Tunka-133: Primary Cosmic Ray Energy Spectrum in the energy range $6\cdot 10^{15}$ – 10^{18} eV

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Abstract: A new EAS Cherenkov array Tunka-133 with 1 km^2 area started data taking in November 2009. The method of energy reconstruction and absolute calibration of measurements are discussed. The preliminary result on the all particle energy spectrum based on data of two winter seasons from 2009 to 2011 is presented. The spectrum is compared with that obtained by the Tunka-25 array as well as with the results of some other experiments.

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

1 Introduction

One of the most informative methods of cosmic ray studies is the registration of Cherenkov light from extensive air showers (EAS). The uncertainty of primary energy reconstruction is strongly reduced if the Earth atmosphere is used as a huge calorimeter. This is possible by recording the optical radiation from EAS during clear moonless nights. The atmosphere, in the absence of clouds and aerosols, is remarkably transparent for visible light.

To study the primary cosmic ray energy spectrum and mass composition in the above mentioned intermediate energy range, the new array Tunka-133 ([1], [2]), with nearly 1 km^2 geometric area, has been deployed in the Tunka Valley, Siberia. Array consists of 133 wide-angle

Cherenkov light detectors, based upon a 20 cm diamenter PMT. All detectors are grouped into 19 clusters with 7 detectores in each one. Each cluster operates as an independent subarray with its own local trigger.

2 Data processing and energy reconstruction

The primary data record of the EAS Cherenkov signal registered by each optical detector of the array contains 1024 amplitude values in step of 5 ns.

Three main parameters of a pulse are derived from this data: front delay at a level 0.25 of the maximum amplitude (t_i), pulse area (Q_i) and full width at half-maximum FWHM$_i$

The relative amplitude calibration is carried out by a comparison of integral spectra of pulse charges Q_i for each detector. The procedure is the same as described in [4]. A detailed description of the total processing procedure was presented in [5].

The EAS arrival direction is derived from the front arrival time for the detectors participating at the event. A conic shape of the EAS front is assumed for the EAS arrival direction reconstruction. The accuracy of the measured arrival direction is better than 0.5° for the energies above 10^{16} eV. All the measured values of Q_i are corrected for the zenith angular acceptance of the array as it is described in [6].

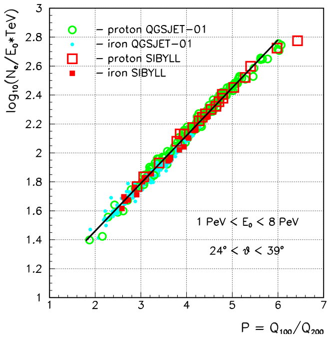

Figure 1: N_e/E_0 vs P

Events with fixed measured energy show a uniform zenith-angular distribution till the zenith angle $\theta = 50°$ [6].

The core position is reconstructed by fitting the measured Q_i by the lateral distribution function (LDF) described in detail in [7]. The LDF shape is described by an expression with a single parameter, a steepness P. The accuracy of recontruction of the core position is better than 10 m.

As a measure of energy we used the density of Cherenkov light flux at a core distance of 175 m - $Q(175)$. Connection between EAS energy E_0 and Q_{175} may be expressed by the following formula:

$$E_0 = C \cdot Q_{175}^g \tag{1}$$

In was found from CORSIKA simulation that for the energy range of $10^{16} - 10^{17}$ eV and zenith angle range $0° - 45°$ the value of index g is equal to 0.95 for pure proton composition and 0.91 for pure iron compositon. For energy reconstruction the value of g equal to 0.93 was chosen.

To reconstruct the EAS energy from Cherenkov light flux one needs to know an absolute sensitivity of Cherenkov detectors and an atmosphere transparency. To avoid these problems a special method has been developed, first realized at QUEST experiment [3]. At that experiment 5 wide-angle Cherenkov light detectors were installed at Gran-Sasso for common operation with EAS-TOP array. The analysis of CORSIKA simulations shows a strict correlation between the size/energy (N_e/E_0) ratio and the steepness (P) of the EAS Cherenkov light lateral distribution.

The relation between N_e/E_0 and P (Fig.1) is independent both from the mass of primary particle and a hadronic interaction model used for the simulation, and provides the primary energy from the measurement of N_e and P. To recontruct the LDF steepness P the knowlege of PMT absolute sensitivity and the atmosphere transparency is not needed. The integral energy spectrum of cosmic rays obtained in QUEST experiment is use as the reference one now. The integral energy spectra obtained for each night of Tunka-133 operation is compared with that reference one.

This method was used first for the absolute calibration of the Tunka-25 array. But as the threshold of Tunka-133 is somewhat higher than that of Tunka-25, we use for the normalisation a higher point of the reference spectrum: $E = 6 \cdot 10^{15}$ eV.

3 All particle spectrum for inside events

The data taking by full Tunka-133 array started in October 2009 and has been continued during two winter seasons of 2009-2010 and 2010-2011. As a result the data were collected for 597 hrs of 102 clean moonless nights. Only the nights with more than 2 hr of clean weather were taken into account. The average trigger rate was about 2 Hz. The number of recorded events was about $4 \cdot 10^6$.

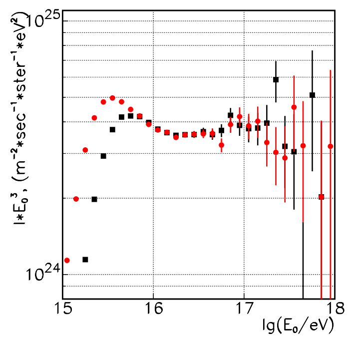

Figure 2: Energy spectrum for two zenith angle intervals. Red points - $0° < \theta < 30°$, black points - $30° < \theta < 45°$

For construction of the energy spectrum the events with core position inside a circle of radius $R < 450$ m from the center of the array were selected. The EAS zenith angle for the events collected into the spectrum is limited by $45°$. The threshold energy of 100% registration efficiency for chosen area and zenith angles is $6 \cdot 10^{15}$ eV. The energy spectra obtained for two different zenith angular ranges ($0° - 30°$ and $30° - 45°$) are in good agreement for energy more than $6 \cdot 10^{15}$ (Fig.2). It was found that the energy spectrum obtained at the fist season of the array operation (2009-2010) is in good agreement with the energy spectrum from the second season (2010-2011) (Fig.3) up to the energy $6 \cdot 10^{16}$ eV. The difference in intensity at higher energies seems to be only due to statistical fluctuation.

The indication of a "bump", found in the first season at the energy $8 \cdot 10^{16}$ eV ([2]), is not seen at the second season spectrum and practicaly disappears in the summary spectrum (Fig.4).

The summary energy spectrum for two seasons of the array operation is presented in Fig.4. It contains ~40000 events with energy $E_0 > 10^{16}$ eV and and ~400 events with $E_0 > 10^{17}$ eV. The energy spectrum of Tunka-133 is compared with that of Tunka-25 [3], the predecessor of Tunka-133, in this figure. The energy spectrum beyond

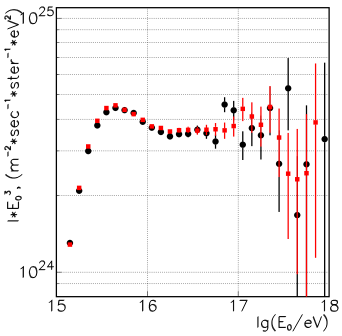

Figure 3: Different energy spectra for two seasons of the array operation. Black points - 2009-2010, red points - 2010-2011

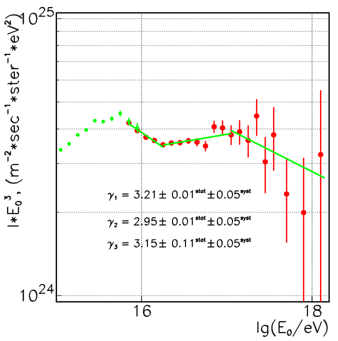

Figure 4: Summary energy spectrum for two seasons of Tunka-133 operation (red points) and Tunka-25 energy spectrum (green points).

the knee looks rather complicated. One can see that the spectrum can be fitted by power laws with 3 different power law indexes:
$3.21 \pm (0.01)^{stat} \pm (0.05)^{syst}$ for $6 \cdot 10^{15} - 2 \cdot 10^{16}$ eV,
$2.95 \pm (0.01)^{stat} \pm (0.05)^{syst}$ for $2 \cdot 10^{16} - 10^{17}$ eV,
$3.15 \pm (0.11)^{stat} \pm (0.05)^{syst}$ for $10^{17} - 10^{18}$ eV.

4 All particle spectrum for outside events

To improve the accuracy of energy reconstruction for the events with the cores located outside the array geomentry we plan to install six new clusters at 1 km radius around the center of Tunka-133 [1]. These additional 42 optical detectors will increase the effective area for $E_0 > 10^{17}$ eV by a factor of 4. The first distant cluster was deployed in autumn 2010, the next five will be deployed during summer-autumn 2011.

It was found out that even without using distant clusters energy spectrum including the outside events can be reconstructed and this spectrum is in good agreement with energy spectrum for inside events beyond some energy threshold. Fig.5 presents comparison of spectrum for the inside events ($R < 450$ m) with spectra for events with core inside circles $R < 550$ m, $R < 650$ m and $R < 800$ m.

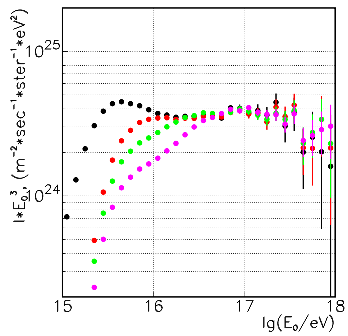

Figure 5: Comparision of energy spectrum for inside events (black points) and spectra for outside events $R < 550$ m (red points), $R < 650$ m (green points) and $R < 800$ m (violet points).

It is seen that threshold energy of 100% registration efficiency increases with increasing of the radius R but for $E_0 > 6 \cdot 10^{16}$ eV all spectra are in good agreement. Based on such the result we construct the combined energy spectrum (Fig.6) from the events with $R < 450$ m for $E_0 > 6 \cdot 10^{16}$ eV and events with $R < 800$ m for the higher energy. This combined spectrum containes about 1200 events with $E_0 > 10^{17}$ eV.

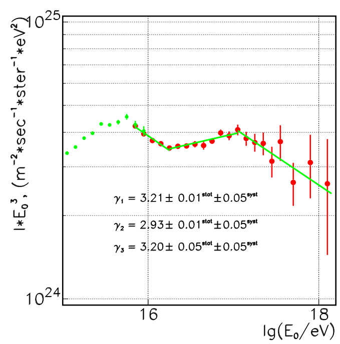

Figure 6: Combined energy spectrum. Green point - Tunka-25 data.

The shape of the combined spectrum is nearly the same as for inside events spectrum and can be fitted by the power laws with 3 different indexes:
$3.21 \pm (0.01)^{stat} \pm (0.05)^{syst}$ for $6 \cdot 10^{15} - 2 \cdot 10^{16}$ eV,
$2.93 \pm (0.01)^{stat} \pm (0.05)^{syst}$ for $2 \cdot 10^{16} - 10^{17}$ eV,
$3.20 \pm (0.06)^{stat} \pm (0.05)^{syst}$ for $10^{17} - 10^{18}$ eV.

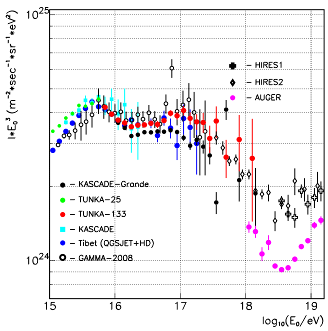

Figure 7: Tunka-133 all paprticles energy spectrum in comparision with results of others experiments

5 Comparison with results of others experiments

Comparison of Tunka-133 spectrum with the results of other experiments is presented in Fig.7. Our spectrum is in good agreemnt with spectra of KASCADE([9]), Tibet ([10]) and GAMMA ([11]) arrays. The energy range covered by our spectrum ($10^{16} - 10^{18}$ eV) is nearly the same as covered by KASCADE-Grande array ([12]) data. The both spectra repoduce the same structures: decreasing of power law index at $2 \cdot 10^{16}$ eV and increasing of it at 10^{17} eV. The difference in absolute cosmic rays flux intensity for Tunka-133 and KASCADE-Grande spectra is smaller than 30% even at 10^{17} eV where the difference reaches the maximum value. It should be mentioned that if we use the value of g (see expession 1) equal to 0.91 the difference in the intensity becomes smaller than 10%.

6 Outlook

The next steps towards study of the energy spectrum are following:
1. Continue data taking for 4-5 seasons.
2. Deployment of the rest 5 distant clusters in the autumn 2011.
3. Deployment of the scintillation array for absolute energy calibration of the measurements at the energy $3 \cdot 10^{16} - 10^{17}$ eV (the new QUEST-like experiment) in 2012-2013.

7 Conclusions

1. The primary energy spectrum in the range $10^{16} - 10^{18}$ eV cannot be fitted by a single power law index. It can be fitted by three ones:
$\gamma_1 = 3.21 \pm 0.01_{stat} \pm 0.05_{sys}$ for $6 \cdot 10^{15} - 2 \cdot 10^{16}$ eV
$\gamma_2 = 2.93 \pm 0.01_{stat} \pm 0.05_{sys}$ for $2 \cdot 10^{16} - 10^{17}$ eV
$\gamma_3 = 3.20 \pm 0.06_{stat} \pm 0.05_{sys}$ for $10^{17} - 10^{18}$ eV
2. Our energy spectrum is in good agreement with results of KASCADE-Grande, Tibet and GAMMA arrays.
3. A "Bump" at $8 \cdot 10^{16}$ eV is not seen in the new 2-seasons spectrum (2009-2011).
4. Upgrade of the array is needed to improve accuracy of energy recontruction for outside events and to make absolute energy calibration at $\sim 3 \cdot 10^{16}$ eV.

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