Simulation Studies on Distortion of EAS Muons by the Earth's Magnetic Field

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Abstract The distortion of the secondary cosmic ray (CR) muon component triggered by the earth's magnetic field is studied using a Monte Carlo (MC) code dedicated to CR air shower physics. In an inclined shower, a clear separation may be put in evidence by studying the dipole defined by both barycentres of negative and positive muons. The length of this dipole as well as its azimuthal orientation depends on the incidence of the shower characterizing by the angle of the shower axis with the components of the magnetic field and the path of the secondary muons. We observed that the new observable *muonic dipole length* might be useful to determine the nature of primary CR species.

Keywords Geomagnetism · Cosmic ray · Muons · EAS modeling · Monte Carlo simulation

1 Introduction

To draw any specific conclusions about CRs from their indirect investigation it is very important to know how they interact with the atmosphere and how the shower develops. This knowledge is obtained by comparison of data with MC predictions. Hence air shower simulations are a crucial part of the design of air shower experiments and analysis of their data. But a MC technique relies heavily on high energy

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hadronic models which suffer with some degree of uncertainties from one model to another and increasing primary energy. Therefore, we have challenges to develop more accurate hadronic interaction models in place to predict robust results. It is expected that the ongoing LHC experiment will provide new experimental inputs to the interaction models and thereby improving the predictive power of extensive air shower (EAS) simulations significantly in the concerned energy range [1].

The radial distribution of EAS particles is generally assumed to be symmetrical in the plane perpendicular to the shower axis. But presence of intrinsic fluctuations (due to stochastic nature of EAS development) from shower to shower, in addition, zenith angle and geomagnetic effects etc. can perturb this axial symmetry noticeably [2]. Consequent upon, highly inclined showers usually manifest significantly large asymmetries in charged particle distribution.

Apart from geomagnetic effect (GE), asymmetries may arise from azimuthal variation of the charged EAS particles and unequal attenuations accounted from different locations of the EAS in the ground plane (GP) with inclined incidence. These are known as geometrical and atmospheric attenuation effects to azimuthal asymmetries. To retain the GEs on the EAS charged particle distribution alone, geometrical and attenuation effects must be corrected out in the analysis. In our data analysis technique these two sources of azimuthal asymmetries are removed from data.

Here, we address the influence of the geomagnetic field (GF) on secondary muons with zenith angle $\geq 50°$ at KASCADE site [3] and express the separation between positive and negative muons as muonic dipole moment from the perturbed configuration. This *muonic dipole length* is found quite sensitive to the nature of the primary particle and hence in principle the parameter can be exploited to estimate primary mass. The practical realization of the method in a ground array experiment will be discussed briefly.

The GF effects on the EAS cascade is discussed in Sect. 2. In Sect. 3, we have given the simulation procedure employed here. Data analysis method is described in Sect. 4. In Sect. 5 we report important results obtained from this work. Our main conclusions are pointed out in Sect. 6.

2 Effects Due to Earth's Magnetic Field on Muons

The study of CRs with primary energies above 10^{14} eV is usually based on the measurements of EASs, which are essentially cascades of secondary particles produced by interactions of CR particles with atmospheric nuclei. During the development of a CR cascade in the atmosphere, the GF affects the propagation of the secondary charged particles in the shower: the perpendicular component of this field causes the trajectories of secondary charged particles to become curved, with positive and negative charged particles separating to form an electric dipole moment. This aspect was first pointed out by Cocconi nearly sixty years back [4].

He further suggested that the geomagnetic broadening effect can be non-negligible in compare to the Coulomb scattering, particularly for the young showers [4]. For instance, the geomagnetic separation of muons can be used to estimate the height of origin of showers. The positive to negative muons ratio could also evaluate the signature of neutrons emitted from close pulsars or other astrophysical sources (Geminga, Vela, Crab etc.) at few kpc distances [5]. The GF induces an azimuthal modulation of the densities of air shower particles, particularly for large angle incidence [6]. For that reason, the estimated energy of CRs may deviate from the true value up to the $\sim 2\ \%$ level at large zenith angles of incidence due to such azimuthal modulation [7].

For the soft component the radiation lengths in atmosphere are very short and electrons and positrons suffer many scatterings and stronger bremsstrahlung effect thereby frequent changing the directions relative to the GF. As a result the lateral spread of the electrons is mainly due to the multiple coulomb scattering and bremsstrahlung, and hence the effect of GF is less pronounced. In contrast after their generation from pion and kaon decays muons travel much longer path without scattering (suffer lesser bremsstrahlung also) and hence come under the influence of GF in a big way. As a result GE should be more pronounced in low momentum muons than very energetic ones, particularly for very large and strongly inclined showers. The work includes more accurate data analysis technique than before by bringing down even the small attenuation contributions from data in order to obtain primary mass information due to GF effects only.

3 Simulation Method

In the framework of the air shower MC simulation program version 6.970 [8], the EAS events are simulated by coupling the high energy (above $80\,\mathrm{GeV/n}$) hadronic interaction models QGSJet 01 version 1c [9] and EPOS 1.99 [10], and the low energy (below $80\,\mathrm{GeV/n}$) hadronic interaction model UrQMD [11]. The EGS4 program library [12] is opted for simulation of the electromagnetic component of shower that incorporates all the major interactions of electrons and photons. We consider the US-standard atmospheric model [13] with planar approximation which works for the zenith angle of the primary particles being less than 70°. The EAS events have been simulated at geographical location corresponds to the experimental site of KASCADE (latitude 49.1°N, longitude 8.4°E, 110 m a.s.l.). The EAS events have been generated for Proton (p) Oxygen (O_2) and Iron (Fe) primaries at fixed primary energy 10^{15} eV taking zenith angles of incidence, between 50° and 68° with FLAT option of the atmosphere. About 10,000 EAS events have been generated for this work.

4 Data Analysis Method

Secondary charged particles in an EAS are generated maintaining a cylindrical symmetry around the shower axis, which is along the arrival direction of EAS initiating particle. As a result in the absence of GF lateral distribution of EAS charged particles should possess such a symmetry for all radial distances from the axis in a plane normal to the shower axis. In the GP, however, such cylindrical symmetry is distorted for inclined EAS due to geometrical and atmospheric attenuation effects. Since the effect (azimuthal asymmetry) of GF is superimposed with those caused by geometric and attenuation effects, it is convenient to transform the density information of charge particles of air showers in the GP to shower plane (SP) so that the effect of the GF can be isolated out. It should be mentioned, however, that the effect of muon attenuation in the transformation is negligibly small and is ignored here.

An EAS experiment and M C technique both provide information about an EAS initiated by a primary from the GP. To extract the actual variation introduced by the GE in EAS observables, it is necessary to take away the contribution added geometrically from data. In Fig. 1, we have shown the transformation of a point of impact by a cascade particle on the GP to shower front plane in polar coordinates. Here, in the figure Z and A denote the primary zenith and azimuth angles respectively, and (r_g, ϕ_g) are polar coordinates of the point of impact (say, P) of an EAS charged particle under consideration at the GP while (r_n, β_n) represent the polar coordinates of the point P at the corresponding SP (plane $\perp^r$ to the shower axis containing P), then

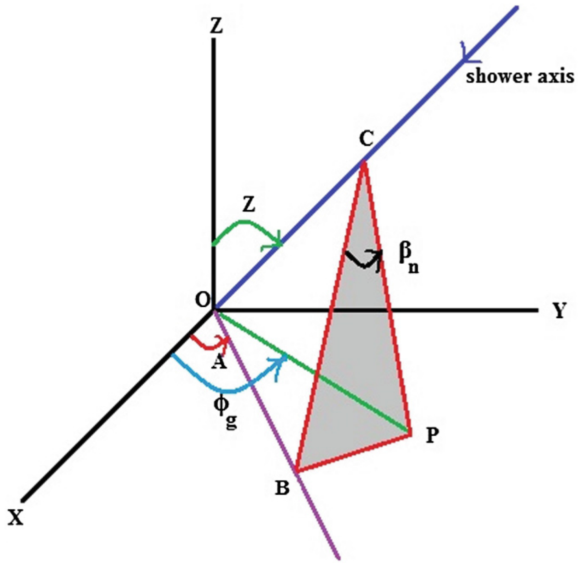

Fig. 1 Geometry for the point of impact P of a cascade charged particle in polar coordinates in ground and shower front planes respectively

$$r_n = r_g\sqrt{1 - \sin^2 Z \cos^2(\phi_g - A)} \quad (1)$$

Using the figure, the corresponding Cartesian coordinates $P(x_n, y_n)$ at the SP can be easily obtained as,

$$x_n = r_g \cos(\phi_g - A)\cos Z \quad (2)$$

$$y_n = r_g \sin(\phi_g - A) \quad (3)$$

The shaded zone in the diagram (*APC*-region) represents the normal plane, where $OP = r_g$, $CP = r_n$ and $CB = x_n$, and $BP = y_n$.

We first consider a hypothetical circular full coverage air shower array of radius 300 m taking the shower core as the center of the circle. Employing the Eqs. (2)–(3) we then transform the simulated density or other quantities of interest at GP to the normal plane/SP.

5 Results

For examining asymmetric characteristics on the azimuthal plane of the charged particle distribution due to GF, we estimated density/total number of charged muons over a small azimuthal angle bin of either 15° or 10° with regard to various situations. The azimuthal variation of total (truncated) muon content at GP and at SP is shown in Fig. 2 for p, O_2 and Fe initiated showers of zenith angle of incidence 55° and arriving from North direction. This figure implies that the azimuthal

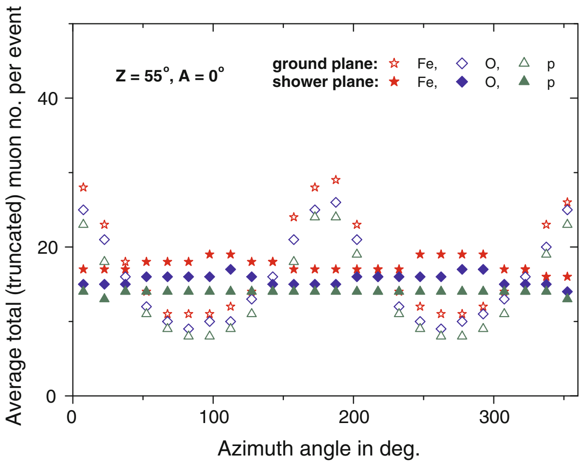

Fig. 2 Azimuthal variation of muon distribution in GP and SP for proton, oxygen and iron primaries in the radial range (0–200 m)

asymmetry in the GP is mainly due to GE while in SP, the observed negligibly small azimuthal asymmetry seems to be due to attenuation effect. It appears that the attenuation effect is small, even at zenith angles of incidence much beyond 50°. Since positive and negative particles behave in an opposite way under GF, the GE is not revealed from the azimuthal variation of the total muon content. To examine GE we draw the angular variation of charged muons in inclined air showers which are shown in Fig. 3 (Left panel—μ^+ and Right panel—μ^-) for proton primaries arriving from north direction (A = 0°). To understand the influence of GF clearly, we also studied azimuthal variation of charged muons by turning off the GF, which is accomplished in CORSiKA simulation by dividing the components of the geomagnetic field by a factor of ten thousand. Such variations for p are also included in Fig. 3. Azimuthal variations of charged muons for both p and Fe primaries arriving from the North direction are displayed in Left and Right panels of Fig. 4. From Figs. 3 and 4, we have found that the asymmetry in μ^+ and μ^- numbers separately in SPs is nearly zero. To quantify the influence of GF as well as to identify some

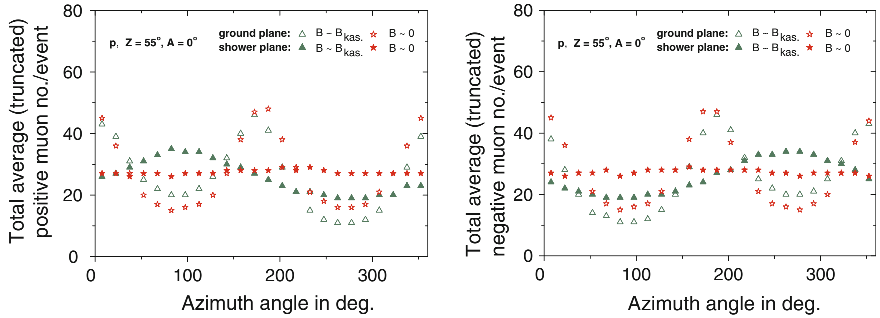

Fig. 3 Azimuthal variation of μ^+ (*left*) and μ^- (*right*) for p primary in GP and SP with B $\approx B_{KAS.}$ and ≈ 0

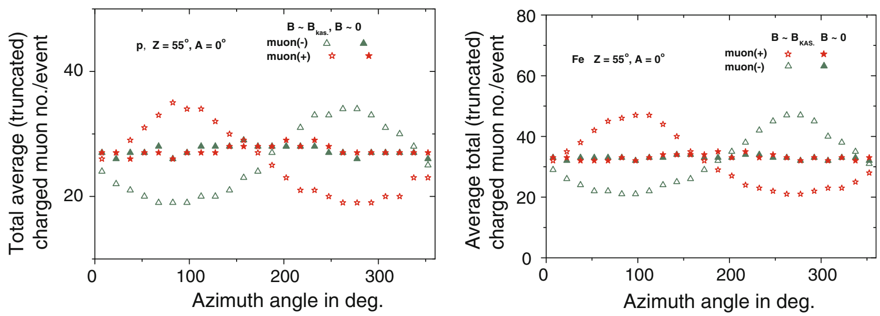

Fig. 4 Azimuthal variation of charged muons for p (*left*) and Fe (*right*) primaries arriving from North direction in SP with $B \approx B_{KAS.}$ and $B \approx 0$

typical signatures of the primary particle we have calculated the coordinates of positive and negative muons barycenters and thereby estimated the average muon dipole length per shower, which is the separation of centre of gravity of negative and positive charged muons in the SP. For this purpose we introduce a procedure of scanning of charged particle density/number with the butterfly (BF) treatment: the BF consists of two opposite wings around the shower core limited by a pair of symmetric arcs corresponding to angle of amount 15° which is called a slim BF. The variation of average muon dipole length/event with azimuthal angle for p, O_2 and Fe initiated EASs of zenith angle of incidence 55° and arriving from North direction is shown in Fig. 5. In this figure the azimuthal variation of average muon dipole length/event is also shown when the GF is switched off. A comparison of the variation of average muon dipole length/event for various primaries is clearly seen from this kind of study. It is found from the Fig. 5 that the average length of the muon dipole increases due to GF up to $\phi_g = 90°$ and then returns to its initial value at $\phi_g = 180°$. The parameter is found sensitive to primary mass; it is largest for Fe and smallest for p at a given primary energy. So the parameter can be used, at least in principle for extracting the nature of primary particles.

The variation of the average maximum value of the muon dipole length against zenith angle is shown in Fig. 6 for p, O_2 and Fe primaries. Here, a maximum value of the parameter is obtained by taking average of all dipole lengths ranging from $\phi_g = 75°$ to $\phi_g = 105°$ corresponding to a particular Z and primary species. This parameter might be useful for the measurements of primary mass composition of CRs from the technique adopted in this work.

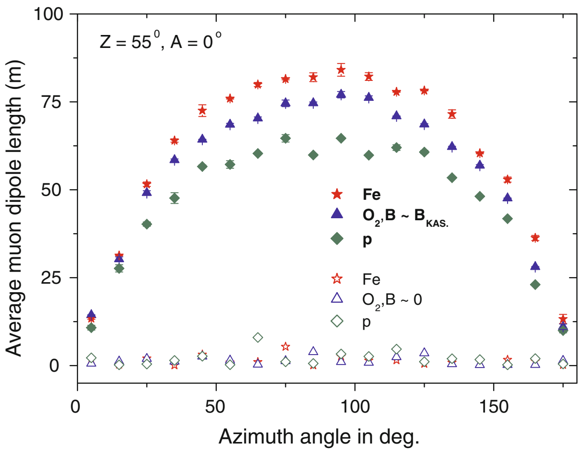

Fig. 5 Azimuthal variation of muon dipole length for p, O_2 and Fe primaries arriving from the North direction

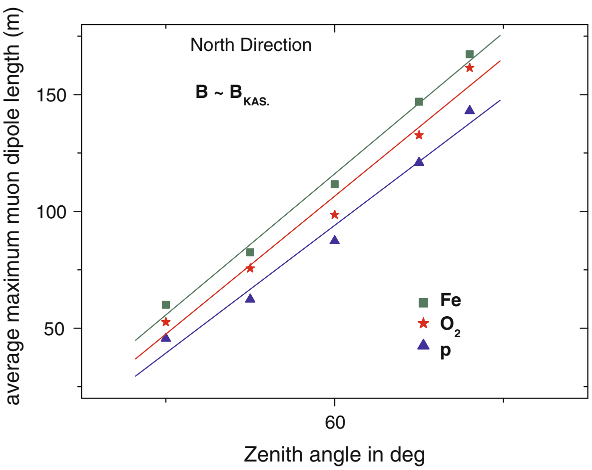

Fig. 6 Variation of average maximum muon dipole length per event with zenith angle for p, O_2 and Fe primaries arriving from North direction

6 Conclusions

Our analysis concerning the effects of the GF on positive and negative muon components of inclined EAS reveals several interesting features such as azimuthal asymmetries, sectorial positive-negative muons relative abundances, amplitude of fluctuations among p, O_2 and Fe induced showers. Such effects are found to persist and are of comparable magnitude if we replace the UrQMD code in the simulation by the Fluka/Gheisha code in the treatment of low energy hadron collisions. For very inclined showers the Earth's magnetic field might be used as magnetic separator at least for muons in the GeV energy regime. It seems very interesting to the experimental detection of these features for the understanding of the EAS development under GF.

There are some recent proposals of studying positive and negative muons separately in individual EAS event. In fact few ongoing experiments, such as the WILLI detector [14] in Bucharest, Romania or the Okayama University, Japan EAS installation, have the capability to extract charge information of high energy muons but these experiments do not have large muon detection area, which is needed to extract information about the nature of primaries from the study of geomagnetic influence on EAS muons. If in future these experiments are extended in order to cover larger detection area, or new installation of large muon detection area with capability of charge identification will come up, the present proposal can be exploited to extract the nature of primary CRs.

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