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Shower age in correlation with zenith angle

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Abstract. The variation of lateral shower age parameter with zenith angle for different shower size ranges is studied. The observed variation is in agreement with the electron-photon cascade theory and with the other EAS observations. It is found that up to zenith angle 30°, shower 'age' is practically independent of zenith angle. So it is difficult to correlate the reported high 'age' value of the excess showers from the direction of plausible point sources with zenith angle. The change in the value of shower age with atmospheric depth is studied and is found to be consistent with the prediction of cascade theory and simulation results. From the study of the variation of shower age with shower size for two different zenith angle intervals it is found that the shower age decreases with size but the rate of change of shower age decreases at higher sizes.

Keywords. Cosmic ray; extensive air showers; characteristics; shower age; zenith angle.

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1. Introduction

The study of cosmic ray extensive air showers (EAS) still remains the unique way to obtain information on the cosmic rays of energy greater than 10^{15} eV. The study of longitudinal development of EAS provides important information on the composition of primary cosmic ray as well as on the nature of high energy (PeV energy) particle interactions. The stage of longitudinal development of an air shower can be described with longitudinal shower age parameter ($s_{\rm II}$). Showers that develop early in the atmosphere have on the average larger 'age' than late developing showers of equal primary energy. Experimentally the age parameter is determined from the shape of the lateral distribution of charged particles (mostly electrons and positrons) in air shower (lateral shower age parameters s, henceforth we shall call it simply as shower age parameter). However in most experiments the observed value of the shower age differs from that predicted by electron-photon cascade theory ($s_{\rm II}$). Some authors conclude from the observational results that the shower age correlates with the longitudinal age parameter via the relation $s_{\rm II} - S \leq 0.2$ [1]. Simulation results also shows similar type of relation ($s_{\rm II} \sim 1.3$ s) [2]. Experimentally it is also observed that a single age parameter is insufficient to describe the lateral distribution of electrons at all distances which means the age parameter changes with the core distance

[3]. But this change is in the reverse direction than that is expected for longitudinal shower age. As a result a question raises on the physical meaning of shower age.

Discrimination of gamma-ray initiated showers from the large background of charged cosmic ray initiated showers based on shower 'age' has been used in several observations [4,5] on the assumption that, for same shower size, photon induced showers are older. But the Monte Carlo simulation results [6–8] show that in 'age' the gamma-ray induced showers are not older than that of normal showers, though in several observations it was found that the excess showers from the direction of discrete point sources are characterised by high 'shower age' value [4,5,9,10]. Though recent observations could not find any clear evidence of ultrahigh energy steady or periodic signal from any discrete point sources but this failure of the detection may be due to highly sporadic nature of the sources. It is difficult to conclude that all early positive observations were due to large statistical fluctuations because in a number of contemporary observations excess EAS were observed from the direction of Cygnus X-3 and the excess showers were observed in phase with the orbital motion of the system. In most of the observations the showers from point sources were observed at large angles during most of the observation time due to high angle of transit of the sources at the arrays. As for example, Cygnus X-3 is observed at Kiel at zenith about 14°, the same source is observed at Ooty at zenith angle nearly 26° at the transit. Though in the search for evidence of UHE emission the source and background events are collected during the same time in the same zenith angle intervals, still there is a remote possibility [7] (because of small statistics) that the source events had higher zenith angle than the background events. With the increase of zenith angle the atmospheric thickness increases, so showers with high zenith angles are expected to differ in the shower age values. Only few observations in this respect had been done in the past and moreover the results of those observations are not consistent with each other. As for example the change of shower age with zenith angle at Mt. Chacaltaya experiment was found much slower in comparison with Mt. Norikura experiment [11]. So a detailed analysis on shower age parameter is necessary to clear the physical significance of the shower age parameter (which will be also helpful in the study of primary cosmic rays by modern EAS arrays through multiparameter study). In the present work this aspect of shower age parameter, its dependence on zenith angle in the range 0°–55° for three different shower size range is examined. The change in the value of shower age parameter with atmospheric depth has been estimated and compared with other observations and simulation results. Variation of shower age with shower size is also studied for two different zenith angle intervals.

2. Experimental set-up

The air shower array at North Bengal University Campus, India (latitude 26°42′N, longitude 88°21′E, 150 m a.s.l.), has been developed in stages since 1980. The set-up has been designed to detect air showers in the size range 10^4–10^6 particles with a close-packed array (detector spacing $\sim$ 8 m). With such a close-packed array, the determination of shower size and other parameters has been precise. At present it is composed of twenty four plastic scintillation counters, each having a size of 50 cm × 50 cm, for the measurement of particle density of air shower, and eight fast timing detectors, each having also an area of 0.25 m^2, for the determination of the arrival direction of the air showers. The efficiency of each plastic scintillation detector in terms of single particle pulse height is nearly

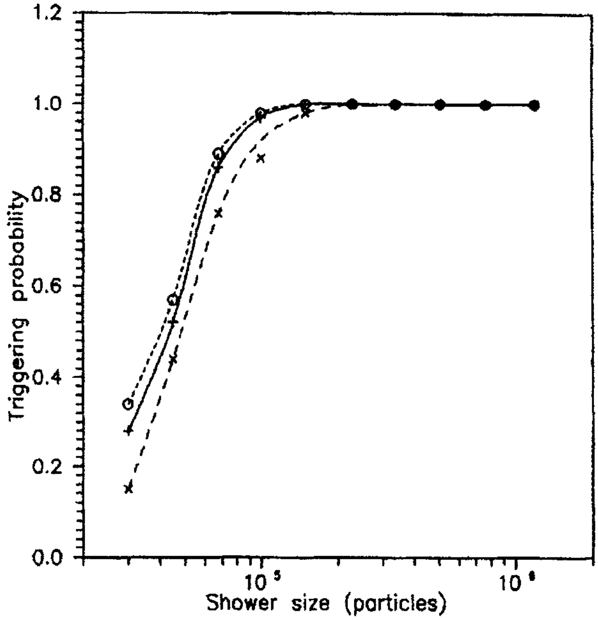

Figure 1. The triggering probability of the array as a function of shower size and shower age o$-s$ = 1.2, + $-s = 1.3$ and × $- s = 1.4$.

uniform (within 90%) from centre to edge. The effective shower size threshold for the array is 1 $\times 10^4$ particles. Two magnet spectrographs of maximum detectable momentum 500 GeV/c, each of area 1m × 1m, under a concrete shielding absorber are also operated in conjunction with the air shower array for the study of muon component of EAS. Each spectrograph consists of a solid iron magnet inbetween four neon flash tube trays (used as muon track detector). The total of shielding thickness and the thickness of the solid iron of the magnet sets the threshold energy at 2.5 GeV for the incident air shower muons. Details of the experimental system and data acquisition are described elsewhere [12,13].

A shower is recorded by the detecting system of the array only if the registered density in four central triggering detectors are $\geq$ 4 particles/m^2 or if the observed particle density in any three of the four central triggering detectors and in any one of the four triggering detectors situated at the four corners of the array are $\geq$ 4 particles/m^2. By generating artificial showers the triggering probability of the array has been calculated for different shower sizes and shower ages (figure 1) and is found that the detecting efficiency of the array (within sensitive detecting area of $\sim$ 2000 m^2) for showers of size $> 7.5 \times 10^4$ particles and average age 1.3 is greater than 90%. In this work, showers with size $> 7.5 \times 10^4$ particles were only accepted for getting the results.

3. Data analysis

The recorded showers have been analysed for core position (X_0, Y_0), shower size (N_e), shower age (s) and arrival direction (l, m, n). Shower size, shower age and core position were determined by fitting the observed particle densities by the method of X^2-minimisation through an iterative process (based on the method of steepest decent) to NKG [14] lateral distribution i.e.

$$\rho(r) = \frac{Nc(s)}{r_0^2}\left(\frac{r}{r_0}\right)^{s-2}\left(1+\frac{r}{r_0}\right)^{s-4.5}$$

where

$$c(s) = \frac{\Gamma(4.5-s)}{\{2\pi\Gamma(s)\Gamma(4.5-2s)\}},\ r_0 = 79\ \mathrm{m},\ 0.6 < s < 1.8.$$

Showers with chi-square <4 and with cores landing within 25 m from the centre of the array (approximately the array boundary) were only accepted. A standard least square derivation procedure applied to artificial showers generated with assumed N_e, s and (x_0, y_0) values in the experimental range with random Poisson errors led to error distribution in N_e, s and (x_0, y_0) with the following error estimates in the shower size region $N_e = 2 \times 10^5$ particles:

i) core location error – ±2m.

ii) Shower age parameter error – ±0.09

iii) Shower size error – $\pm 0.14\ N_e$, N_e being the true size.

With the increase of the shower size the errors in estimating the shower parameters are found to be reduced. As for example the uncertainty in shower age value is decreased from 0.10 to 0.07 as shower size increases from 8×10^4 to 1×10^6.

The arrival directions were obtained by measuring the relative arrival times (t) of the shower particles at different points. Using conical shower front and radial distance dependent weight factors the arrival direction of each shower event was calculated by a least square fit to the timing data. Deviation from the plane shower front was taken through the empirical equation (as measured by the array, [12])

$$\mathrm{d}t = 0.19r - 1.97ns.\ \text{(for } r \text{ up to 40 m)}$$

To incorporate the variation of shower front thickness with core distance the weight factor used in the analysis is given by

$$w_1 = \frac{1}{(\sigma_t^2 + \sigma_{\text{inst}}^2)}$$

where σ_t is the spread of the arrival of the shower front particles and was taken as [15]

$$\sigma_t = \frac{\sigma_0}{\sqrt{n}}\left(1+\frac{r}{r_t}\right)^b,$$

with $\sigma_0 = 1.6$ ns, $r_t = 30$ m and $b = 1.65$, n is the number of particles that hit the detector. σ_{inst} is the instrumental error of the timing detector. Instrumental uncertainty of the timing detectors of the array was found to be around 1.25 ns.

The angular resolution of the array has been estimated by the conventional 'split the array' method and is nearly 1.1° in zenith. However at higher zenith angles (> 40°) the resolution becomes increasingly poorer e.g. at zenith angle (z) = 55°, resolution in z becomes $\sim$ 4°.

4. Results

The results of the present work are based on a sample of nearly 14000 EAS events which were collected by the array during 1994 to 1996. The general features of the EAS (e.g. lateral distributions of electrons and muons, shower age distribution, $N_\mu - N_e$ relation etc.) observed by the array were reported earlier [16,17,18 etc.] and are consistent with the well known characteristics of air showers.

4.1 Distribution of zenith angle

With the increase of zenith angle shower traverse an increased thickness of atmosphere and due to atmospheric absorption the flux of showers monotonically decreases with the increase of zenith angle. However, the solid angle of acceptance of the array increases with zenith angle (as sin (z)) and the number of events for a zenith angle bin initially increases with zenith angle. At higher zenith angle atmospheric absorption part dominates over the solid angle of acceptance part and as a result the number of events within a zenith angle bin falls. The zenith angle distribution of the observed showers in the shower size range 7.5×10^4 to 1×10^6 is given in figure 2. The peak of the distribution is observed at around 20°. The mean age of the observed showers in the same size range is found to be 1.31.

4.2 Variation of mean shower age with zenith angle

The variation of mean shower 'age' (s) with zenith angle for three shower size range, $(7.5 - 8.5) \times 10^4$, $(1.5 - 2.5) \times 10^5$ and $(5.5 - 6.5) \times 10^5$ particles, are shown in figures 3–5. The figures show that the nature of the variation does not vary much with shower size. The variation of s with zenith angle (z) is found to be slow and up to zenith angle 30° the shower age is practically found to be independent of zenith angle. In the shower size range $(1.5 - 2.5) \times 10^5$ the mean shower age is 1.28 at $z = 5°$ and at $z = 50°$ the mean 'age' reaches only 1.42 though at zenith angle 50° the atmospheric overburden is nearly double. The observed variation can be expressed by the relation

$$s = s_0 + A \sec(z) \tag{1}$$

where the value of s_0 and A for different mean shower sizes are given in table 1.

The development of electron-photon cascade is approximately described [14]

$$s_{\mathrm{II}} = \frac{3t}{(t + 2w)} \tag{2}$$

and

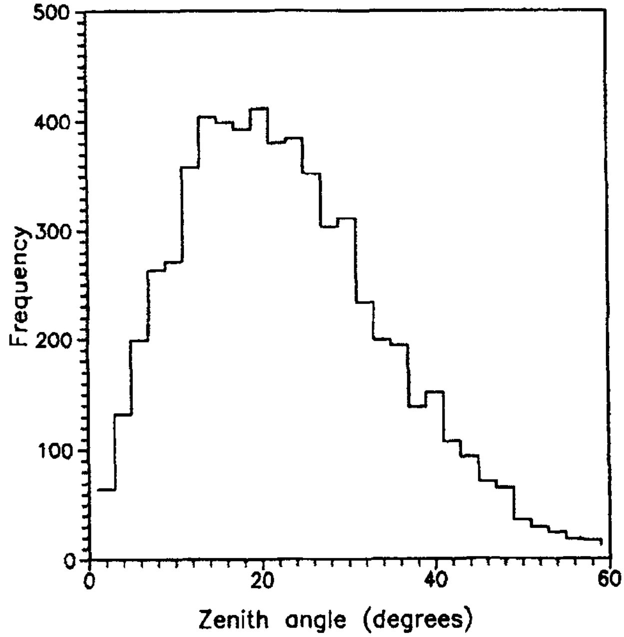

Figure 2. Distribution of the zenith angle of the observed showers for the showers in the size range $7.5 \times 10^4 < N_e < 1 \times 10^6$.

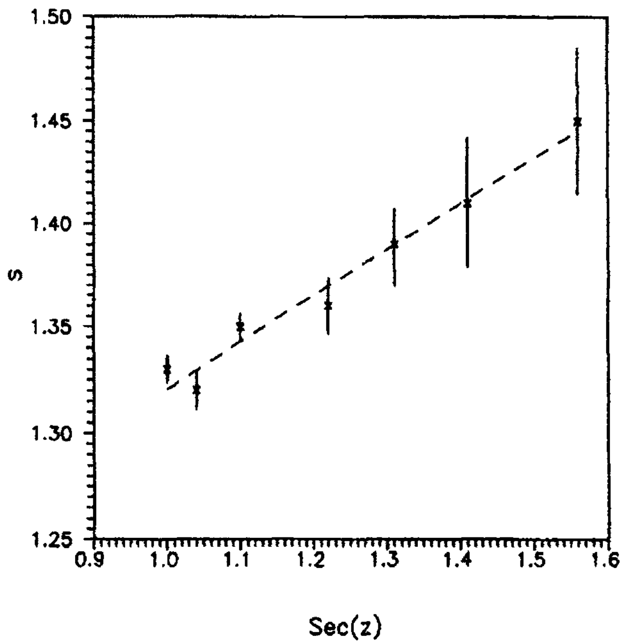

Figure 3. Variation of shower age with zenith angle (Sec (z)) in the size range $(7.5-8.5) \times 10^4$.

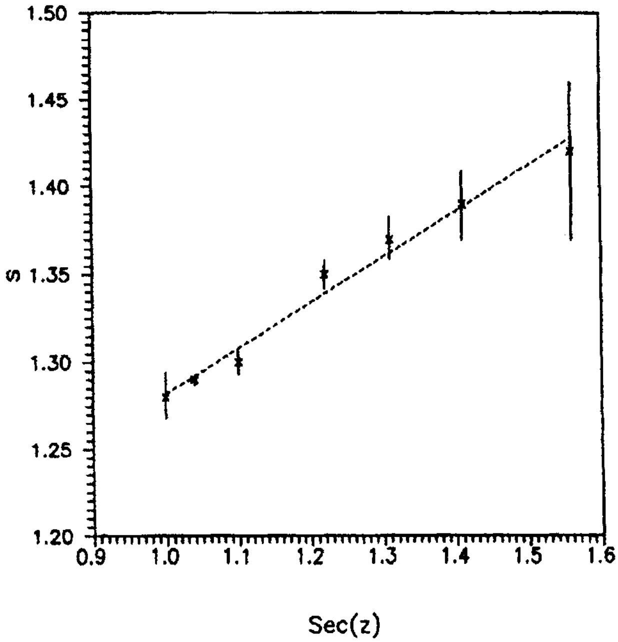

Figure 4. Same as figure 3 but in shower size range $(1.5 - 2.5) \times 10^5$.

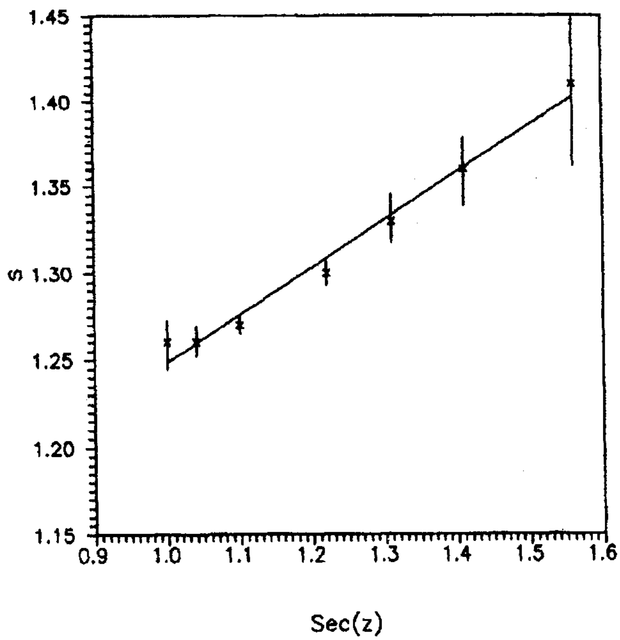

Figure 5. Same as figure 3 but in shower size range $(5.5 - 6.5) \times 10^5$.

Table 1. Comparison of the observed variation of age parameter with zenith angle with the cascade theory for three different shower sizes.

N_e		8×10^4	2×10^5	6×10^5
Observed	s_0	$1.098 \pm .003$	$1.031 \pm .002$	$0.973 \pm .003$
	A	$0.223 \pm .004$	$0.261 \pm .003$	$0.275 \pm .004$
Theory	s_0	1.15	1.11	1.05
	A	0.27	0.28	0.30

Table 2. Observed values of change in shower age per 100 g.cm^{-2} depth of atmosphere for different mean shower sizes and the same according to the cascade theory.

N_e		8×10^4	2×10^5	6×10^5
$\mathrm{d}s/\mathrm{d}x$ (/100g.cm^{-2})	Observed	0.022	0.026	0.027
	Theory	0.026	0.027	0.029

$$N_e = \left(\frac{0.31}{\sqrt{w}}\right) \exp[t(1 - 1.5 \ln s_{\Pi})] \tag{3}$$

where $w = \ln E/\varepsilon_0$, ε_0 is the critical energy ($\sim$ 81 MeV) and t is the atmospheric depth in radiation length. Again $t = t_v \sec(z)$ where t_v is the vertical atmospheric depth at the observation level. Using (2) and (3) and expressing the variation of s_{Π} with z for three different shower sizes through the relation as given in (1) the values of s_0 and A for different N_e are also given in table 1. The result shows that the observed variation is in accordance with the cascade theory. It should be borne in mind that the longitudinal development of showers are approximately described by the equations used as stated above. Also in reality showers are generated by different species, protons and heavy nuclei.

4.3 Change in the value of shower age with atmospheric depth

Equation (1) can be written as

$$s = s_0 + Ax/x_v$$

where x and x_v are the atmospheric thicknesses travelled by the shower and vertical atmospheric depth respectively. Therefore

$$\frac{\mathrm{d}s}{\mathrm{d}x} = \frac{A}{x_v} \tag{5}$$

The change of shower age over an atmospheric depth 100 gcm^{-2} for three different shower size ranges is given in table 2. The theoretical value (from cascade theory) is also given in table 2 for comparison. The present results agree well with the Mt. Norikura experiment

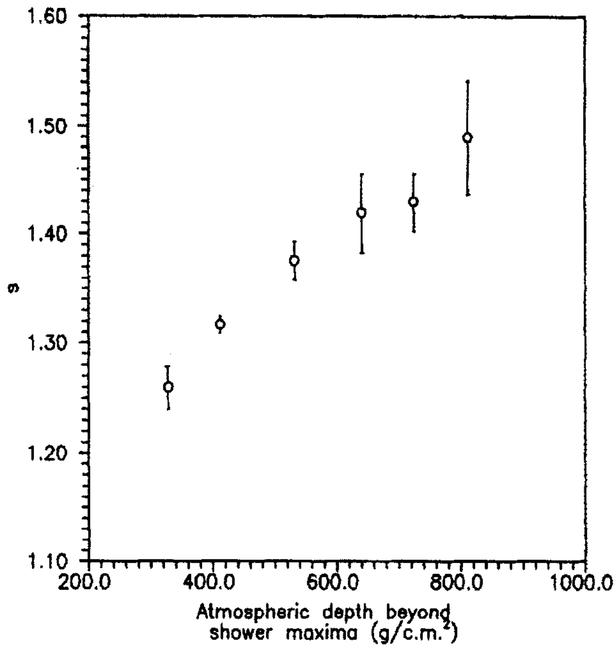

Figure 6. Variation of shower age with atmospheric depth beyond the shower maxima ranges for $N_e > 10^5$ particles.

[19] where the change of the value of shower age over an atmospheric depth 100 gcm^{-2} was obtained as 0.034. Monte Carlo simulation result of Bourdeau *et al* [20] predicts slightly lower value of $\mathrm{d}s/\mathrm{d}x$ ($1.9 \times 10^{-4}/\text{gcm}^{-2}, N_e \sim 10^6 - 10^7$, using CKP model, fragmentation model as well as superposition model, for both proton and iron primary).

According to cascade theory atmospheric depth beyond shower maxima for showers of mean age s is given by

$$\mathrm{d}x = 1.5x(s_{\Pi} - 1)/s_{\Pi} \tag{6}$$

(taking shower maxima occur at the value of shower age equal to 1). Assuming the above equation holds for lateral shower age also, the atmospheric depth beyond shower maxima for each shower has been estimated from s and z. Showers are then grouped in small bins of $\mathrm{d}x$ and for each bin mean of shower age has been calculated. The variation of mean shower age with atmospheric depth beyond shower maxima for $N_e > 10^5$ particles is presented in figure 6. The value of change in shower age per 100 gcm^{-2} atmospheric depth beyond shower maxima is 0.064 for $N_e > 10^5$ particles which is obtained by fitting the observed data points to $s(x) = 1(\delta s/\delta x)\mathrm{d}x$. In the Buckland Park experiment [21] value for the same is obtained as $\sim .05$ (for $N_e > 5 \times 10^5$) which is slightly lower than the present observation. In the Buckland Park experiment, depth of shower maxima was obtained independently, unlike the present case, from the study of Cerenkov radiation associated with EAS.

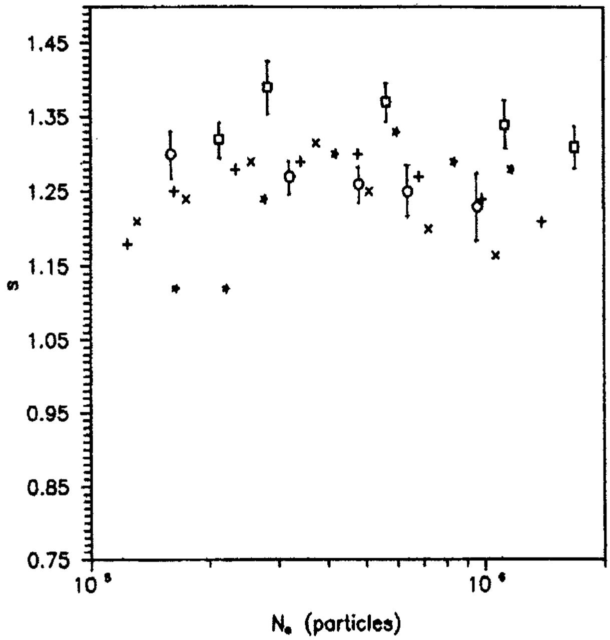

Figure 7. The variation of mean shower age with shower size in the shower size range $10^5 - 10^6$ for two different zenith angle intervals – o for $0° < z < 30°$ and □ for $40° < z < 55°$. Buckland Park observation – × for $z < 20°$, + for $20° < z < 30°$ and * for $30° < z < 45°$.

4.4 Variation of shower age with shower size

The variation of mean shower age with shower size in the shower size range 10^5–10^6 for two different zenith angle intervals is presented in figure 7. The result is compared with the observation of Buckland Park experiment [22]. For effective comparison and to understand the longitudinal development properly all mean shower sizes have been normalized to those at an atmospheric depth 1060 gcm^{-2} assuming the showers attenuate in size with an attenuation length of 200 gcm^{-2} [23]. For both the zenith angle intervals it is found that shower age decreases with shower size but the rate of decrease slows down at higher shower size.

5. Conclusion

Present results of the variation of shower age with zenith angle for different shower size interval at sea level agree with the prediction of cascade theory. In a number of EAS observations [19,22,24,25] similar trend of variation was observed. This suggests that shower age parameter can be used to describe the longitudinal development of cosmic ray EAS. As mentioned earlier in the positive observations of UHE gamma ray sources the excess showers from the direction of discrete point sources are characterised by high 'shower age' value and there is a possibility that the source events had higher zenith angle than the background events. However in the Kiel observations, showers with zenith angle less than 30° only were accepted for the analysis and present result indicates that up to 30° zenith angle shower age practically remains constant. So, it is difficult to correlate the high 'age' value of the directional excess showers with zenith angle.

The observed value of change in shower age with atmospheric depth is close to the theoretical value and simulation results. The observed value is slightly less than that observed by Mt. Norikura experiment [19] at mountain altitude (735 gcm^{-2}) and by MAKET–ANI experiment [24] also at the mountain altitude (700 gcm^{-2}). Using the expression of shower age according to cascade theory depth of shower maxima for each shower has been estimated and the variation of shower age with the atmospheric depth beyond the shower maxima has been studied. The present result is consistent with the result of Burkland Park observation. Interestingly in the Buckland Park experiment the depth of shower maxima has been measured directly by Cerenkov technique.

The variation of shower age with shower size for two different zenith angle intervals is studied and compared with other observations. For both the zenith angle intervals, the observed mean age decreases with the increase of shower size but the rate of change of s decreases at higher sizes, an effect which is probably due to radial variation of shower age and the finite area of the array as discussed by Capdevielle *et al* [11].

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