Spectrum and mass composition of cosmic rays in the energy range $10^{15} - 10^{18}$ eV derived from the Yakutsk array data

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Abstract: A spectrum of cosmic rays within energy range $10^{15} - 3 \times 10^{17}$ eV was derived from the data of the small Cherenkov setup, which is a part of the Yakutsk complex EAS array. In this work a new series of observation is covered. These observations lasted from 2000 till 2010 and resulted in increased number of registered events within interval $10^{16} - 10^{18}$ eV, which in turn made it possible to reproduce cosmic ray spectrum in this energy domain with better precision. A sign of a thin structure is observed within the shape of the spectrum. It could be related to the escape of heavy nuclei from our Galaxy. Cosmic ray mass composition was obtained for the energy region $10^{16} - 10^{18}$ eV. A joint analysis of spectrum and mass composition of cosmic rays was performed. Obtained results are considered within the framework of theoretical computations have been performed with the use of galactic and meta-galactic hypotheses of cosmic ray origin.

Keywords: extensive air shower, Cherenkov light, CR spectrum, mass composition

1 Introduction

Energy spectrum of cosmic rays (CR) in energy range $3 \times (10^{15} - 10^{18})$ eV could not be studied in detail with compact arrays due to their small acceptance at energy above $10^{17}$ eV. At the same time this area of the spectrum is of a great interest, since local irregularities are manifested there: production of kinks (thin structure at $3 \times 10^{15} - 10^{17}$ eV) arising from non-uniform distribution of heavier CR components in our Galaxy. On the other hand, this effect is smoothed by addition of a new component (of meta-galactic or other origin) to the cosmic ray flux near Earth. As a result, presence/absence of significant irregularities in spectra measured by various compact arrays allows one to speculate on the CR origin and propagation in our Galaxy [1, 2].

The Yakutsk array in this sense appears as a unique scientific tool. It is related to medium-sized arrays, capable of effective measuring cosmic rays in a wide energy range ($10^{15} - 10^{19}$ eV). Other important traits of the array are its model-independent technique of cosmic ray estimation, ability to track longitudinal EAS development with the use of detection of Cherenkov light emission. Factors mentioned above make possible to adopt the unique method, combining the studies of CR spectrum and mass composition aimed at exploration of astrophysical aspect of cosmic rays [3, 4].

2 Methodical issues

For more than 15 years the small Cherenkov setup has been operating as a part of the Yakutsk array. It measures Cherenkov light emission from EAS of lower energies (see Fig.1) using standard detectors which are designed to operate in winter conditions. The area of modern prototype was significantly increased in comparison with the original setup, its border forms a circle of 500 m radius. The number of optical detectors was increased accordingly (see Fig.1). Table 1 presents the information on operation of the setup (on annual basis) combined with mean spectral atmosphere transparency at wavelength 430 nm.

All the information on each shower is stored in the database, which is controlled by a multipurpose program. This program includes units for gathering, sorting and storing of the experimental data. The software also includes mathematical units for data processing and statistical analysis. Further, the results of the analysis are presented.

2.1 Selection, processing and choice of the classification parameter for showers

In order to reconstruct cosmic ray spectrum we used following criteria for shower selection: 1. atmospheric transmittance $p_\lambda \geq 0.65$; 2. shower axis must lye within 250 m from the center of array (for showers with primary energy $E_0 \leq 3 \times 10^{16}$ eV) and within 500 m (for showers with $E_0 \geq 10^{16}$ eV); 3. zenith angle of shower arrival direc-
Table 1: Characteristics of different observational periods

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</table>

Figure 1: Location of observational points of the small Cherenkov setup.

Figure 2: Atmospheric transmittance averaged by months for wavelength 430 nm. Numbers represent months, during which optical observations were carried out at the Yakutsk array: 1 — September, 2 — October, 3 — November, 4 — December, 5 — January, 6 — February, 7 — March, 8 — April.

2.2 Monitoring of the atmosphere

It is believed that photon losses in clear atmosphere arise from Relay scattering (5% from total flux). In real conditions there is significant loss in received light due to Mie aerosol of various size. In winter (in the region where array is located the climate is sharp-continental) the atmosphere above the array is non-standard, its parameters change significantly from autumn to winter and vice-versa. According to work [5] all this factors should be tracked on an operational basis and taken into consideration when analysing different observational periods. On Fig. 2 perennial data are presented on Cherenkov light transmission in atmosphere during different periods of optical observations. These data were used during generation of shower samples from which cosmic ray spectrum had been calculated.
2.3 Estimation of primary energy of the shower

Energy was estimated with quasi-calorimetric method, from joint measurements of main shower component. Recently, thanks to significant increase in acceptance for showers with energy \(E < 500\) PeV, it has become possible for Yakutsk array to measure total number of charged particles on observation level with the precision 15% and density of Cherenkov light flux at any given distance from shower axis with the precision 15%. Such distances for small and large Cherenkov setups are \(r = 150\) m and \(r = 400\) m accordingly. The densities of Cherenkov light fluxes at these distances were adopted as classification parameters. On fig. 3, energy dependence of classification parameters is shown. From the data presented on Fig. 3, a connection between classification parameters and primary energy of a shower \(E_0\) has been derived:

\[
E_0 = (9.12 \pm 2.28) \times 10^{16} \cdot \left(\frac{Q(150)}{10^7}\right)^{0.99\pm0.02} \tag{1}
\]

\[
E_0 = (8.91 \pm 1.96) \times 10^{17} \cdot \left(\frac{Q(400)}{10^4}\right)^{1.03\pm0.02} \tag{2}
\]

Expression (1) is used in energy range \((5 \div 500)\) PeV and expression (2) — to estimate primary energy of showers above \(5 \times 10^{17}\) eV.

2.4 Calculation of the \(s_{\text{eff}}\).

The effective area \(s_{\text{eff}}\) of the array was taken into consideration for each energy interval according to the method of shower selection. If time of observations and the spatial angle are always defined accurately, then underestimation and overestimation of the \(s_{\text{eff}}\) usually results in systematic errors in the estimation of the absolute EAS spectrum intensity. This is why the thresholds of Cherenkov detectors (3 \(\cdot\) 10\(^5\) photons/m\(^2\)) and the effectiveness of shower

![Figure 3: Energy dependence of classification parameters. 1 — \(Q(150)\), 2 — \(Q(400)\).](image1)

![Figure 4: Effective area \(s_{\text{eff}}\) of the small Cherenkov setup for showers from different triggers. Solid line — showers with smaller energies (axes within \(r = 250\) m), dotted line — showers with \(E_0 \geq 10^{17}\) eV (axes within \(r = 500\) m).](image2)

3 Results

3.1 Energy spectrum of cosmic rays within energy interval \(10^{15} \div 10^{18}\) eV

Energy spectrum of cosmic rays with the account of the new data on showers from the selection is presented on Fig. 5. Statistical accuracy allows one to speculate of a thin structure within the shape of the spectrum. A comparison with model calculations performed within various hypotheses of CR sources and models of their propagation in the galaxy gives possible interpretation of the experimental data. As it is seen from the Fig. 5, within the energy range \((5 \div 8) \times 10^{16}\) eV there is a small peak generated by iron nuclei. At lesser energies, where a peak from the CNO group is expected according to the model, a slight increase in the intensity is observed. According to our data and the data from KASCADE-Grande, this exceeding is not signif-
significant and could be related to the presence of CR of another origin in the total flux [2].

3.2 Mass composition

The mean natural logarithm of the CR atomic number \langle \ln A \rangle derived from the \( x_{\text{max}} \) measured at the Yakutsk array is shown on the Fig. 6. The \( \langle \ln A \rangle \) calculations were performed with the use of the \( x_{\text{max}} \) predictions of QGSJet II and SIBYLL models for proton and iron and with the relation (3) proposed by Hörandel et al [6]:

\[
\langle \ln A \rangle = \frac{x_{\text{max}} - x_{\text{Fe}}^{\text{max}}}{x_{\text{Fe}}^{\text{max}} - x_{\text{p}}^{\text{max}}} \cdot \ln 56
\]

The data from the Fig. 6 point towards the slight change of the \( \langle \ln A \rangle \) value right after the kink in the spectrum. For example within the energy range \( 10^{16} - 10^{17} \) eV the \( \langle \ln A \rangle \) value gets its maximum \( \sim 3 \) at \( E_0 = (5 - 8) \times 10^{16} \) eV (the composition becomes heavier) and above the energy \( 3 \times 10^{17} \) eV a decrease of the \( \langle \ln A \rangle \) is pointed out (i.e. the composition becomes lighter). The data from other EAS arrays testify of the same tendency [6]. If one plots the mass composition data versus the CR energy spectrum (see Fig. 6), then the coincidence between the peak of CR intensity and the maximum of the \( \langle \ln A \rangle \) value could be clearly seen. Then it follows that the nature of the peak in the spectrum is related to a heavier component of cosmic rays.

References