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Reconstruction of charged particle density at fixed distance from the shower are by various methods

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Abstract. The simulation of charged particle density by the intensity-cut method and by direct estimation from the cascade curve has been performed. The results obtained by the intensity-cut method are in perfect correspondence with the data observed at Yakutsk array. The attenuation length has been calculated. The direct simulation of the shower development curve and calculations of the attenuation length at its base display some discrepancy with the results, estimated by the intensity-cut method.

1 Introduction

The detection of cosmic rays with energies above 10^{20} eV is of great importance because these energies are well above the threshold of the GZK's cut-off (Greizen, 1966; Zatsepin and Kuzmin, 1966). If the sources of highest energy particles are at the cosmological distances, then the energy spectrum in the region of E_0~10^{19}÷10^{20} eV is expected to drop sharply due to interactions of the primary protons with the microwave background radiation. However, recent observations (Efimov et al., 1990; Hayashida et al., 1994; Bird et al., 1995) display the existence of cosmic rays with energies well above 10^{20} eV. This allows to state that the sources of most energetic particles should be sought within ~30 Mpc. Due to high magnetic rigidity, their arrival directions may point approximately towards the location of their sources.

It is therefore important to estimate energy of the registered particle as precise as possible. As it is impossible to reconstruct the shower development curve by observation of only charged particle densities at the level of observation (in contrast with the experiments on the Fly's Eye array, which allow to register the fluorescent light from different heights) the indirect intensity-cut method (Clark et al., 1963) was used in estimations of the charged particle densities for vertical showers. In several works (Dedenko, 1975; Gaisser and Hillas, 1977) it was shown that this method is inadequate in the reconstruction of the shower development curve. Moreover, it has been calculated that the attenuation length of the charged component estimated by direct calculation of the cascade curve – the basic value of the intensity-cut method – is equal to λ~350 g/cm^2 while the observations at Yakutsk and AGASA arrays show the value of λ~480-540 g/cm^2 (Efimov et al., 1990).

Above mentioned observations make it important to estimate charged particle density by the intensity-cut method and estimate the attenuation length. It would be also useful to perform the direct simulations to produce the quantity of interest and compare the results.

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2 The simulations by the intensity-cut method

All calculations have been performed using hybrid MC method based on QGS model with the LPM-effect taken into account. The total statistics was about 100.000 showers. This huge amount of calculations was possible with help of the computational cluster of RCC of the MSU. The calculations have been carried out in the energy range of 10^{19}÷$10^{20.5}$ eV and in the range of the cosine of zenith angle 0.45÷0.95. First of all, the values of the density of charged component on the ground level obtained from the code were used to build histograms. These histograms allowed to construct the probability density functions for the showers with the fixed energy and zenith angle to generate the density of charged particles above the fixed values. Afterwards the averaging over the experimental accuracy range was performed, and then over the cosine intervals (5 cosine intervals from 0.5 to 1.0 with step 0.1), and, at last, over energy spectrum. Each averaging was made with corresponding weight coefficients. This procedure allowed us plot the spectra of showers with the density of the charged component above fixed values for 5 cosine intervals mentioned above. Reconstructed shower development curves were estimated by the intensity-cut method for three values of energy of the primary particles (Fig. 1). Approximation of the right part of the shower development curve in the half-logarithm scale by the straight line allow to find the value of the attenuation length which happens to be $\lambda=530\pm60$ g/cm^2 which is in correspondence with the experimental estimates observed in (Efimov et al., 1991).

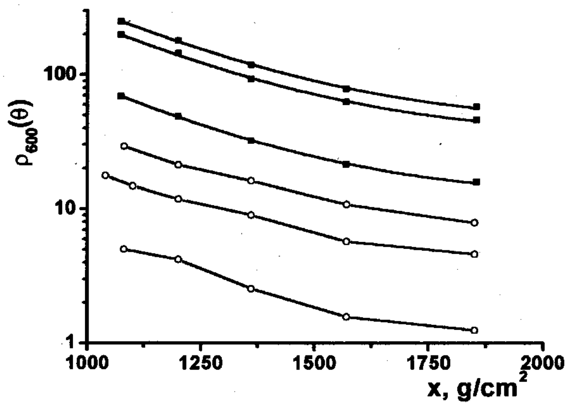

Figure 1. Shower development curves. Solid squares - reconstructed curve. Empty circles – experimental data (Efimov et al., 1991).

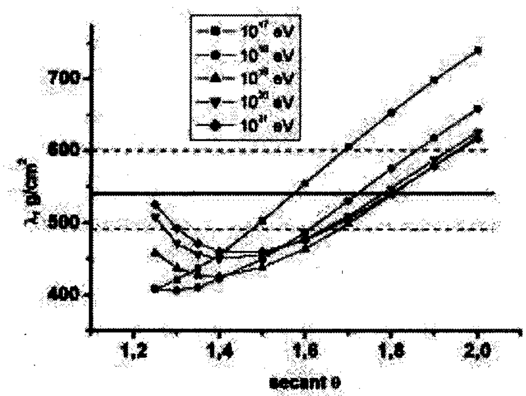

Figure 2. The attenuation length of the charged component vs. secant of zenith angle for different energies. The horizontal line with error bars – simulation by the intensity-cut method.

3 Direct simulation of shower development curve

The shower development curve can also be estimated by the direct method. First, the density of charged component at various distances from the shower core was calculated for energy range of the primary particles of $10^{17}\div10^{21}$ eV and for secant of zenith angle range of 1.0÷2.0. The total statistics of simulated showers was nearly 10.000 events. It should be mentioned that the array of initial random numbers was fixed for each value of energy. This procedure was similar to the calculations carried out for different depths of the same cascade. Then the attenuation length was estimated as $\lambda=1020\cdot(\sec\theta_i-1)/\ln(\rho_{600}(0^\circ)/\rho_{600}(\theta_i))$ for individual showers and then averaged. The results are shown on Fig. 2.

4 Discussion and conclusions

As it can be seen from Fig. 1, the simulation of charged particle density by the intensity-cut method may reproduce well experimental data. However, the direct simulations display different results as it is shown on Fig. 2. The above mentioned results lead us to the following conclusions. The intensity-cut method may not be considered as a reliable one for reconstruction of the shower development curve and the evaluation of energy of the primary particles. As it was shown the direct simulations produce better approach to the values of interest.

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