

# Simulations of Lateral Distributions of a Signal Produced in Scintillation Detectors by Giant Air Showers

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The lateral distributions of a signal, a response of scintillation detectors, have been simulated for vertical giant air showers in terms of the quark-gluon string model. Simulations have been carried out with the help of the suggested 5-level scheme. The estimated lateral structure function is more steep than the standard function used at the Yakutsk array to interpret data. At the same time this distribution of a signal coincides rather well with the lateral structure function observed at the Yakutsk array for experimental data sampled with the help of the Cherenkov radiation. The more steep function used to interpret data would result in increasing a number of giant air showers with energies above the threshold of the Greizen-Zatsepin-Kuzmin effect. The dependence of a signal at 600 m from the shower core for the vertical giant air showers on the energy of the primary particles have been also estimated.

## 1. Introduction

Observations of extensive showers (EAS) at Volcano Ranch [1], Haverah Park [2], Yakutsk [3], AGASA [4], SUGAR [5], Fly's Eye [6] and HiRes [7] have shown that the energy of the primary cosmic rays may be well above the value of  $10^{20}$  eV. The famous Greizen-Zatsepin-Kuzmin (GZK) effect [8,9] seems not to be accounted for by these observations. New observations such as with the help of the Pierre Auger Observatory [10] are needed to solve the GZK enigma. At the same time the more rigorous analysis of data should be carried out. The responses of detectors should be simulated to interpret data. To interpret responses of the scintillation detector stations one has to know the lateral distribution function of these signals. For many years the Nishimura-Kamata theory [11] and mainly the Nishimura-Kamata-Greizen (NKG) approximation [12] have been used to describe the lateral distribution of charged particles. Then the modified NKG approximation have been suggested [13]. Some new approach has been also developed [14]. When the Geiger-Muller (GM) counters were used these approaches were useful. But then the scintillation detector stations come to replace the old (GM) counters. J. Linsley [15] have suggested new empirical function to interpret data:

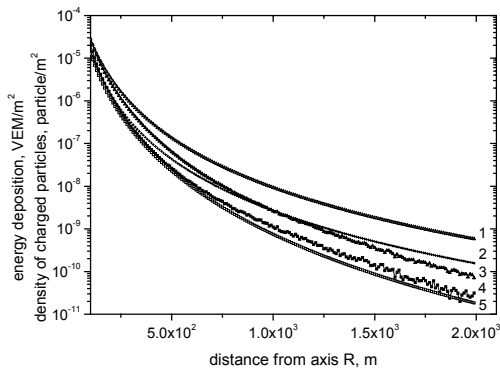
$$f(r) \approx r^{-a} (1+r)^{a-b} \quad (1).$$

Here  $r=R/R_m$ ,  $R$  is the radial distance and  $R_m$  is the Moliere radius (for the Yakutsk array its value is equal to 70 m),  $a$  and  $b$  some constants to be estimated by fitting procedure.

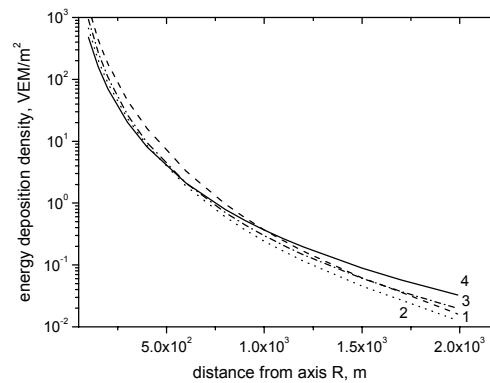
## 2. Results and Discussion

This function as a new standard approach has been used at many EAS arrays where scintillation detectors were exploited. In this paper with the help of simulation we made an attempt to compare various approaches developed.

Figure 1 shows results of simulations of various lateral structure functions for the electron-photon cascade generated by the gamma quantum with the energy of 10 GeV at the depth of  $750 \text{ g}\cdot\text{cm}^{-2}$  and observed at the sea level. Calculations have been carried out with help of the CORSIKA [16] code and GEANT4 code [17]. The density of charged particles is measured in  $\text{particle}/\text{m}^2$  and the energy deposition in a scintillation detector is expressed in  $\text{VEM}/\text{m}^2$  (VEM – vertical equivalent muon, energy deposition by vertical muon in a detector station). The curve 1 illustrates the NKG [12] approach for the lateral distribution of density of charged particles. The curves 4 and 5 show also lateral distributions of densities of charged particles estimated with help of the CORSIKA code [16] and approximation [14] accordingly. The curve 2 [13] shows an energy deposition normalized at a distance of 600 m from the shower core to experimental data observed at the Yakutsk array [18]. At last the curve 3 shows the lateral distribution of a signal (a response of a scintillation detector) estimated with the help of CORSIKA and GEANT4 codes. The model of a detector used at the Yakutsk array have been exploited [19]. One can clearly see that approximation [14] may be used to estimate the charged particle lateral distribution. But as far as a signal is concerned only simulations with help of the CORSIKA and GEANT4 codes are reliable (see curve 3).



**Figure 1.** Lateral distributions of a signal and charged particles. Curves: 1- [12], 2 – [18], 3 – responses, 4 – charged particles, 5 – [14].

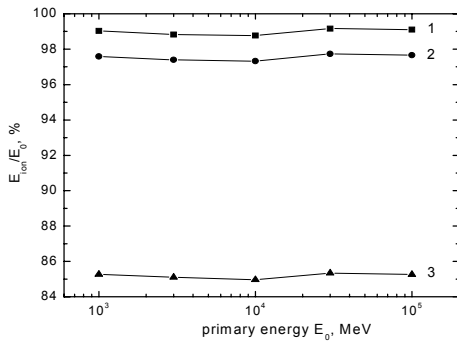


**Figure 2.** Lateral distributions of a signal in EAS. Curves: 1,2 – simulations, 3 – observations at Yakutsk array, 4 – the standard formula (1).

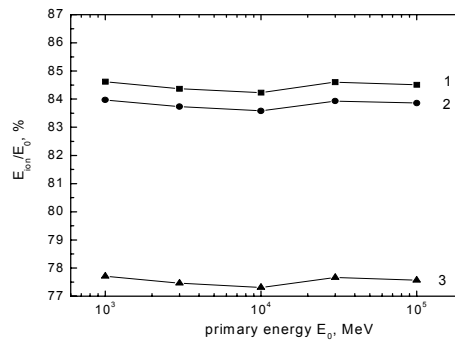
To interpret the EAS data (responses of the scintillation detectors) the standard approach (some empirical formula suggested by J.Linsley) have been used. This approach is shown as curve 4 at Figure 2. With help of measuring the Cherenkov radiation it is possible to select showers nearly with the same energy of the primary particle. The lateral distribution function [10] with Cherenkov light detection observed at the Yakutsk array is shown as a curve 3 at Figure 2. Simulations in terms of the test functions are shown as curves 1 and 2. It is clearly seen that simulated curve 1 may fit rather good the data shown as a curve 3. If this more steep function is used to interpret data then estimates of energy of the primary particles will be increased. Thus it was estimated that at last 4 showers observed at the Yakutsk array have energies above  $10^{20}$  eV giving more support to the GZK enigma. Then it should be mentioned that the lateral distribution function may be used in case of symmetry of the lateral spread of particles. In case of inclined showers

and when deflections of particles by the geomagnetic field (at large distances from the shower core) all detectors readings should interpreted in terms of calculated responses.

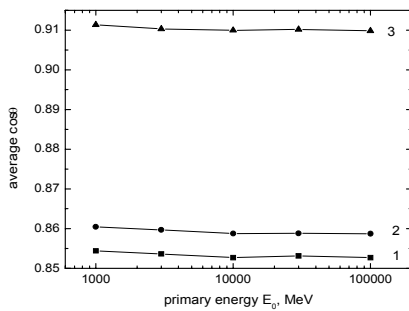
As far as observations of the fluorescent light are concerned some remarks may be made. It is of importance to take into account correctly the angular distribution of particles in a shower. With help of GEANT4 code nearly  $10^4$  showers have been simulated to check the energy balance in a shower. Figure 3 shows how energy balance in a shower depends on the energy of the primary particle for different threshold energies of secondary particles. The curve 1 is calculated for the threshold of 0.05 MeV and curves 2 and 3 were simulated for 0.1 MeV and 1 MeV accordingly. It is clearly seen that a balance is confirmed only if the threshold energy of secondary particles is rather low (below 0.05 MeV). Figure 4 shows the same balance if the lateral spread of secondary particles is disregarded. That means that not a full length of a track of particle contribute to energy balance but only its projection on the vertical direction. In this case a balance is not confirmed. At last Figure 5 shows average values of the zenith angle cosine for particles with the thresholds mentioned above. One can see that the value of this average cosine for low energy particles is equal to  $\approx 0.85$ . Thus these simulations may be used to interpret more correctly data when the fluorescent light is observed.



**Figure 3.** Energy balance in a cascade. Thresholds for secondary particles: 1 – 0.05 MeV, 2 – 0.1 MeV, 3 – 1 MeV.



**Figure 4.** Energy balance in a cascade when the angular spread of particles is disregarded. Thresholds: 1 – 0.05 MeV, 2 – 0.1 MeV, 3 – 1 MeV.



**Figure 5.** The average cosine of charged particles. Thresholds for secondary particles: 1 – 0.05 MeV, 2 – 0.1 MeV, 3 – 1 MeV.

### 3. Conclusion

The more steep lateral structure function than the standard approach should be used to interpret the EAS data. This more steep function was also observed at the Yakutsk array. The lateral structure functions may be used as a first approximation. For inclined showers with effects by geomagnetic field taken into account all detector readings should be interpreted in terms of simulated densities. Some angular distribution of secondary particles should be taken into account to interpret data with fluorescent light observations more correctly.

## 4. Acknowledgements

We thank G.T. Zatsepin for useful discussion, the RFFI (grant 03-02-16290), INTAS (grant 03-51-5112) and LSS-1782.2003.2.

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