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Energy Estimation and Mass Composition Determination in Extensive Air Showers for Primary Cosmic Rays

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Abstract

In this work. the CORSIKA code will be used to simulate a part of an Extensive Air Showers (EAS) that describes the lateral distribution function (LDF) with the Yakutsk array. The EAS development has been estimated for several particles like helium, proton, and Gamma-ray (He, P, and γ). The simulation was performed using the high-energy QGSJetII-04 model with the Yakutsk array. primary particles with energies $\geq 10^{14}$ eV and zenith angles with less than 60° degrees are considered during the shape development of EAS in the Earth's atmosphere. Mean particle densities increase from Yakutsk at 600 m from the shower axis therefore, this distance from the shower axis was used during the simulation. Depending on the Polynomial Fit (PF) function a parameterization of the density of the shower as a function of the primary mass was reconstructed based on this simulation for primary protons, gamma rays, and helium nuclei at several zenith angles. Protons and helium nuclei make up the majority of the mass composition of cosmic rays up to energies of around 10EeV, with a tiny fraction of heavy nuclei, according to the QGSJetII-04 model for a variety of primary nuclei, including a gamma ray. The comparison of the calculated LDF shows a perfect agreement with the experimental data on the Yakutsk and CORSIKA simulation at energies $\geq 10^{14}$ eV. Comparison of the calculated data and the experimental data includes the assumption that air showers with a very low muon concentration, are thought to be created by primary gamma rays.

Keywords: lateral distribution function, Cosmic Rays, Extensive Air Showers, CORSIKA simulation.

تقدير الطاقة وتحديد تكوين الكتلة في الشوار الهوائي الواسع النطاق للأشعة الكونية الأولية

كاظم ف. فاضل

المديرية العامة لتربية ديالى، وزارة التربية، بغداد، العراق

الخلاصة

في هذا العمل. سيتم استخدام كود كورسيكا لمحاكاة جزء من الشوار الهوائي الواسع النطاق (EAS) التي تصف دالة التوزيع الجانبي (LDF) مع منظومة ياكوتسك. تم تقدير تطور EAS للعديد من الجسيمات مثل الهيليوم والبروتون وأشعة جاما (He وP وγ). تم إجراء المحاكاة باستخدام نموذج QGSJetII-04 عالي الطاقة مع منظومة ياكوتسك. يتم أخذ الجسيمات الأولية ذات الطاقات $\geq 10^{14}$ الكترون فولت وزوايا السمت التي تقل عن 60° درجة في الاعتبار أثناء تطوير شكل EAS في الغلاف الجوي للأرض. يزداد متوسط كثافة الجسيمات من ياكوتسك على بعد 600 متر من محور الشوار، لذلك تم استخدام هذه المسافة من محور الشوار أثناء المحاكاة. اعتمادًا على دالة متعدد الحدود (PF)، تمت إعادة بناء معلمات كثافة الشوار كدالة للكتلة الأولية بناءً على هذه المحاكاة للبروتونات الأولية وأشعة جاما ونواة الهيليوم عند عدة زوايا سمتية. أظهر نموذج QGSJetII-04 للنوى الأولية المختلفة، بما في ذلك أشعة جاما، أن التركيب الشامل للأشعة الكونية حتى طاقات ~10 EeVيتكون بشكل أساسي من البروتونات ونواة الهيليوم، مع عدد صغير من النوى الثقيلة. تُظهر مقارنة LDF المحسوبة اتفاقًا تامًا مع البيانات التجريبية الخاصة بمحاكاة ياكوتسك وكورسيكا عند الطاقات $\geq 10^{14}$ eV. تتضمن مقارنة البيانات المحسوبة والبيانات التجريبية الافتراض بأن الشوار الهوائي ذات تركيز منخفض جدًا من الميونات يُعتقد أنها تنشأ بواسطة أشعة جاما الأولية.

الكلمات المفتاحية: دالة التوزيع الجانبي، الأشعة الكونية، الشوار الهوائي الواسع، محاكاة كورسيكا.

1. Introduction

Research in the field of astrophysics concerning cosmic rays with energies above 1 eV is crucial to understanding the universe's operations and evolution[1]. One of the major unsolved issues in astroparticle physics is locating and comprehending the sources of high-energy cosmic rays[2]. The long-standing mystery of the genesis of high-energy cosmic rays can only be resolved with an understanding of the mass composition of cosmic rays. Strong limitations on the acceleration of cosmic rays and their propagation through the galactic and extragalactic Universe can be obtained from the distribution of mass. Measurements of the mass composition near structures seen in the cosmic ray energy spectrum are of particular interest[3]. which is detectable for energy over roughly 10^{14} eV in ground-based detector arrays. These particles have the highest energy of all known particles in the universe, at the top end of the energy spectrum. Consequently, there is a great deal of interest in the concerns about their mass composition and origin, and cosmic-ray air showers are recorded in observatories all over the world [4]. Cosmic particles are continually present in the Earth's atmosphere. These high-energy particles' origins and acceleration methods remain unclear. The mass composition of cosmic rays is one of the key variables in this field of study. Understanding the origin, the process of acceleration, and the propagation from the origin to Earth is aided by this parameter [5]. The chaotic galactic magnetic fields cause charged particles to move across space in an arbitrary manner. Consequently, arrived charged particles (except from ultra-high energy ones) cannot trace their way back to their sources. Thus, to understand the nature of cosmic rays, one must be aware of their energy spectrum and mass composition[6,7]. Ultra-high energy charged particles cosmic rays are defined as those with an energy greater than 10^{18} eV. Investigating these particles and their origins is crucial because it can provide critical details about cosmic accelerators that help us comprehend the universe. When a sufficiently energetic cosmic rays particle enters the Earth's atmosphere, a series of secondary particles known as EAS are created[8].

Investigating the traits of EAS produced by cosmic rays with extremely high energies cosmic rays is essential. In addition, the chain reaction EAS showers that are generated in the atmosphere surrounding the Earth have been used to detect high-energy cosmic rays[9]. Since some primary particles are not observable immediately, consequently, they need to be looked into based on the showers in EAS that were measured in various ways. Due to their incredibly low taxes, the Ultra High Energy Cosmic Rays (UHECR) that reach the Earth cannot be directly observed in space[10]. These particles interact with atmospheric molecules as they enter the atmosphere, causing secondary particles known as EAS[11]. There are millions of collisions and secondary particle decay in the EAS caused by cosmic rays or cosmic rays with extremely high energies. These showers can be seen with fluorescence detectors, which can track energy depositions as they grow along the atmosphere, or surface detectors, which track depositions as the particles hit the ground[12]. The charged particle local density at different distances from the shower center is one of the primary EAS features that huge ground-based air shower arrays can monitor with remarkable accuracy. The only reliable way to determine a cosmic rays basic energy spectrum, composition, and to validate hadronic interaction models at superhigh energies is to compare experimental data with the output of EAS simulations[13]. Because of this, precise theoretical predictions on the LDF of the primary EAS components over a wide range of radial distances are essential for both the physical interpretation of previous experimental findings and future experiment design studies in the field of cosmic rays research[14]]. Processing and analyzing experimental data has yielded comprehensive details on the experimental setup, simulation technique detection in EAS, and one of the fundamental tools of numerical simulation for examining EAS characteristics is the Monte Carlo method, which can be used to identify the primary particle energy type and shower axis from the traits of LDF of secondary charged particles[15]. This array enables a systematic analysis of the mass composition and energy spectrum of cosmic rays in the energy range 10^{16}–10^{18} eV. The depth of the EAS maximum X_{max} might be determined by analyzing the LDF and time structure of the EAS[16]. In the current work, CORSIKA simulation code (v.6.0, QGSJET model) of hadronic processes of the EAS showers of LDF for circumstances and configurations of the Yakutsk EAS array was used[17]. Based on the Polynomial Fit function, a method for describing the lateral 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 Yakutsk was examined. The primary benefit of this strategy is the ability to recapture LDF events that were observed using the Yakutsk array. A good chance for primary particle identification, mass composition, and the characterization of its energy around the knee and ankle areas has been demonstrated by comparing the approximated LDF with the reconstructed EAS showers recorded with the Yakutsk EAS array.

2. Simulation Lateral Distribution in EAS

In this study, the evolution of the atmospheric cascade and the lateral dispersion in EAS are simulated using the QGSJET model for interactions of hadrons with energies $\geq 10^{14}$ eV. The CORSIKA algorithm is used to simulate the interactions and decay of various nuclei, photons, hadrons, electrons, and muons in the atmosphere. Until the particles interact with an air nucleus or, in the case of unstable secondary particles, decay, they are tracked as they travel through the atmosphere. The simulation results include information regarding the type, energy, position, and arrival time of the generated secondary particles at a selected altitude above sea level. In the simulation, especially for hadronic cascades with energy in the "knee" and "ankle" regions, the atmosphere was predicted to be near the shower maximum at this observation level. Consequently, the differences in shower generation are less pronounced than at lower observation levels, which permits the simulations to yield flatter distributions of the different shower constituents, particularly the atmospheric LDF. Helium, Proton, and Gamma-ray act as the primary nuclei that start the simulation of LDF densities in EAS. The acquired lateral distribution of densities in EAS with less uncertainty leads to a significant reduction of statistical fluctuations. A comparison LDF simulation in EAS created by primary helium, proton, and Gamma-ray with a vertical EAS shower and different primary energies (10^{14}, 10^{16}, 10^{18}, and 10^{20}) eV is shown in Figure1 using simulation software CORSIKA cod. The measured lateral distributions of atmospheric LDF are caused by various cosmic ray nuclei around the "knee" and "ankle" regions. The zenith angle effects like (0˚and 45˚) of the lateral distribution of primary particles such as (helium, proton, and Gamma-ray) by using CORSIKA code at the primary energy 10^{19} eV is shown in Figure 2. The EAS shower's development-related variations predominate in the high-energy range over 10^{15} eV.

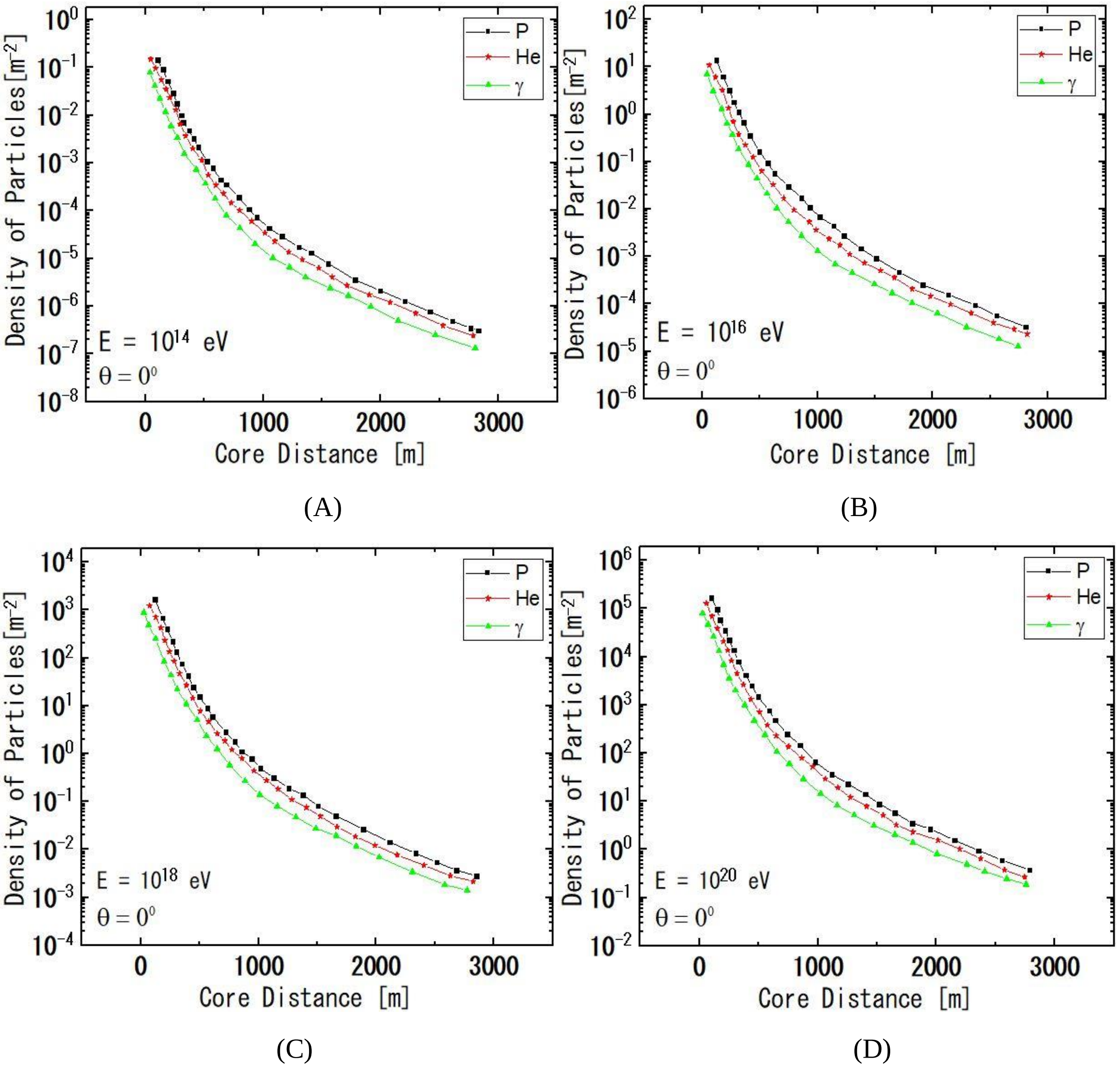

Figure -1 A simulation of the lateral distribution using the CORSIKA code for several primary particles including helium, proton, and Gamma-ray, and different primary energies (A) 10^{14} eV, (B) 10^{16} eV, (C) 10^{18} eV, and (D) 10^{20} eV at vertical EAS shower.

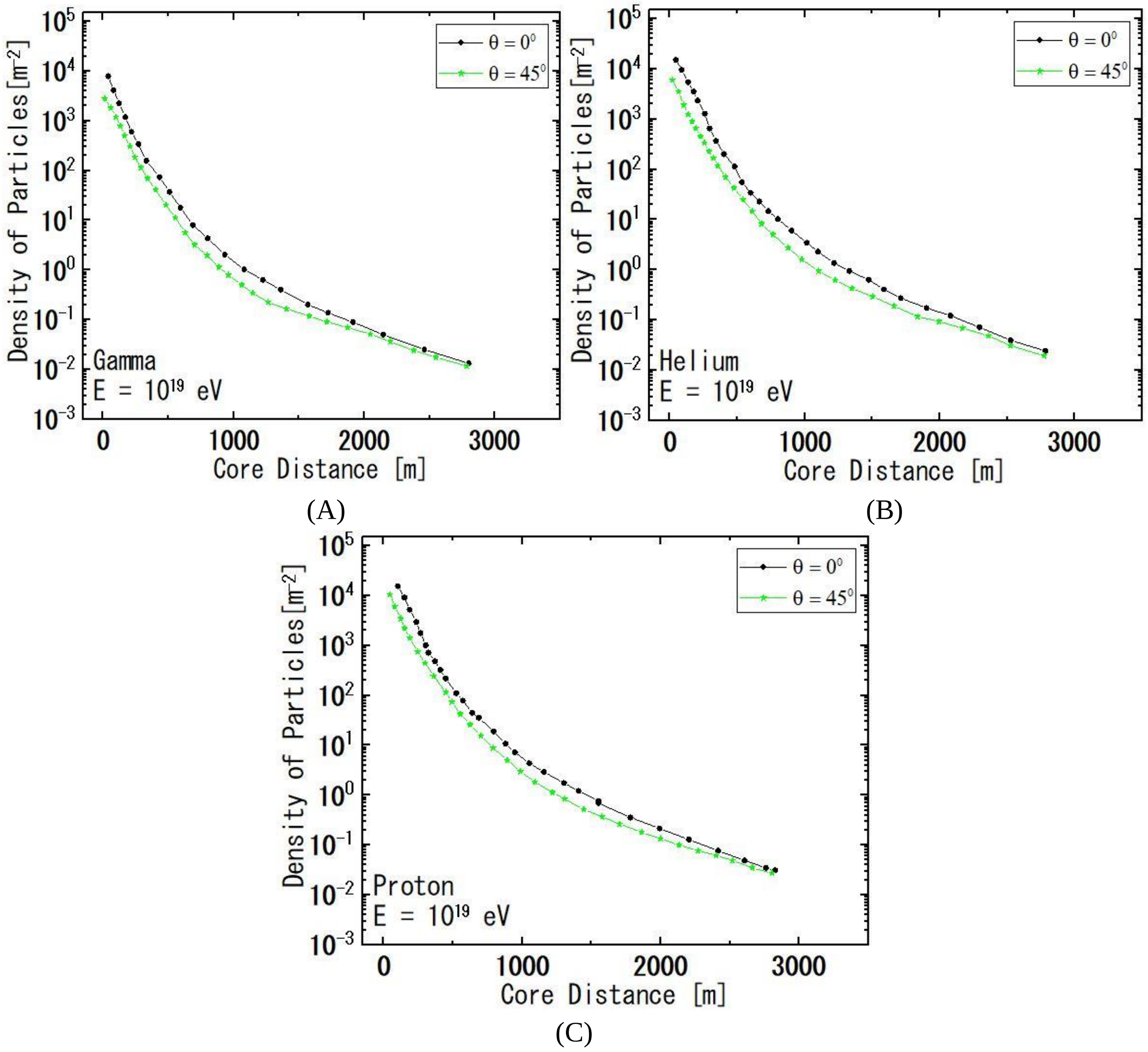

Figure -2 The zenith angles effects like (0˚and 45˚) of LDF by primary particles (A) Gamma-ray, (B) helium, and (C) proton using CORSIKA code at the primary energy 10^{19} eV.

3. Parameterization of Lateral Distribution

The flow of LDF to learn more about primary particles and event reconstruction is often used to describe how LDF 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 total number of secondary particles (Q) emitted by primary particles in the EAS, is directly proportional to the primary energy E_0 which is equal to 81.4 MeV, critical energy for secondary particles. Since it is challenging to determine this magnitude experimentally, density, or the number of particles (Q) per unit area which varies with distance from the shower axis and energy.

The CORSIKA code simulation was used for the helium, proton, and Gamma-ray and explores the LDF for the hadronic model. The LDF showers that began in EAS were parameterized using a polynomial fit function, which provided four parameters for the different primary particles. The secondary particles generated in the atmosphere were also varied using the polynomial fit function, which is represented by:

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$$Q_{(E)} = \xi_0 + \xi_1 \lg(E_0) + \xi_2 \lg(E_0)^2 + \xi_3 \lg(E_0)^3 \quad (1)$$

where Q is the density of particles of EAS showers as a function of the primary mass; ξ_0, ξ_1, ξ_2, and ξ_3 are obtained coefficients for LDF (see Table 1). These coefficients are obtained by fitting the CORSIKA results, which are given by the polynomial form:

$$Q_{(\theta)} = \eta_0 + \eta_1 \lg(M_0) + \eta_2 \lg(M_0)^2 + \eta_3 \lg(M_0)^3 \quad (2)$$

where $Q_{(E)} = \xi_0, \xi_1, \xi_2$, and ξ_3 are parameters of Eq. (1) as a function of primary energy and η_0, η_1, η_2, and η_3 (eV) are their coefficients (see Table 1).

Table 1- Using the parameterized CORSIKA code simulation for various primaries with energies $\geq 10^{14}$ eV and two zenith angles (0°, and 45°), one can calculate the exponential function's coefficients (Eq. 1) for the given energy.

Primary particles	$(\theta)^\circ$	$Q_{(\theta)}$(eV)	Coefficients			
			ξ_0	ξ_1	ξ_2	ξ_3
P	0°	η_0	963402.16	-3.346×10^{-18}	6.05×10^{-17}	-1.35×10^{-35}
		η_1	5.66×10^{6}	2.608×10^{-17}	1.03×10^{-11}	-2.36×10^{-36}
		η_2	298.57	8.92×10^{-18}	4.64×10^{-10}	2.71×10^{-31}
		η_3	30.62	-9.86×10^{-17}	5.32×10^{-18}	3.12×10^{-30}
	45°	η_0	11540.62	9.15×10^{-18}	1.99×10^{-18}	-1.37×10^{-35}
		η_1	28205.409	2.83×10^{-18}	8.51×10^{-12}	-2.92×10^{-36}
		η_2	280.65	1.22×10^{-15}	2.92×10^{-10}	1.14×10^{-32}
		η_3	78.16	3.67×10^{-18}	5.33×10^{-18}	-9.54×10^{-32}
He	0°	η_0	33668.68	1.79×10^{-17}	2.14×10^{-18}	-1.87×10^{-35}
		η_1	65080.05	9.15×10^{-18}	-8.75×10^{-14}	-5.39×10^{-36}
		η_2	280.1	2.83×10^{-18}	4.51×10^{-12}	3.06×10^{-32}
		η_3	76.82	1.22×10^{-15}	-1.43×10^{-17}	-1.81×10^{-31}
	45°	η_0	-66120.98	9.973×10^{-17}	-2.29×10^{-18}	-1.8×10^{-35}
		η_1	-1.22×10^{6}	3.75×10^{-19}	-1.73×10^{-13}	-5.82×10^{-36}
		η_2	321.16	-2.96×10^{-18}	9.14×10^{-12}	-3.78×10^{-31}
		η_3	37.75	2.53×10^{-17}	-7.56×10^{-18}	5.45×10^{-30}
γ	0°	η_0	1.352	1.539×10^{-17}	-3.248×10^{-17}	7.866×10^{-39}
		η_1	-11.254	1.74×10^{-19}	-1.519×10^{-19}	-5.857×10^{-38}
		η_2	0.554	6.319×10^{-16}	8.926×10^{-16}	-2.795×10^{-39}
		η_3	91.037	-1.09×10^{-17}	-1.97103×10^{-17}	1.231×10^{-33}
	45°	η_0	1.246	6.23×10^{-17}	-4.345×10^{-18}	4.363×10^{-34}
		η_1	123.237	4.267×10^{-19}	2.274×10^{-20}	1.93×10^{-35}
		η_2	43.664	1.312×10^{-17}	-1.344×10^{-15}	7.604×10^{-38}
		η_3	1281.271	4.166×10^{-18}	-4.76×10^{-16}	-7.14×10^{-37}

Figures 3, 4, and 5 show the parameterization of the LDF in EAS shower as a function of the primary mass using (Eq.1) the polynomial fit function, by CORSIKA code for different primary particles including helium, proton, and Gamma-ray (He, P, and γ) at primary energies (10^{14}, 10^{16}, 10^{18}, and 10^{20}) eV for vertical EAS shower.

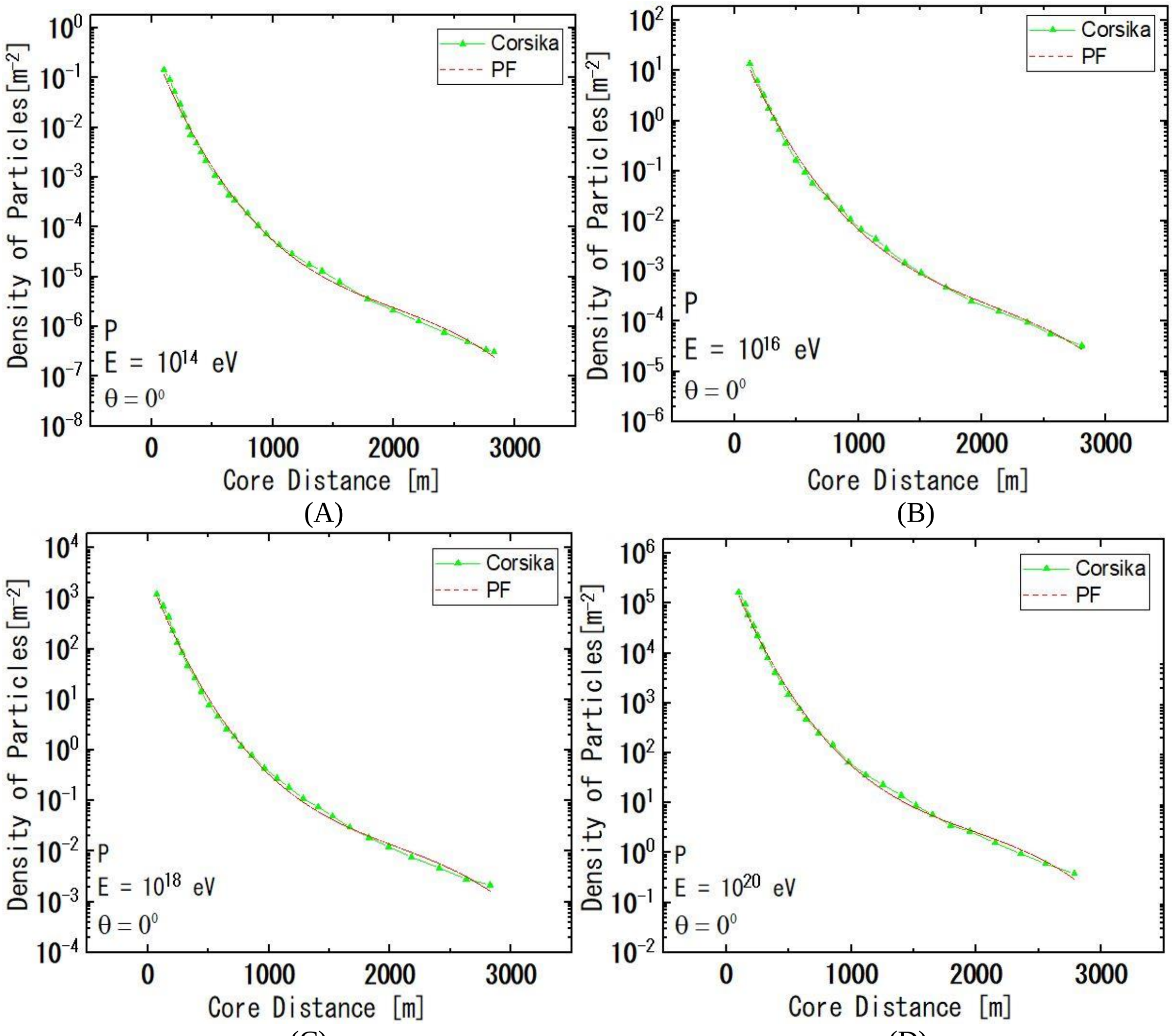


Figure -3 A lateral distribution simulation for proton primary particles at primary energies (A) 10^{14} eV, (B) 10^{16} eV, (C) 10^{18} eV, and (D) 10^{20} eV at vertical EAS shower, estimated with Eq. (1) (scattered), and one using the CORSIKA code (solid lines).

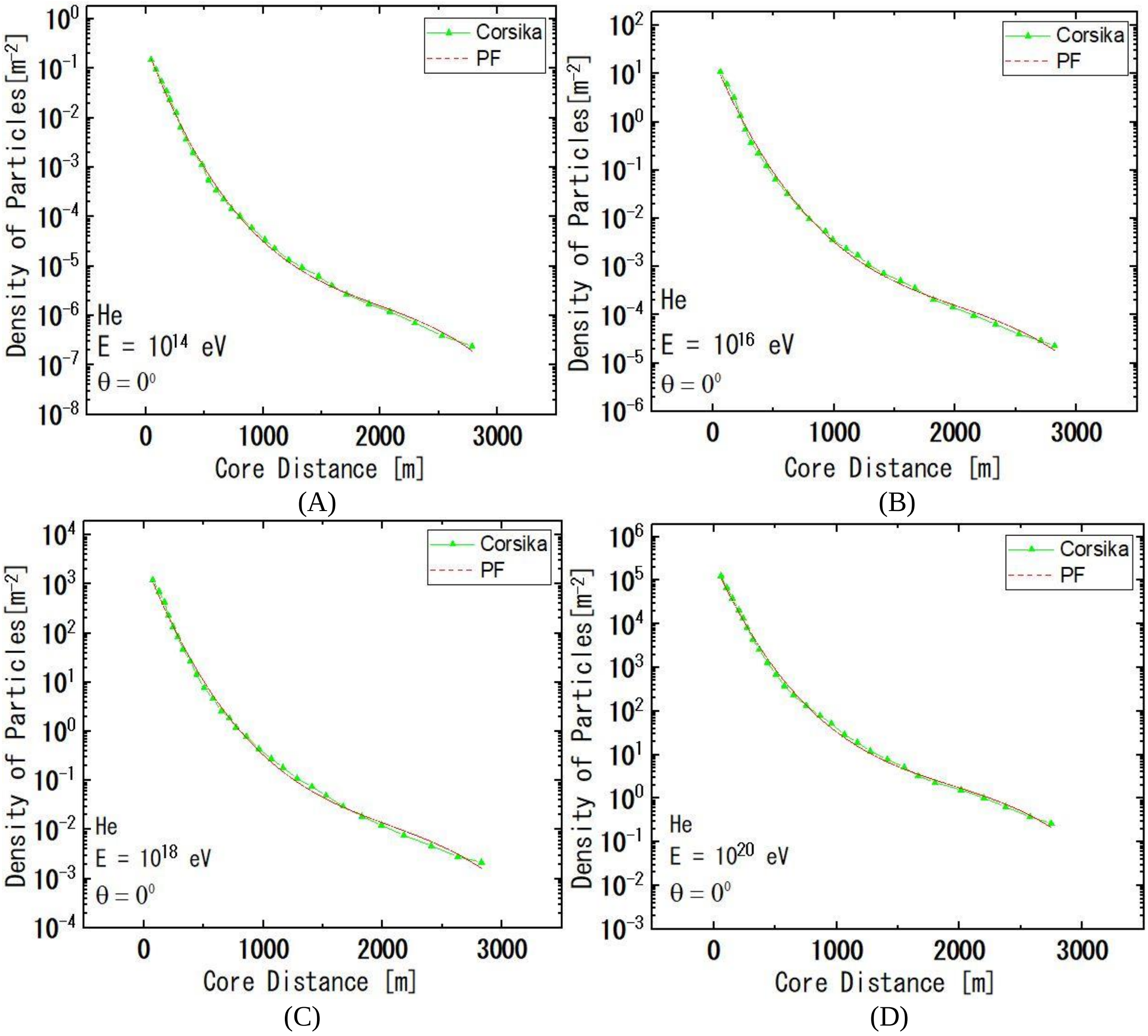
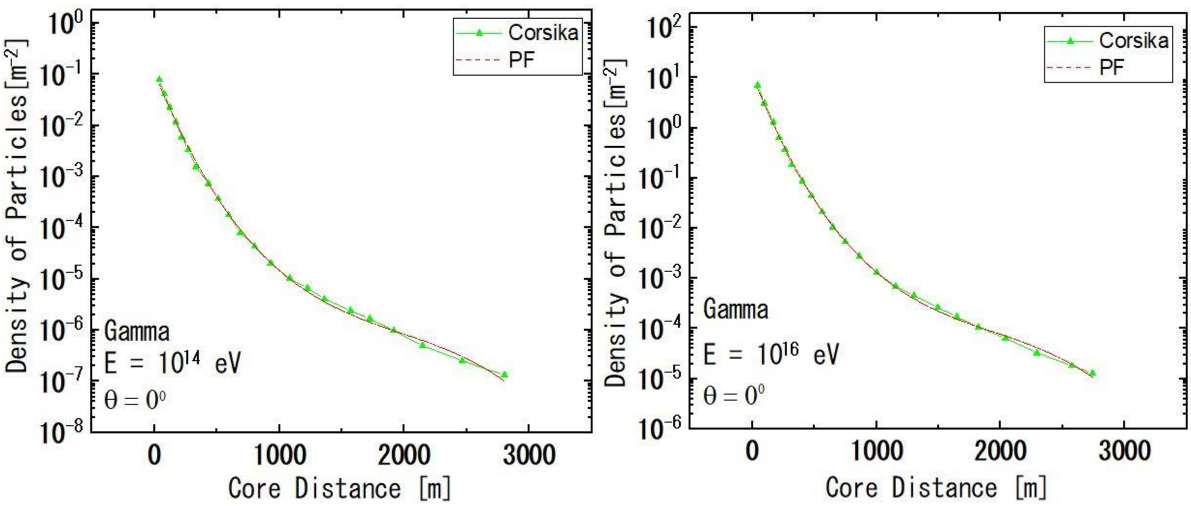
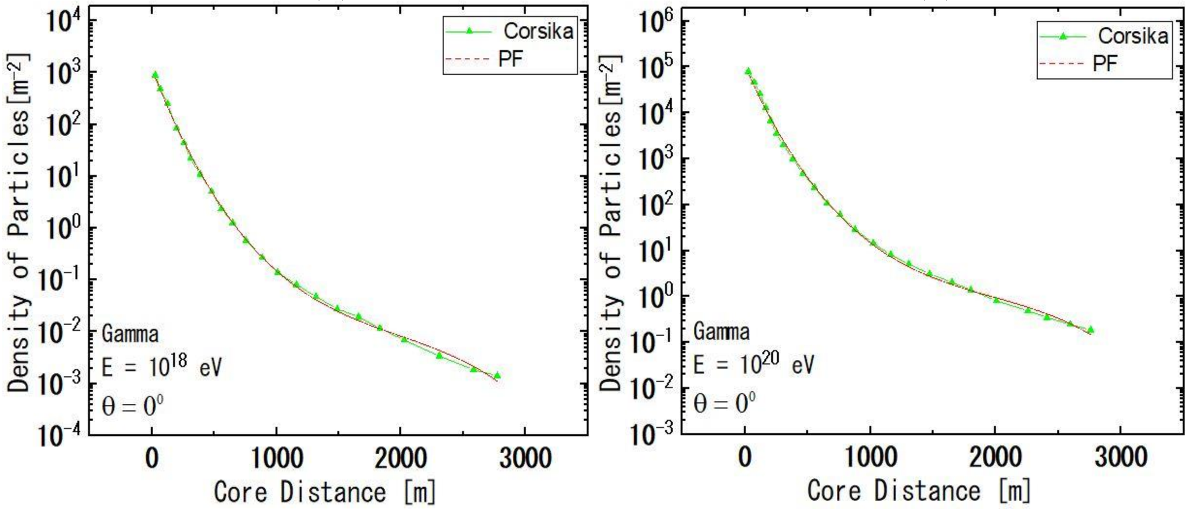


Figure -4 A lateral distribution simulation for helium primary particles at primary energies (A) 10^{14} eV, (B) 10^{16} eV, (C) 10^{18} eV, and (D) 10^{20} eV at vertical EAS shower, estimated with Eq. (1) (scattered), and one using the CORSIKA code (solid lines).



(A) (B)

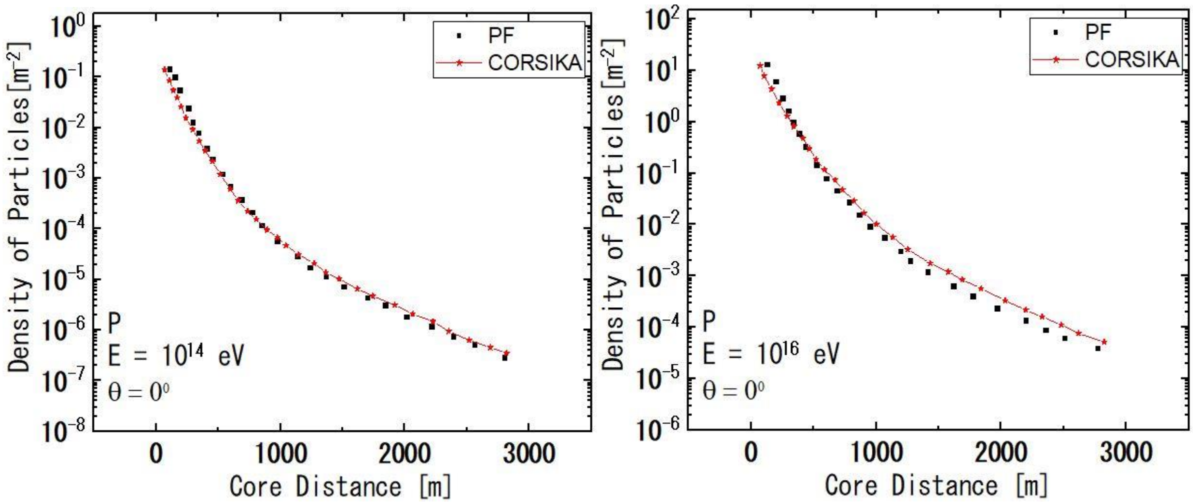


(C) (D)

Figure -5 A lateral distribution simulation for primary gamma-ray at primary energies (A) 10^{14} eV, (B) 10^{16} eV, (C) 10^{18} eV, and (D) 10^{20} eV at vertical EAS shower, estimated with Eq. (1) (scattered), and one using the CORSIKA code (solid lines).

4. Comparison of the Approximated LDF with CORSIKA code and Yakutsk observable array

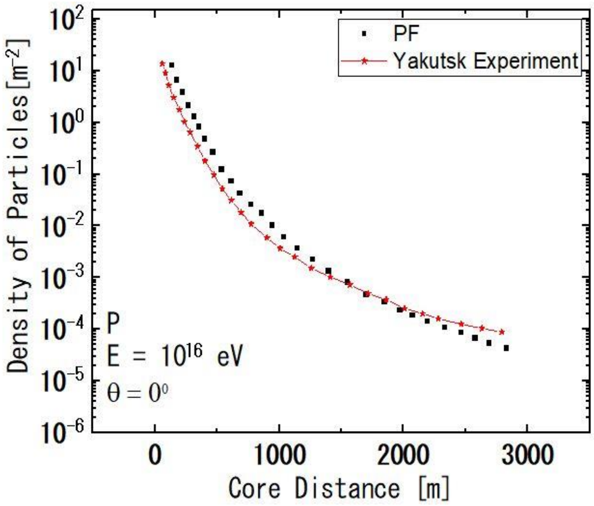
The resultant simulation of LDF exhibits, in agreement with the previous simulation model CORSIKA code. The parameterized LDF that was obtained by Eq.1 (Polynomial function) was compared with the CORSIKA code simulation for the energy spectrum of cosmic rays. This study revealed good agreement between the range of fundamental energies (10^{14} and 10^{16}) eV for vertical EAS showers and the beginning proton primary particle, as shown in figure 6.



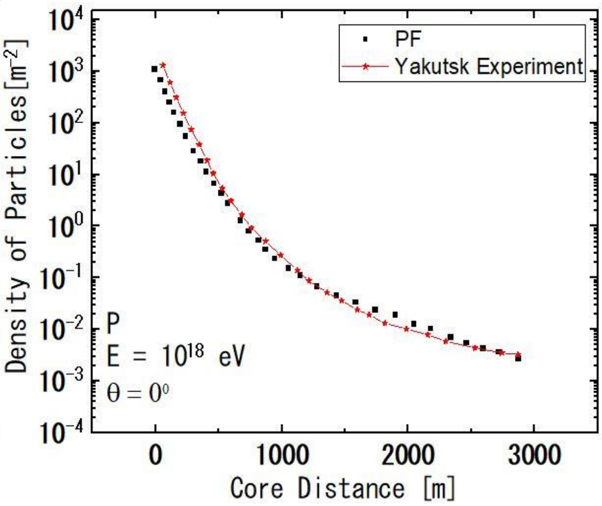
(A) (B)

Figure -6 Comparison with the parameterized LDF obtained using (Polynomial Fit function) (scattered) and the simulation of CORSIKA[18] code (solid lines) for proton primary particle at the energies (A) 10^{14} eV and (B) 10^{16} eV at vertical EAS shower.

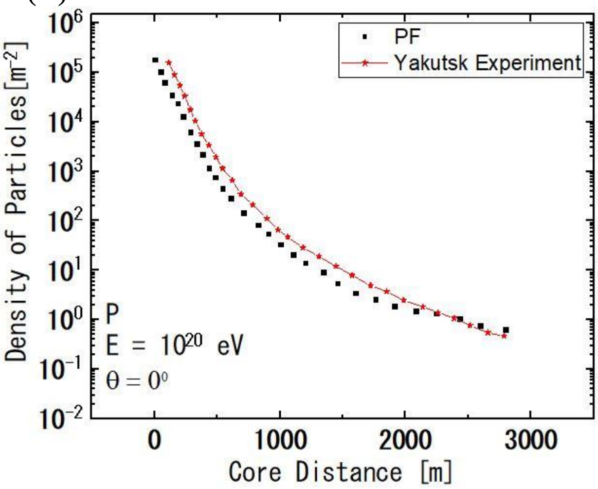
The Yakutsk EAS array studies the dynamic field of cosmic ray astrophysics, which is at the forefront of fundamental research. The two observable main goals of the Yakutsk array are to recreate the astrophysical features of the primary intensity, energy spectrum, mass composition, and origin, and to study primary particle cascades in the atmosphere that are initiated by primary particles. The main parameters in EAS observations include shower core location, LDF density of photons, and zenith angles. Figure 7 illustrates the feasibility of reconstructing the kind of EAS primary by comparing the approximate LDF with that acquired using the Yakutsk EAS shower array for primary proton at a distance of 600 m from the shower core.



(A)



(B)



(C)

Figure -7 Comparison parameterized LDF obtained by (Polynomial Fit function) with the experimental data by Yakutsk[17] observable for the primary proton at the energies (A) 10^{16} eV, (B) 10^{18} eV, and (C) 10^{20} eV at the EAS vertical shower.

5. Conclusions

The LDF from particles of EAS initiated by primaries such as helium, proton, and Gamma-ray simulations have been performed in the energies $\geq 10^{14}$ eV and zenith angles that are smaller than 60˚ CORSIKA code. Set of approximation functions were developed for the primary particles, such as helium, proton, and gamma-ray, based on this simulation, which relied on the Polynomial Fit function. Additionally, zenith angles of less than 60˚ degrees were considered. By comparing the approximated LDF with that recorded by the Yakutsk EAS array, it has been shown that it is possible to identify the particle responsible for EAS occurrences and determine its energy in the knee and ankle areas of the cosmic ray spectrum. The results collected with the CORSIKA cod are extrapolated for energies $\geq 10^{14}$ eV using the LDF parameterization. The principal advantage of the proposed method is the possibility to rapidly generate an LDF pattern library that can be applied to both the reconstruction of the energy spectrum and the analysis of real events identified by the Yakutsk EAS showers array, as well as to the analysis of actual events.

References

[1] S. P, Knurenko, and Petrov, I. S. "Mass composition of cosmic rays determined by the muon fraction with ϵ thr≥ 1 GeV in air showers with energy greater than 5 EeV." *Physical Review D* 102.2 (2020): 023036.

[2] David, d'Enterria, et al. "Constraints from the first LHC data on hadronic event generators for ultra-high energy cosmic-ray physics." *Astroparticle Physics* 35.2 (2011): 98-113.

[3] Kampert, Karl-Heinz, and Michael Unger. "Measurements of the cosmic ray composition with air shower experiments." *Astroparticle Physics* 35.10 (2012): 660-678.

[4] A., Corstanje, et al. "Depth of shower maximum and mass composition of cosmic rays from 50 PeV to 2 EeV measured with the LOFAR radio telescope." *Physical Review D* 103.10 (2021): 102006.

[5] F. Fadhel, Kadhom, and Al-Rubaiee, A. A. "EAS Cherenkov LDF Analysis: CORSIKA Simulations for Tunka-133 and Chacaltaya Arrays." *Academia Open* 9.2 (2024).

[6] K., Kawata, et al. "Energy determination of gamma-ray induced air showers observed by an extensive air shower array." *Experimental Astronomy* 44 (2017): 1-9.

[7] Rastegarzadeh, Gohar, and Saba Mortazavi Moghaddam. "An approach to identify the mass and energy of the primary cosmic rays around the knee region using arrival time distribution of secondary charged particles in extensive air showers." *Advances in Space Research* 65.10 (2020): 2456-2466.

[8] Moradalizadeh, Maryam, et al. "STUDY ON MASS COMPOSITION OF EXTENSIVE AIR SHOWER WITH ULTRA HIGH ENERGY COSMIC RAYS USING Q PARAMETER AND THEIR MUON COMPONENT." *UPB SCIENTIFIC BULLETIN, SERIES A: APPLIED MATHEMATICS AND PHYSICS Учредители: Universitatea Politehnica Bucuresti* 79.3 (2017): 221-234.

[9] Schoo, Sven. *Energy Spectrum and Mass Composition of Cosmic Rays and How to Publish Air-Shower Data*. Diss. Dissertation, Karlsruhe, Karlsruher Institut für Technologie (KIT), 2016, 2016.

[10] Gottowik, Marvin, et al. "Determination of the absolute energy scale of extensive air showers via radio emission: systematic uncertainty of underlying first-principle calculations." *Astroparticle Physics* 103 (2018): 87-93.

[11] Ostapchenko, Sergey. "LHC data on inelastic diffraction and uncertainties in the predictions for longitudinal extensive air shower development." *Physical Review D* 89.7 (2014): 074009.

[12] M., Holt, Ewa, G. Frank, Schröder, and Andreas Haungs. "Enhancing the cosmic-ray mass sensitivity of air-shower arrays by combining radio and muon detectors." *The European Physical Journal C* 79.5 (2019): 371.

[13] Ostapchenko, Sergey. "Monte Carlo treatment of hadronic interactions in enhanced Pomeron

scheme: QGSJET-II model." *Physical Review D* 83.1 (2011): 014018.
[14] Supanitsky, Alberto Daniel. "Determination of the Cosmic-Ray Chemical Composition: Open Issues and Prospects." *Galaxies* 10.3 (2022): 75.
[15] R. K., Dey, et al. "Determination of the mass and energy of primary cosmic rays above 100 TeV." *Indian Journal of Physics* 92 (2018): 1357-1365.
[16] Bellido, Jose, et al. "Depth of maximum of air-shower profiles at the Pierre Auger Observatory: measurements above'10 POT. 17.2'eV and composition implications." *Proceedings of Science* 301 (2017): 506-1.
[17] S. P., Knurenko, et al. "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* (2006).
[18] L., Alexandrov, et al. "Estimation of the primary cosmic radiation characteristics." *Proceedings of ICRC*. Vol. 2001. No. 257. 2001.