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CORSIKA modification for electric field simulations on pions, kaons and muons

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Large variations in muon flux above 1 GeV are observed in GRAPES-3 muon telescope during thunderstorm activity as a result of acceleration of muons in the atmospheric electric fields. To interpret this phenomenon quantitatively, detailed Monte Carlo simulations had to be carried out using the CORSIKA package. In CORSIKA the effects of applied electric field can be simulated by the option EFIELD. However, this option works only for electrons, and positrons as a consequence the variation observed in the GRAPES-3 muon flux could not be simulated. To address this issue, we extended the EFIELD option to simulate applied electric field on charged pions, kaons, and muons. This extension also allows the user to define the cloud height where the electric field exists. Initial simulations show that at high electric potentials, the muon flux decreases irrespective of its polarity. Detailed results of the simulations will be presented at the conference.

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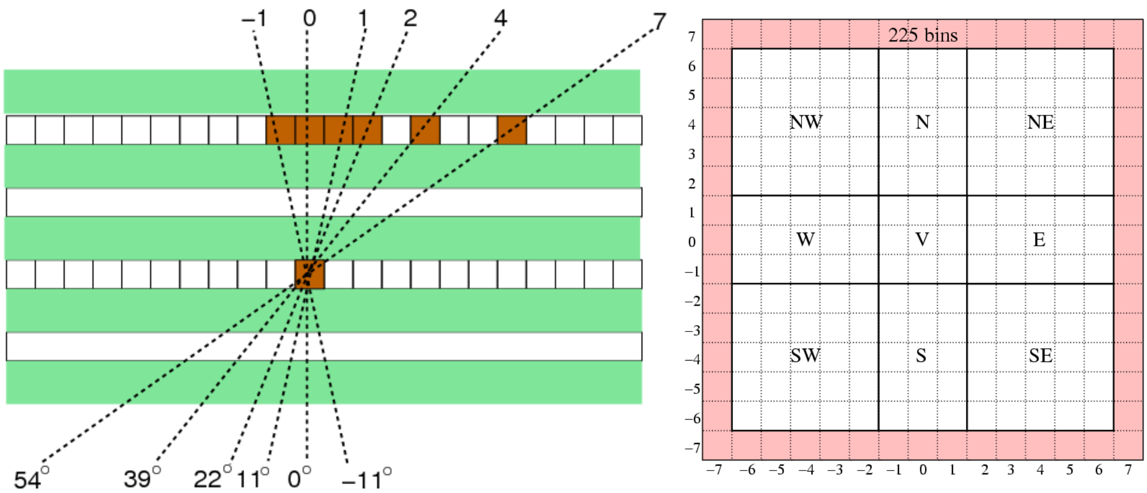
1. Introduction

During the propagation of secondary cosmic ray (CR) particles in the atmosphere, the flux observed in ground based experiments are affected by atmospheric electric field (AEF) present in thunderclouds. These effects can be studied through large scale Monte Carlo (MC) simulations. There are many CR simulators like CRY [1], AIRES [2], and CORSIKA [3] to study extensive air shower (EAS) development. Out of these, CORSIKA package provides an option EFIELD which can be used for air shower simulations in the presence of AEF [4]. Since electrons and positrons are major observable quantities in most CR experiments, the EFIELD in CORSIKA is limited to study the electric field effects only on electrons and positrons. Due to high degree of accuracy in GRAPES-3 muon flux measurement, any tiny variations can be studied with large significance. Therefore, the simulations have to be done for muons. The extended EFIELD option allows user to study the effects on muons. The GRAPES-3 muon detector simulation code was used as a calibration tool to study the effects on muons. The CORSIKA simulations were carried out with modified EFIELD and the results are discussed here. The thunderstorm observations at GRAPES-3 are compared with simulations in another work [5].

2. The GRAPES-3 tracking muon telescope

Muon telescope of the GRAPES-3 experiment, operating at Ooty, India was designed to study high energy CR astrophysics [6]. The muon telescope is used to differentiate primary gamma rays from charged CR in GRAPES-3 EAS and to obtain CR composition and probe various solar phenomena with high degree of precision [7].

The muon telescope uses proportional counter (PRC) as the basic element. Each PRC is made of mild steel tube of 600 cm long, 10 cm$\times$10 cm cross section with a wall thickness of 2.3 mm. A muon telescope module consists of 232 PRCs arranged in 4 layers, with alternate layers placed in mutually orthogonal directions which gives an sensitive area of 35 m^2. The total area covered



(a) Angle reconstruction in one projection

(b) Telescopic view of 225 directions

Figure 1: The GRAPES-3 muon angle system

by all 16 module is 560 m^2 with coverage of 2.3 sr. Two successive layers of PRCs are separated by 15 cm thick concrete which permits a two-dimensional reconstruction of muon tracks in two vertical, orthogonal planes (Fig. 1a). The vertical separation of two layers of PRCs in the same plane is 50 cm which allows the muon tracks in 225 directions (Fig. 1b) to be measured to an accuracy of 4° in the projected plane. The outer most bins are overflow bins which can be ignored and muons from inner 169 directions can be used. To achieve an energy threshold of 1 GeV for vertical muons, a total thickness of $\sim$550 g cm^{-2} in the form of concrete blocks of 2.4 m thickness is used as absorber. The concrete blocks have been arranged in the shape of an inverted pyramid to achieve an energy threshold of sec(θ) GeV for muons incident at a zenith angle θ (with coverage up to 45°).

The GRAPES-3 experiment records 4×10^9 muons daily with statistical error of 0.002%. The muon data has been successfully corrected for efficiency variation [8].

3. Introduction to CORSIKA

Understanding any experimental phenomena require detailed MC simulations. In EAS experiments, it is important to understand shower development in the atmosphere to study properties of primary CR (PCR) and the measurable quantities at the observational level. To draw quantitative conclusions from observed quantities, it is necessary to model the EAS in detail.

CORSIKA is a package to do MC simulation of EAS development. It has $\sim$80000 lines of code developed in FORTRAN and few optional C routines. It can be used with various hadronic event generators like DPMJET [9], EPOS LHC [10], NEXUS [11], QGSJET 01C [12], QGSJETII-04 [13], SIBYLL 2.1 [14] and VENUS 4.12 [15] for high energy event generators and GHEISHA [16], FLUKA [17] and UrQMD [18] for low energy event generators. It performs simulation in energy range from 10^9 eV to 10^{20} eV of various PCRs. The secondary particles are tracked through the atmosphere until they decay. At given observational level, the physical quantities of secondary particles like position, momentum and time are recorded.

4. Extension of EFIELD

We have used CORSIKA v74001 for our implementation. In CORSIKA, subroutine ELECTR treats the transport of electromagnetic components in Earth's magnetic field. This subroutine was modified by authors for official implementation of electric field simulation on electrons and positrons. The selection of code for EFIELD is managed through preprocessor directives.

For hadrons and other particles, the transport is done by subroutine UPDATE. By adopting the existing preprocessor directive, the subroutine UPDATE was modified to incorporate electric field effect on pions, kaons and muons. Since pions and kaons are the major decay modes of muon production, the modifications were done also for pions and kaons. The existing EFIELD implementation assumes user given electric field uniformly spreads over the entire atmosphere. However, the thunderclouds have limited cloud thickness compared to entire range. Therefore, the height of the thundercloud is considered in our implementation. During the particle transport, when the particle passes the defined boundary of the atmosphere, the potential energy is calculated for every steplength which is later added or subtracted, depends on electric charge of the particles. As

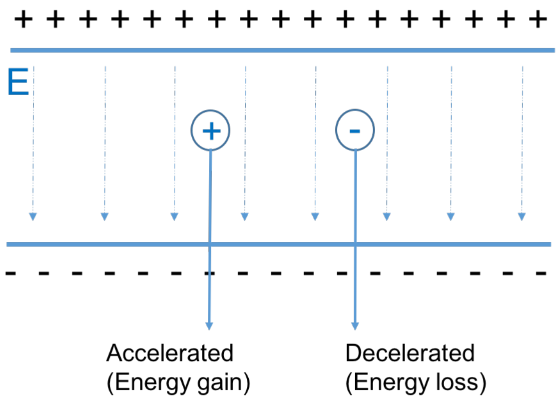


Figure 2: Charged particle motion in electric field

mentioned in Fig. 2, for upward going field, which is positive, the positive particles are accelerated and negative particles are decelerated and vice-versa.

The user selection of EFIELD option and inputs of electric field components remain unchanged.

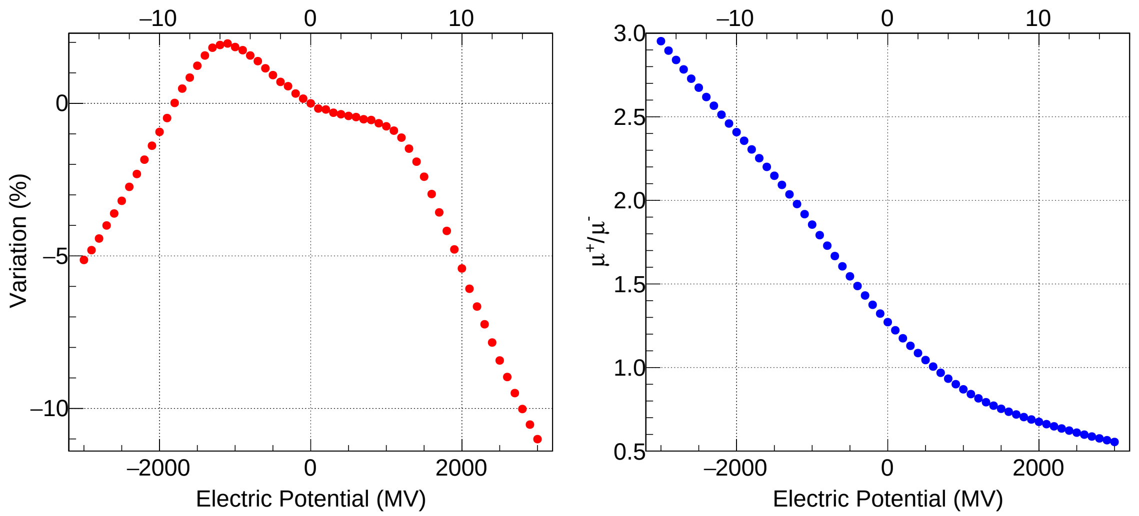
5. CORSIKA simulations

With the extended EFIELD option, 7.4×10^{10} proton showers were simulated using SIBYLL and FLUKA generators in the energy range of 10 GeV - 10 TeV. The zenith angule range was $0^\circ \leq \theta \leq 60^\circ$ and the azimuthal angle range was $0^\circ \leq \phi \leq 360^\circ$. The energy cutoff of secondary particles were set to 50 MeV for hadrons, 10 MeV for muons, 1 GeV for electrons and 1 GeV for gammas. The primaries are selected based on their directional cutoff rigidity using another modification in CORSIKA [19].

Totally 60 steps of simulations were done for electric field ranging from -15 to 15 kV cm^{-1} with step size of 0.5 kV cm^{-1}. And a set was simulated without electric field for background. The field was applied 6 km above Ooty with the cloud thickness of 2 km. From simulation, muons above 1 GeV observed at Ooty altitude (2200 m above msl.) were selected for detector simulation. The in-house developed detector simulation code was used to track CORSIKA muons for various trigger conditions and to get the angular distribution of muons in 169 directions.

6. Results and discussions

The simulations show that the overall effect of electric field on muon intensity has quadratic dependence (Fig. 3a) of applied electric field. At GRAPES-3 observational level, there are 25% excess positive muons than negative (Fig. 3b). Due to this asymmetry in muon charge ratio (μ^+/μ^-), the total muons decreases for upward electric field and increases for downward electric field. However, at certain potential, there is a rapid decrease in muon rate variation irrespective of the polarity of the field. This is due to increase in muon decay probability at mean energy of muons at GRAPES-3. The quadratic dependence of electric field is also explained by a theoretical estimation [20]. The GRAPES-3 muon telescope allows us to probe the dependence of electric field in



(a) Variation in muon intensity (b) Variation in muon charge ratio (μ^+/μ^-)

Figure 3: Electric field simulations

169 directions in future which is expected to have different profiles due to asymmetry in muon charge ratio.

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References

[1] Monte Carlo Simulation of Proton-induced Cosmic-ray Cascades in the Atmosphere, **UCRL-TM-229452.**

[2] AIRES: A system for air shower simulations, **arXiv:astro-ph/9911331v1.**

[3] D. Heck, J. Knapp, J.N. Capdevielle, G. Schatz, and T. Thouw, Report **FZKA 6019** (1998), Forschungszentrum Karlsruhe; available from http://www-ik.fzk.de/corsika/physics_description/corsika_phys.html

[4] D. Heck et al., **DOI(KIT): 10.5445/IR/1000028191** http://publikationen.bibliothek.kit.edu/1000028191

[5] B. Hariharan et al., **Proceedings of Science PoS(ICRC2017)481.**

[6] Y. Hayashi et al., **Nucl. Instrum. and Methods A 545 (2005) 643-657.**

[7] S.K. Gupta et al., **Nucl. Instrum. Methods A 540 (2005) 311.**

[8] P.K. Mohanty et al., **Proceedings of Science PoS(ICRC2017)357**

[9] J. Ranft, *Phys. Rev.* **D51** (1995) 64; arXiv:*hep-ph/9911213* and *hep-ph/9911232* (1999)

[10] T. Pierog et al., arXiv:1306.0121[hep-ph] (2013)

[11] H.J. Drescher, M. Hladik, S. Ostapchenko, T. Pierog, and K. Werner, *Phys. Rep.* **350** (2001) 93 (preprint hep-ph/0007198 (2000))

[12] N.N. Kalmykov, S.S. Ostapchenko, and A.I. Pavlov, *Nucl. Phys. B* (Proc. Suppl.) **52B** (1997) 17

[13] S.S. Ostapchenko, *Phys. Rev.* **D83** (2011) 014018

[14] R. Engel, T.K. Gaisser, P. Lipari, and T. Stanev, *Proc.* 26^{th} *Int. Cosmic Ray Conf.*, Salt Lake City (USA), **1** (1999) 415; E.-J. Ahn, R. Engel, T.K. Gaisser, P. Lipari, and T. Stanev, *Phys. Rev.* **D80** (2009) 094003

[15] K. Werner, *Phys. Rep.* **232** (1993) 87

[16] H. Fesefeldt, Report **PITHA-85/02** (1985), RWTH Aachen; available from: http://cds.cern.ch/record/162911/files/CM-P00055931.pdf

[17] A. Fassò, A. Ferrari, S. Roesler, P.R. Sala, G. Battistoni, F. Cerutti, E. Gadioli, M.V. Garzelli, F. Ballarini, O.Ottolenghi, A. Empl and J. Ranft, *The physics models of FLUKA: status and recent developments*, Computing in High Energy and Nuclear Physics 2003 Conference (CHEP2003), La Jolla, CA (USA), March 24-28, 2003 (paper MOMT005); eConf C0303241 (2003); arXiv:hep-ph/0306267;
http://www.fluka.org/references.html

[18] S.A. Bass et al., *Prog. Part. Nucl. Phys.* **41** (1998) 225; M. Bleicher et al., *J. Phys. G: Nucl. Part. Phys.* **25** (1999) 1859;
http://urqmd.org/

[19] B. Hariharan et al., **Proceedings of Science PoS(ICRC2015)448.**

[20] V.V. Alexeenko et al., in Proceedings of the 20th International Conference on Cosmic Rays (Nauka, Moscow, 1987), Vol. 4, p. 272