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Investigation of atmosphere thickness on EAS events by an array of particle detectors and CORSIKA simulations.

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Abstract: The atmosphere effect before shower maximum is dominantly : $'$an environment for development of Extensive Air Shower(EAS) events$'$, but after that, the $'$absorbtion effect of the atmosphere$'$ will be dominant. The shower maximum for about 100 TeV is near 500 gr/cm^2($\sim$5200m a.s.l), and most of EAS arrays in this energy range are at heights below the shower maximum height, specially for higher zenith angle EAS events, so we need to more concentration on the absorbtion effect specially in this energy range and our site. Therefore for this investigation we logged 476,675 true EAS events by an array of particle water Cherenkov detectors. We calculated the local coordinates (θ,ϕ) of each EAS event by least square method. The zenith distribution of the logged events is $dN/d\theta = \sin\theta(P_0 A_0 \cos\theta + P_{90} A_{90} \sin\theta)\cos^n\theta$ with $n = 6.80 \pm 0.7$. We obtained the energy threshold $E_{th} = 90$ TeV and rate of our experiment $\lambda = 0.0395 \pm 0.0002$ Hz. Also by coincidences of the CORSIKA simulated EAS events (114,341 event) which are imposed on the constraints of our experimental setup, we obtained detection probability distribution, and the distribution of the number of the secondary particles in the simulated events vs. θ. Then by the imposed constraints we investigated the atmosphere thickness effect on the EAS events and its distributions. At the end we found a correlation between the investigated effect and a few reported results of some observatories.

Introduction

Atmosphere as a matter environment affects on EAS events. Each array of secondary particle detectors for the detection of the EAS events is only a part of the detector, the other part is the atmosphere of the earth, so that it is the most important part of matter environment of the detector. Procedure of the development of the EAS events in the atmosphere [1] affects directly on the characteristics of the secondary particles. So investigation of its characteristics in different aspects is very important . But for the investigation of the atmosphere effects [2, 3] on the EAS events the accessibility to experimental observable variables is limited. So we need to recognize well, the experimental results and then try to guess the effective factors on the observable variables. One of the observable variables is the zenith distribution of the EAS events. Without a doubt the distribution ($dN/d\theta$), is a complicated function of so many atmospheric effects but we have to guess only the dominant affecting factors on the EAS events with the order of importance and try to investigate them. In this investigation we fitted the function $dN/d\theta = \sin\theta(P_0 A_0 \cos\theta + P_{90} A_{90} \sin\theta)\cos^n\theta$ to the zenith distribution of our data, which naturally is a function of our detectors efficiency.

In the atmosphere and in lower heights the number of secondary particles is decreasing with decreasing the height [4] which is a signature of absorbtion effect. In this report we tried to investigate this effect with more details, specially on the secondary particles and present an explanation based on the number of secondary particles in zenith distribution.

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 $dN/d\theta = A_0 \sin\theta(P_0A_0\cos\theta + P_{90}A_{90}\sin\theta)\cos^n\theta$. 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 $A_{eff} = P_0A_0\cos\theta + P_{90}A_{90}\sin\theta$. 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.

Investigation of the zenith distribution by the simulated events

investigation of the distribution similar to our experiment

In our simulated data from 114,341 simulated event 36,519 events satisfied the trigger condition ($N_{sq} \geq 1$) which is about %32. We drew the distribution of the satisfied events vs. θ with the free number of N_{sq} with the condition $n = 6.80$ we obtained $N_{sq} \geq 18$. For the confidence from the accuracy of the above procedure we averaged over energy of 1459 events with $16 \leq N_{sq} \leq 20$ and in zenith angles $0 \leq \theta < 30$, we found $\bar{E} = 87.6$ TeV which is very near to our E_{th} (=90 TeV).
Also mean number of N_{sq} in 5 degree bins vs. θ_0 (generated by CORSIKA) is proportional to the probability of EAS detection by our array. Since it is normalized to the number of showers in each bin, so it is independent of solid angle, so we fitted it with $A\cos^n\theta$ and we obtained $n = 7.09$.

investigation of the distribution via the secondary particles distribution

We drew the mean number of secondary particles with energies higher than E_{th} in 5 degree bins for 114,341 simulated events, independent of N_{sq}, then we fitted the function $A\cos^n\theta$ and we obtained $n_{secondaries} = 6.02$. Of course this graph is independent of our detector array and only it

depends on the environmental effects like atmosphere effects which affect on the number of secondaries. There is a meaningful difference between the power n and the distribution of the experiment (6.02 & 6.80), so it seems that it also depends on the detection condition.
For the investigation of the detection procedure we did as follows :
1) From the CORSIKA simulated events we obtained the lateral distribution of secondary particles in different radii in 1m thick ribbons. 2) We fitted the Greisen lateral distribution function on them in different zenith angles θ [9] :

$$\rho(r) = \frac{N_0}{2\pi} \frac{\exp(-r/r_0)}{r_0(1+r)} \qquad (1)$$

we obtained the functionality of $r_0(\theta)$ and $N_0(\theta)$ from these points. 3) With the new Greisen lateral distribution function $\rho(r,\theta)$ we distributed constant number of 8586 secondary particles (mean number of secondaries for all of the simulated events with energies higher than E_{th}), base on the above distribution and by the monte carlo method. We distributed the 8586 secondary particles in an array of (-150:150×-150:150) pixels, then we repeated the calculation of N_{sq} (finding squares as like as our experiment) with the effective surface of our detectors in different zenith angle bins. 4) We repeated the procedure 1000 times and finally we found the distribution of the number of satisfied conditions ($N_{sq}(\theta)$) vs. θ. The distribution is decreasing slowly with increase of θ. by fitting the function $\cos^n\theta$ on the distribution we obtained $n_{detection} = 0.49$.
Of course it was predictable because with distributing of about 8600 secondaries in 90,000 pixels with the Greisen lateral distribution, probability of satisfaction conditions (N_{sq}) decreases with more distributions in larger zenith angles. Now we can say roughly that the sum of two powers $n_{secondaries} + n_{detection}$ is equal to 6.51 and actually the meaningful difference has been less. But we guess that the remaining difference is due to the other effects which have not been calculated.

Investigation of thickness effect of the atmosphere on the number of secondary particles

We know that showers with higher zenith angles pass through more matter. If the thickness of the atmosphere for zenithal events is X_0 (890 gr/cm^2 at Tehran), then the thickness for zenith angle θ events is $X(\theta) = X_0/\cos\theta$ [1]. So actually when we see the higher zenith angle events, we can investigate development of EAS events in deeper atmosphere. But since we have no access to higher depths than our site levels in our CORSIKA simulated data set, we observed the higher zenith angle(θ) events but in higher levels, levels equal to $X_\perp = X_0\cos\theta$ which the matter in front of the secondary particles $X(\theta)$ is equivalent to the slant depth of our site. We investigated these 114,341 simulated EAS events and base on zenith angle of the events. We obtained the mean number of secondary particles in 5 degree bins from 0 to 60°. So with this order actually in all directions there is an equal amount of matter and we expect that we obtain equal number of secondary particles in different directions which is equal to $16500(1 \pm 0.046)$.

Investigation of the power $n(X)$ in different slant depths

There are so many natural effects which affect on the logged EAS events in different observatories. For example these effects are thickness of the atmosphere, arrangement of detectors, Geomagnetic field of the Earth, meteorological effects like pressure, temperature and humidity and so on, which make some variations in the data of different observatories in different parts of the world.
In this work we investigated the effect of the atmosphere thickness on the EAS events. So we used the log files of our CORSIKA simulated data to obtain the distribution of the secondary particles vs. θ, 20 gr/cm^2 to 20 gr/cm^2 slant depths from 20 to 900 gr/cm^2. By fitting the function $dN/d\theta = A\cos^n\theta$ on the 45 points we obtained two distributions, $A(X)$ and $n(X)$. These distributions respectively are shown in Fig.1(a & b). These points may be useful for the observatories higher than our site, because we saved the data of our simulations until 1200m a.s.l. (890 gr/cm^2). Of course

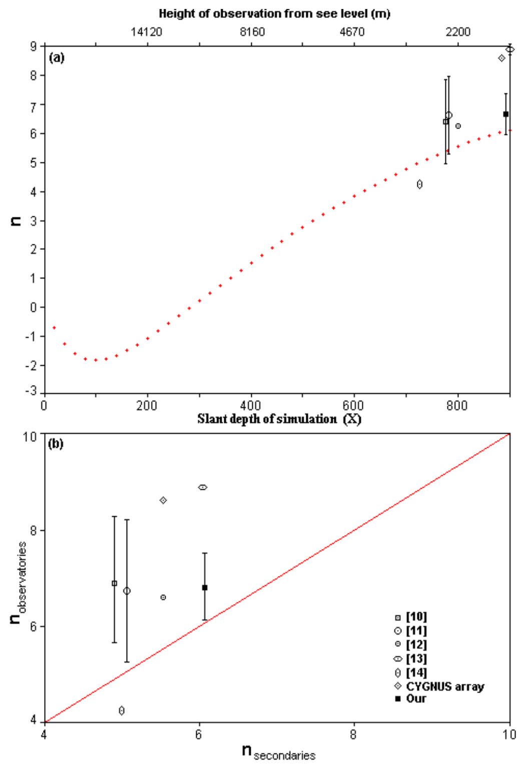

Figure 1: Behavior of the a) power $n(X)$ and few n's from different observatories [10, 11, 12, 13, 14], b) The observed power n of the observatories vs. $n_{secondaries}$.

for the lower height observatories we are able to extrapolate the functions and compare it to the results of them.

Discussions and concluding remarks

The zenith distribution '$dN/d\theta$' depends on so many factors (e.g. thickness of the atmosphere, Geomagnetic field, geographical position and height of observation level, Meteorological effects and so on). We studied the cosmic ray flux assuming that the absorbtion in the atmosphere is the dominant effect, just as our experimental results show a good agreement with the simulations.
In this work we obtained the $n_{secondaries} + n_{detection} = 6.02 + 0.49 = 6.51$ which shows the dominance of the atmosphere thickness effect ($n_{secondaries} \gg n_{detection}$). Therefore it is possible to predict the power n for different observatories in different points of the earth.
In Fig.1(b) it is seen that the power 'n' from different observatories is compared with the '$n_{secondaries}$' which is obtained from the distribution of secondary particles. it is approximately in an agreement with the 45° slope but is higher than it because of the absence of the detection factor which an order of magnitude is smaller than the atmosphere effect.
It is seen that the atmosphere thickness has a strong effect on the EAS events. So the exact recognition of this effect is very important for analysis of data in all extensive air shower arrays.

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