The energy spectrum of cosmic rays above $10^{15}$ eV as derived from air Cherenkov light measurements in Yakutsk

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Abstract

The Yakutsk array observes the Cherenkov light emitted by UHECR in atmosphere. Recently, an autonomous subarray is added consisting of photomultipliers to measure the showers in the knee region. Our aim is to analyze the combined data set in order to derive the cosmic ray spectrum in the energy range as wide as possible using the same technique.

The advantage of the air Cherenkov light measurement is the model independent estimation of the EAS primary energy using the total light flux emitted in the atmosphere. A set of the light lateral distributions observed in the extended energy range is presented also.

PACS numbers: 95.85.R, 96.40

Keywords: Cosmic rays; Yakutsk array; Cherenkov light; Energy spectrum

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I. INTRODUCTION

The Cherenkov light emitted in atmosphere by ultrarelativistic electrons of extensive air showers (EAS) of cosmic rays (CRs) carries the important information on the primary energy and shower development in atmosphere. At the Yakutsk array air Cherenkov light measurements are used to estimate the primary energy in the model independent manner, and the lateral distribution form of the light on the ground is used to infer the position of shower maximum in atmosphere, $X_{max}$. In this paper we have derived the energy spectrum of cosmic rays in the range $\sim 1$ to $6 \times 10^4$ PeV using the independent measurement technique via air Cherenkov light and compared it with our previous spectrum obtained with EAS charged particle measurements as well as the results of other giant arrays.

II. AIR CHERENKOV LIGHT MEASUREMENTS WITH THE YAKUTSK ARRAY

During more than 30 years of lifetime the Yakutsk array is detecting muonic, electronic and Cherenkov light components of EAS. The actual detector arrangement of the array is shown (Fig. 1). Open circles are charged particle detectors given as the background here. Filled circles show the Cherenkov light detectors - open photomultiplier tubes (PMTs) of 176 cm$^2$ and 530 cm$^2$ acceptance area, forming a medium subarray. Filled squares indicate PMTs of autonomous subarray with independent trigger. This subarray was added in 1995 with the aim to study air showers in the energy range $10^{15} - 10^{17}$ eV via the Cherenkov light measurements.

During $\sim 15000$ hours of observation in moonless nights there were detected $\sim 60000$ showers of energy above $6 \times 10^{16}$ eV by the medium array. They were selected using the double trigger condition: i) three or more scintillator stations have detected the charged particle density above the threshold 1 particle/m$^2$; ii) The Cherenkov light intensities in three or more PMTs are greater than $2.4 \times 10^5/4.5 \times 10^5$ photons/m$^2$ depending on the acceptance area of PMT.

The autonomous array data consist of $\sim 200000$ showers with $E > 1.2 \times 10^{15}$ eV detected during $\sim 3200$ hours of observation. The Cherenkov trigger condition only is used to select these showers.
FIG. 1: The detector arrangement of the Yakutsk array. A description of the points is given in the text.

For absolute calibration of PMTs the Cherenkov radiation of relativistic particles in distilled water was used \[1\]. The variations in cosmic ray intensity measured with Cherenkov detectors itself are used to monitor the atmospheric transparency \[2\].

III. LATERAL DISTRIBUTION OF THE CHERENKOV LIGHT

We have summarized our lateral distribution function (LDF) measurements of the Cherenkov light intensities in Fig. 2. The data of both subarrays (zenith angle $\theta < 30^0$) are parameterized by the light intensity at 150 m from the shower core, $Q_{150}$, the only core distance really present in the shifting range of measurements when the primary energy is rising from $\sim 10^{15}$ to $10^{19}$ eV. The data are consistent with the previous results of the Yakutsk array concerning the Cherenkov light and can be described by the suitable EAS model simulation \[1\]. There’s seen no abrupt change of LDF parameters, so we choose
TABLE I: The fraction of $Q_{\text{tot}}$ actually measured ($\Delta$).

| $Q_{150}$, m$^{-2}$ | $10^6$ | $10^7$ | $10^8$ | $10^9$ |
|---------------------|-------|-------|-------|-------|
| $\Delta$, %         | 50    | 70    | 90    | 85    |

rather smooth approximation curve to fit the experimental data in the whole energy range:

$$Q(R) = Q_{150} \frac{(R_1 + 150)(R_2 + R)^{1-b}}{(R_1 + R)(R_2 + 150)^{1-b}},$$  \hspace{1cm} (1)

where $R_1 = 60$ m; $R_2 = 200$ m; $b = (1.14 \pm 0.06) + (0.30 \pm 0.02) \times \log Q_{150}$

IV. ESTIMATION OF THE PRIMARY ENERGY OF AIR SHOWERS

The total flux, $Q_{\text{tot}}$, of the Cherenkov light emitted by the shower in atmosphere is used to estimate the primary energy. The detector design of the Yakutsk array is appropriate to measure $Q_{\text{tot}}$ in the range above about $Q_{150} = 10^7$ m$^{-2}$ (Table I).

In each $Q_{150}$ bin the LDF extrapolation formula is used to calculate the total flux. In order to connect $Q_{\text{tot}}$ with the ionization loss, $E_i$, of the shower in atmosphere one needs to know the atmospheric transparency factor for the Cherenkov light and model predictions of the shower development. We refer to where this factor was given on the basis of model calculations and transparency measurements in Yakutsk:

$$E_i = \frac{2.18 \times 10^4 Q_{\text{tot}}}{0.37 + 1.1 \times 10^{-3} X_{\text{max}}},$$  \hspace{1cm} (2)

This factor is nearly model-independent in a sense that the model dependence is parameterized by $X_{\text{max}}$.

The fraction of the primary energy deposited in atmosphere can be evaluated using the total number of electrons and muons measured with the Yakutsk array, the attenuation length of the shower and the mean energy of muons. The model calculation results are used to estimate the energy of EAS nuclear active component and neutrinos. The resulting apportioning of the primary energy $10^{18}$ eV is given in Table II.

We have used these values to derive the primary energy, $E$, of showers with measured
FIG. 2: Air Cherenkov light radial distributions. Our experimental data are given by the points. The curves are approximations along Equation 1 for given $Q_{150}$. 
TABLE II: Estimation of the primary energy portions gone with the shower components.

| Energy deposit channel                                      | The portion of energy, % |
|-------------------------------------------------------------|--------------------------|
| Ionization loss above sea level                             | 78                       |
| The total electromagnetic component energy                   | 87                       |
| Energy transferred to muons and neutrinos                   | 9                        |
| Energy carried by the nuclear active component              | 4                        |

\[ Q_{150} : \]

\[ E = (1.07 \pm 0.27) \times 10^{-5}Q_{150}^{0.99\pm0.02}, \text{PeV} \]  

(3)

V. THE ENERGY SPECTRUM OF COSMIC RAYS DERIVED FROM AIR CHERENKOV LIGHT MEASUREMENTS

In order to evaluate the intensity of the primary flux we have collected data during the observation periods with atmospheric transparency better than 0.65, shower axes within area of corresponding subarray, zenith angle \( \theta < 30^\circ \). Acceptance area of the array, \( S_{\text{eff}} \), depends on the primary energy and zenith angle. We have calculated \( S_{\text{eff}} \) as a function of \( Q_{150} \) averaged in zenith angle interval \( (0^\circ, 30^\circ) \) for each subarray (Fig. 3). Lateral distribution fit \( \text{I} \) is used along with instrumental and statistical errors to model the trigger of each subarray with 100000 fake showers. In the case of autonomous array the Cherenkov trigger is simulated while in the medium case the double trigger for scintillator and PMT signals is modeled. The shower data gathered after the array was re-configured were used to work out the spectrum. Namely, 1993-2001 for the medium, and 1995-2001 for autonomous subarray.

The resulting differential all-particle spectrum of cosmic rays is given (Fig. 4, Tables III, IV) together with the Yakutsk array spectrum carried out by the charged particle measurements with the trigger-500 m \( \text{I} \). Spectra are compatible above 2000 PeV within errors but are contradictory at lower energies. We have to re-analyze our data near the threshold energy of the scintillator trigger-500. Both methods confirm the spectrum irregularity near \( E \sim 10^4 \text{ PeV} \) (an ’ankle’), and the autonomous subarray data is compatible
FIG. 3: Acceptance area of the Cherenkov subarrays. The solid curve is for autonomous, and the dotted one represents the medium subarray.

with a 'knee' at \( E \sim 3 \) PeV. Our next spectrum obtained with trigger-1000 measurements of charged particles [5] is in the energy range beyond both shown spectra, out of reach of the Cherenkov subarrays, therefore is not given here.

The autonomous subarray spectrum in the range 1 to 100 PeV was given in comparison with other relevant results earlier [6]. Comparison with results of other giant arrays (Fig. 5) shows a satisfactory agreement of the flux with Akeno [3] and AGASA [4] data in the energy range covered by the Cherenkov detectors of the Yakutsk array. The data of HiRes-I and HiRes-II from the preprint [7] have the divergence with our spectrum which can be explained, presumably, by the difference in the primary energy estimation \( \sim 30\% \). Re-evaluated energy spectrum of the Haverah Park array [8] in the range \( 3 \times 10^2 \) PeV to \( 4 \times 10^3 \) PeV coincides with the HiRes-II spectrum and isn’t given here.
FIG. 4: The cosmic ray flux measured by the air Cherenkov light (squares for autonomous and circles for medium subarrays) and charged particle detectors (trigger-500, triangles) of the Yakutsk array. Each data point represents the differential flux scaled up by a factor of $E^3$. Error bars represent statistical errors only.

VI. CONCLUSIONS

The independent measurement technique using air Cherenkov light detectors of the Yakutsk array enabled us to obtain the cosmic ray energy spectrum in the range $\sim 1$ to $6 \times 10^4$ PeV. Although the PMTs arrangement of the array isn’t convenient to study air showers above $10^4$ PeV, there is an objective field of activity below that border, wide enough. Our preliminary ‘Cherenkov’ spectrum contradicts previous ‘scintillator’ spectrum around the threshold energy of the trigger-500. At the higher energies two spectra agree within errors. Both spectra exhibit an ‘ankle’ feature around $10^4$ PeV. The autonomous subarray data confirm the ‘knee’ at $E \sim 3$ PeV. A comparison of our results with the data of other giant EAS arrays shows the similarity of spectra within $\sim 30\%$ uncertainty in the primary
FIG. 5: Our energy spectrum in comparison with other experiments. The data are from HiRes-I (open triangles), HiRes-II (filled triangles), Akeno (filled squares), AGASA (open squares). Our results are from the autonomous subarray (filled circles) and medium subarray (open circles).

Acknowledgments

The authors are grateful to Russian ministry of Science and Technology for the support of the Yakutsk array under the program #01-30 'Unique research facilities in Russia'. Our special thanks to the Yakutsk group members who made the essential contributions to data acquisition and analysis. This work is supported by RFBR grants #00-15-96787, #02-02-
TABLE III: CR flux measured with the autonomous subarray. Errors represent the statistical uncertainties.

| Primary energy bin | Differential flux $J(E)$  |
|--------------------|---------------------------|
| $\log_{10}(E/1eV)$ | (m$^{-2}$sr$^{-1}$s$^{-1}$eV$^{-1}$) |
| 15.15 – 15.25      | $8.54 \times 10^{-22}$    |
| 15.25 – 15.35      | $4.63 \times 10^{-22}$    |
| 15.35 – 15.45      | $2.56 \times 10^{-22}$    |
| 15.4 – 15.5        | $1.80 \times 10^{-22}$    |
| 15.5 – 15.6        | $1.05 \times 10^{-22}$    |
| 15.6 – 15.7        | $4.83 \times 10^{-23}$    |
| 15.7 – 15.8        | $2.32 \times 10^{-23}$    |
| 15.8 – 15.9        | $1.68 \times 10^{-23}$    |
| 15.9 – 16.0        | $9.06 \times 10^{-24}$    |
| 16.0 – 16.1        | $2.83 \times 10^{-24}$    |
| 16.1 – 16.2        | $1.60 \times 10^{-24}$    |
| 16.2 – 16.3        | $7.27 \times 10^{-25}$    |
| 16.3 – 16.4        | $3.33 \times 10^{-25}$    |
| 16.4 – 16.5        | $1.73 \times 10^{-25}$    |
| 16.5 – 16.6        | $(8.77 \pm 0.42) \times 10^{-26}$ |
| 16.6 – 16.7        | $(4.95 \pm 0.23) \times 10^{-26}$ |
| 16.6 – 16.7        | $(4.95 \pm 0.23) \times 10^{-26}$ |
| 16.7 – 16.8        | $(2.71 \pm 0.14) \times 10^{-26}$ |
| 16.8 – 16.9        | $(1.20 \pm 0.07) \times 10^{-26}$ |
| 16.9 – 17.0        | $(7.10 \pm 0.43) \times 10^{-27}$ |
| 17.0 – 17.1        | $(3.80 \pm 0.25) \times 10^{-27}$ |
| 17.1 – 17.2        | $(8.11 \pm 0.66) \times 10^{-28}$ |
| 17.2 – 17.3        | $(7.43 \pm 0.66) \times 10^{-28}$ |
| 17.3 – 17.4        | $(4.25 \pm 0.63) \times 10^{-28}$ |
| 17.4 – 17.6        | $(1.10 \pm 0.23) \times 10^{-28}$ |
TABLE IV: Cosmic ray flux measured with the medium subarray detectors.

| Primary energy bin | Differential flux \( J(E) \) |
|--------------------|-----------------------------|
| \( \log_{10}(E/1\text{eV}) \) | \( \text{m}^{-2}\text{sr}^{-1}\text{s}^{-1}\text{eV}^{-1} \) |
| 17.1 – 17.3 | \( 9.24 \times 10^{-28} \) |
| 17.3 – 17.5 | \( 2.16 \times 10^{-28} \) |
| 17.5 – 17.7 | \( 5.91 \times 10^{-29} \) |
| 17.7 – 17.9 | \( 1.60 \times 10^{-29} \) |
| 17.9 – 18.1 | \( 4.20 \times 10^{-30} \) |
| 18.1 – 18.3 | \( 1.11 \times 10^{-30} \) |
| 18.3 – 18.5 | \( (2.62 \pm 0.13) \times 10^{-31} \) |
| 18.5 – 18.7 | \( (6.38 \pm 0.58) \times 10^{-32} \) |
| 18.7 – 18.9 | \( (9.47 \pm 2.55) \times 10^{-33} \) |
| 18.9 – 19.1 | \( (2.93 \pm 1.10) \times 10^{-33} \) |
| 19.1 – 19.3 | \( (3.00 \pm 1.62) \times 10^{-33} \) |
| 19.3 – 19.5 | \( (6.26 \pm 4.55) \times 10^{-34} \) |
| 19.5 – 19.7 | \( (3.48 \pm 2.90) \times 10^{-34} \) |
| 19.7 – 19.9 | \( (1.71 \pm 1.57) \times 10^{-34} \) |

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