Primary Cosmic Rays Energy Spectrum and Mean Mass Composition by the Data of the TAIGA Astrophysical Complex

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Abstract

The corrected dependence of the mean depth of the EAS maximum X_{max} on the energy was obtained from the data of the Tunka-133 array for 7 years and the TAIGA-HiSCORE array for 2 year. The parameter $\langle \ln A \rangle$, characterizing the mean mass compositon was derived from these results. The differential energy spectrum of primary cosmic rays in the energy range of $2 \cdot 10^{14}$ – $2 \cdot 10^{16}$ eV was reconstructed using the new parameter Q_{100} the Cherenkov light flux at the core distance 100 m.

It would be nice to indicate a main conclusion in the abstract.

Contents

1 Introduction

The energy spectrum and mass composition of primary cosmic rays are the main characteristics that can be obtained by study of extensive air showers (EAS). The total flux of Cherenkov light is proportional to the total energy scattered by the shower in the atmosphere. The lateral distribution function (LDF) of the EAS Cherenkov light reflects the position of the shower development maximum, which in turn characterizes the mass of the primary particle.

It would be nice to have a sentence or two on what you aim to achieve with the work reported, here in the introduction.

2 Brief description of the arrays

Several arrays that detect the EAS Cherenkov light were successively constructed in the Tunka Valley. The most productive arrays were the Tunka-25 (2000 - 2005) [1], which consisted of 25 detectors with a sensitive area of 0.1 m^2 each, covering a total area of approximately 0.1 km^2, and the Tunka-133 (2009 - 2017) [2], consisted finally of 175 detectors with a sensitive area of 0.03 m^2, covering an area of approximately 3 km^2. The experimetal data was accumulated over 350 clear moonless nights. The total time of the data acquisition was 2175 h. Their modern successor is the TAIGA-HiSCORE [3] array, a part of the TAIGA experimental complex [4]. TAIGA-HiSCORE sigle station has a sensitive area of 0.5 m^2.

This work presents the TAIGA-HiSCORE data that was obtained using 67 stations (two first clusters) during 135 clear moonless nights in the seasons of 2019 - 2020 and 2020 - 2021. The total data acquisition time was 327 h.

This section should include a brief description of the detection technique

3 Reconstruction of the EAS parameters

The reconstruction of the EAS parameters for the Tunka-133 array is described in [2]. The same algorithms and the fitting functions are used for the TAIGA-HiSCORE data process-

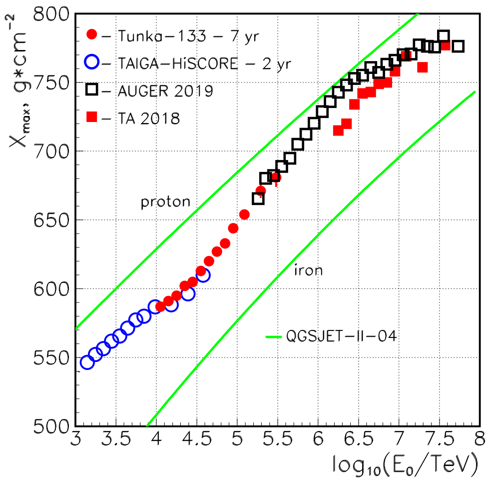

Figure 1: Mean experimental X_{max}

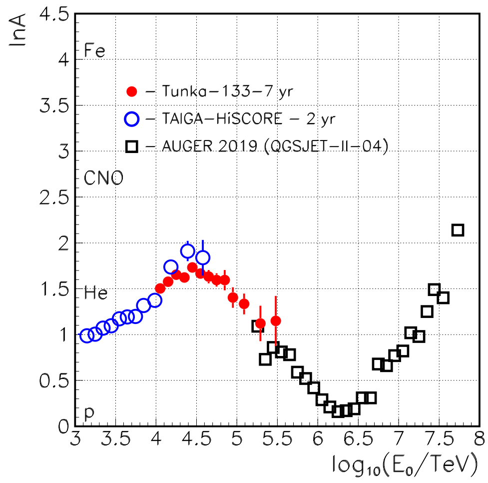

Figure 2: Mean $\langle \ln A \rangle$

ing [3]. We use the ratio $P = Q(80)/Q(200)$ as a quantitative parameter of LDF steepness. Here, $Q(R)$ is the Cherenkov light flux at distance R in meters. One has to control that there are the measurements of light flux at the core distance more or equal to 200 m and less or equal to 80 m. The first of these conditions is carried out for about all the events for the primary energy more or equal 10^{16} eV for Tunka-133 and more or equal 10^{15} eV for the TAIGA-HiSCORE. CORSIKA simulation [5] confirmed that the Cherenkov light LDF steepness is uniquely determined solely by the thickness of the atmosphere between the array and the depth of the EAS maximum ($\Delta X_{max} = X_0/sec\theta - X_{max}$), regardless of the energy, shower zenith angle, and type of primary nucleus. Here, X_0 is the total depth of the atmosphere. The calculated connection between P and ΔX_{max} inside the limitted range of parameter P from 2.5 to 9 can be fitted by th following expression ([5]):

$$\Delta X_{max} = \begin{cases} 929 - 103 \cdot P, & \text{if} \quad P \leq 3.9 \\ 882 - 91 \cdot P, & \text{if} \quad P > 3.9 \end{cases} \tag{1}$$

The standard deviation of simulated points from the fitting line for this range is approximately 15 g/cm^2 ([5]).

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4 Mean experimental depth of the EAS maximum

The above described parameter of the LDF steepness P was applied to analyze the data of both the Tunka-133 and TAIGA-HiSCORE arrays. The depth of the maximum is found by the formula:

$$X_{max} = 965/sec\theta - \Delta X_{max} \tag{2}$$

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where 965 g/cm^2 is the total depth of the atmosphere at the location of the arrays in the Tunka Valley. To obtain undistorted estimations of the depth of the maximum, showers are selected for the zenith angle $\theta \leq 30°$ and the energy above 10^{16} eV for the Tunka-133 array and above 10^{15} eV for TAIGA-HiSCORE. We have 69000 events for 7 years of operation of the Tunka-133 and 380000 events for 2 years of operation of TAIGA-HiSCORE. The experimental results are shown in Fig. ??. The data of both arrays, despite the difference in their

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geometry, agree well with each other, providing a wide energy range from 10^{15} to $3 \cdot 10^{17}$ eV. Our experimental data are compared with the direct measurements of the depth of the maximum obtained by observing the fluorescent EAS light at the PAO [10] and Telescope Array (TA) [11]. A close agreement of our data with the PAO data is observed at an energy of $\sim 3 \cdot 10^{17}$ eV. All the experimental results are compared with theoretical curves calculated using the QGSJET-II-04 model [12] for primary protons and iron nuclei.

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Fig. **??** shows the results of recalculation from the mean depth of the maximum to the parameter $\langle \ln A \rangle$ the average logarithm of the atomic number using the QGSJET-II-04 model. Qualitatively, the behavior of the mean mass composition repeats what was published in our previous studies [13] becomng heavier in the energy range of $3 \cdot 10^{15}$ - $3 \cdot 10^{16}$ eV and lighter with a further increase in energy. However, the mean composition in the entire energy range under consideration is estimated as mostly light.

5 Cherenkov light flux at a core distance 100 m as a new estimator of energy

The TAIGA-HiSCORE array structure is a sqare net of stations with a step of about 100 m. So the minimal core distance for which light flux can be reconstructed for almost all the events is about 100 m. Our previous parameter for the energy reconstruction was light flux at a core distance 200 m Q_{200} [3]. It was almost independent on the EAS zenith angle θ. It was found by the new CORSIKA simulaion that light flux Q_{100} depends on both energy E_0 and zenith angle θ. So first one needs to recalculate from the measured light flux to the $\theta = 0\circ$ using the new CORSIKA results:

$$\log_{10}(Q_{100}(0)) = \log_{10}(Q_{100}(\theta)) + (\sec\theta - 1) \cdot (1.25 - 0.083 \cdot \log_{10}(Q_{100}(\theta)) \tag{3}$$

Then $Q_{100}(0)$ can be recalculated to the primary energy E_0 using the result of the new CORSIKA simulation:

$$\log_{10}(E_0/GeV) = 0.88 \cdot \log_{10}(Q_{100}(0)) + 5.14 \tag{4}$$

6 Experimental energy spectrum by the data of TAIGA-HiSCORE

The experimental energy estimation differs from that described at the previos section because the real atmosphere light absorbtion is different from night to night in contradiction with standard absorption assumed at CORSICA simulation. So first we obtain the integral energy spectrum for the single night using the expression (4). Then we normalize this spectrum to the reference energy spectrum measured by the QUEST experiment [6]. The mean difference of normalization constant from that in the expression (4) is 0.03. The differential energy spectrum obtained from the data of TAIGA-HiSCORE array is shown in Fig. 3. Efficienscy of the events at the first left point (starting from the energy $2 \cdot 10^{14}$ eV) is more than 95%. Points for the lower energy obtaind from the events with lower efficiency are removed. The low energy points of our spectrum are in good agreement with direct balloon [7], satellite [8] and mountain [9] measurements.

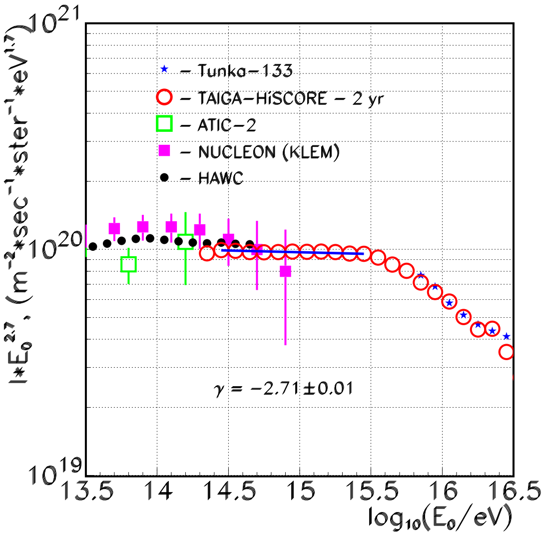

Figure 3: Differendial prmary CR cpectrum by TAIGA-HiSCORE data

7 Conclusions

1. The new estimations of X_{max}, derived from the steepness parameter $P = Q(80)/Q(200)$ provide the good agreement both between the results of our arrays Tunka-133 and TAIGA-HiSCORE and the results of Tunka-133 and the results of the direct measurements of X_{max} at the Pierre Auger Observatory (PAO).

2. The primary composition, derived from X_{max} is lighter than it seemed in our previous publications. It is mostly light (p+He) in all enery range.

3. The observed increase of $\langle \ln A \rangle$ in the energy range 10^{16} - 10^{17} eV demends the new theoretical explanation.

4. Change of the parameter for the energy reconstruction for the TAIGA-HiSCORE from Q_{200} to Q_{100} provides the decreasing of the energy threshold for the spectrum to about 200 TeV.

5. All particle energy spectrum at the energy range 200 TeV - 3 PeV has no essential distorsion from the pure power law with index 2.71 ± 0.01.

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