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The Spectrum of Cosmic Rays in the Energy Range 10^{16} - 10^{18} eV According to the Small Cherenkov Array in Yakutsk

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The experimental data on the energy spectrum cosmic rays, obtained from Small Cherenkov Array in Yakutsk on the measurement of Cherenkov radiation in showers with energy 10^{15} - 10^{18} eV are discussed. The data were obtained by means of continuous array operation since 1994. Found that the spectrum of the all particle in this energy region has a complex shape and cannot be described by a simple exponential function with a single slope indicator g. After the first kink at energy $3 \cdot 10^{15}$ eV (knee), the spectrum becomes steeper at Dg = 0.4 to energy $< 2 \cdot 10^{16}$ eV, then part of the spectrum to $> 8 \cdot 10^{16}$ eV becomes flat, the slope of the spectrum is g = 2.92 ± 0.03 and then again changes slope to Dg = 0.32 ± 0.05, since about energy $\sim 2 \cdot 10^{17}$ eV. The second kink in the spectrum observed at the Yakutsk EAS array at $\sim 2 \cdot 10^{17}$ eV, or also called second knee is the significant result for space astrophysics of ultra-high cosmic rays. In this paper we discuss possible scenarios for spectrum formation of cosmic rays by the galactic sources to energies $< 10^{17}$ eV, mainly supernovae remnants SNR and Metagalactic origins in the energy range 10^{17} - 10^{18} eV. Most likely, that measurement of second knee is related with transitional region, galactic to extragalactic origin of cosmic rays.

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1. Introduction

The main objectives of cosmic rays (CR) research of ultra-high energies is to determine the anisotropy of the energy spectrum and chemical composition of the primary CR particles. These characteristics of CR have an important role in understanding the origin, acceleration and propagation of the primary particle of different energies. In the energy range 10^{12}-10^{14} eV such measurements are carried out with the use of satellites and the launch of balloons at heights $\sim$ 35 km. These experiments allows to directly measure the chemical composition of the particles, and their partial spectra. The only disadvantage of these experiments is the low luminosity of the arrays and the limited time of observations. At energies higher than 10^{14} eV, because of the low intensity, the only method to study characteristics of the CR is by measuring extensive air showers (EAS), i.e. indirectly, tracking of cascade processes in the atmosphere and the registration of charged particles, muons, ionization and emission of Cherenkov light of EAS at sea level. Because of the wide range of energies of the primary particles, the registration of EAS is conducted on small arrays, the area of which is s <1 km^2 up to 10^{18} eV energy, medium arrays with area s < 20 km^2 energies up to 10^{19} eV, and in very large arrays such as Auger and Telescope Array.

2. Experiments at Yakutsk

The main Yakutsk EAS array consists small arrays with equipment designed to perform both general and specific objectives, such as the measurement of muon by Large Muon Detector, the measurement of the profile of the cascade curve system by Cherenkov detectors, measurement of radio emission, monitoring of the atmosphere during the registration period of air shower etc. This equipment controlled by a system of computers connected in a local network [1].

In the year 1994, at the central part of Yakutsk array was created Small Cherenkov array for registration of EAS moderate energies [2]. One of the tasks that had to be settled - was the task of studying the spectrum of cosmic rays (CR) in the energy range 10^{15} - 10^{17} eV [3], where, according to [4], the expected manifestation of the fine structure in the spectrum of CR due to the interaction of cosmic ray particles with the magnetic field of the Galaxy.

2.1 Current status of Small Cherenkov array

The main difference of Small Cherenkov array from other compact arrays is that the array uses hybrid type of registration of multiple air shower components: electrons, muons and Cherenkov radiation. It allowed us to determine shower energy [5] using quasi calorimetric method, to reconstruct air shower cascade development [6], to plot the spectrum and estimate the mass composition of CR [7].

Small Cherenkov array consists of 27 integral and track Cherenkov detectors with different reception area: type 1 has an area of 176 cm^2 photocathode, Type 2 - 530 cm^2 and 17 scintillation detectors of different sizes, 2 m^2, 1 m^2, 0.5 m^2 and 0.25 m^2 each [16]. The stations are arranged at 25, 50, 100, 250 & 500 m from each other. Also the array consists 3 muon telescopes with a threshold of 1 GeV. Stations at distance of 500 m from the center, not connected directly to a main registration point but their data are used in the processing of events at the same time registered by both units.

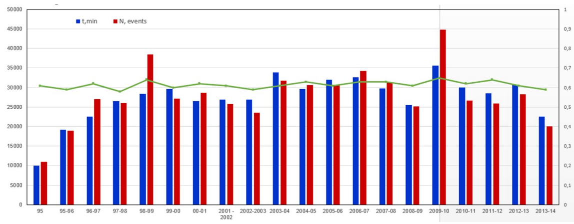


Figure 1: Small Cherenkov array. Statistics of showers with energy more than $2{\cdot}10^{15}$ eV. Blue bars - time of observation in minutes. Red bars - number of registered air shower events. Green line - average spectral transparency of the atmosphere for wavelength λ = 430 nm

2.2 Observations and event selection

Small Cherenkov array works continuously for 20 years (Fig. 1). Duty cycle of the array is from September to April, during moonless, clear nights [8]. Selection of EAS produced by coincidence signals from stations that make up an equilateral triangle for 2.5 μs. To plot a spectrum of CR we used following criteria to select air shower from collected data: coefficient of atmospheric transparency was $P_\lambda \geq$0,65; shower axis was located within the perimeter of the array with a radius R $\leq$ 500 m, the zenith angle of arrival of the EAS 50. These criteria were determined first of all by aperture, threshold of Cherenkov detectors and state of the atmosphere during optical observation.

3. Simulation

Simulation algorithm includes not only brute force search of triangles, but also accounts the threshold of detectors and their fluctuations in backlight conditions when measuring the flow of Cherenkov photons. In each case, the selection of air shower events analyzed coincidence criterion for 2.5 μs, signals from three stations constituting an equilateral triangle with a different base for the distance, i.e. C3. Exceptions were station of Small Cherenkov array that make up triangles with sides of 100, 50 and 25 m. This case also considered trigger of the other triangles or even quadruple coincidence. The purpose of these trigger was to improve the efficiency of selection of events in the transition region from the energies of 10^{15} eV to energies $5{\cdot}10^{15}$ eV. Since EAS events of different energies were selected by different trigger systems, then transition from one trigger that selects showers with less energy to the trigger that selects showers with more energy should give the effect. This is understandable, since at some point trigger system changes as well as effective area of air shower detection. The simulation showed that the magnitude of this effect $\sim$30%. In our case an account of the transition effect to plotting the spectrum decreased from 30% to 15% due to correction of area of air shower detection.

3.1 Precision of obtained air shower characteristics

The precision of measurements of air shower characteristics was determined by simulation of Small Cherenkov array measurements, using Monte Carlo method. The results are shown in Table 1. The table shows that EAS characteristics that used in analysis is determines with a good precision and we used them for further determination of individual air shower energy.

Under real conditions, there is a significant contribution of the light loss by aerosol particles with different sizes. Some uncertainty also makes extreme subarctic climate in the region of the

Table 1: Precision of EAS characteristics measurements achieved at the Yakutsk array

E_0,PeV	σ(R), m	δ N_s	σ(Q(100)) phot/m^2	σ(Q(200)) phot/m^2	σ(Q(400)) phot/m^2	$\sigma(\rho_s(300))$ 1/m^2	$\sigma(\rho_s(600))$ 1/m^2	θ°
2	9.7	0.15	0.17					1.3
10	7.2	0.11	0.15					1.0
100	15.5	0.27	0.15	0.25				5.7
200	34.6	0.32	0.20	0.20	0.22	0.25		5.4
1000	26.7	0.35	-		0.20	0.17	0.19	3.3

array, i.e. during winter above the array sets abnormal atmosphere, properties of which is changes dramatically from autumn to winter and vice versa. Because of that, at Yakutsk array continuous observations of the atmosphere during periods of optical observations are conducted [8, 9] and data on the transparency of the atmosphere are taken into account in the determination of some characteristics of air showers.

3.2 Energy of the shower estimation. Energy balance method

Evaluation of the shower energy was determined using the method and the experimental data presented in [5, 10]. Table 2 shows the results of the partial energies measured by array at each of the components of EAS. Their sum is evaluation of the total energy of the shower. According to the results of Table 2 the connection formula of the shower energy and density of Cherenkov light flux at distance 100m and 150 m - Q(100) & Q(150) was derived. Formulas (1) & (2) are valid for the energy range (2 - 500)$\cdot 10^{15}$ eV and was used to plot cosmic ray spectrum

$$E_0 = (5.75 \pm 1.39) \cdot 10^{16} \cdot (Q(100)/10^7)^{0.96\pm0.03} \tag{3.1}$$

$$E_0 = (9.12 \pm 2.28) \cdot 10^{16} \cdot (Q(150)/10^7)^{0.99\pm0.03} \tag{3.2}$$

It is significant that the method is based on experimental data and does not depend on the model of hadron interactions that describes the physics of EAS development in the atmosphere. Therefore, the method used for determining the energy of the shower at the Yakutsk EAS more realistic, unlike other systems where energy is used to determine one or two versions of the models.

4. Air Shower Energy Spectrum

From the data obtained at Yakutsk Small Cherenkov array from 1994 to 2014 and selected using criteria described above, we evaluated the frequency of EAS events registered in a given range in energy δE and zenith angle $\Delta\theta_i$ per unit of effective area of Small Cherenkov array. Further, by introducing corrections to the transition effect in the corresponding energy intervals, we have specified spectrum in the energy $2\cdot10^{15}$ - $2\cdot10^{16}$ eV and $8\cdot10^{17}$ - $3\cdot10^{18}$ eV. Final energy spectrum is shown in Figure 2. To switch from a classification parameter Q (150) to the energy E_0 we used energy balance method as described above.

As one can see from Fig. 2, the spectrum above 10^{15} eV has a complex shape and it can't be described by a single power law in the energy range from 10^{15} eV to 10^{18} eV. Even if we take into

Table 2: The energy transferred to the different components of the EAS

n/n	lg E_ei	lg $E_e l$	lg E_μ	lg E_{hi}	lg(E_{mi}+E_ν)	lg E_0
1	15.687	14.506	14.840	14.465	14.721	15.823
2	15.830	14.612	14.951	14.608	14.832	15.961
3	16.064	14.876	15.175	14.842	15.056	16.195
4	16.345	15.199	15.410	15.123	15.291	16.471
5	16.540	15.362	15.506	15.318	15.387	16.650
6	16.669	15.473	15.644	15.447	15.526	16.783
7	16.797	15.726	15.783	15.575	15.664	16.916
8	16.874	15.851	15.899	15.652	15.780	17.002
9	17.014	16.001	16.015	15.792	15.896	17.139
10	17.116	16.122	16.081	15.894	15.962	17.238
11	17.208	16.269	16.173	15.986	16.054	17.334
12	17.297	16.435	16.306	16.075	16.187	17.436

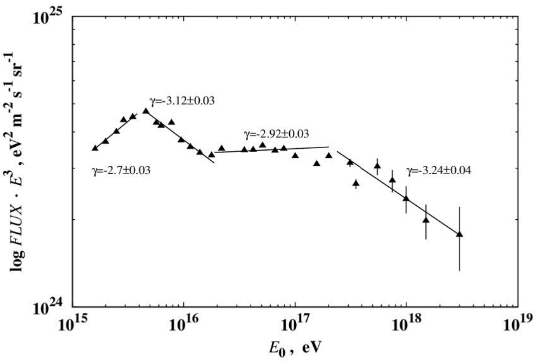


Figure 2: A spectrum of cosmic rays in the region 10^{16} - 10^{18} eV by Yakutsk data. There is a second knee at energy $\sim 2{\cdot}10^{17}$ eV.

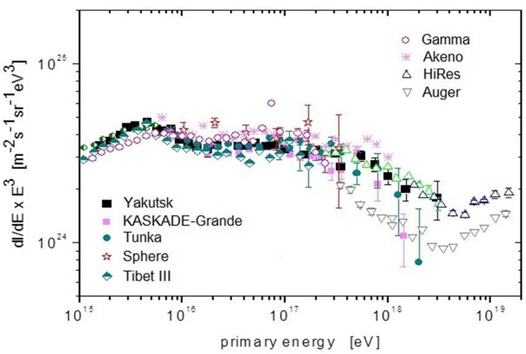


Figure 3: Cosmic ray spectrum for different arrays. Yakutsk data obtained from Small Cherenkov array

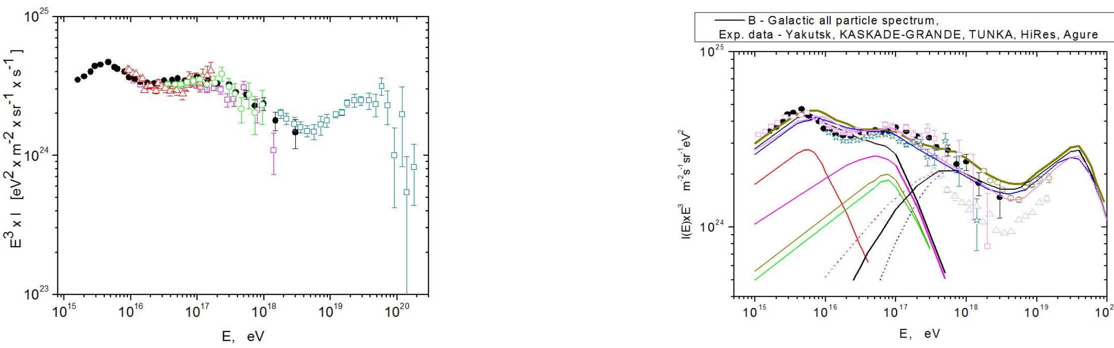
account presence of systematic errors for plotting the spectrum (see. Modeling section), its shape does not change much and marked irregularities in the spectrum at $\sim 3{\cdot}10^{15}$ eV and $\sim 2{\cdot}10^{17}$ eV is not going to disappear. Let's approximate the spectrum by a simple power law function:

$$dN/dEdAd\Omega dt = I_0(E/1eV)^{-\gamma+1} \tag{4.1}$$

we determined constant coefficients of equation (4.1) for four intervals of energies. The first knee is characterized by slope γ_1 = 2.70 ± 0,03 and γ_2 = 3.12 ± 0.03, and the second knee γ_1 = 2.92 ± 0.03 and γ_2 = 3.24 ± 0.04. In the second case, the difference of the slopes is $\Delta\gamma_{23}$ = (0.32) ± 0.03 ± 0.05, which is less than that in the case of the first knee $\Delta\gamma_{12}$ = (0.42) ± 0.03 ± 0.05 . We can assume that less distinguished kink in the spectrum may be due to the cosmic ray flux of different nature, such as the influx of metagalactic components to our galaxy.

4.1 Comparison of the Spectrum with Other Arrays Results

Fig. 3 shows the combined spectrum in the energy range 10^{15} - 10^{18} eV, obtained at different arrays. There is a good agreement with the shape of spectrum obtained at Yakutsk array and these data are consistent with the hypothesis of a second knee at $\sim 2{\cdot}10^{17}$ eV. The analysis showed: a) shape of the spectra in the energy range 10^{15} - 10^{17} eV is the same and repeats of each other; b) the intensities have spread between arrays in the range $\sim$20%, it is more clearly visible at energies above $5{\cdot}10^{16}$ eV. This is partly due to the different methods for estimating the energy in each of the EAS arrays and to some extent different effective thresholds of the arrays themselves. Much greater variation in the intensity of the spectrum is observed above the energy $2{\cdot}10^{17}$ eV. On the one hand all the settings indicate a kink in the spectrum, but the degree of change in the slope of the spectrum is different. Much larger spread in the intensity of the spectrum is observed above the energy $2{\cdot}10^{17}$ eV. On the one hand all arrays indicate a kink in the spectrum, but the degree of change in the slope of the spectrum is different. For example, the data of Yakutsk and Tunka arrays in better agreement with the data of large arrays Hires and TA, while data of KASKADE-Grande and Tibet III is in better agreement with Auger. It is possible that here the same reasons as listed above. However, it should be noted that at energies above 10^{17} eV air showers statistics at such arrays as Tibet III, Gamma is not enough to clearly say with which of large arrays they in a better agreement.



a) b)

Figure 4: a) Experimental data of Small Cherenkov array (dots), TA Cherenkov data (triangles), TA hybrid (circles), TA data for last 6 years (squares). b) All particle spectrum measured by different experiments: Yakutsk, KASCADE Grande, Tunka and HiRes, Auger.Calculations [11] and [12]. Galactic cosmic rays are presented separately: dark green line (total), red line (H+He), blue line (Z>6), green line (Z>14), orange line (Z>20). Dot lines denote 3 fits of extragalactic protons, covered predictions [11]. Thick lines of the same colours represent galactic + extragalactic particles

Highest statistics of EAS in the energy range 10^{17} - $2{\cdot}10^{18}$ eV has the Yakutsk Small Cherenkov array because it runs continuously for 20 years. As one can see from Figure 3, its data are in good agreement with the data of HiRes array and TA.

Fig. 4a shows the data of Small Cherenkov array and new data of TALE Cherenkov and TALE Bridge. TA data are taken from ISVHECRI-2014. At energies above 10^{18} eV - results obtained at TA within last six years of observations. As one can see from Fig.4a, the data of the Yakutsk Small Cherenkov array in a very good agreement in the energy range 10^{16} - 10^{18} eV with the new data of TALE Cherenkov and TALE Bridge, pointing to the second kink in the spectrum at $\sim 2{\cdot}10^{17}$ eV. At energies above 10^{18} eV is also agreement of the spectra of both systems within experimental error. As can be seen from Fig. 3, there is no agreement in spectra with Auger experiment. The reason for such differences are likely related to the method of energy estimation of the array. For example, the estimation of the energy of air showers obtained by the registration of energy loss by charged particles in the ionization of the atmosphere, in arrays TA, HiRes and Yakutsk Small Cherenkov array within 5% [5] with each other, which causes such a nice agreement of spectra.

4.2 Results Discussion

Cosmic ray spectrum cut off due to iron nuclei leaving the galaxy according to Peters cycle [4] for a given magnetic field rigidity R_c should be observed at the cutoff energy E_c = 26 eR_c, i.e. at $\sim 8 \cdot 10^{16}$ eV. According to the Yakutsk data break exist at energies $\sim 2 \cdot 10^{17}$ eV. Actual change of slope is $\Delta\gamma = 0.32 \pm 0.07$. This is a bit less than in the case of first break at energies $3 \cdot 10^{15}$ eV. A little difference in slope $\Delta\gamma$ can be explained by cosmic ray injection from metagalactic sources [13], and thus some compensation of dramatic change of slope at break point in the energy range $5 \cdot 10^{16}$ - $3 \cdot 10^{18}$ eV by protons and lighter nuclei from metagalaxy. In this case, we can assume that border between galactic and metagalactic CR with a great possibility lies in the energy region $2 \cdot 10^{17}$ - $3 \cdot 10^{18}$ eV. Other version of explanation of second break of the spectrum would be contribution of one or even multiple sources of cosmic ray such as SNR with maximum luminosity.

4.3 Nearby sources which provides transition region from galactic to extragalactic CR

In paper [14] was hypothesized about the transition region from galactic to extragalactic cosmic rays in the energy range 10^{17} - 10^{18} eV. Last spectrum data of Small Cherenkov array confirms that [15].

Following the idea that the SNR are candidates for the sources of cosmic rays, in the paper [11] performed calculations for the three propagation models of galactic and metagalactic component in the universe (see. Fig.4b). The purpose of these calculations was the interpretation of the experimental spectrum in the energy range 10^{15} - 10^{20} eV, obtained according to the compact and large EAS arrays. In, particular, attempted to explain the formation of second knee as the birth and propagation processes of cosmic rays in the galaxy and beyond. Calculations [11] have shown that the behavior of protons in the energy range 10^{16} - 10^{17} eV depends on the average strength of the magnetic field B_0 = 0.3 - 3 nG, the coherence length lc 30 - 300 kpc, the source density n = 10^{-5} - 10^{-6} Mpc-3 and other factors. For protons born outside the galaxy, as shown by calculations [13, 11], an open proton spectrum will be in the range of energies 10^{17} - 10^{18} eV. Data about spectrum of CR obtained recently at compact array can serve as a proof of this.

Fig. 4b. Shows the partial spectra for individual nuclei and total spectra of all particles separately for galactic component (obtained in [12], using the above described assumptions about the magnetic fields, the source model and varying the chemical composition of the particles to the galactic component). Believed that cosmic rays are produced and accelerated in SNRs to energies E_{max} by law N ($> E_{max}$) $\sim E_m ax^{-0.17}$ [11] and the upper limit of the acceleration of galactic cosmic rays equal E = 26 $\cdot$ (4$\pm$1) PeV. Spectrum in the source had the inclination $\gamma \sim$ -2,2 up to E_{max} and becomes steeper on the value d$\gamma \sim$ -1.5 higher energy E_{max} with parameter ω 4 that imitated a break in the spectrum. The chemical composition of cosmic rays at the source has been selected as a "normal" ($\sim$36% of H, $\sim$24% of He, $\sim$10% of CNO, $\sim$9% of Fe), at energy of 1 TeV. To describe the spectrum of heavy nuclei at energies $\sim 10^{18}$ eV cosmic rays in the remnants of SN Ia corrected by iron nuclei, increasing their share to 15%. Ultimately, the chemical composition of galactic cosmic rays at 1 TeV become different from "normal" composition (17% of H, 46% of He, 8% of CNO, 16% of Fe). Thus obtained in [12] calculations of the spectra practically coincide with the experimental data, indicating the existence of a second knee in the energy range 10^{17} - 10^{18} eV, i.e. at the energy $\sim 2 \cdot 10^{17}$ eV. Thus, second knee, as predicted in [11] and shown by calculations [12], formed by a sharp steepening of the spectrum of galactic iron nuclei in the energy range (2 - 8) of 10^{16} eV at $4 \cdot 26$ PeV and growth of contribution of metagalactic protons from $2 \cdot 10^{16}$ eV, which leads to the formation of second knee.

5. Conclusion

By the time of observation (20 years of continuous observations) and statistics of EAS events above 10^{17} eV of energy to advance in the study of the CR spectrum in the energy range 10^{16} - 10^{18} eV are most managed at Yakutsk.

CR spectra obtained at the Small Cherenkov array, indicates the existence of second knee at energy $\sim 2 \cdot 10^{17}$ eV. There are all reason to believe that the physics of the observed second breaks (kinks) associated with astrophysical processes occurring both within our own Milky Way galaxy as well as beyond of our galaxy. The second break points can be explained by the transition border from galactic to metagalactic cosmic rays.

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