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 $X_{\text{max}}$. The distribution of $X_{\text{max}}$ reflects the primary mass composition. Data of the new array Tunka-133 are used to derive $X_{\text{max}}$ 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 $X_{\text{max}}$ 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 $X_{\text{max}}$ 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 $X_{\text{max}}$ of the extensive air shower (EAS) maximum:

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

Experimental $X_{\text{max}}$ 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 397 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 $X_{\text{max}}$

Recording of the pulse waveform by each detector provides two methods of $X_{\text{max}}$ 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]:

$$\Delta X_{\text{max}} = C - D \cdot \log_{10}(\Delta H_{\text{max}}).$$  \hspace{1cm} (4)

This relation is correct for any primary nucleus, 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 $H_{\text{max}}$ 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 $t = -30^\circ$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:

$$\Delta X_{\text{max}} = C - D \cdot \log_{10}(\Delta H_{\text{max}}).$$  \hspace{1cm} (5)

To fix the absolute value of $< H_{\text{max}} >$ we need to fix the mean value $< X_{\text{max}} >$ for the above mentioned energy. The most reliable experimental estimation of the mean depth of maximum by the data of our previous Tunka-25...
5 Experiment: $<X_{\text{max}}>$ vs. $E_0$

The experimental dependence of mean $<X_{\text{max}}>$ 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 nuclei. 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 $<X_{\text{max}}>$ 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 $X_{\text{max}}$ 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 $<\ln A>$ 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 $X_{\text{max}}$ between these models is about $20 g \cdot cm^{-2}$. Using of this last model can increase the estimation of $<\ln A>$ to about 0.8 for the same experimental value of $<X_{\text{max}}>$.

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

6 Conclusions and perspectives

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

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