Study of EASs inclination due to geomagnetic field by 50 TeV to 5 PeV CORSIKA simulated events

M. Khakian Ghomi*, M. Bahmanabadi†, H. Hedayati†, F. Sheidaei‡, A. Anvari† and J. Samimi†

**Amirkabir University of Technology, 15875-4413, Tehran, Iran*
†Sharif university of Technology, 11555-9161, Tehran, Iran
‡ALBORZ observatory, Sharif university of Technology, 11555-9161, Tehran, Iran

***Abstract*. Previously it was shown that the most important inclination of the EAS events due to geomagnetic field is the effect over the secondary particles of them and the contribution of the primary is so small [1]. These secondary particles are mostly $e^{\pm}$ and $\mu^{\pm}$, so we limited our study over these particles. It was simulated over 520,000 EAS events with (ON) and without (OFF) geomagnetic field for our site ($B_0 = 28.1\ \mu T\ \hat{\mathrm{i}} + 38.4\ \mu T\ \hat{\mathrm{k}},\ h = 1200$m a.s.l.). It is observed a quite North-South anisotropy in ON events and a quite random anisotropy in OFF events. This anisotropy is comparable with the recorded results in our site (ALBORZ observatory), but the simulated anisotropy is a little more than the experiment. We investigated two aspects in this way: A) Tracing of a large number of Particles in the atmosphere independent of CORSIKA results and finding the inclination of them. By this method trend of the obtained anisotropy is in agreement with the experiment but it shows a slighter anisotropy than the experiment. B) Investigation of the inclination effect of the geomagnetic field over particles of 520,000 CORSIKA simulated EAS events. There are some asymmetric factors which are the ratios of $N_{e^-}/N_{e^+} \simeq 1.57$ and $N_{\mu^-}/N_{\mu^+} \simeq 0.97$. It seems that, one of the important factors is the N_{e^-}/N_{e^+}. Also the mean energy of e^+, e^-, μ^+ and μ^- for ON and OFF events are 0.1585, 0.1099, 16.883, 17.113 GeV and 0.1568, 0.1091, 16.982, 17.967 GeV respectively. The meaningful difference between energies of e^+, e^- is the key point of the problem which is under investigation.**

***Keywords*: Geomagnetic field, Extensive Air Showers, Azimuthal anisotropy**

I. Introduction

EAS events are developing in the last few 10 kilometers near the ground. But geomagnetic field has been extended until a few thousand kilometers around earth [2]. Geomagnetic field deflects charged particles. Low energy charged particles lose completely their directions and come to the earth from north and south poles, which make auroras. By increasing the energy of the charged particles, the deflection becomes less and less. For Ultra high energy cosmic rays or Gamma-rays ($E\ \geq$50TeV) there is an Extensive Air Shower (EAS) which is created by the UHE particle [3], which its secondary particles are mostly charged and deviate from direction of the first particle due to geomagnetic field [4]. Therefore when we reconstruct the direction of the primary particle from the secondaries, there will be exist a deviation from the first direction. This deviation has been seen in the data of a few observatories [5], [6]. In this paper we tried to understand this effect for correcting the direction of the logged EAS events.

There is a question here: Is the deflection due to the primary particle before coming to the atmosphere or due to the secondaries in the atmosphere? Primary particle is so much energetic then secondaries, but its time of impact outside the atmosphere is so larger than the secondaries' inside the atmosphere. Therefore we tried to investigate these effects more accurately. We investigated 100TeV primaries from H=20,000 kilometers far from center of earth (B_H=0.03B_0) to the ground. It was obtained that the deflection of primaries is less than a millionth of a radian in azimuth angles [1]. Therefore in follow, we investigated this effect over the secondary particles.

II. Experimental setup

We logged about 800,000 EAS events by a 4-fold array of water Cherenkov detectors in a square 6.08×6.08 m^2 at the roof of the physics department, Sharif University of Technology (51° 20$'$E, 35° 43$'$N, 1200 m a.s.l. ≡[890 g cm^{-2}]), more experimental details has been explained in [7], [8].

Since we need to compare the experimental results with CORSIKA simulations, therefore we should harmonize the simulated events with experimental events. Random generator of CORSIKA code has been designed for flat array of detectors (e.g. scintillation detectors), and uses the pattern $\sin\theta\cos\theta$ [9] for choosing zenith angles of the simulated events, so we need to select only a part of the simulated events which are in agreement with our type of detection. We have 318,400 simulated events in presents of magnetic field, but we need to separate events in agreement with $dN/d\theta = A_0 \sin\theta(\cos\theta + 2.4\sin\theta)\cos^n\theta$ distribution. So we used monte carlo method for the selection and separated 182,103 events. In follow of the work we used only the data set.

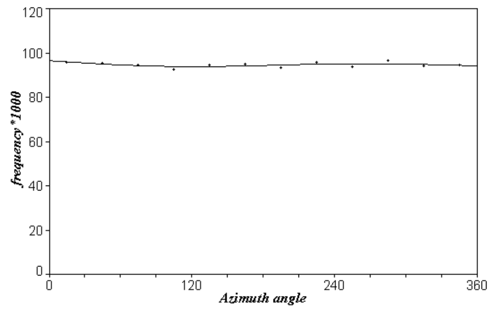

Fig. 1: Anisotropy due to the geomagnetic field on secondary particles, is about %1.3.

III. Secondary particles are our probes

We logged about 800,000 EAS events. Azimuth distribution of the events shows a slight anisotropy (7%) in the north south directions. It was fitted a double harmonic function over the distribution, and it is obtained, the first harmonic is more important. Also we separated these data in 12 five degree intervals from 0 to 60°. It is seen that:

- Trend of the anisotropy is similar for all of the intervals
- Zeroth harmonic obey the zenith distribution
- The amplitude of the first harmonic is increasing with increase of zenith angle

For the investigation we used 318,400 CORSIKA simulated events with the magnetic field of our site and 204,204 events without magnetic field in the energy range of 50TeV to 5PeV. Then we investigated the North-South anisotropy in these simulated and experimental data. Also in the last step we did an investigation on the effect of the magnetic field on the secondaries and specially on electrons.

With $0 \leq \eta \leq \omega$ and $0 \leq \psi \leq 2\pi$ we obtain the new angles θ' and ϕ' which are $\theta + \delta\theta$ and $\phi + \delta\phi$. So we calculated $\Delta\theta_B + \delta\theta$ and $\Delta\phi_B + \delta\phi$ in each step and finally we find the final direction in the last step. The differential angles $\Delta\theta = \theta_{final} - \theta_0$ and $\Delta\phi = \phi_{final} - \phi_0$ are obtained.

At the end with random θ (with the function $\sin\theta\cos\theta$) between 0 to 60° and white random ϕ between 0 and 360° we obtain the final distribution of the detected θ and ϕ.

In this part we simulated 24 layers for the secondary particles, (24 ≅ 890/37.7 gr/cm^2) for electrons. we obtained the mean energy of secondary particles of 1000 EAS event for $e^{\pm}$ and $\mu^{\pm}$ in the 24 layers. Then we used the energy E and $\gamma = E/m_0c^2$ in the following steps. But in this step we did't see any acceptable anisotropy(Fig 1).

In the energy range of our experiment ($E \leq 10^{16}$eV), it is expected a symmetric and isotropic ϕ distribution for detected EAS events. But in the azimuth distribution of the EAS events it has been observed a slight North-South anisotropy([5]).

We investigated the ϕ distribution with double harmonic function. The North-South anisotropy is stronger in higher zenith angle events, and also in higher geographical latitudes. We expect that the anisotropy depends on the local effects like the meteorological effects([10]), moving of the earth and solar system in a special direction of the Galaxy ([11]), or geomagnetic field of the earth ([6]). In this report we have investigated the geomagnetic field effects on the events in two categories, 1) on the primary particles and 2) on the secondary particles of EAS events. It is very interesting that, at higher (lower: near to equator) latitude observatories the first (second) harmonic is dominant ([6]), and also the amplitudes of the anisotropy depend on the zenith angle of the EAS events.

A. Simulation of the experiment

The effective surface of each Cherenkov detector for each EAS event with zenith angle θ is $A_{eff} = A_0\cos\theta + A_{90}\sin\theta$. To compare the experiment results with CORSIKA simulations, we approximated it to a square with the side $\sqrt{A_{eff}}$. So actually for each EAS event, we have a large array which contains so many squares like our experiment. If at least one particle pass through a detector, the detector will motivate ([7]), so For the detection condition in the simulation we need to have at least one particle at A_{eff}. We distributed the secondary particles of our simulated data on concentric circles with the center of shower core and radial difference of 1 m. With all of the simulated events it is seen that at 59 m away from the core we have ρ = 1particle/0.71 m^2. So we projected each shower on a square array (-150:150×-150:150), each pixel is a square with the side $\sqrt{A_{eff}}$.

Since our electronic circuits (TACs) are set to a time difference 200 ns is equivalent to about 60 meters, (larger than the thickness of EAS fronts), so actually in our experiment most probably we detect the first particles of shower front. Therefore in the analysis of each EAS event we projected all of the secondary particles on the square array and in each pixel we recorded the arrival time of the first secondary particle. In the simulation we used a trigger condition similar to our experiment, activation of four pixels in a square with the side n pixels(n=Round$(6.08/\sqrt{A_{eff}})$) simultaneously. We call this situation as 'trigger condition' of our experiment. Then with the least square method (exactly similar to our experiment data analysis) we found zenith (θ) and azimuth (ϕ) angles of each trigger condition. This procedure was done over 318,400 events (Fig 2) with and 204,204 events (Fig 3) without magnetic field.

IV. Geomagnetic field effect over secondary charged particles

As it is explained above, we tried to extract some information from the simulated events. In this way we found 26 extracted information from the events. These identifications(IDs) of each event is 1,2)θ and ϕ, which is calculated by fitting a flat plane over the shower. 3,4) θ and $\pm\Delta\theta$ by calculation of direction of each secondary

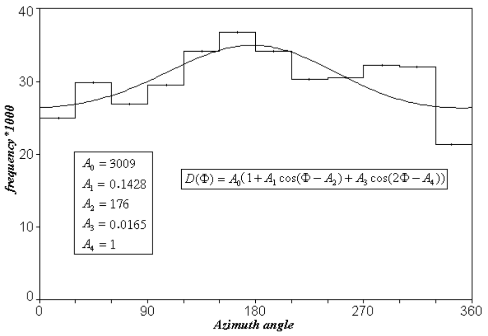

Fig. 2: Anisotropy of the CORSIKA simulated events with magnetic field of our site which were detected by the condition of the experiment, which shows anisotropy about %14.

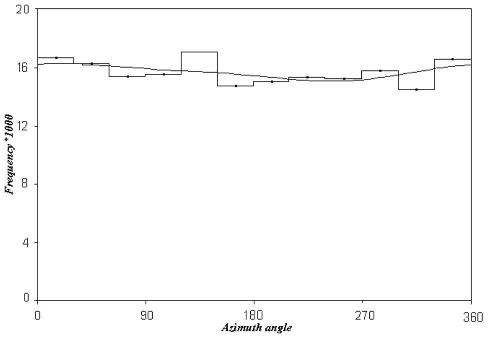

Fig. 3: Anisotropy of the CORSIKA simulated events without magnetic field of our site which were detected by the condition of the experiment, which shows a random effect

particle and averaging over all of the secondaries. 5,6) ϕ and $\pm\Delta\phi$ similar to 3,4 but for ϕ. 7,8) θ and $\pm\Delta\theta$ by calculation of direction of each EAS event by applying the trigger condition of our array. 9,10) ϕ and $\pm\Delta\phi$ similar to 7,8. 11,12) γ and $\pm\Delta\gamma$, the direct angle of each secondary particle with the primary particle. 13) Number of trigger condition for each EAS. 14,15,16) Number, mean energy, and energy standard deviation of positrons of each EAS event. 17,18,19) The same as 14,15,16 but for electrons. 20,21,22) The same as 14,15,16 but for μ^+. 23,24,25) The same as 14,15,16 but for μ^-. and finally 26) total number of charged secondary particles of each EAS event. With these 26 IDs plus the primary IDs of CORSIKA simulated events (θ_0, ϕ_0, E_0) we are able to compare so many things that may be useful for distinguishing the EAS events which are affected with or without geomagnetic field.

A. Geomagnetic field

The geomagnetic field in a zone not so far from the earth (When the tail effect is not so important, ~few times of the earth radius) is approximated as a magnetic dipole, which is located at a point inside the earth. Its magnetic dipole moment is 8.017×10^{22} Tesla.m^3 and straights of its poles on the earth surface are at $79.74°$S and $108.22°$E as north pole and $82.7°$N and $114.4°$W as south pole. When we observe the recorded EAS events closer to the north we receive more deficit of these EAS events there. It is guessed that, this is based on the geomagnetic field effect on primaries, which has been passed through a stronger magnetic field. This effect depends on two factors, one is the location of the observatory and the other is higher northern recorded events. Passed particles through stronger (weaker) magnetic fields are affected more (less) and displaced more (less) than the final destination on the earth.

Norther events in the Northern observatories like ours, are displaced more than southern ones, so we expect a deficit in the north direction and the dominance of the first harmonic function. But in equatorial observatories actually there is no different magnetic fields for northern and southern events, so we expect the same deficit for both north and south directions and dominance of the second harmonic function.

B. Inclination of secondary particles

For obtaining the geomagnetic field values at different points around our site, we used the data from "http://www.ngdc.noaa.gov". Geomagnetic fields components at our site is $B_x = 28.1\mu T$ and $B_z = 38.4\mu T$. Since we investigate the geomagnetic effect on the primary particles in this work, we need to investigate the geomagnetic field from farther zones. In the previous investigation [12], it is assumed that the magnetic field B is constant in the path of the secondary particles, in different points and heights and also it is assumed that the atmosphere is planar. With these approximations the displacement for each charged particle is $x = qcBh^2 \sin\chi/2E_0 \cos^2\theta$ [12].

These approximations are true for secondary particles are creating in developing stage of EAS events in atmosphere. The process occurs in a few kilometers near the ground (~ 15km). But we need to investigate the geomagnetic field from very farther zones. In the large zone the spherical shape of the earth with the atmosphere and also different amount of the geomagnetic field in different points and heights must be considered. For this purpose we calculated the components of the geomagnetic field effects on the passed charged particles. (**F**=q**v**×**B**). For the **B** components (B_x, B_y and B_z) in different heights we used the data from "http://www.ngdc.noaa.gov". Since in the web site only there is data from the ground until the height 600 km, we fitted the function $B = \alpha/r^3$ (magnetic field of a dipole moment) and obtained α_x, α_y and α_z and used them for calculation of the magnetic fields in different heights until 20,000 km far from the ground level which the magnetic field is 0.03 B_0.

V. A SIMPLE PICTURE OF GEOMAGNETIC FIELD EFFECT AND THE ANISOTROPY

For the investigation of the secondaries we have to consider new assumptions. Here the development zone

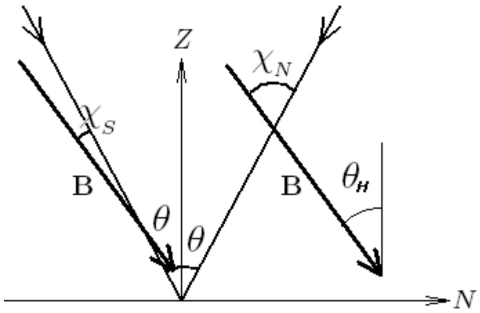

Fig. 4: There is an anisotropy between the north and south, the anisotropy is in the direction of magnetic field.

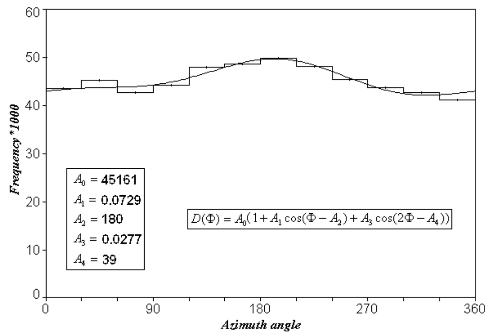

Fig. 5: Anisotropy due to the geomagnetic field on the logged experimental data is about %7.

of the shower is small and the effect of geomagnetic variation and curvature of the earth is negligible, but there is another factor which makes an anisotropy in North-South directions. It is the 'Angle between the Direction of EAS event and the geomagnetic field (χ)'. For the northern EAS events angle between the direction of the events and geomagnetic field is larger than southern EAS events. So the magnetic force is larger in northern events and there is a deficit in north due to the deflection. The force $F = q\mathbf{v}\times\mathbf{B}$ verifies the prediction (Fig 4). . Actually particles which come from North, incline more due to the angle between them and the geomagnetic field, but particle from south, not to be affected. It is the same as tidal force for water of oceans on the other side of the earth, which stays back.

A. Double harmonic function of the experiment data

We separated the data in 12 bins of 5 degree data sets from 0 to 60° base on their zenith angles. Then we fitted the two harmonic function $ASYM = A_0(1+A_1\cos(\phi-\phi_1)+A_2\cos(2\phi-\phi_2))$, then we obtained 12 sets of A_0, A_1, A_2, ϕ_1, ϕ_2 (Fig 5). . Then we obtained the $A_0(\theta)$, $A_1(\theta)$, $A_2(\theta)$, $\phi_1(\theta)$, $\phi_2(\theta)$. $A_0(\theta)$ shows the function $dN/d\theta = A\sin\theta\cos^n\theta$. $\phi_1(\theta)$, $\phi_2(\theta)$ are approximately constant. But $A_1(\theta)$, $A_2(\theta)$ show interesting functions of θ. An interesting subject is the peak in $A_1(\theta)$ which is near to $\theta_H = 38°$ in Tehran, which is in agreement with the upper prediction. Also the $A_2(\theta)$ shows an increasing function with θ.

VI. DISCUSSION

There are some asymmetric factors which are the ratios of $N_{e^-}/N_{e^+} \simeq 1.57$ and $N_{\mu^-}/N_{\mu^+} \simeq 0.97$. It seems that, one of the important factors is the N_{e^-}/N_{e^+}. There are a few evidences that are in agreement with it. Also the mean energy of e^+, e^-, μ^+ and μ^- for ON and OFF events are 0.1585, 0.1099, 16.883, 17.113 GeV and 0.1568, 0.1091, 16.982, 17.967 GeV respectively. There is a meaningful difference between energies of e^+, e^-. But differences between events with and without magnetic field is so small. we are trying to find some distinguishable effect that can explain the anisotropy.

REFERENCES

[1] M. Khakian Ghomi et al., 30th ICRC, V.4, P.11, HE0263 (2005)
[2] E. Dormy, Europhysicsnews, N.2, V.37, P.22 (2006)
[3] T.K. Gaisser, *Cosmic Ray and particle Physics* (Cambridge University Press, 1990).
[4] L. Dorman, *Cosmic Rays in Magnetospheres of the Earth and other Planets* (Springer, 2009)
[5] A.A. Ivanov et al. 1999 JETP letters, 69(4), 288.
[6] M. Bahmanabadi et al., 2002, Experimental Astronomy, 13(1), 39
[7] Sheidaei, F., et al. , arXiv:0705.4234v1 [hep-ex] 29 May 2007
[8] khakian Ghomi, M., Bahmanabadi, M., Samimi, J., 2005, A&A, 434, 459
[9] Hech, D., et al., report **FZKA 6019**(1998), Forschungszentrum Karlsruhe; http://www-ik.fzk.de/corsika/physics_description/corsika_phys.html.
[10] Bahmanabadi, M. et al. 2003, Experimental Astronomy, 15(1), 13
[11] Bahmanabadi, M., et al. 2006, PASA, 23, 129
[12] He, H.H., et al. , 29th ICRC (2005) **00**,101-106