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Energy Spectrum of Primary Cosmic Rays, According to TUNKA-133 and TAIGA-HiSCORE EAS Cherenkov Light Data

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Abstract—The Tunka-133 Cherenkov complex for recording extensive air showers (EAS) collected data over seven winters from 2009 to 2017. The differential energy spectra of all particles was acquired in the 6×10^{15}–3×10^{18} eV range of energies over 2175 h. The TAIGA-HiSCORE complex is continually being expanded and upgraded. Data acquired by 30 first-line stations over 35 days during the period 2017–2018 is analyzed in this work. As at the Tunka-133 setup, the primary particle energies above 10^{15} eV are measured using the density of the Cherenkov light flux at a distance of 200 m from a shower's axis. Data on lower energies are collected by determining the energy of the light flux near a shower's axis. This results in a spectrum of 2×10^{14}–10^{17} eV. The combined spectrum for the two systems covers a range of 2×10^{14}–2×10^{18} eV.

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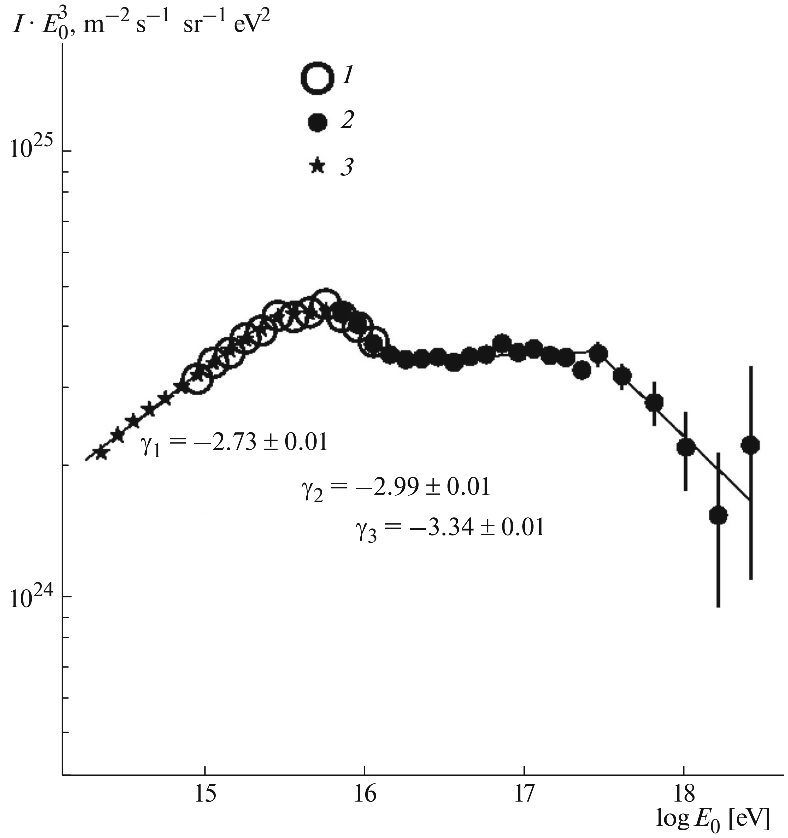

Fig. 1. Differential energy spectra (multiplied by factor E^3) acquired by the (*1*) Tunka-25, (*2*) Tunka-133, and (*3*) TAIGA-HiSCORE installations.

INTRODUCTION

The Tunka-133 complex [1, 2] collected data over seven winter seasons in the periods 2009–2014 and 2015–2017, allowing information to be acquired for 350 clear (moonless) nights (total acquisition time, 2175 h).

The TAIGA-HiSCORE facility is continually being expanded and upgraded. This work presents data collected by 30 first-line stations over 35 moonless nights in 2017–2018. The total time of acquisition was 180 h. Data was processed using software in which all approximating and scaling functions were obtained by analyzing artificial events simulated by the CORSIKA programming tool for energies of 10^{14} to 10^{18} eV [1, 3, 4]. The direction of arrival, the axis coordinates on the plane of observation, and the primary particle energy were reconstructed for each shower. This allowed the joint differential energy spectrum to be acquired for all particles in the 2×10^{14}–2×10^{18} eV range of energies.

DATA PROCESSING AND RECONSTRUCTING EAS PARAMETERS

Data processing for the Tunka-133 facility was described in [1, 2]. It is worth noting that the position of an EAS axis is determined by fitting the measured pulse amplitudes with an amplitude–distance function (ADF) [1]. The direction of shower arrival, characterized by zenith and azimuth angles of the axis, can be found by fitting measured delays with a curve front [5]. The energy of a shower is determined from density Q_{200} of the Cherenkov light flux at a distance 200 m from the axis. Data at a distance of 200 m are interpolated from measured values Q_i using the IPF in [4]. The relationship between the energy and parameter Q_{200} is also obtained using the CORSIKA software [1].

The main EAS parameters of the TAIGA-HiSCORE data can be reconstructed using the same algorithms and fitting functions as at the Tunka-133 facility. EAS energies above 10^{15} eV can be found from density Q_{200} of the Cherenkov light flux at a distance of 200 m from the axis. The effective area for event selection is assumed to be that of an ellipse with semi-axes of 300 and 225 m.

At energies below 10^{15} eV, not all showers are suitable for measuring the light flux at a distance of 200 m from the axis. Another approach to determining the energy was therefore developed that consists of reading data from detectors near the axis. The position of a shower's axis is in this case found as the center of gravity for the amplitudes measured by four stations in

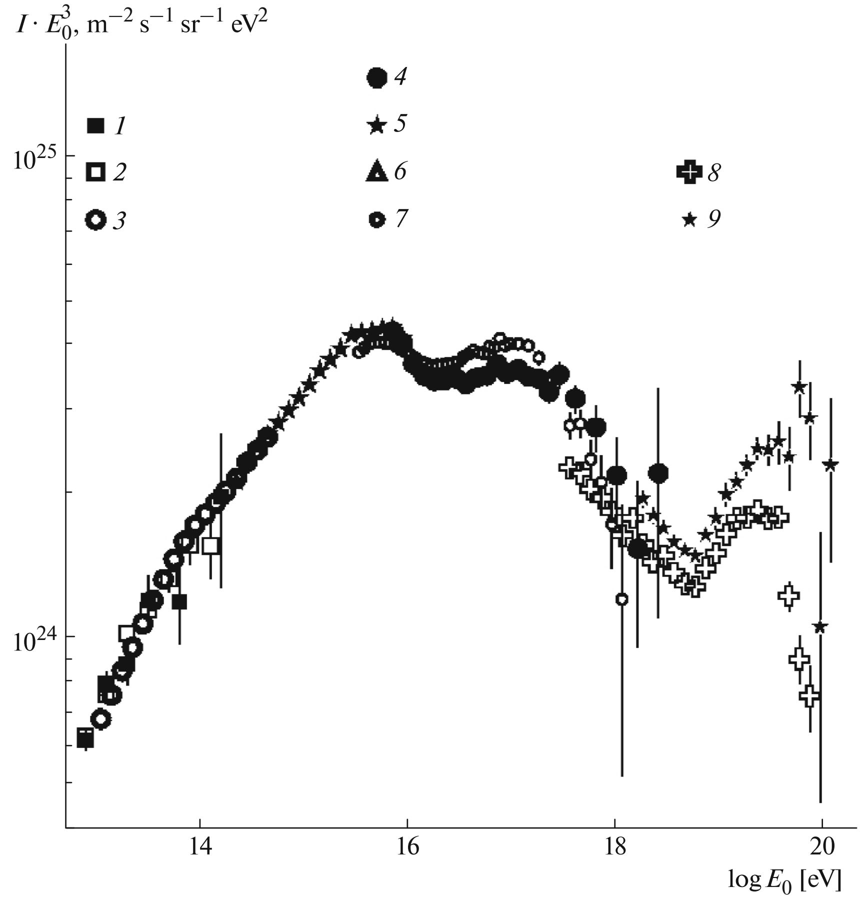

Fig. 2. Our data, compared to those in other works: (*1*) ATIK2, (*2*) NUKLON (KLEM), (*3*) HAWC, (*4*) Tunka-133, (*5*) TAIGA-HiSCORE, (*6*) KASCADE-Grande, (*7*) IceTOP, (*8*) TA, (*9*) PAO.

close proximity to the axis. Calculations show that in the current geometry, the density of the light flux is in this case measured at an average distance of 70 m from the axis. Correlations Q_{70} with the zenith angle of a shower and the primary energy are determined using the experimental results for energies of 10^{15} to 3×10^{15} eV, allowing us to determine both Q_{70} and Q_{200} for each shower. Q_{70} is rescaled to the vertical direction relative to the measured zenith angle as

$$\log Q_{70}(0) = \log Q_{70}(\theta) + 1.06(\sec\theta - 1).$$

The value of $Q_{70}(0)$ relative to the energy can be rescaled as $E_0 = CQ_{70}(0)^g$, where $g = 0.88 \pm 0.01$.

Determining the EAS axis relative to the center of gravity can result in substantial errors at the edge of the station's location. To obtain an undistorted spectrum, a belt 50 m wide is subtracted from the effective area at the edge of the facility; i.e., the effective area is an ellipse with semi-axes of 250 and 175 m.

As with other operations performed in the Tunka Valley, the absolute calibration of primary particle energies is done by normalizing the obtained integral spectra to the one acquired in the Tunka-25 experiments [7]. The latter is in turn normalized to the absolute cosmic ray intensity obtained in the QUEST experiment [8].

ENERGY SPECTRUM

To plot the spectrum according to the results from processing the data collected by the Tunka-133 facility, events with zenith angles $\theta \le 45°$ and axial positions in a circle with radius $R_c < 450$ m were selected for energies $E_0 < 10^{17}$ eV, and in a circle with radius $R_c < 800$ m for showers with energies $E_0 \ge 10^{17}$ eV. The efficiency of event selection was ~100% for energies $E_0 > 6 \times 10^{15}$ eV in a circle with a radius of 450 m, and for energies below 10^{17} eV in a circle with a radius of 800 m. The spectrum was thus plotted using ~375000 events. Approximately 4200 events had energies above 10^{17} eV.

A spectrum based on TAIGA-HiSCORE data was obtained by selecting events with zenith angles $\theta \le 30°$. The spectrum contained more than 170000 events with energies higher than 10^{15} eV, along with around 700000 events with energies of 3×10^{14}–10^{15} eV. The points in the range of 2×10^{14}–3×10^{14} eV are associated with observations made on an exceptionally clear night (October 28, 2018) and contain ~29 000 events.

Figure 1 displays the combined differential energy spectrum alongside Tunka-25 data [7]. The initial spectral range (2×10^{14}–3×10^{15} eV) can be approximated by a power function with a factor of 2.73 ± 0.01. In addition to the statistical error, there is the systematic error associated with the possible imprecision of the factor used for scaling parameter Q_{70} to the energy. At higher energies, the spectrum exhibits a considerable number of deviations from a power law. In the range of 3×10^{15}–6×10^{15}, there is a gradual rise in the spectrum's slope. The subsequent points up to an energy of 2×10^{16} eV are described by a power function with factor $\gamma = 3.3$. Then the spectrum suddenly slopes more gently, obeying a power law with $\gamma = 2.99 \pm 0.01$ in the range of $2 \times 10^{16} < E_0 < 3 \times 10^{17}$ eV. At high energies, the factor grows abruptly to $\gamma = 3.34 \pm 0.09$ (a second knee). Figure 2 compares the spectrum to data from other works. The left edge of the profile matches the spectra of all particles obtained during direct experiments with the ATIK-2 bottle [9] and the NUKLON (KLEM) satellite system [10]. The best statistics in this spectral range come from terrestrial (mountain) HAWC measurements [11] in Mexico. Its spectrum is perfectly consistent with direct experimental data and our results.

The spectra of this work in the range of 10^{16}–10^{17} eV coincide with those collected by the KASCADE-Grande [12] and Ice-TOP [13] facilities. The notable difference between these spectra and one acquired at the Tunka-133 facility (Fig. 2) can be eliminated by raising the KASCADE-Grande energy estimate by 3% and reducing the Ice-TOP estimate by the same amount. These changes are much lower than the absolute accuracy of the experiments.

Data acquired at energies extremely high for the Tunka-133 experiment coincide with those of the Telescope Array (TA) [14] and PAO [15] experiments.

CONCLUSIONS

The combined spectra of the Tunka-133/TAIGA-HiSCORE Cherenkov facilities exceed in terms of energy those obtained individually by four orders of magnitude and demonstrate the good agreement between data acquired via direct satellite and balloon experiments and those of large terrestrial facilities.

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