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. We discuss the change of the X_{max} distribution parameters with energy in the range of $10^{16} - 10^{18}$ eV.

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: $< X_{max} >=< X_p > -\delta X_{max}/\delta lnE \cdot < \ln A >$ – which is well-known from electromagnetic cascade theory. X_{max} is derived for every event from the steepness of the atmospheric Cherenkov light lateral distribution function (LDF). We extend here the simplest method of performing such analysis (i.e. of relating the average $< X_{max} >$ and $< \ln A >$ values) to the more correct one based on the analysis of the whole X_{max} distribution.

2 Experiment: statistics and data processing

The data acquisition by the completed 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 EAS parameters

The EAS core is reconstructed with better accuracy the higher the value of the fitting function derivative is. A de-

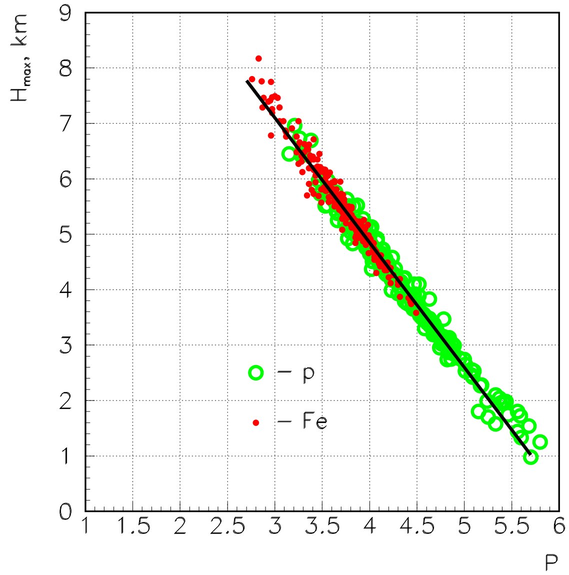

Figure 1: MC simulation: H_{max} vs.P dependence.

tailed study of the LDF obtained from CORSIKA simulations [3] has shown that the derivative $d\lg Q/dR$ fluctuates very much from event to event in the distance range from 0 to 100 m, but has an almost stable negative value in the range 100 - 200 m. The LDF shape is described by an expression with a single parameter, the steepness P [3]. 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 parameter reconstruction.

P is strictly connected with the distance from the array to the EAS maximum [4]:

$$H_{max} = A - B \cdot P \quad (1)$$

MC simulations shows, that this relation does not depend from energy and mass composition (Fig.1).

The second parameter sensitive to the position of the EAS maximum is the pulse width at some fixed distance to the shower core. We fixed this distance to 400 m and recalculate values measured at detectors 200 to 400 meters away from the core to this value. To recalculate the FWHM, the width-distance function (WDF) is used. This function was constructed on the basis of CORSIKA simulation and descibed in [5]. Also it was shown ([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:

$$\Delta X_{max} = C - D \cdot lg\tau_{400}. \quad (2)$$

Recording the pulse waveform for each detector provides a more reliable measurement of the EAS maximum depth X_{max}, using two different methods of LDF steepness and pulse width at 400 m $\tau(400)$ measurement simultaneously.

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 (Fig.1) 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 $E_0 = 3 \cdot 10^{16}$ eV is shown in Fig.2. This mean dependence was constructed using all the 2250 events from the energy bin $16.4 < log_{10}(E_0/eV) < 16.5$. 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:

$$H_{max} = \frac{96}{cos\theta} \cdot (1 - \left(\frac{X_{max} \cdot cos\theta}{X_0}\right)^{0.0739} \quad (3)$$

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 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.3. It can be fitted with a linear expression:

$$H_{max} = 12.79 - 2.085 \cdot P \quad (4)$$

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

A similar approach for the second parameter sensitive to the position of EAS maximum τ(400) results in an expression connecting it with the thickness of matter between the array and the EAS maximum in $g \cdot cm^{-2}$:

$$\Delta X_{max} = 3522 - 1699 \cdot \tau(400) \quad (5)$$

We note once more that both expressions give a measurement of X_{max} normalized at the same point ($E_0 = 3 \cdot 10^{16}$ eV, $X_{max} = 560 g \cdot cm^{-2}$).

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 $5 \cdot 10^{15} - 3 \cdot 10^{16}$ will be shown at the Conference.

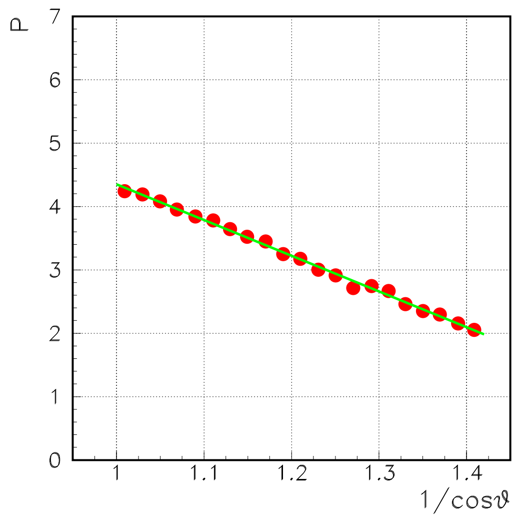

Figure 2: P vs.θ dependence from experiment

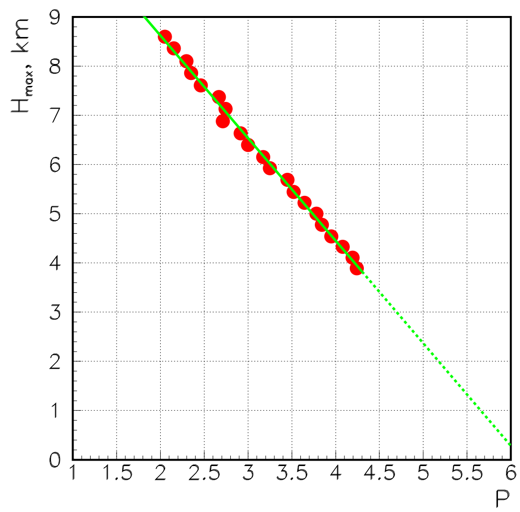

Figure 3: H_{max} vs.P dependence from experiment

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 will be shown at the Conference too.

6 Acknowledgments

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