sigma, \varphi,$ and ω as a function of the EAS shower for primary energy, (show Table 2). Fitting the CORSIKA code yields these coefficients, which are provided by the polynomial form:

$$K_{(E)} = A_0 + A_1 \lg(E_0) + A_2 \lg(E_0)^2 + A_3 \lg(E_0)^3 \tag{8}$$

where $K_{(E)} = \ \gamma, \sigma, \varphi,$ and ω are several sets of shower parameters of Eq. (7) as a function of the EAS shower's primary energy and A_0, A_1, A_2, and A_3 are their coefficients (show Table 2).

There are 500 EAS simulated for every energy. The lateral distributions of Cherenkov EAS shower densities that were collected are displayed in figures 3 and 4 (dotted lines). Depending on the primary and its energy, the lateral distribution reaches its highest plateau near the shower axis before gradually decreasing to zero beyond a few hundred meters. The atmospheric Cherenkov light distribution's model function must belong to a class of functions that exhibit this kind of behavior. The model function is searched using a variety of criteria. The model needs to fit well. The proposed method depends on the model parameters' monotonic behavior as a function of the EAS shower's primary energy. The statistical approximation (Gauss Amp) with auto regularization is carried out using the equation to solve the inverse issue of an overdetermined system of Eq.7.

Table 2. The coefficients can be found using Eq.7 for statistics (Gauss Amp) function to the specified energy range by using the parameterized CORSIKA code simulation initiated by primary iron nuclei as well as protons within the energy range (10^{14}-10^{17}) eV.

Primary particles	*(E) eV*	$K_{(E)}eV$	Coefficients				R^2
			A_0	A_1	A_2	A_3	
Iron	10^{14}	σ	-33747.79	1.17×10^{-17}	-4.9×10^{-33}	1.852×10^{-16}	0.99896
		γ	184210.8	5.27×10^{-12}	-7.48×10^{-32}	$-3.99327\text{x}10^{-18}$	0.89897
		φ	353.53	5.45×10^{-10}	-5.86×10^{-36}	1.97×10^{-17}	0.99885
		ω	112.5	8.04×10^{-17}	8.06×10^{-37}	6.117×10^{-18}	0.99492
	10^{15}	σ	-52708.5	1.01×10^{-17}	-5.09×10^{-33}	5.74×10^{-17}	0.89899
		γ	354834.54	2.96×10^{-12}	-1.58×10^{-31}	-6.719×10^{-19}	0.89998
		φ	-11.743	3.44×10^{-10}	-5.9×10^{-36}	-1.56×10^{-13}	0.99871
		ω	4.83	8.08×10^{-17}	4.73×10^{-37}	5.63×10^{-12}	0.97896
	10^{16}	σ	76.82	2.5×10^{-17}	2.71×10^{-31}	7.11×10^{-17}	0.99792
		γ	-66120.98	9.02×10^{-13}	3.12×10^{-30}	-6.93×10^{-18}	0.99785
		φ	-1.22×10^{6}	2.59×10^{-10}	$- 1.37\times10^{-35}$	-4.06×10^{-13}	0.97891
		ω	321.16	1.48×10^{-16}	$- 2.92\times10^{-36}$	1.14×10^{-11}	0.98894
	10^{17}	σ	37.75	3.11×10^{-17}	1.14×10^{-32}	7.14×10^{-17}	0.99895
		γ	-55072.2	$- 2.16\times10^{-13}$	$- 9.54\times10^{-32}$	-3.94×10^{-38}	0.96897
		φ	-67779.47	3.82×10^{-12}	$- 1.87\times10^{-35}$	-2.45×10^{-37}	0.99862
		ω	323.05	1.001×10^{-15}	$- 5.39\times10^{-36}$	-7.05×10^{-38}	0.98495
Proton	10^{14}	σ	0.473	-1.07×10^{-17}	5.77×10^{-16}	1.59×10^{-35}	0.99376
		γ	148.329	-4.55×10^{-17}	-8.6×10^{-18}	-1.41×10^{-37}	0.96899
		φ	-11.73	1.29×10^{-19}	-8.186×10^{-17}	3.83×10^{-36}	0.99092
		ω	4.83	9.15×10^{-18}	1.45×10^{-20}	-1.36×10^{-38}	0.99708
	10^{15}	σ	-1.019	2.83×10^{-18}	1.79×10^{-17}	5.8×10^{-35}	0.99829
		γ	1.117	1.22×10^{-15}	6.45×10^{-18}	-3.6×10^{-37}	0.99875
		φ	-9.842	3.67×10^{-18}	1.194×10^{-15}	-2.39×10^{-37}	0.97899
		ω	356.31	-1.52×10^{-19}	-8.36×10^{-19}	1.61×10^{-35}	0.98979
	10^{16}	σ	112.24	8.926×10^{-16}	2.246×10^{-17}	-1.57×10^{-37}	0.97998
		γ	963402.16	$-1.973\text{x}10^{-17}$	8.55×10^{-18}	-4.175×10^{-37}	0.98999
		φ	5.66×10^{6}	-4.35×10^{-18}	-1.95×10^{-16}	-2.74×10^{-37}	0.89991
		ω	298.57	2.47×10^{-20}	1.561×10^{-18}	7.598×10^{-36}	0.99098
	10^{17}	σ	30.62	8.36×10^{-16}	2.58×10^{-17}	9.27×10^{-38}	0.99895
		γ	11540.62	-2.37×10^{-17}	9.562×10^{-18}	8.22×10^{-35}	0.99898
		φ	28205.409	1.53×10^{-17}	-8.351×10^{-17}	1.65×10^{-36}	0.99893
		ω	280.65	1.829×10^{-19}	-1.003×10^{-18}	2.814×10^{-36}	0.99187

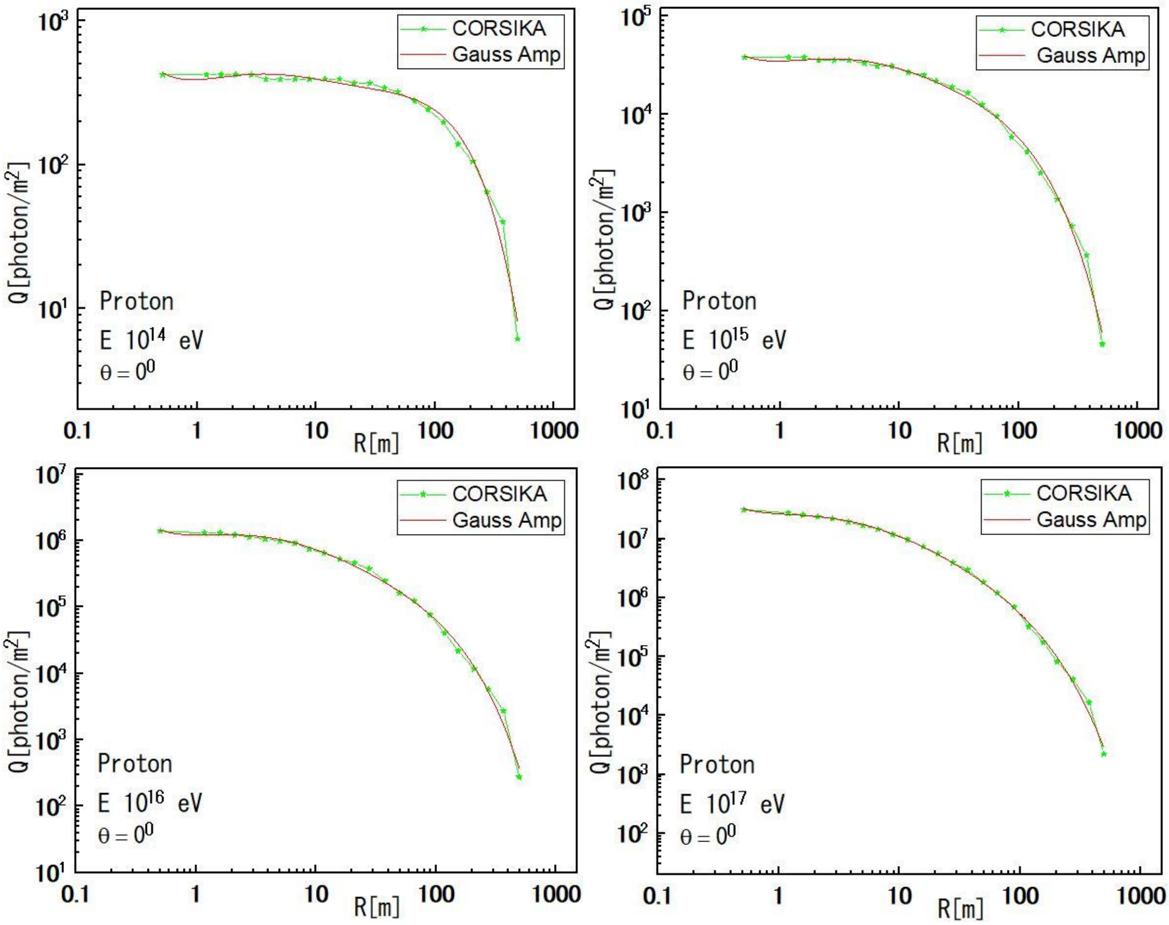

Figure 3. For primary proton, the resulting approximation equation (7) (solid line) and the CORSIKA code were used to model the lateral distribution of Cherenkov light (dotted line).

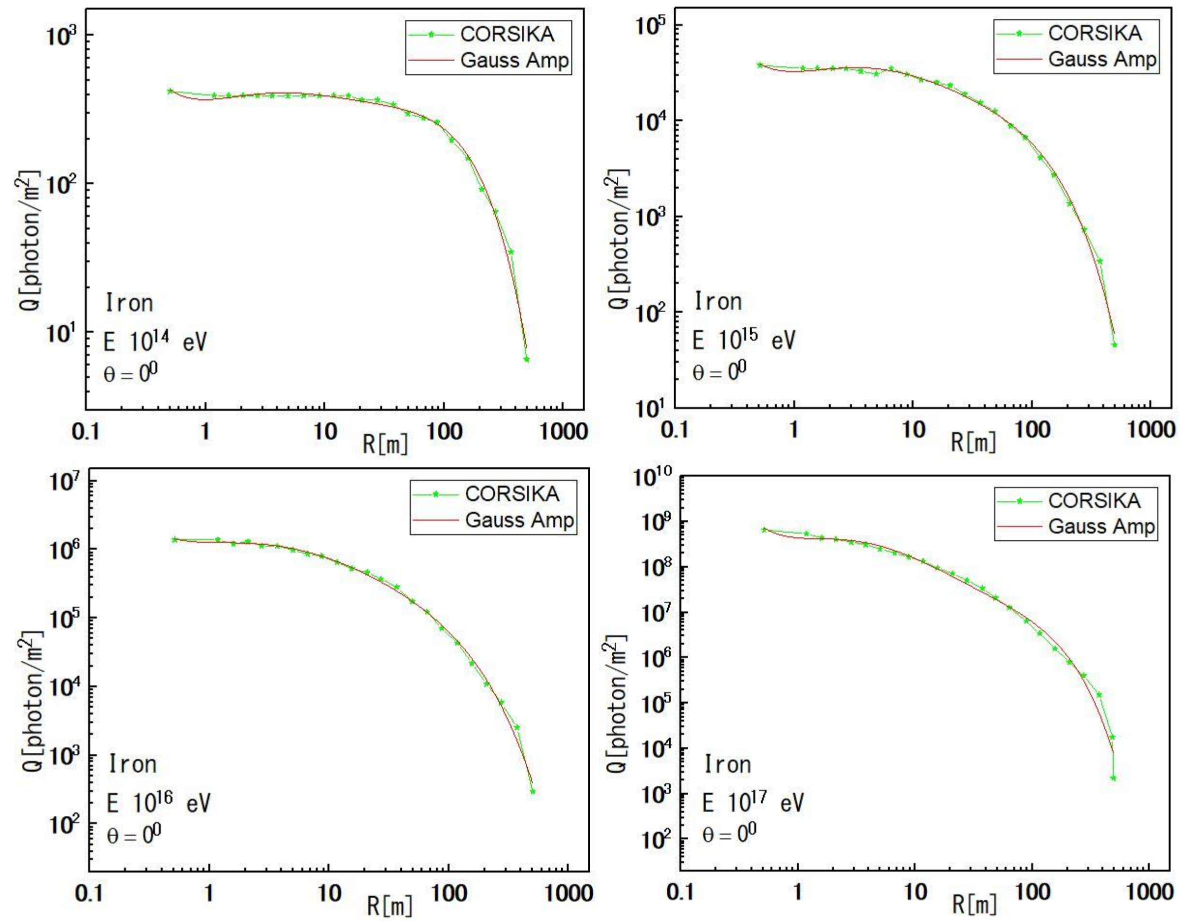

Figure 4. For primary iron, the resulting approximation equation (7) (solid line) and the CORSIKA code were used to model the lateral distribution of Cherenkov light (dotted line).

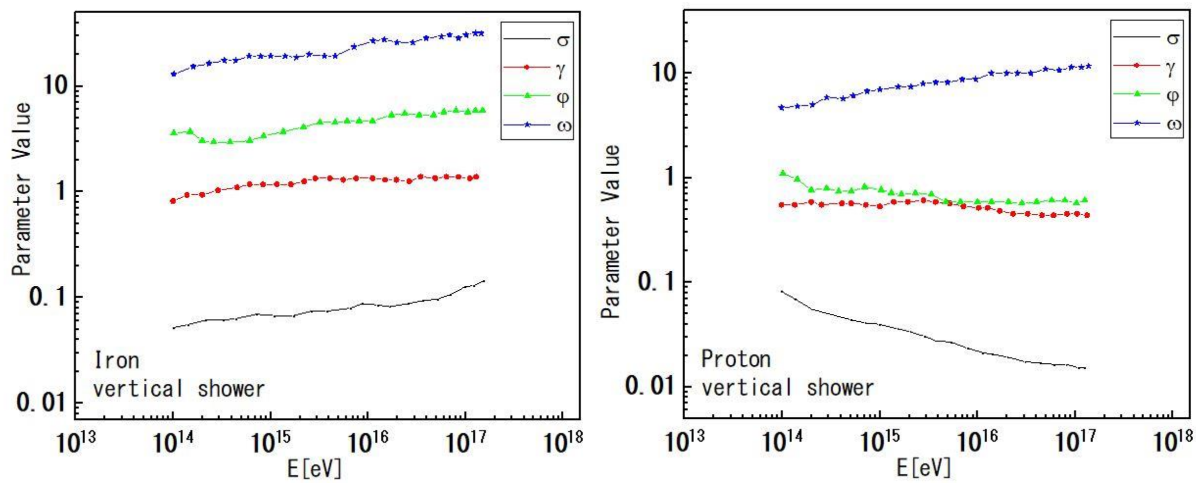

Figure 5. Iron and primary proton model parameter values as a function of primaries.

3. 2 Comparison of Approximated LDF with Data Measurements

The discipline of cosmic ray astrophysics, which is dynamic and on the cutting edge of fundamental research, is studied by the Moussala EAS array. The Moussala array observable has two primary goals are to investigate primary particle cascades in the atmosphere that are initiated through two primary particles and to reconstruct the astrophysical characteristics of their origin, mass composition, energy spectrum, and primary intensity. Shower core position, azimuth and zenith angles, and individual LDF for Cherenkov photon flux $Q(R)$ are the primary factors in EAS observations. Figure 6 compares the approximate Cherenkov photon flux LDF obtained by Eq. 7 statistics (Gauss Amp) with the Chacaltaya, Moussala, and Yakutsk observation levels Regarding iron and the primary proton, the energies (10^{15}, and 10^{16}) eV to demonstrate the potential for reconstructing the kind of EAS primary particles at the knee area of the EAS for CR spectrum in the vertical shower at a distance of 100 to 400 m from the shower core. By analyzing the simulation results obtained with the CORSIKA code using the Gaussian function and comparing with the experimental data of the arrays mentioned above, a good match was shown for the elementary protons and iron with different zenith angles.

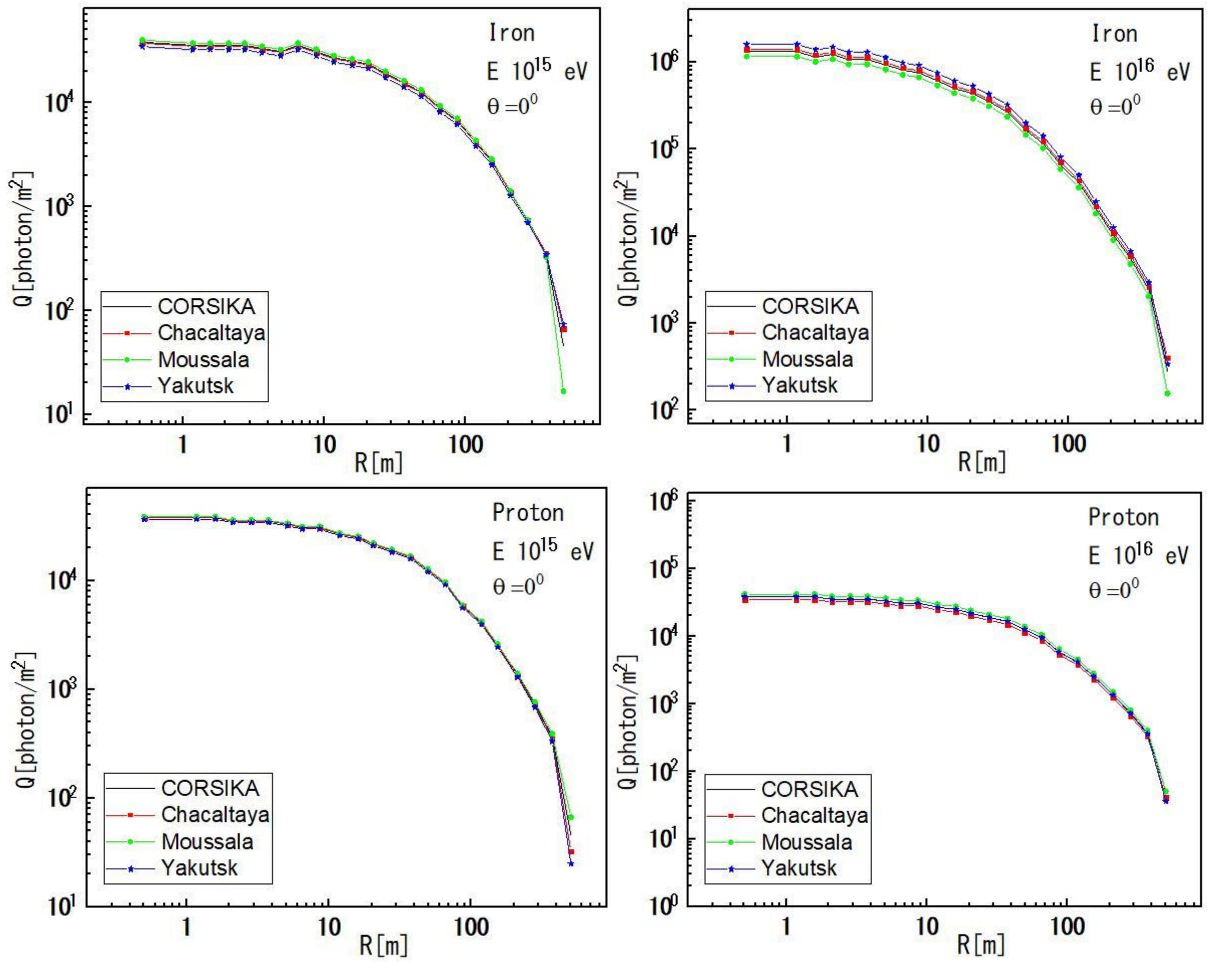

Fig. 6. Comparison of parameterized LDF obtained by statistics (Gauss Amp) function and the experimental data by Chacaltaya, Moussala, and Yakutsk EAS arrays at 10^{15} and 10^{16} eV for iron and primary proton.

4. Conclusions

Using CORSIKA 5.62, the Cherenkov photon flux LDF from EAS particles that are started by producing different primary shower particles in a wide energy range has been simulated in the energy range of 10^{14} to 10^{17} eV. Based on this simulation, which depended on the statistics (Gauss Amp) function, for two fundamental particles, such as oxygen and a proton, sets of approximation functions were developed simultaneously. Vertical showers and inclined showers up to a zenith angle of 30 degrees were also considered. It has been demonstrated that the particle responsible for EAS events can be identified and its energy in the knee area of the CR spectrum can be determined by comparing the approximated Cherenkov photon flux LDF with that observed by the Moussala EAS shower array. The results collected with the CORSIKA code are extrapolated for energies between 10^{14} and 10^{17} eV using the Cherenkov photon flux LDF parameterization. The primary advantage of the proposed approach is the possibility of rapidly creating a library of Cherenkov photon flux LDF patterns for use in analyzing detected actual events by the Moussala EAS array and to reconstruct the mass distribution and energy spectrum of CR showers. The shower-to-shower fluctuation of the lateral distribution is very important, the dependences of the distribution on energy, mass, and zenith angle are different for different events.

By utilizing the Gauss Amp function and relying on parameters as a function of elementary energy, a large library of data was created that can be reliably used to identify the elementary particle of cosmic rays and determine its energy.

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Nomenclature

CRs	Cosmic Rays
UHECR	*Ultra High Energy Cosmic Rays*
EAS	*extended air showers*
N_γ	*total photon Cherenkov flux*
E_0	*primary energy for the shower*
ξe	*is equal to 81.4MeV*
ΔS	*detector area*
$Q(R)$	*distance from the shower axis*
R	*the shower axis's radius*
$\alpha, \sigma, \gamma, \omega, \varphi$, and r_0	*parameters model*
A_0, A_1, A_2, and A_3	*The coefficients*
R^2	***R-squared***

References

[1] Ave, M., Cazon, L., Hinton, J. A., Knapp, J., Lloyd-Evans, J., & Watson, A. A. (2003). Mass composition of cosmic rays in the range 2× 1017–3× 1018 eV measured with the Haverah Park array. Astroparticle Physics, 19(1), 61-75.

[2] HO, Klages. "The muon lateral distribution function as a transformation of the height-of-origin distribution in hadronic extensive air showers," J. Phys. G Nucl. Part. Phys., vol. 25, no. 6, pp. 1235–1248, 1999, doi: 10.1088/0954-3899/25/6/313.

[3] Ogio, S., Kakimoto, F., Kurashina, Y., Burgoa, O., Harada, D., Tokuno, H., ... & Velarde, A. (2004). The energy spectrum and the chemical composition of primary cosmic rays with energies from 1014 to 1016 eV. The Astrophysical Journal, 612(1), 268-275.

[4] Espadanal, J., & Gonçalves, P. (2017). 3D simulation for Cherenkov emissions in Extensive Air Showers. arXiv preprint arXiv:1702.03276.

[5] Swordy, S. P., & Kieda, D. B. (2000). Elemental composition of cosmic rays near the knee by multiparameter measurements of air showers. Astroparticle Physics, 13(2-3), 137-150.

[6] Takeda, M., Sakaki, N., Honda, K., Chikawa, M., Fukushima, M., Hayashida, N., ... & Yoshii, H. (2003). Energy determination in the akeno giant air shower array experiment. Astroparticle Physics, 19(4), 447-462.

[7] Rasekh, I., & Purmohammad, D. (2021). On the estimation of the depth of maximum of extensive air showers using the steepness parameter of the lateral distribution of Cherenkov radiation. Astroparticle Physics, 132, 102619.

[8] Bartoli, B., Bernardini, P., Bi, X. J., Cao, Z., Catalanotti, S., Chen, S. Z., ... & ARGO-YBJ Collaboration. (2017). EAS age determination from the study of the lateral distribution of charged particles near the shower axis with the ARGO-YBJ experiment. Astroparticle Physics, 93, 46-55.

[9] Lagutin, A. A., Raikin, R. I., Inoue, N., & Misaki, A. (2002). Electron lateral distribution in air showers: scaling formalism and its implications. Journal of Physics G: Nuclear and Particle Physics, 28(6), 1259-1274.

[10] Al-Rubaiee, A. A. (2014). Extension of cherenkov light LDF parametrization for tunka and yakutsk EAS arrays. Journal of Astrophysics and Astronomy, 35(4), 631-638.
[11] Klepser, S. (2008). Reconstruction of extensive air showers and measurement of the cosmic ray energy spectrum in the range of 1-80 PeV at the South Pole.
[12] Fadhel, K. F., & Al-Rubaiee, A. A. (2022). Reconstruction of Air-Shower Parameters Through the Lateral Distribution Function of Ultra-High Energy Particles. arXiv preprint arXiv:2201.01368.
[13] Mishev, A. (2012). Analysis of lateral distribution of atmospheric cherenkov light at high mountain altitude towards event reconstruction. International Scholarly Research Notices, 2012(1), 906358.
[14] Drescher, H. J., & Farrar, G. R. (2003). Dominant contributions to lateral distribution functions in ultra-high energy cosmic ray air showers. Astroparticle Physics, 19(2), 235-244.
[15] Kalmykov, N. N., Kozhin, V. A., Korosteleva, E. E., Kuzmichev, L. A., Panasyuk, M. I., Prosin, V. V., ... & Wischnewski, R. (2007). Tunka-133 EAS cherenkov array: Status of 2007. In Proceedings of the 30th International Cosmic Ray Conference, ICRC 2007 (pp. 973-976).
[16] Alexandrov, L., Mavrodiev, S. C., Mishev, A., & Stamenov, J. (2001). Estimation of the primary cosmic radiation characteristics. In Proceedings of ICRC (Vol. 2001, No. 257).
[17] Rada, W. S., Smith, A. C., Stewart, T. R., Thompson, M. G., & Treasure, M. W. (1979). High-energy muons in extensive air showers. Il Nuovo Cimento A (1965-1970), 54(2), 208-216.
[18] Ostapchenko, S. (2011). Monte Carlo treatment of hadronic interactions in enhanced<? format?> Pomeron scheme: QGSJET-II model. Physical Review D—Particles, Fields, Gravitation, and Cosmology, 83(1), 014018.
[19] Ulrich, R., Engel, R., & Unger, M. (2011). Hadronic multiparticle production at ultrahigh energies and extensive air showers. Physical Review D—Particles, Fields, Gravitation, and Cosmology, 83(5), 054026.
[20] Mishev, A., & Hristova, E. (2011). Gamma Background Measurements at BEO Moussala. arXiv preprint arXiv:1104.2685.
[21] Knurenko, S. P., Ivanov, A. A., Pravdin, M. I., Sabourov, A. V., & Sleptsov, I. Y. (2006). Recent results from Yakutsk experiment: development of EAS, energy spectrum and primary particle mass composition in the energy region of 10^ 15-10^ 19 eV. arXiv preprint astro-ph/0611871.
[22] Gupta, S. K., Aikawa, Y., Gopalakrishnan, N. V., Hayashi, Y., Ikeda, N., Ito, N., ... & Yoshikoshi, T. (2005). GRAPES-3—A high-density air shower array for studies on the structure in the cosmic-ray energy spectrum near the knee. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 540(2-3), 311-323.
[23] Antoni, T., Apel, W. D., Badea, F., Bekk, K., Bernlöhr, K., Blümer, H., ... & KASCADE Collaboration. (2001). Electron, muon, and hadron lateral distributions measured in air showers by the KASCADE experiment. Astroparticle Physics, 14(4), 245-260.
[24] Ivanov, A. A., Knurenko, S. P., & Sleptsov, I. Y. (2009). Measuring extensive air showers with Cherenkov light detectors of the Yakutsk array: the energy spectrum of cosmic rays. New Journal of Physics, 11(6), 065008.
[25] Mishev, A., Angelov, I., Duverger, E., Gschwind, R., Makovicka, L., & Stamenov, J. (2001). Experimental study and Monte Carlo modeling of the Cherenkov effect. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 474(2), 101-107.
[26] Mavrodiev, S. C., Mishev, A. L., & Stamenov, J. N. (2004). A method for energy estimation and mass composition determination of primary cosmic rays at the Chacaltaya observation level based on the atmospheric Cherenkov light technique. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 530(3), 359-366.