Tunka-133: Primary Cosmic Ray Mass Composition in the Energy Range $6 \cdot 10^{15}$ - 10^{18} eV

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Abstract: The analysis of spatial and time structure of EAS Cherenkov light allows to estimate the depth of the EAS maximum X_{max}. The distribution of X_{max} reflects the primary mass composition. Data of the new array Tunka-133 are used to derive X_{max} by two different methods: from the Cherenkov light LDF steepness and form the FWHM of pulses. We present the results of applying of these methods to data obtained during two winter seasons from 2009 till 2011. The mean depth of EAS maximum X_{max} vs. primary energy in the range of $6 \cdot 10^{15} - 3 \cdot 10^{17}$ eV is presented. The mean logarithmic mass corresponding to the measured mean X_{max} is estimated.

Keywords: EAS Cherenkov light array, primary cosmic rays, energy spectrum

1 INTRODUCTION

The study of primary mass composition in the energy range $10^{15} - 10^{18}$ eV is of crucial importance for the understanding of the origin of cosmic rays and of their propagation in the Galaxy. The change from light to heavier composition with growing energy marks the energy limit of cosmic ray acceleration in galactic sources (SN remnants), and of the galactic containment. An opposite change from heavy to light composition towards higher energy would testify the transition from galactic to extragalactic sources. Both changes are expected in the energy range of interest in the present investigation.

To study the mean composition we use the relation between the logarithm of mass $\ln A$ and the depth X_{max} of the extensive air shower (EAS) maximum:

$$< X_{max} >= X_0 - Const \cdot (\ln E_0 - < \ln A >) \quad (1)$$

Experimental X_{max} is derived for every event from the steepness of the atmospheric Cherenkov light lateral distribution function (LDF) and from the pulse width at a some fixed shower core distance.

2 Experiment: statistics and data processing

The data taking by the full Tunka-133 array started in October 2009 and continued during two winter seasons 2009-2010 and 2010-2011. As a result the data were collected for 597 hrs of clean moonless nights. The average trigger rate was about 2 Hz. The number of recorded events was about $4 \cdot 10^6$. Such an amount of recorded data provided the possibility of calibration of the apparatus using the data itself. The methods of calibration were described in [1].

A detailed description of the total processing procedure was presented in [2].

3 Reconstruction of X_{max}

Recording of the pulse waveform by each detector provides two methods of X_{max} reconstruction. The first one is based on the analysis of the shape of LDF and is called below as P-method. The second one called below as W-method is based on the analysis of the EAS Cherenkov light pulse width.

The LDF shape is described by an expression with a single parameter, the steepness P [3]. The parameter P is strictly connected with the distance from the array to the EAS maximum [4]:

$$H_{max} = A - B \cdot P \tag{2}$$

MC simulations shows, that this relation does not depend from energy, zenith angle of the showers, mass composition and the model of nuclear interaction used for the simulation. To get a uniform estimation for P over a wide range of energies we remove from the analysis the detectors at core distances more than 200 m during the last step of parameters reconstruction.

The W-method is the usage of the pulse width at some fixed core distance as a parameter sensitive of the position of the EAS maximum. We fixed this distance to 400 m and recalculated the pulse widths measured at the detectors from 200 to 400 meters away from the core to this distance. We use the effective pulse width τ which can be measured with better accuracy than the FWHM:

$$\tau = S/(1.24 \cdot A_{max}), \tag{3}$$

where S is the area of the pulse, A_{max} is the maximum amplitude of the pulse. The coefficient at A_{max} makes the absolute value of τ closer to that of the FWHM.

To recalculate the pulse width to 400 m, the width-distance function (WDF) is used. This function was constructed on the basis of CORSIKA simulation and descibed in [5]. It was shown at [5], that the value of $\tau(400)$ is connected with the thickness of the atmosphere between the detector and X_{max} ($\Delta X_{max} = X_0/cos\theta - X_{max}$) by the expression:

$$\Delta X_{max} = C - D \cdot lg\tau_{400}. \tag{4}$$

This ralation is correct for any primary nuclus, any energy and zenith angle of the shower and any interaction model as in the case of LDF steepness mentioned above.

4 Phenomenological approach

The parameters derived from CORSIKA simulations may slightly differ from the experimentally measured parameters. For instance, the linear relation between P and H_{max} observed for MC calculation may hold also for experiment, but with a slightly different slope. For our recalculation procedure we used the slope derived from experimental data, not from MC, i.e choosing a "phenomenological approach".

In our case we can use the zenith angle dependence of the parameter P. This experimental dependence for the fixed energy $E_0 = 10^{16}$ eV is shown in Fig.1. This mean dependence was constructed using all the 14400 events from the energy bin $16.0 < log_{10}(E_0/eV) < 16.1$. The mean zenith angle can be recalculated to the mean distance to the EAS maximum. To make this recalculation we use the model of the atmosphere from [6] for the real experimental conditions $< t > = -30°$C and X_0 = 965 $g \cdot cm^{-2}$. This model gives the following expression for the inclined distance to the EAS maximum in units of km:

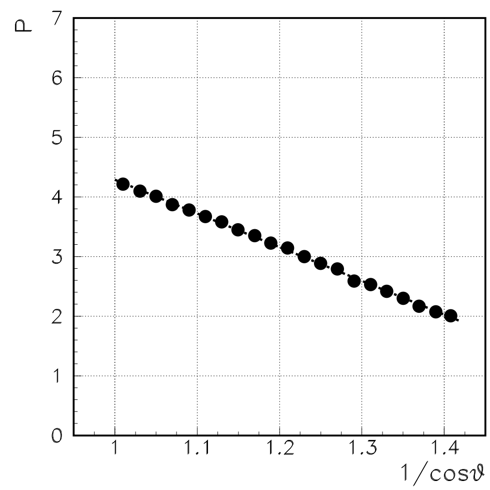

Figure 1: P vs.θ dependence from experiment.

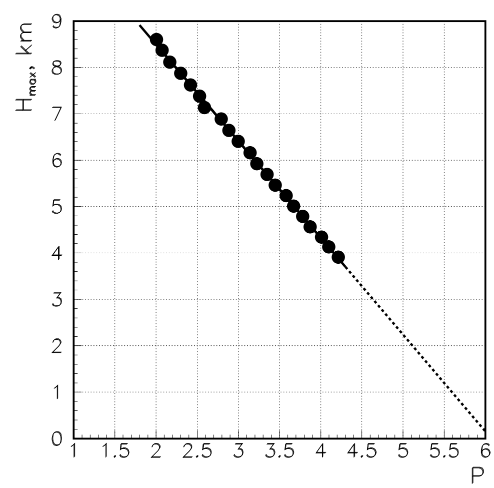

Figure 2: H_{max} vs.P dependence from experiment.

$$H_{max} = \frac{96}{cos\theta} \cdot \Big(1 - \Big(\frac{X_{max} \cdot cos\theta}{X_0}\Big)^{0.0739}\Big) \tag{5}$$

To fix the absolute value of $< H_{max} >$ we need to fix the mean value $< X_{max} >$ for the above mentioned energy. The most reliable experimental estimation of the mean depth of maximum by the data of our previous Tunka-25

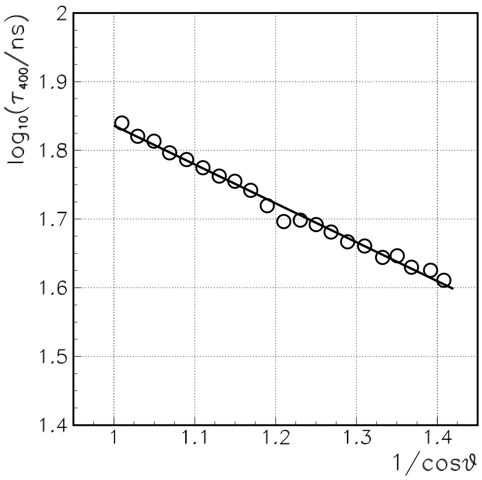

Figure 3: τ_{400} vs.θ dependence from experiment.

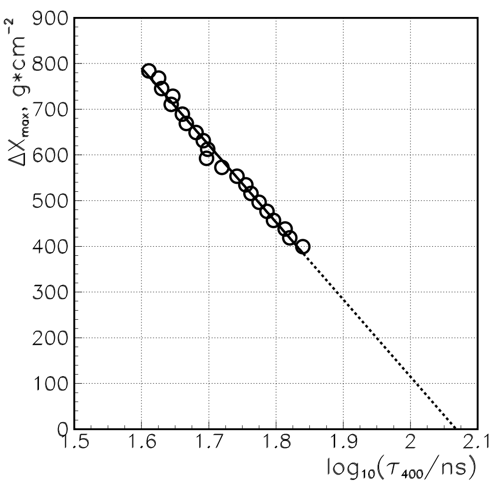

Figure 4: ΔX_{max} vs.$\tau(400)$ dependence from experiment.

experiment is $< X_{max} >$ = 560 $g \cdot cm^{-2}$ [4]. Recalculated to the mean $< lnA >$ this value is in good agreement with the results of some other experiments [7]. The so derived experimental recalculated dependence H_{max} vs. P is shown in Fig.2. It can be fitted with a linear expression:

$$H_{max} = 12.67 - 2.09 \cdot P \qquad (6)$$

This expression was used for the estimation of X_{max} for each individual event.

A similar approach for the $\tau(400)$ can be used in W-method but for higher energy because of the greater energy threshold of this method. The zenith angular dependence of τ_{400} for the logaritmic energy bin $16.5 < log_{10}(E_0/eV) < 16.6$ eV is shown in Fig.3. In W-method $cos\theta$ is recalculated to the ΔX_{max} using X_{max} obtained from the P-method for the abobe mentioned energy bin. This approach results in an expression connecting τ_{400} with the thickness of matter between the array and the EAS maximum in $g \cdot cm^{-2}$:

$$\Delta X_{max} = 3493 - 1689 \cdot \tau(400) \qquad (7)$$

The result of the analysis is shown in Fig.4. It is used for X_{max} estimation at the W-method.

5 Experiment: $< X_{max} >$ vs. E_0

The experimental dependence of mean $< X_{max} >$ vs. primary energy E_0 obtained with two methods described above in the energy range $5 \cdot 10^{15} - 3 \cdot 10^{17}$ is presented in Fig.5. The new measurements are compared with that obtained with our previous array Tunka-25 and with the theoretical curves simulated with QGSJET-01 model for primary protons and iron nuclea. The first what we can conclude is that the threshold of the W-method is higher that that of the LDF steepness method but the experimental points obtained by two methods coinside in the frame of the statistical error bars.

Much higher statistics of Tunka-133 points has led to the much smooth behavior of the experimental dependence as compared with the Tunka-25 data. The experimental points go closer to the iron curve with energy grow from the knee to about 10^{17} eV. There is a tendency of backwards movement of the experimental points to the proton curve at the energy more than 10^{17} eV, but the statistical errors are too big to insist on such conclusion.

The mean values of $< X_{max} >$ can be recalculated to the mean values of $< \ln A >$ by a simple method of interpolation taking into account the corrections to the asymmetry of the X_{max} distribution, estimated at our previous work [8]. The result of such approach for the points derived from LDF steepness analysis (P-method) are shown in Fig.6.

We have to note that this procedure can give different absolute values of $< lnA >$ for different supposed models of nuclear interaction. The model QGSJET-01 we use for the analysis provides the highest position of the EAS maximum as compared with the other models used now for simulations. The most deep position of EAS maximum can be obtained using the QGSJET-II-03 model. The mean difference in X_{max} between these models is about 20 $g \cdot cm^{-2}$. Using of this last model can increase the estimation of $< lnA >$ to about 0.8 for the same experimental value of $< X_{max} >$.

The experimental points are compared in Fig.6 with that, obtained from the analysis of the muon/electron ratio at KASCADE [7] experiment.

6 Conclusons and perspectives

1. Primary mass composition changes from light at the knee region to heavy one at the energy about 10^{17} eV.

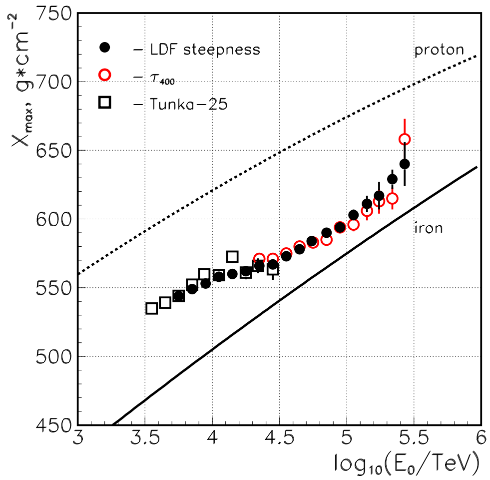

Figure 5: Experimental $< X_{max} >$ vs.E_0 dependence.

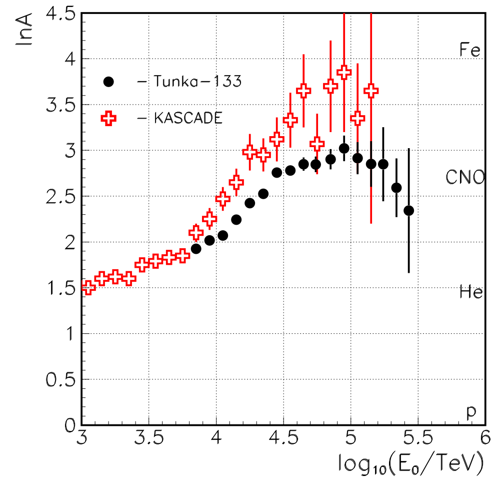

Figure 6: Experimental $< lnA >$ vs.E_0 dependence.

2. There is a hint of change from heavy to light composition with energy beyond 10^{17} eV.

3. More statistics is needed at the energy range $10^{17} - 10^{18}$ eV.

To obtain the more precise results on the mean logarithmic mass and to attempt to estimate the persentage of different mass groups in the total composition we plan to analyze the X_{max} distributions in each narrow logarithmic energy bin as it was done in our previous work devoted to the Tunka-25 results [8].

To solve the problem of the composition change at the energy range $3 \cdot 10^{17} - 10^{18}$ eV we plan to add 6 external clusters at the distance of about 1 km around the center of Tunka-133 array and thus make the effective area for such energies 4 times more. Of course, the Cherenkov light steepness will be estimated in the different core distance range 200 - 1000 m than it was before.

7 Acknowledgments

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