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Longitudinal development of EAS in the energy range 10^{15}-10^{20} eV by observation in the period of 1994-2014 at the Yakutsk

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The paper presents air shower data with Cherenkov radiation for the period 1994-2014. The energy interval 10^{15}-10^{20} eV and zenith angle $\theta = 0^\circ$ - 55° was considered. Dependence of average depth of maximum development of air showers on air shower energy are found. Fluctuation of X_{max} are determined. Comparison of the experimental data with the calculations based on the QGSjetII-04 model for the primary proton and iron nuclei is presented. Mass composition of primary cosmic rays in the wide range of energies are made by interpolation.

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1. Introduction

An important role in the study of the characteristics of cosmic rays by the method of extensive air showers (EAS) is played by the recording of Vavilov-Cherenkov radiation produced by shower particles in the optical wavelength range. The first researchers of the EAS showed that the flux of the Cherenkov light EAS can serve as a measure of the energy of the primary particle, and its spatial distribution at sea level holds information about the nature of the development of showers in the atmosphere. These ideas were further developed at the Yakutsk EAS array. Due to hybrid measurements of the main components of the shower: electrons, muons, and Cherenkov light, EAS, a method were proposed for a model-free estimate of the energy of a primary particle forming a shower, using the total flux of Cherenkov light from the EAS. In individual showers, energy was determined from the density of the Cherenkov light flux at a distance R = 200 m from the shower axis, because, according to calculations, this characteristic reflected the total ionization losses of electrons in the atmosphere at sea level and fluctuated little from shower to shower. Later, it was shown theoretically and experimentally that the depth of the maximum of the shower development is related to the slope of the spatial distribution of Cherenkov light EAS, at medium distances from the shower axis (200 <R <600 m). In the following, the inverse problem of reconstructing the cascade development curve of the EAS N (X) from the measured spatial distribution of the Cerenkov light Q (R) was mathematically correctly posed and solved.

In this paper we present the results of long-term measurements of the Cherenkov light of the EAS and an analysis of the longitudinal development of showers in the region of ultrahigh energies.

2. The Yakutsk array

The Yakutsk array is medium in size, between compact ones with an area s $\leq$ 1 km^2 and large arrays with s $\geq$ 1000 km^2 [1]. The energy range of the array is from 10^{15} eV to 10^{20} eV, which allows it to study both galactic and metagalactic cosmic rays. The structure and location of the detector base of the array are shown in Fig. 1.

The array consists of 120 main scintillation detectors with a threshold of 10 MeV, a reception area of 2 m^2 and 72 channels for registration of the integral and differential fluxes of the air shower Cherenkov light. Three muon stations with an area of 20 m^2 with a threshold of 1 GeV, located at a distance of 300, 500 m and 800 m from the center of the installation. One muon point with an area of 190 m^2 with a threshold of 0.5 GeV, located in the center of the installation. Each of the stations has two scintillation detectors and one Cherenkov detector with a receiving area of the photocathode of 176 cm^2 or 530 cm^2.

Observation stations are located in the area $\sim$13 km^2 and 500 m spacing. In the central part of the array, there is a network of standard observation stations with 25 m, 50 m, 100 m and 250 m apart that have one scintillation and Cherenkov detectors. These stations, together with other observation stations, form the basis of a compact array aimed at studying air showers with an energy higher than 10^{15} eV (Fig. 1) [2]. The control and selection of the EAS events is carried out by the "trigger-500" in the case of the main array and by the Cherenkov "trigger 25, 50, 100, 250" at the small Cherenkov unit. By "trigger-500" here is meant the coincidence of signals from three observation stations that form equilateral triangles. This is the main trigger of the Yakutsk

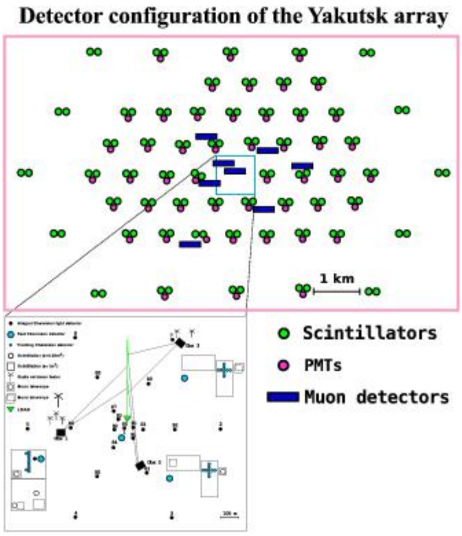

Figure 1: Arrangement on observation stations at the Small Cherenkov array.

array. Similarly works Small Cherenkov array but in this case triggering is performed by the Cherenkov detectors. The main array includes experiments on the study of radio emission of EAS at frequencies of 30-35 MHz [3], points for studying the space-time structure of the EAS disk and delayed particles [4], laser sounding of the atmosphere at a wavelength of 532 nm and spectrometric measurements of the aerosol of air [5], etc.

3. Measurement of Cherenkov radiation from air shower particles

3.1 Cherenkov detectors and measurements

At the Yakutsk array, there were several types of optical detectors for Cherenkov light registration throughout the experiment. Fig.2 shows the generation of Cherenkov detectors for amplitude measurements, integral detectors measuring the total flux of Cherenkov photons at sea level [1]. Photoelectron multipliers (photomultipliers) with a photocathode area of 176 cm^2 were used as the receiver of Cherenkov light. In the detector of type C, three photomultipliers with a total area of 530 cm^2 were used to increase the aperture of the detector in order to detect small fluxes of photons at large distances from the shower axis. At the Yakutsk array, also differential detectors, or tracking Cherenkov detectors (obscure-camera [6] and wide field-of-view Cherenkov telescope [7]), are used to register the longitudinal development of the EAS. These are detectors with a good time resolution for measuring the flux of Cherenkov photons arriving from a narrow region in height [6].

Measurements are conducted on dark and clear nights, beginning in September and ending in the month of April. The total observation time for one year is 450 - 600 hours, which occupies from 6 to 10 % of the operating time of the array. When conducting optical observations at the array, the atmosphere is thoroughly monitored, special attention is paid to the measurement of transparency and the aerosol component of the atmosphere [8 - 10]. Both these characteristics significantly

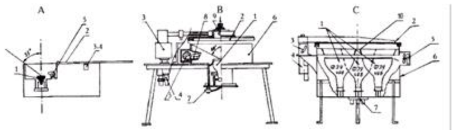

Figure 2: Cherenkov light detectors at the Yakutsk array. a - detectors used in 1966; b - detectors used in 1973; c - detector used in 1993.

affect the quality of measurements of the integral and differential flux of Cherenkov light [11], and therefore the energy estimate [12] and the restoration of the cascade curve of the EAS.

Fig. 3 shows the function of the spatial distribution of the Cherenkov light of individual events with energy of EAS E = $1.3 \cdot 10^{19}$ eV and zenith angle $\theta = 25^\circ$. The shower axis is in the center of the array, where most of the Cherenkov detectors are located, so the accuracy of the measurements are equal. Axis: X = 17 m, V = 24 m, and flux density 15%. According to such data, the cascade curve of shower development is reconstructed with good accuracy.

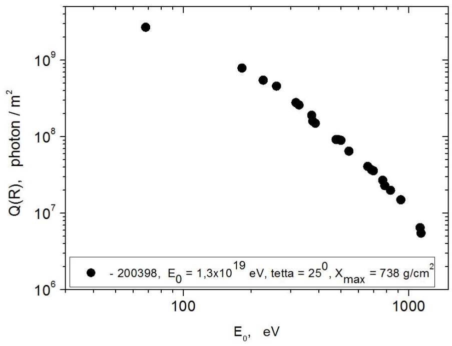

Figure 3: LDF of Cherenkov light of individual air shower. The event is registered in 20.03.98

3.2 Reconstruction of EAS development cascade curve

Longitudinal development of the shower at the Yakutsk plant is reconstructed by recording the Cherenkov light of the EAS [13, 14], using the mathematical apparatus used in solving inverse problems [15, 16].

For this, the experimental LDF of Cherenkov light [15], and the algorithm developed for reconstructing the cascade curve are used by the method of solving the inverse problem [16]. The algorithm is described in detail in [13, 14]. This algorithm is based on the Fredholm equation of the first kind (3.1), whose solution was carried out using the adaptive method [17].

$$Q_{exp} = \delta_Q + \int_{X_1} G(R, X/X_2) \cdot N(E_0, X) \cdot K(\lambda, X) dX \tag{3.1}$$

where $G(R, X/X_2)$ - the function defined by lateral-angular distribution of electrons in partial electron-photon cascade, $N(E_0, X)$ - cascade curve; δ_Q - level of "noises", depends on measurement uncertainties, statistical processing of the data, function $G(R, X/X2)$, integration etc.; $K(\lambda, X)$ - transmittance of the atmosphere; X_1 and X_2 - upper and lower limits of the atmosphere area.

As can be seen from equation (3.1), the method takes into account the physics of the development of the electron-photon shower component and the characteristics of atmospheric conditions during the Cherenkov radiation observation [9, 10] in the region of the Yakutsk EAS array. Using this technique, an EAS database with a reconstructed cascade curve was created and a sample of X_{max} showers was made. Fib. 4 and Fig.5 shows reconstructed air shower cascade curves of individual air shower and average by LDF of Cherenkov light distribution for energies $\sim 10^{18}$ eV[19].

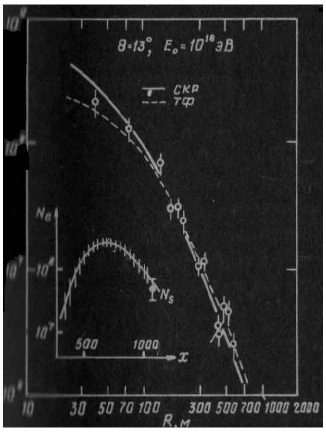

Figure 4: Individual air shower cascade curve.

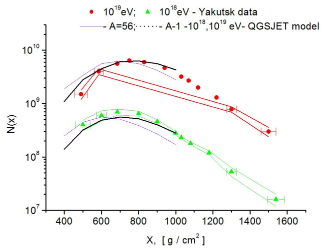

Figure 5: The mean experimental cascade curves (Yakutsk data) and calculations by QGSJET model for proton and iron

4. Experimental data

4.1 Depth of maximum development X_{max}

From the database, a sample of the X_{max} showers was made to study the depth shift of the development of the EAS dX/dlgE and its fluctuations σX_{max} in different energy intervals. Fig. 6 shows the distribution of X_{max} of individual showers as a function of the classification parameter of the shower Q (200) - flux density of Cherenkov light at a distance of 200 m from the shower axis. In this case, the shower energy was determined by the energy balance method of all the EAS components [12], and the transition from the Q (200) energy was made by the formula (4.1):

$$E_0 = (1.78 \pm 0.44) \cdot 10^{17} \cdot \left(\frac{Q(200)}{10^7} \right)^{(1.01 \pm 0.04)} \tag{4.1}$$

It is seen from Fig. 6 that in the distribution there are air showers with $X_{max} \geq 800$ g / cm^2, i.Đţ. have a low maximum development of the shower in relation to the events formed by the nucleus of iron and even the proton. These showers can be used to search for neutral component, gamma rays and neutrinos. Fig. 7 shows the dependence of the mean values of X_{max} on the energy of the EAS. It is also given by comparison with the data obtained in [18] for a time-limited sample. Fig. 8 shows that within the limits of statistical errors the data are consistent. In addition, the figure shows that the progress of X_{max} with energy is not linear. The rate of displacement of X_{max} per decade for energy E.R is given below in the text. As can be seen, the inflection points fall on the energy

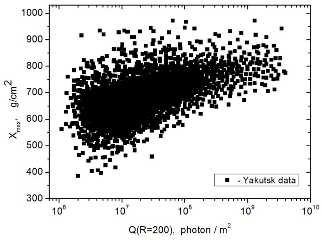

Figure 6: Dependence of X_{max} from classification parameter Q (200) - EAS Cherenkov light flux density at a distance of 200 m from the shower axis. Data obtained in 1973-2014.

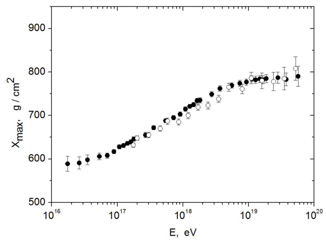

Figure 7: Experimental data comparison obtained for a long-term observations (1974-2014) with selection made in 2010 [18].

of $\sim 10^{17}$ eV and $\sim 8 \cdot 10^{18}$ eV, i.e. on the "second knee" and "bump-deep". It can be assumed that such a character of the advancement of X_{max} to sea level is associated with a change in the mass composition of CR. a) ΔQ(200) = 10^6 - 10^7 photon/m^2. E.R. = 48$\pm$6, b) ΔQ(200) = 10^7 - 10^8 photon/m^2. E.R. = 78$\pm$5, c) ΔQ(200) = 10^8 - 10^9 photon/m^2. E.R. = 63$\pm$6, d)ΔQ(200) = 10^9 - 10^{10} photon/m^2. E.R = 50$\pm$7 [g/cm^2].

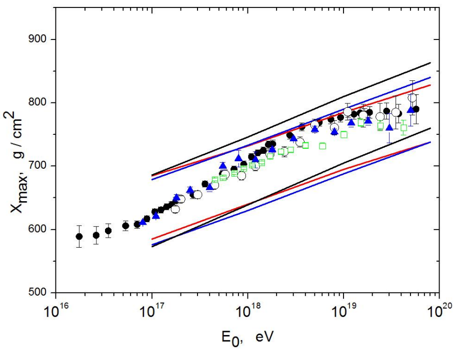

Figure 8: Dependence of X_{max} on energy, obtained from Cherenkov light observations in the period 1974-2014 at the Yakutsk array. Lines are calculations by models: QGSjetII-04 (dash), SIBYLL2.1 (dot) and EPOSv1.99 (solid).

4.2 Dependence of X_{max} on air shower energy. Model calculation comparison

The averaged data of the Yakutsk array together with the data of the Auger and HiRes experiments are shown in Fig. 8 It can be seen that the experimental data of all experiments within the achieved accuracy are in good agreement with each other. Fig. 8 also shows the calculations for the hadron interactions QGSjetII-04 (dash), SIBYLL2.1 (dot) and EPOSv1.99 (solid) for the proton and iron nucleus. Comparison of the experimental data with the models indicates a variable MC. In the energy range 10^{16}-10^{17} eV, the composition more likely has more heavy nuclei, at energies 10^{17}-10^{18} eV, the composition mainly consists of protons and light nuclei and above 10^{19} eV the composition is enriched with heavy nuclei. The analysis of the displacement velocity of X_{max} in a wide range of energies does not contradict with this conclusion.

Thus, it can be concluded that long-term observations at the Yakutsk array have established an irregularly high maximum development of the air showers in the energy range 10^{16}-10^{20} eV.

4.3 X_{max} fluctuations. Different nuclei comparison with model calculations

To analyze the fluctuations of X_{max}, a database on the Cherenkov light of the EAS was used for the period from 1970 to 2015. Since the air shower statistics was big enough, the data array was divided into small energy intervals with a step of 1.5 and in each interval, the value of $\sigma()$ was found. The results of the Yakutsk array are shown in Fig. 9. In the same place, data of other arrays and calculations on modern models of hadronic interactions (see Fig. 9) for the primary proton, CNO nuclei and iron nuclei are plotted. The experimental data of all facilities within the limits of statistical errors are consistent, therefore we can say that the obtained dependence of the fluctuations of X_{max} is due to the mass composition of the primary particles that are likely to vary with energy. In the energy range 10^{16}-10^{17} eV, the fluctuations of the X_{max} are (50-60) g·cm^{-2} and tend to grow. In the energy range 10^{17} - 10^{18} eV, they are almost constant and above 10^{18} eV noticeably decrease, reaching values (50-40) g·cm^{-2}.

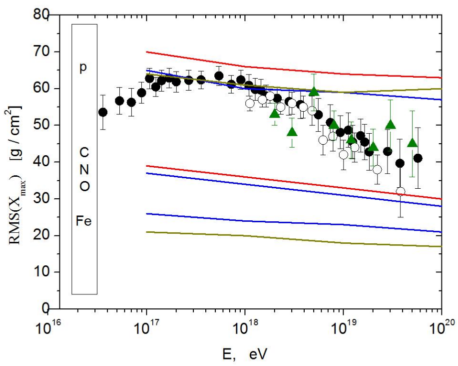

Figure 9: Fluctuations in the depth of the maximum of the EAS development in the energy range 10^{17} - 10^{20} eV. The lines are calculated by the models QGSjet-01 [18], QGSjetII-04 [19] and EPOSv1.99 for the primary proton, CNO nuclei (models QGSjet-01, QGSjetII-04) and iron nucleus. Circles are Auger installation data [20]. Triangles - data of the HiRes installation [21, 22].

5. Conclusion

The Yakutsk array for more than 45 years is operating continuously, measuring electrons, muons, Cherenkov radiation and radio emission. At the same time, more than $5 \cdot 10^6$ EAS events were recorded in the energy region above 10^{15} eV. Using a large database of experimental data, we analyzed the Cherenkov component of the EAS, namely, Cherenkov light LDF. Using the LDF, we reconstructed the longitudinal development of showers in the energy region 10^{16} - 10^{20} eV and the dependence of X_{max} and $\sigma(X_{max})$ on energy was found. It is shown that the advancement of X_{max} with an increase in energy is not linear. The rate of displacement of X_{max} per decade for energy E.R. Takes the values 48 ± 6, 78 ± 5, 63 ± 6, 50 ± 7 in the intervals indicated above in the text. As can be seen, the curve points fall on the energy of 10^{17} eV and $\sim 8 \cdot 10^{18}$ eV, i.e. on the "second knee" and "bump-deep". From this we can assume that such a character of the propagation of X_{max} to sea level is associated with a change in the MC of CR. Comparing the experimental data $\sigma(X_{max})$. With model calculations for different nuclei, we can tell that the experiment at the Yakutsk array indicates a change in the MC. Qualitatively, it looks like this: in the region of lower energies, there are noticeably more nuclei with an atomic weight of 4-56, at an energy of 10^{17}-10^{18} eV, the proton fraction reaches a maximum and is 60-80%, then gradually decreases and in the energy range 10^{19}-10^{20} eV cosmic rays consist of nuclei of helium, CNO and more heavy elements.

Acknowledgments

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