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An analysis of the shower age parameter in the size range $10^{4.25} - 10^{6.45}$

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ABSTRACT

The importance of the shower age parameter as an indicator of the longitudinal development of an extensive air shower (EAS) and its radial variation in the size range $10^{4.25}$ – $10^{6.45}$ have been discussed. The radial shower age obtained from different lateral distribution functions are experimentally analyzed to find out its relationship with the longitudinal age.

Introduction:

The longitudinal development of the electron-photon cascade in cosmic ray extensive air showers (EAS) is described by a parameter called the shower age (S). This parameter increases monotonically, within the bounds $0<S<2$, as the cascade develops in the atmosphere. In the EAS experiments the shower age is determined from the lateral distribution of shower particles by the standard least-squares fitting technique differs from the theoretical value at all atmospheric depths. The proposal to describe an EAS by two age parameters, one for its longitudinal development and the other for its lateral development, is under investigation for many years (Hara et al, 1981,1983; Capdevielle & Gawin, 1982,1985; Cheung & MacKeown, 1987; Idenden, 1990; Dai et al, 1990). The age parameter is the subject of further investigation because it had been used to distinguish between the showers initiated by ultra-high-energy (UHE) photons and charged cosmic particles (Samorski & Stamm, 1983; Cheung & MacKeown, 1987; Idenden, 1990) . In this paper an experimental investigation on the radial shower age will be made and compared with the theoretically obtained values.

Experiment:

The EAS array is located at the North Bengal University (NBU) Campus, Darjeeling, India (latitude $26^0 42^/$ N, $88^0 21^/$ E, atmospheric depth 1000 gm.cm. $^{-2}$). The electron densities are sampled at twenty one points on the EAS-front over an area of ~2000 m^2 by plastic scintillation detectors and the shower arrival direction is measured by eight fast timing scintillation detectors. Each scintillation detector has been built up with a 50cm. X 50cm. X 5cm. plastic scintillator (NE102A) block fixed at the upper end of an inverted pyramidal shaped light tight box made of galvanized iron sheet which is viewed by a photomultiplier (PM) tube from the lower end. For the electron density measuring detectors any one of Dumont 6364 / RCA 5819 / Philips XP2050 PM tubes are used while Philips XP2020 fast PM tubes (rise time ~2nS) are used for the fast timing detectors. The array has a circular symmetry with ~8m spacing between the detectors in the central part and its integral multiples in the peripheral part of the array.

The detectors are operated under an EAS trigger generated by four- fold coincidence of the fast timing detectors located around the center of the array. This fast coincidence generates the reference time for the time delay measurements by the fast timing detectors. To digitize the relative arrival time delay between the timing detectors the LeCroy 2228A time-to-digital converter (TDC) module is used. The analog pulses from the electron density measuring detectors are digitized using the 8-bit analog-to-digital converters (ADC 0809). The digitized information from the entire ADC and the TDC channels along with the event time are sent to the memory units (62256) for subsequent transfer to the interfaced Computer for permanent storage.

Data analysis and results:

The recorded electron densities are corrected for transition effect in plastic scintillator (Asakimori et al, 1981). The estimation of the EAS parameters are performed by means of a chi-squared minimization routine using gradient search technique in which the recorded electron densities are compared with the theoretical NKG lateral distribution function (Greisen , 1960).

$$\rho(N_e, S, r) = N_e f_N(S,r),$$

$$\text{with,} \quad f_N(S,r) = C(S)(r/r_o)^{S-2} [1+(r/r_o)]^{S-4.5},$$

$$\text{and} \quad C(S)= \Gamma(4.5-S)/[2\pi r_o^2\Gamma(S)\Gamma(4.5-2S)],$$

where $\rho(N_e,S,r)$ is the density of the shower particles at a distance r from the shower core of size N_e and age S, r_o is the Moliere radius. The quoted value (Greisen, 1960) of r_o=79m in air at sea level.

From the QGSJET model Kalmykov et al (1997) modified the NKG function, which is given by,

$$f_Q(S,r) = A(S,c)(r/r_o)^{S-2} [1+(r/r_o)]^{S-4.5}[1+c(r/r_o)],$$

$$\text{and} \quad A(S,c)= \Gamma(4.5-S)/[2\pi r_o^2\{\Gamma(S)\Gamma(4.5-2S)+c\Gamma(3.5-2S)\Gamma(1+S)\}].$$

They obtained the value of the Moliere radius, r_o=60m at sea level and the value of c=0.5 for the energy interval $10^{15} - 10^{17}$ eV.

Using the structure function obtained from the QGSJET model and assuming that the normalization constants do not vary much at two neighbouring radial points r_i and r_j , the radial age parameter at location r_i-r_j is obtained as,

$$S_{ij}(r) = \ln (F_{ij} X_{ij}^2 Y_{ij}^{4.5} / M_{ij}) / \ln (X_{ij} Y_{ij}),$$

Where $F_{ij}= f(r_i)/f(r_j)$, $X_{ij}= r_i/r_j$, $Y_{ij}=(1+x_i)/(1+x_j)$, $M_{ij}= (1+cx_i)/(1+cx_j)$ with $x=r/r_o$.

Substituting the measured electron densities at r_i and r_j in the above expression gives $S_{ij}(r)$.

With the NKG function under the same assumption the expression for $S_{ij}(r)$ was obtained (Capdevielle et al, 1982) as,

$$S_{ij}(r) = \ln (F_{ij}\ X_{ij}^{2}\ Y_{ij}^{4.5}) / \ln (X_{ij}\ Y_{ij}).$$

The obtained values of $S_{ij}(r)$ derived from both the lateral structure functions (e.g. QGSJET and NKG) for three different shower sizes are given in table 1.

Table 1. Radial variation of shower age, $S_{ij}(r)$ for different shower sizes.

(a) $N_e = 10^{4.5}$							
Radial interval (m)	5-10	10-15	15-20	20-25	25-30		
S_{ij} (QGSJET)	1.37±0.12	1.38±0.07	1.47±0.06	1.29±0.10	1.25±0.09		
S_{ij} (NKG)	1.36±0.13	1.37±0.07	1.47±0.07	1.28±0.10	1.26±0.08		
(b) $N_e = 10^{5.13}$							
Radial interval (m)	10-15	15-20	20-25	25-30	30-35	35-40	40-45
S_{ij} (QGSJET)	1.30±0.08	1.28±0.05	1.32±0.06	1.25±0.05	1.32±0.05	1.23±0.07	1.29±0.08
S_{ij} (NKG)	1.28±0.08	1.27±0.06	1.32±0.06	1.26±0.06	1.34±0.05	1.25±0.09	1.33±0.11
(c) $N_e= 10^{6.2}$							
Radial interval (m)	35-40	40-45	45-50	50-55	55-60	60-65	
S_{ij} (QGSJET)	1.20±0.03	1.20±0.03	1.18±0.03	1.18±0.02	1.18±0.02	1.20±0.05	
S_{ij} (NKG)	1.22±0.03	1.24±0.03	1.22±0.03	1.24±0.02	1.25±0.02	1.28±0.05	

The average radial age parameter (S_{av}) of a shower of particular size is defined as,

$$S_{av} = [\ 2/(r_j^2-r_i^2)\ ] \int_{ri}^{rj} S(r)\ rdr,$$

where r_i and r_j are the internal and external radii of the annular region within which the radial age parameters are measured experimentally. A numerical integration over the whole annular region gives the value of S_{av}. The calculations have been carried out for three shower sizes with the data obtained for S(r) using both the QGSJET and NKG lateral structure functions.

According to the electron-photon cascade theory, the shower age is given by,

$$S_t = 3t/[t+2\ln(E/\epsilon_o)],$$

where t is the atmospheric depth measured in radiation length, ϵ_o=0.0842 GeV is the critical energy of an electron in air and E is the energy of the primary particle.

The primary energy is calculated from the shower size, the transformation of which is obtained through CORSIKA + HDPM simulation (quoted in Aglietta et al, 1999) for primary protons:

$$E\ (\text{TeV}) = \alpha\ N_e^{\beta},$$

with α=0.0093 and β=0.903.

In Table 2 the average radial age parameter (S_{av}) is compared with the age parameter (S) obtained directly from the electron density data by means of chi-squared minimization routine and the theoretical shower age (S_t).

Table 2. Comparison of S_{av} with S and S_t for different N_e.

N_e	S_{av}(QGSJET)	S_{av}(NKG)	S	S_t
$10^{4.5}$	1.34	1.33	1.38	1.45
$10^{5.13}$	1.28	1.30	1.29	1.39
$10^{6.2}$	1.19	1.24	1.21	1.29

Conclusion:

From Table 1 it is seen that the lateral structure obtained through QGSJET model is characterized by more gently sloping compared to NKG function at large core distances. The average radial age parameter reflects approximately the same value as obtained directly from the electron density data by chi-squared minimization routine using gradient search technique for both the QGSJET and the NKG functions, where the theoretical values are higher at all shower sizes in the measured size range.

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