Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008
Vol. 4 (HE part 1), pages 11–14

ID 263

30TH INTERNATIONAL COSMIC RAY CONFERENCE

ICRC'07 Mérida, México

Investigation of Geomagnetic field effect on azimuth distribution of EAS events

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Abstract: EAS events are developing in the last few 10 kilometers of their path in the atmosphere. But geomagnetic field has been extended until a few thousand kilometers around the Earth. This field deflects charged particles and the deflection is different for different directions and observers. These differences depend on the amount and direction of the geomagnetic field (a dipole inside the earth) and direction of the charged particle. It was accurately investigated for 100 TeV primary particles from $H_0 = 20,000$ kilometers from the center of the earth ($B_H = 0.03 * B_0$) to the ground and it was observed that the deflection is less than 10^{-6} degrees in azimuth angle ϕ. Therefore we investigated the geomagnetic field effect on the secondary particles. We accumulated about 500,000 EAS events by a 4-fold array of water cherenkov detectors with a configuration of 6.08×6.08 m^2 square. Distribution of the events shows a slight anisotropy (4%). We fitted a double harmonic function on the distribution, it is seen that the first harmonic is more important. Also we separated these data in 12, 5 degree intervals from 0 to 60 degrees. It is seen that: 1- In all of them, total structure is similar. 2- The zeroth harmonic (Constant number) obey well the $dN = \sin\theta(\cos\theta + 2.4\sin\theta)\cos^n\theta d\theta$. 3- The amplitude of the first harmonic is increasing until 35-40 interval and then it decreases. For the investigation of the geomagnetic field on the EAS events we simulated 220,000 events with the magnetic field at Tehran ($B_x = 28.1$, $B_z = 38.4$) and 40,000 events without magnetic field ($B_x = B_z = 0$), from 50 TeV to 5 PeV by CORSIKA code. Then we investigated the simulated events by the approach that there is an anisotropy in North-South direction due to angle between secondary charged particles and geomagnetic field direction ($\mathbf{B} = B_x\hat{\imath} + B_z\hat{k}$)

Introduction

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([1]).
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([2]), moving of the earth and solar system in a special direction of the Galaxy ([3]), or geomagnetic field of the earth ([4]). 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 ([4]), and also the amplitudes of the anisotropy depend on the zenith angle of the EAS events.

Experimental setup and data analysis

The array is constructed of 4 water Cherenkov detectors at the roof of the physics department, Sharif University of Technology, 51° 20$'$E and 35° 43$'$N, elevation 1200 m a.s.l. (890 g cm^{-2}) in Tehran; more details is explained in [5]. Also more detail about data analysis is in [6, 7].
Since we need to compare the experimental results with CORSIKA simulations, and random generator of CORSIKA code has been designed for flat array of detectors, it uses the pattern $\sin\theta\cos\theta$ for choosing zenith angles, so we need to select

only a part of the simulated events which are in agreement with our type of detection. We have 198,829 simulated events which are generated by the function $\sin\theta\cos\theta$ but we need to separate events which are in agreement with $dN/d\theta = A_0\sin\theta(\cos\theta + 2.4\sin\theta)\cos^n\theta$. So we used monte carlo method for the selection, finally we separated 114,341 events from the 198,829. In follow of the work we used only the data set([8]).

Simulation of our array

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 ([5]), 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 $\rho = 1$particle/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 and finally we found the $\bar{\theta} \pm \sigma_\theta$ and $\bar{\phi} \pm \sigma_\phi$ for each event. One of the meaningful parameters is the 'number' of triggering conditions(N_{sq}), it depends on the probability of detection of each EAS event for our array which is different in different directions.

Study of the geomagnetic field and its effects on 10^{14}eV primary charged particles

We separated the geomagnetic field effects in two stages, 1) the effect on the primary particles, and 2) on the secondary particles of the EAS events.
We investigated this effect on the primary particles and compared them with the results on secondaries, because the effective zone of the geomagnetic effect on these primary particles is very larger. Secondary particles are restricted to a very small zone (Inside the atmosphere) which has a thickness smaller than 15 km, of course their energy is smaller. It is in case that the primary particles are affected from thousands of kilometers farther than the earth. For the investigation of the secondary particles in the atmosphere we need to create an EAS event and investigate this effect on it. For this purpose we need to use the simulation codes in this way like CORSIKA code.

Explanation of the geomagnetic field effect

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.

Calculation of the displacement of these 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 ([9]), 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 $x = qcBh^2 \sin\chi/2E_0 \cos^2\theta$ ([9]).
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 ($\sim$ 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 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 13,000 km far from the ground level which the magnetic field is 0.03 B_0.

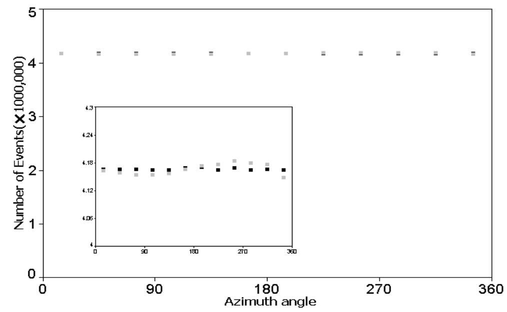

Figure 1: Anisotropy due to the geomagnetic field on primary particles, is about 0.48%.

Study of the geomagnetic field and its effects on the secondary charged particles

We observed that the geomagnetic effect on the azimuthal anisotropy of the primary particles is not so important. From the above analysis it is seen that the anisotropy is 0.48% (smaller than a percent), it is in case that the azimuthal anisotropy in the experiment is about a few percents. So we must investigate this effect on the secondary particles too. But for the investigation of the secondaries we have to consider new assumptions. Here the development zone 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. 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.

Investigation of double harmonic function on 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. 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

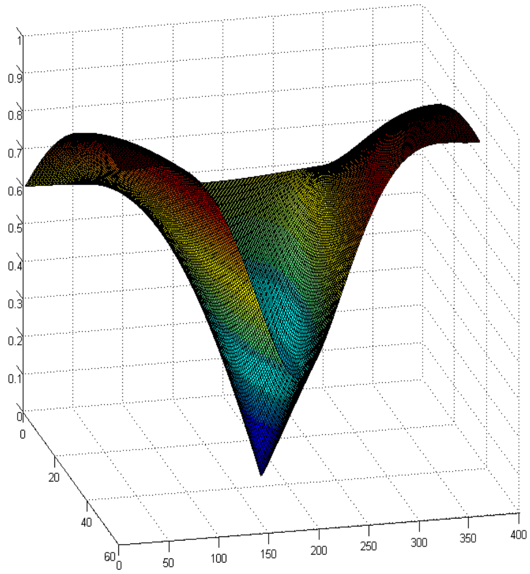

Figure 2: Normalized geomagnetic force on secondary particles on an EAS event in different θ and ϕ .

$dN/d\theta = A \sin\theta \cos^n\theta$. $\phi_1(\theta)$, $\phi_2(\theta)$ 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.

Investigation of double harmonic function on CORSIKA simulations

We are simulated about 200,000 EAS events by CORSIKA code and from the secondary particles of them we calculated the direction of detection of them in three different ways. Calculation of zenith and azimuth angles of each simulated EAS event by :

- Least square method. We considered a unique plane with all of the secondaries of each event.
- The detection condition of our experiment which has been explained before.
- calculation of direction of each secondary particle and averaging over all of the secondaries. We obtained zenith and azimuth angles with their standard deviations.

From the 3 procedures we obtained three ASYM functions and 3 sets of the 12 boxes of θ intervals. These results are shown an approximate agreements which may be due to the smallness of our simulated data set.

Discussions and concluding remarks

The anisotropy in azimuth distribution depends on so many things that may make some perturbations. For example, meteorological effects, inclination of the ground level, geomagnetic field, location of the observation and so many other factors. But because of the complication of the subject we have to investigate the effects one by one and very accurately. We investigated the effect of the atmospheric pressure with the accuracy of 0.1 mbar on it too but because of the small difference of the pressure during our experiment this effect is not so observable. But all of the effects with more simulations and better investigations are in front of us.

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