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Physical significance of the lateral shower age

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Abstract. We analyze the experimentally observed characteristics of lateral shower age parameter of cosmic ray extensive air showers (EAS). It has been found that like longitudinal age, lateral age also describes the development stage of EAS though it exhibits different radial dependence. An effort has been made to explain such behavior of lateral age.

1. Introduction.

There are only few observable parameters in EAS, which are supposed to reflect EAS development. Shower age is one such parameter associated with soft component of air shower. This parameter represents the slope of the lateral distribution of soft component in EAS. In the seventies and eighties and even in the early nineties several investigations had been made by many workers of the field to examine characteristics of shower age and its physical meaning. Discrimination of gamma ray initiated showers from the large background of charged cosmic ray initiated showers based on shower age parameter has been used in several observations (e.g. Samorski and Stamm, 1983; Protheroe *et al,* 1984). Later on, however, Monte Carlo simulation results show that in age photon showers are not older than that of normal showers (Fenyves, 1985; Hillas, 1987; Cheung and Mackeown, 1988). Probably due to anomalous radial dependence (in hadron initiated showers) of shower age parameter it looses importance and now usually it is treated as mere parameter without having any physical significance.

Since shower age is supposed to relate with longitudinal development, its variation with atmospheric depth is more important aspect than its radial dependence. Concentrating on this point, in the present work we critically examine the experimentally observed characteristics of shower age parameter, particularly its variation with atmospheric depth. We also make an effort to explain the observed characteristics of shower age parameter from simple argument.

2. Longitudinal and lateral shower age

The observable EAS characteristics are the result of superposition of many electromagnetic and nuclear cascades.

According to the cascade theory, the developmental stage of a pure electromagnetic cascade can be expressed by a single parameter s_L, known as longitudinal shower age. This parameter is the saddle point in the inverse Melline transformation of cascade transport equation. Under approximation B, it takes the simple form (Kamata and Nishimura, 1958)

$$s_L = 3t/[t+2\ln(E/\varepsilon_o)+2\ln(X)] , \qquad (1)$$

where t is the atmospheric depth, E is the energy of the primary photon, ε_o is the critical energy and X is the radial distance from the shower axis in the unit of Moliere radius ($X= r/r_m$). In the same theoretical framework the lateral density distribution of cascade particles can be approximated by the well known NKG structure function (Greisen, 1960), given by

$$f(r)=C(s)X^{(s-2)}(1+X)^{(s-4.5)} , \qquad (2)$$

where the normalization constant C(s) is given by

$$C(s) = \frac{1}{2\pi}\frac{\Gamma(4.5-s)}{\Gamma(s)\Gamma(4.5-2s)} . \qquad (3)$$

The relation $s_L = s$ was obtained by Nishimura and Kamata (1958) for electromagnetic showers. In the same article

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they further demonstrated that for hadron initiated EAS, both longitudinal structure and lateral structure of soft components can be described by that of a single cascade, assigning a suitable value to the age parameter. However, it is not clear from their analysis whether this effective lateral age (s)(henceforth we shall call it simply as shower age) has any connection with the longitudinal development of showers.

3. Observed characteristics of shower age parameter.

In most experiments the observed value of shower age differs from the longitudinal age for EAS having hadron primary. It was suggested from experimental results (Dedenko et al., 1975; Stamenov, 1987) that these two age parameters are related through the expression $s_L \geq s + \delta$, with $\delta \sim 0.2$. Simulation results also indicates similar type of relation ($s_L \sim 1.3s$)(Capdevielle and Gabinski, 1990). Comparison of ages measured by different groups is problematical. The main reason is that age parameter varies with core distance though usually constancy (independent of radial distance) of shower age parameter is taken a *priori* in the treatment of raw experimental data and different group estimated it differently according to detectors span area in the array.

3.1 Variation of shower age with atmospheric depth.

(1) Mt. Chacaltaya observation: Chacaltaya group made a detail study (Matano *et al.*, 1983) on the relation between the shower age parameter and depth past the maximum. They obtained longitudinal development curve from equi-intensity cuts on the integral size spectrum at different zenith angles. They also determined the average age at each depth on the equi-intensity curves. The age parameter is found to increase with atmospheric depth. We calculate the rate of change of shower age with atmospheric depth from published data, which is nearly .07 per 100 $g.cm^{-2}$ and 0.10 per 100 $g.cm^{-2}$ at integral intensities 10^{-6} $m^{-2}sec^{-1}Sr^{-1}$ and 3.16×10^{-7} $m^{-2}sec^{-1}Sr^{-1}$. They also came with the same conclusion by studying variation of shower age with burst size (which is a measure of primary energy) under 15 cm of Pb (Matano *et al.*, 1981; 1983).

(2) Mt. Norikura observation: Studying lateral structure and arrival direction of EAS for $7 \times 10^5 \leq N_e \leq 5 \times 10^8$ at Mt. Norikura, Miyake *et al.* (1979) observed variation of shower age with slant depth for fixed shower size. The observation shows that average age increases with atmospheric depth. The change of s is ~ 0.04 for a change in the atmospheric depth of 100 $g.cm^{-2}$. Since the constancy of shower size at higher zenith angle corresponds to higher primary energy, the relation between shower age and depth seems to be stronger than what they found.

(3) NBU observation: For the experiment performed at the sea level, shower age is found to increase with atmospheric depth (Bhadra, 1999). The observed value of change in shower age per 100 $g.cm^{-2}$ of atmospheric depth is ~ 0.03 at mean shower size 2×10^5, which is in accordance with the cascade theory but nearly half of that found at Mt. Norikura experiment. Here also fixed shower size was considered at different zenith angles rather than fixed primary energy. So the correlation between shower age and depth should be stronger. It is also observed that age parameter increases more with depth at larger size than at smaller size. In another analysis, the variation of the ratio of muon-to-electron density at certain core distances with shower age for fixed shower size at muon threshold energy 2.5 GeV was studied (Bhadra, 2001). It is found that the ratio increases sharply with shower age. This result could be explained as at a fixed shower size, to have a higher shower age value (i.e. in the case of early development of shower in the atmosphere), the primary energy needs to be higher and for higher primary energy, muon density will be obviously higher. Thus the result implies that shower age can indicate early or late development of showers.

(4) Akeno observation: In an important observation Akeno group found that the average shower age is almost constant over muon size range between 10^5 to 10^7 particles (Nagano *et al.*, 1984). This corresponds to a change of s about 0.075 per 100 $g.cm^{-2}$ of atmospheric depth when primary energy is fixed. A change of s about 0.037 per 100 $g.cm^{-2}$ of slant depth was reported when shower size is kept constant.

(5) Buckland Park observation: The Adelaide group obtained (Liebing *et al.*, 1983) the depth of shower maximum from the study of Cerenkov radiation associated with EAS. The age parameter is determined from the particle array. They reported that the showers become older as depth increases. The change in s is ~ 0.05 for 100 $g.cm^{-2}$ depth change for showers with s ~ 1.3.

(6) MSU experiment: In the Moscow State University experiment (Vashkevich *et al*, 1988) muon lateral distribution was studied for two groups of showers, one for old showers ($s > s'$, s' is the mean age) and other for younger showers (at $s < s'$). They found that the muon content is higher in old showers than in younger showers. As explained earlier (in case of NBU observation), this result suggests that shower age represents developmental stage of showers.

In KGF experiment (Acharya *et al*,1981) also shower age is found to increase with atmospheric depth.

3.2 Variation of shower age with radial distance

A number of authors have pointed out (Khristiansen *et al*, 1971; Linsley 1973; Miyake *et al*, 1973; Kawaguchi *et al*, 1975; Chudakov *et al*, 1979; Nagano *et al*, 1984) that NKG function with a single age value does not give a good description of the density data of electrons at all distances. Usually constancy of lateral shower age (independent of radial distance) is postulated in the treatment of experimental data. But it was found experimentally that the particle density data at far away from the axis are better fitted with a higher shower age value whereas data close to the shower core are fitted well with a smaller age value in contradiction with equation (1). Capdevielle and Gawin

(1982) introduced the concept of local age parameter (LAP) for better understanding of the radial variation of shower age parameter. Akeno observation shows that LAP, after an initial decrease, increases with core distance (Nagano et al., 1984). Similar behavior has been noticed in NBU observation too (Sanyal et al., 1993). Highlighting this point, Dai et al., (1990) concluded that these two age parameters are different concepts.

4. Discussion

Observations strongly suggest that for hadron's initiated showers, shower age has a close relation with the air shower development. The radial dependence of shower age is, however, different than that of longitudinal age parameter.

In the quest for possible physical explanation of the observed behavior of shower age we rely on simple analytical argument rather than going into the detail simulation. For hadron's initiated showers the observed electron structure is due to superposition of number of electron-photon cascade developed at different developmental stages from the decay of $\pi^o \rightarrow \gamma + \gamma$. The major contribution in the observed particle density comes from the cascade generated at the early stages. The particle density distribution of each electromagnetic cascade can be well represented by NKG function. So when one expresses the observed electron structure of EAS by the NKG function, we have

$$N_e C(s) X^{s-2}(1+X)^{s-4.5} = \sum_i \left[N_{ei} C(s_i) X^{s_i-2}(1+X)^{s_i-4.5}\right] \quad (3)$$

where N_e and s are the effective shower size and age of the resultant particle density distribution and N_{ei} and s_i are the size and age for the ith electron-photon cascade. Here we take the assumption that the sources of cascade showers are on the shower axis. This may be a good assumption, because the nuclear cascade does not spread much laterally. If s' denotes the age of an equivalent electromagnetic cascade that also gives same particle size N_e, then we may write from equation (3)

$$s = s' - \frac{\ln[C(s)/C(s')] - \ln \sum_i \alpha_i C(s_i)/C(s')h^{\delta_i}}{\ln(h)} \quad (4)$$

where $\alpha_i = N_{ei}/N_e$, $h = X(1+X)$, and $\delta_i = s_i - s'$. The radial dependence of s will be different than that of s' due to the presence of the 2nd term (unless it is zero which may happen only in a rare case) in the right hand side of the above equation. At small core distance, main contribution in the resultant particle density comes from the electromagnetic cascades having higher energy (most likely progenies of secondaries (π^o) of 1st few interactions) i.e. having small longitudinal age whereas at far distance showers of higher age (low primary energy) will contribute more. So near core, the net particle density spectrum is expected to be steeper in contrast with large distances where spectrum should be flatter. Variation of shower age with radial distance as obtained in simulation results (Capdevielle and Gawin, 1982) supports the present view. The observed variation of shower age against atmospheric depth can by analyzed in the light of equation (4). In equation (4) δ_i, the difference between ages of two electromagnetic cascades will not change much with atmospheric depth, so is the ratios of particle numbers. Hence it follows that the change of s with atmospheric depth will mainly govern by s', the age parameter of an electromagnetic cascade. For better understanding we consider a simple situation where the resultant density distribution is due to n number of electromagnetic cascades, each having same shower size and same age s'', all showers start at a same atmospheric depth. In this situation we have from equation (4), $s = s' - \delta$, where δ is positive. So the effective shower age will be smaller than longitudinal age of equivalent cascade. For the variation of atmospheric depth, we have, $\frac{ds}{dt} = 2\frac{ds'}{dt} - \frac{ds''}{dt} > \frac{ds'}{dt}$. In this simple case, however, radial dependence of shower age is similar to longitudinal age.

5. Conclusion.

Experimentally observed characteristics, particularly in connection with longitudinal development, of shower age parameter is examined. It is found that though shower age exhibits anomalous radial dependence but all observations clearly and equivocally support the candidature of shower age as a sensitive parameter of longitudinal development of EAS. The difference in radial dependence of shower age in hadron shower from that of longitudinal age can be explained as the result of superposition of several electromagnetic showers of different ages and sizes; each of those is represented by NKG structure function. This superposition effect also generates a difference in the numerical values of shower age and longitudinal age.

Some authors argued that Kamata-Nishimura calculations were made for the infinite primary energy and hence is the discrepancy. Experimentally it was found that for pure electromagnetic cascades lateral distribution is steeper than that predicted by NKG (Allan *et al*, 1975; Procureur *et al*, 1988). Modifications of NKG distribution were also introduced on the basis of finite primary energy (Lagutin *et al*, 1979) or from the analytical description of the results of a Monte Carlo simulation (Hillas and Lapikens, 1977; Hillas 1981). But present argument suggests that even if Uchaikin (Lagutin *et al*, 1979) or similar distribution is considered as true structure function for electromagnetic showers, the radial variation of shower age in hadron-initiated showers will be different than that of longitudinal age.

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