The GZK Paradox and Estimation of Energy of the Primary Cosmic Rays

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Abstract

The new model to interpret giant air showers data has been suggested. Monte-Carlo approach and transport equations are used for high energy particles. Responses of detector stations are accounted for by CORSIKA and GEANT4 codes.

1. Introduction

The new phenomenon, the giant air showers (GAS) with energies above 10^{20} eV, has been observed [1, 2, 3]. This discovery has put forward an enigma as due to the Greisen-Zatsepin-Kuzmin (GZK) effect [4, 5] no such showers should be detected. The Pierre Auger Observatory is expected to shed more light of this puzzle [6]. But the observed data are of importance. The inclined GAS detected at the Yakutsk array consists mainly of muons. The GAS observed at AGASA have also a large fraction of muons. Thus the photon primaries are not favoured particles as it was suggested [7]. Then to undo the GZK paradox a new model of interpretation of data should be developed. It was shown that standard procedure has many disavantages [8]. The method of the equi-intensity cuts used to estimate the attenuation lengths for the charged particles gives no reliable results then fluctuations are large. To estimate the energy of a GAS correctly all detector readings should be used. Besides the responses of detector stations to the passage of a shower in terms of QGSJET model [9] should be calculated. Cross-checking of energy estimations at the AGASA and the Yakutsk array are also of importance. A new model of interpretation of data is discussed in this paper.

2. Methods

a) Responses of detector stations. The first step was to find out the responses of the Yakutsk detector stations to various particles which hit this

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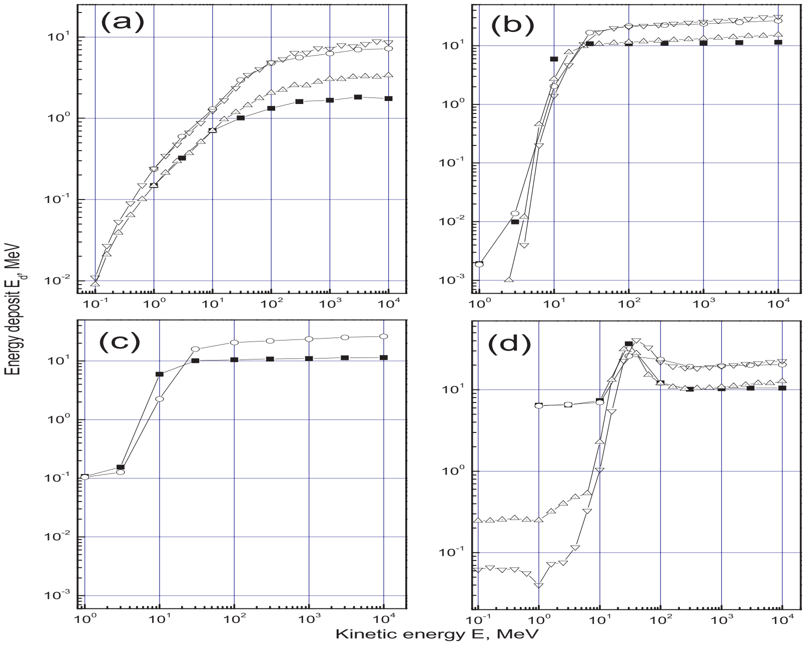

Fig. 1. The simulated distribution of energy deposit (in MeV) in the scintillator of Yakutsk detector. The AGASA data are also shown. (a)-photons, (b)-electrons, (c)-positrons, (d)-muons

detector. It was assumed that a detector consists of a plastic scintillator of 5 cm thick covered by a 2 mm sheet from aluminium and a 15 mm cover from wood. The energy deposit in the scintillator was taken as the signal. Calculations have been carried out for photons, electrons, positrons and muons which struck a detector using GEANT4 [10]. Fig.1 displays the responses of the Yakutsk detector to photons (a), electrons (b), positrons (c) and muons (d) for $sec\Theta = 1$ (black squares) and $sec\Theta = 2$ (open circles). For cross-checking data of responses of the AGASA detector are also shown by triangles for $sec\Theta = 1$ and inverse triangles for $sec\Theta = 2$. Some differences at energies above the kinetic energy $E = 10$ MeV for photons and $E = 100$ MeV for electrons may be due to the 2.4 mm thick steel cover of the AGASA detector. At lower energies the agreement is good. The differenses for muon curves at energies below 10 MeV may be account for using GEANT4 instesd of GEANT3.21.

b) Electron-photon cascades in the atmosphere. As the Coulomb scattering of the shower electrons and positrons with energies below some threshold is of importance the CORSIKA code [11] was used to simulate the electron-photon cascades in the inhomogeneous atmosphere. Such cascades have been calculated for various starting points in the atmosphere and for energies in the range of $0.1 \div 10$ GeV. As an example Fig.2 shows the lateral distributions of charged particles estimated with help of the CORSIKA code (triangles) and re-

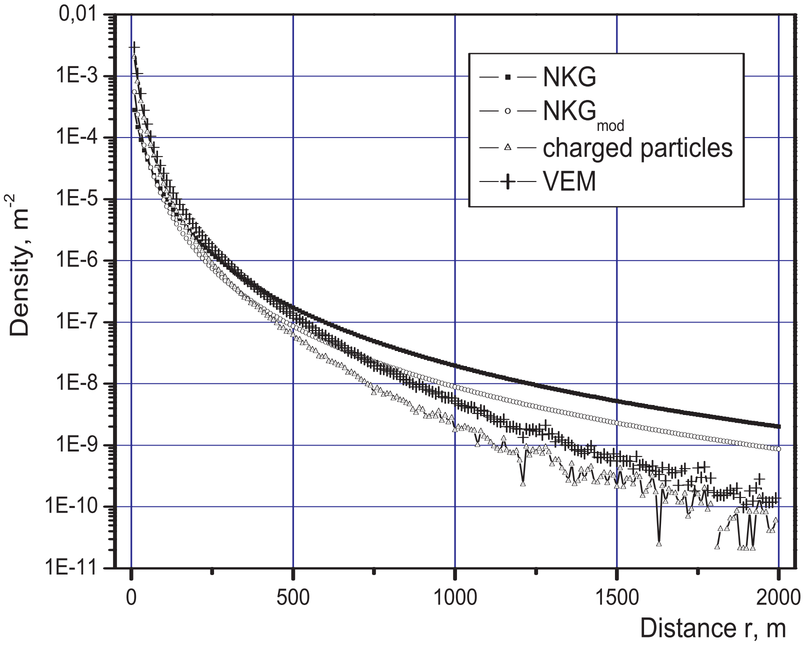

Fig. 2. Lateral distributions of charged particles, the reproduce of scintillator in VEM, the NKG and the NKG_{mod} function for 10 GeV photon for the starting depth $x_0 = 650\ g/cm^2$.

sponses (crosses) of the detector stations in units of VEM (vertical equivalent muon) for the cascade generated by a photon with energy $E = 10$ GeV at 650 g/cm^2. The NKG and NKG_{mod} distributions are also shown. It is of importance that the charged particle density is approximately 25% lower than the signal in units of VEM up to $\sim$ 100 m. But at distances above 500 m this difference increases to a factor of $2 \div 3$. So the readings of the Geiger-Muller counters differ much from responses of the scintillation detector stations. The NKG function with the Molier radius of 80 m and its modification (NKG_{mod}) with the Molier radius of 43 m [12] are also shown. It is remarkable that at distances $R \sim 600$ m the NKG_{mod} function produces the same reading as a response in VEM. But at other distances there is no agreement. The original NKG function shows no agreement with the simulated results.

c) Monte-Carlo simulations. One possible approach to utilize the above responses is to use the CORSIKA code and thinning techniques. Then the development of an individual shower is not possible to responce. Besides, because of very large fluctuations a plenty of showers should be generated. At last the efficiency of simulations is less than $\sim 10^{-3}$ because of the widely separated detectors the simulations should be carried out for distances above 500 m from the shower core. To take into account main fluctuation in the development of individual showers we suggest to use the Monte-Carlo approach only for the primary particle (possibly to small number of secondary particles generated in the first interaction). A large number of secondary particles does not contribute much to fluctuations in a shower. So they may be regarded by other approach.

d) Transport equations. Secondary particles (hadrons, photons, electrons) have high energies. So the one-dimensional approach may be used to transport these particles through the atmosphere. The transport equations for hadrons and for photons and electrons with the source term are suggested to use for secondary particles, generated by the leading particle. In this approach the development of an individual shower may be simulated.

e) Equi-intensity cut method. The equi-intensity cut method should not be used because of large fluctuation in development of inclined showers. Instead results of simulations for such showers may be used to interpret data.

3. Conclusion

The new model to interpret the GAS data has been suggested. The estimates of energy are increased.

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