Proceedings of ICRC 2001: 145 © Copernicus Gesellschaft 2001

ICRC 2001

Cerenkov radiation of cosmic ray extensive air showers. Part 2. Cosmic ray energy spectrum in the region of $10^{15} \div 10^{17}$ eV

S. Knurenko, V. Kolosov, Z. Petrov, I. Sleptsov, and S. Starostin

Institute of Cosmophysical Research and Aeronomy, 31 Lenin Ave. 677891 Yakutsk, Russia

Abstract. By data of small autonomous Cherenkov array the spectra by the EAS Cherenkov light fluxes and total numbers of the charged particles at sea-level have been obtained. The coupling coefficient between the primary energy and charged particle numbers has been determined. The comparison of experimental data with the calculations by the QGSJET model for the primary pure protons and the pure iron nuclei has shown that the knee in the energy spectrum is perhaps connected with the change of the primary particle mass composition. Before the knee the mass composition is close to the normal. After the knee the fraction of heavy nuclei increases.

1 Introduction

There is an unambiguous opinion about the nature and acceleration of cosmic rays (c. r.) in the region of $10^{15} \div 10^{17}$ eV. The c. r. acceleration theory on shock waves (Berezhko and Krymsky , 1988) cannot explain the form of the c. r. energy spectrum above 10^{15} eV observed experimentally. The proposed hypothesis (Erlykin and Wolfendale, 1997) about the close single c. r. source also cannot completely decide this task. Up to the present there is not any data on significant anisotropy in this energy region. In (Efimov, 1967; Pogorely, 1992) it is shown, that c. r. in the $\sim 10^{13} \div 10^{16}$ eV region are propogated isotropically. One cannot exclude the hypothesis about the possible new, unknown yet processes occurring at so high energies and their influence on the EAS spectrum until will be known precisely the model of interaction of hadrons in the energy region above 10^{15} eV. It is not inconceivable that sequence account of the strong and weak interactions in the pionization and fragmentation regions of the secondary particle generation in such processes (Nikolsky,1992) can initiate in turn the irregularity in the energy EAS spectrum.

In our opinion, only the complex study of all EAS characteristics including the dependence of them on the energy before and after the knee in the energy spectrum is the most perspective direction in the answer the first question of the origin and nature of an irregularity in the primary cosmic ray energy spectrum.

2 Experiment and Shower Treatment

After modernization in 1993, the Yakutsk EAS complex array (see Fig.1) represents the branching local network operating in the real-time regime (Afanasiev et al., 1996). The network includes the main array of ~ 12 km^2 control area, the small Cherenkov array of $\sim 3 \cdot 10^5$ m^2 control area and the large muon detector with the threshold energy 0,5 GeV and the area of 190 m^2.

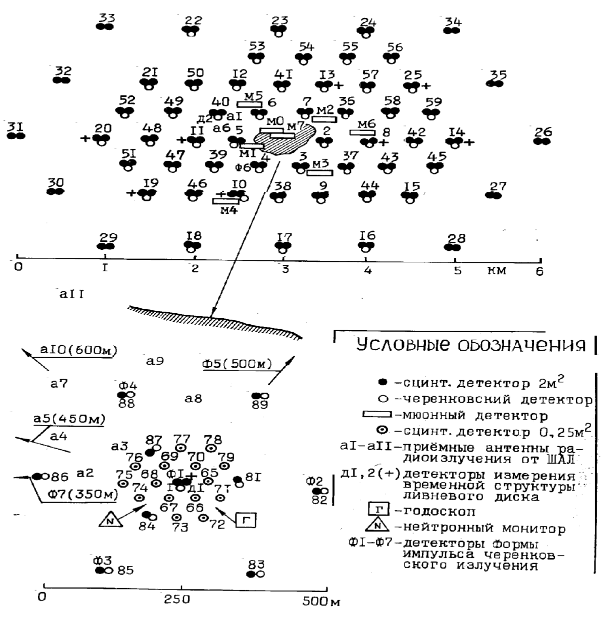

Fig.1. Schematic view of the Yakutsk Complex Array. (•)- the scintillation detector of 2m^2; (o)- the Cherenkov light receiver.

The small Cherenkov array addited by new observation points is located in a center of the main array. The observation points are located symmetrically relative to the center of the main array and form a net of the equilateral triangles the sides of 50, 100, 250, 500 m. The EAS events are selected by the coincidence of responses from three Cherenkov detectors located at the tops of equilateral triangles for the time of 2,5 ms. For showers with $E_0 > 10^{17}$ eV the small array operates synchronouly with the large array. Since the operation of the small Cherenkov array we carried out observations of the EAS Cherenkov during ~2716 hour observations and registered ~ $2{,}5\cdot10^5$ eV EAS events with energies above 10^{15} eV. The showers are selected by the parameter Q(100) - the density of the Cherenkov light flux at a distance of 100 m of the shower core. This parameter, as the calculations (Belayev et al., 1980) have shown, depends weekly on a zenith angle and is measured in every shower. The transition to the shower primary energy has been made according to the formula:

$$E_0 = (5{,}2\pm1{,}1)\cdot(Q(100)/10^7)^{0{,}96\pm0{,}02} \qquad (1)$$

which is obtained by the calorimetric method (Afanasiev et al., 1993). In Eq. (1) the condition of the atmosphere are taken into account.

3 Results and Discussion

By the measurement results the EAS spectra have been constructed by the Q(100) and $N_s(0°)$ parameters. Here $N_s(0°)$ is the total particle number at sea level. The transition to the vertical has been carried out by the barometric height formula:

$$N_s(0°) = N_s(\theta)\cdot exp(X_0(sec\theta - 1)/\lambda), \qquad (2)$$

where λ is the charged particles absorption path being equal to

$$\lambda = (215 \pm 20) + (10 \pm 3)\cdot lg(N/10^6) + 150\cdot(sec\theta - 1) \qquad (3)$$

The dependence (3) has been obtained from the correlation analysis of the N_s and Q(100) parameters in showers arriving at various zenith angles (see in Part. 3). The transition from N_s to E_0 has been carried out by the formula

$$N_s(0°) = (5{,}74 \pm 1{,}15) + (1{,}10 \pm 0{,}02)\cdot lg(Q(r = 100)/10^6) \qquad (4)$$

and by using (1). The differential EAS spectrum by the N_s parameter has the irregularity at $N_s \sim (3{,}3 \pm ,8)\cdot10^5$ of particles in a simple power presentation has the following power indices: before the knee ($\gamma_1 = -2{,}42 \pm 0{,}03$) and after the knee ($\gamma_2 = -2{,}85 \pm 0{,}02$). Fig.2 presents the differential cosmic ray energy spectrum. It is seen that the region of the spectrum irregularities falls on the energy interval $(2 \div 4)\cdot10^{15}$ eV (i.e. at Q(100) ~ $(6{,}5 \pm 1{,}0)\cdot10^5$ phot. / m2. If we approximate the spectrum by a simple power law then the power index before the knee is $\beta_1 = (-2{,}63 \pm 0{,}03)$, and after the knee is $\beta_2 = (-3{,}12 \pm 0{,}02)$.

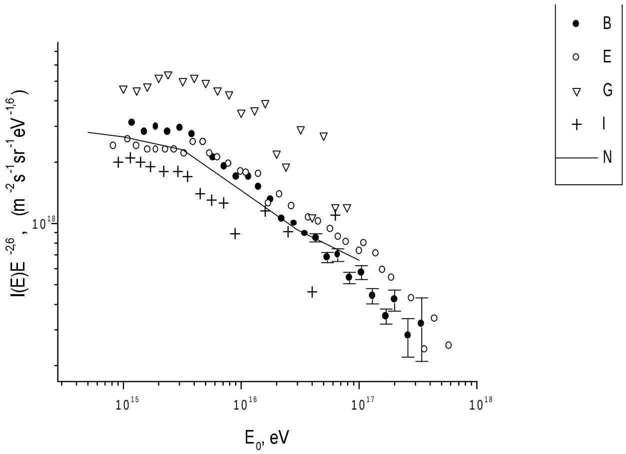

Fig.2. The differential energy cosmic ray spectrum. B is our result; E – is the Akeno array (Nagano et al., 1984); G – is the Tunka array (Gress et al., 1999); I – is the CASA – BLANCA array (Fowler et al., 2000); N – is the KASCAD array (Kampert et al., 2000).

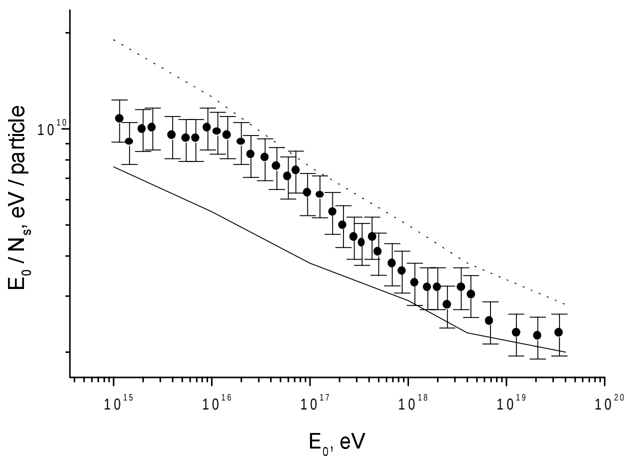

Fig.3. Dependence of the ratio E_0/N_s on primary energy E_0. Curves: primary protons (---) and primary nuclei of iron (…).Calculations by the QGSJET model (Knurenko et al, 1999).

The differential energy spectrum obtained using (2), (3), (4) from the spectrum by the N_s parameter within the experimental errors coincides with the spectrum obtained from the EAS spectrum by the Q(100) parameter. If we consider the spectrum form in detail then it is necessary to mark a step the intensity doesn't change practically in the energy range of $10^{16} \div 2 \cdot 10^{16}$ eV. Such a form of the spectrum is also observed by data from other arrays (see Fig. 2). But it is prematurely to say unambiguously about a thin spectrum structure in the interval $10^{16} \div 2 \cdot 10^{16}$ eV. Firstly, the spectra measured at various arrays coincide well by a form, but considerably differ in intensity. Secondly, some compact EAS arrays have different registration effectiveness of showers at $E_0 < 10^{16}$ and $E_0 > 10^{16}$ eV. It may occur that this effect is connected with a different measurement methods, calculations of intensity and shower energy. By our opinion, the most correct method is the determination of the shower primary energy by the EAS Cherenkov radiation flux because the model of the EAS development is not yet known.

Fig.3 shows the coefficient k from formula $E_0 = k \cdot N_s$ versus the primary energy. The result is obtained by the averaging of a great number of showers registered at small and large arrays. Only 20 % systematic errors in determination of E_0 are shown. In Fig.3 the calculations by the QGSJET model for the primary protons and iron nuclei are given. The calculations are carried out for the fixed energies 10^{15}, 10^{16}, 10^{17}, $3 \cdot 10^{17}$, 10^{18}, $5 \cdot 10^{18}$, 10^{19} and $3 \cdot 10^{19}$ eV (Knurenko et al., 1999). The thresholds of the scintillation (0,5 particl/m^2), Cherenkov (15 and 8 phot./cm^2) detectors and selection peculiarities of the EAS event by the array have been taken into account. For every energy about 500 EAS events at zenith angles θ = 10, 20, 30, 40, 50 and 60° have been simulated. Then, to find the EAS parameters the a standard program of the treatment and analysis of showers is used. From Fig.3 one can make a conclusion that the knee in the cosmic ray energy spectrum at $E_0 \sim 3 \cdot 10^{15}$ eV is probably connected with the change of the mass composition of primary particles if the QGSJET model is true for the description of the EAS development of such energies. Perhaps, the next analysis of all EAS components at a fixed energy including fluctuations the distribution form of the shower parameters and their correlation's will help to resolve this task.

References

Afanasiev B.N. et al. // Proc. ISEHECR: Astrophysics and Future Observatories. Tokyo (1996), p. 412.

Afanasiev B.N. et al. // Proc. Tokyo Workshop on Techniques for the Study of Extremely High Energy Cosmic Rays. Tokyo (1993), p. 35.

Belayev, A.A., Ivanenko, I.P., Kanevsky, B.L. et al., M.: Nauka., Electron - Photon cascade of Cosmic Rays for Highest Energy., 305p (1980).

Berezhko E.G., Krymsky G.F. // УFH, 1988, v. 154, p. 49.

Efimov N.N. Thesis. MSU NIYAF (1967).

Erlykin A.D., Wolfendale A.W. // Astroparticle Physics, 7, 1 (1997).

Fowler J.W. et al. // arXiv:astro-ph/0003190 v2.

Gress O.A. et al. // Nucl. Phys. B (Proc. Suppl.) 75A (1999), p. 299.

Kampert K.-H. et al. // arXiv:astro-ph/0102266.

Knurenko S.P., Sleptsova V.R., Kalmykov N.N. et al. // Proc. 26th ICRC, v.1 (1999), p. 372.

Nagano M. et al. // J. Phys. G., 10, 1295 (1984).

Nikolsky S.I. Preprint FIAN. 15 (1992).

Pogorely V.G. Thesis. MSU (1992).