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Characteristics of air showers with energy more than 10^{17} eV reconstructed by the Yakutsk array radio emission measurements

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Abstract. The paper presents results on the longitudinal development of air showers of ultra-high energies obtained from radio emission measurements at the Yakutsk array. The energy, the depth of maximum development of individual showers are determined and a statistical analysis of X_{max} in order to estimate the fluctuation of air shower development $\sigma(X_{max})$ in the energy region 10^{17}-10^{18} eV is performed. It is shown that $\sigma(X_{max})$ in the energy region 10^{17}-10^{18} eV is equal to 50-60 g·cm^{-2}, which doesn't contradict with a mixed composition of cosmic rays - protons and helium nuclei. This is also indicated by data of the X_{max} value dependence on energy.

1 Introduction

To study cosmic rays (CR), the Extensive Air Shower (EAS) method uses ground and underground particle detectors. These detectors register muons, electrons, positrons, and photons. Another type of observation is the optical method that records the electron-photon component of the shower: Cherenkov light and fluorescent emission. Cherenkov light of EAS propagates along the shower axis and this light can be detected with Cherenkov light detectors, and fluorescent emission is emitted isotropically by nitrogen molecules in the air when excited by EAS particles, which allows them to be observed from a long distance by fluorescent telescopes [1].

Another method of registering air showers is radio emission observation [2]. The antennas of the radio emission register the same component of the shower as the optical detectors - the electromagnetic component. Two mechanisms are responsible for the generation of radiofrequency EAS. The first mechanism, more dominant, is geomagnetic [3, 4], as electrons and positrons are deflected to mutually opposite directions by the Earth's magnetic field, creating a time-varying current that generates radio emission. The second mechanism is that an excess of negative charge is formed in the EAS disk when air showers propagate in the atmosphere, which also leads to the emission of an electromagnetic wave in the radio frequency [5].

Unlike optical detectors, antenna registration is possible under almost any weather, light condition and has a low dependence on the atmospheric transparency. Thus, the radio method is perfect to be an additional air shower observation method to increase the available information for arrays with already existing charged particle detector infrastructure. As was shown in [6–9], it is possible to determine parameters of the air showers by measuring radio emission.

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2 Yakutsk Radio Array

First radio emission of air showers registration work at the Yakutsk array was carried out in 1986-1989. There were 6250 air shower events with radio emission and energies above 10^{17} eV, including several events with $E_0 \geq 10^{19}$ eV [10, 11]. In 2009, six antennas (half-wave dipoles) were arranged at the Yakutsk array to continue the radio emission experiment. To determine the optimal frequency for radio emission observation the background spectrum of frequencies from 1 to 100 MHz was analyzed [12].

For 24h observation times at frequencies up to 20 MHz, it is not possible to distinguish radio pulses with sufficient efficiency because of the presence of a large natural radio noise of predominantly thunderous origin [13]. Therefore, it is reasonable to select frequencies above 20 MHz, since ionosphere noise decreases dramatically in the transition to higher frequencies and is about (0.5-1) μV·m^{-1}·MHz^{-1} at frequency ~20 MHz. The amplitude of galactic noise decreases much slower with frequency and is about 1-2 μV·m^{-1}·MHz^{-1} at 32 MHz [12]. Thermal noise of the antenna is much smaller than galactic noise at frequencies up to 100 MHz and negligible. Therefore, the most favorable frequency range for the measurements at the Yakutsk array is 30-40 MHz, where the best signal-to-noise ratio is expected because at higher frequencies the spectrum is limited by strong interfering anthropogenic signals, e.g. broadcast television [14].

The Yakutsk array antennas are arranged in 2 groups of 4 and 2. Antennas are located near the center, inside the Small Cherenkov Array perimeter (Fig. 1). The distances between antennas are 50, 100 and 500 m and 50-100 m from the station to prevent interfering noise signals from PMTs of scintillation detectors [1].

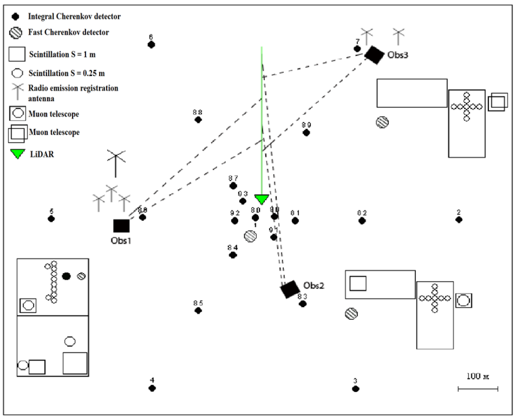

Figure 1. The plan of the Small Cherenkov Array. Placement of the charged particles detectors, muon detectors, and Cherenkov light detectors

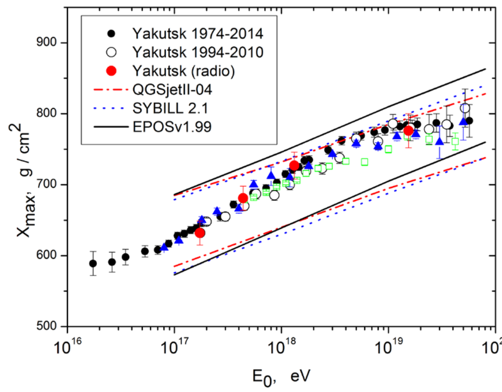

Figure 2. The dependence of X_{max} on energy, obtained from observations of Cherenkov radiation for the period 1974-2014. and 1994-2010, at the Yakutsk array of the EAS. Comparison with X_{max} received on the radio extension with model calculations

Such an arrangement of the antennas near the observation stations of the Yakutsk array allows one to obtain information on the fundamental parameters of the EAS, such as shower energy, the depth of the maximum distribution, the coordinates of the shower, and the direction of arrival. In addition, it allows using the trigger of the Yakutsk array from scintillation detectors and a Small Cherenkov Array from Cherenkov light detectors. The scintillation detectors trigger registers air showers with energies higher than 10^{17} eV over an area of 12 km^2. The Small Cherenkov array trigger registers air showers with energies in the range 10^{15} - $5 \cdot 10^{17}$ eV.

The use of additional data from other detectors of the Yakutsk array allowed us to find correlations between radio emission and air shower parameters [13].

3 Relationship between LDF shape and X_{max} development of EAS

In the calculations, the sensitivity of the slope of the lateral distribution function of the EAS radio signal (P = A_1 / A_2) to the depth of the shower maximum (X_{max}) was shown. The relationship between the parameter P and X_{max} is exponential and can be described by the following formula:

$$X_{max} = 856.1 \left[\ln \left(0.3149 \frac{A(175)}{A(725)} \right) \right]^{0.434} \quad (1)$$

At the Yakutsk array, the connection P = A (R1) / A (R2) with X_{max} was obtained empirically, using synchronous measurements of radio and Cherenkov radiation [15]:

$$X_{max} = (660 \pm 15) + (100 \pm 5) \cdot \frac{P - 11.5}{3} \quad (2)$$

As practice has shown, the formula (2) with sufficient accuracy is valid for the depth interval ΔX_{max} = 600-800 g·cm^{-2}. Below these depths, the errors in the determination of X_{max} increase.

Further, formula (2) was used mainly to determine X_{max} in individual radio showers with energies of 10^{17} - 10^{18} eV.

Using equation (2), which is based on the shape of the LDF radio emission of EAS, we estimated X_{max} for different primary energies (Fig. 2).

4 Dependence of X_{max} on shower energy. Comparison with model calculations

The data of the Yakutsk array, obtained from the measurements of Cherenkov light (black dots) and the radio emission of the EAS (red dots), together with the data of the Auger and HiRes arrays, are shown in Fig.2. It can be seen that the experimental data of all arrays within the limits of the achieved accuracy are in good agreement with each other and indicate an irregular advance of the X_{max} into the atmosphere. If we consider different energy intervals, we see that elongation rate (ER) has the following values of 48±6, 78±5, 63±6, 50±7 g·cm^{-2}. Such a progression of X_{max} most likely means that the atomic weight of the primary particles changes upon transition from one interval of energy to another and is due to the processes occurring in the sources and the interaction of particles in the drift process in the magnetic fields of outer space. Also, in Fig. 2, calculations are also made for the models of hadronic interactions QGSjetII-04, SYBILL 2.1 and EPOSv1.99 for protons and iron nuclei. Comparison of the experimental data with the calculations also indicates a variable mass composition of the primary particles. 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.

This does not contradict the analysis of the offset velocity X_{max} in a wide range of energies. Thus, it can be concluded that long-term observations at the Yakutsk EAS setup have revealed an irregularly high development of the EAS in the energy range 10^{16}-10^{20} eV.

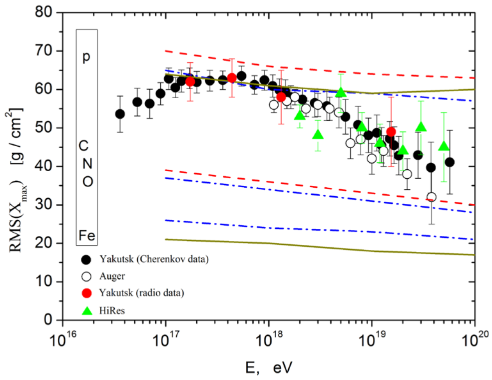

Figure 3. Fluctuations in the depth of the maximum of EAS development in the energy range $3{\cdot}10^{16}$-10^{20} eV. Lines calculations for the QGSjet-01 [16], QGSjetII-04 [17] and EPOSv1.99 models for primary protons, CNO nuclei (models QGSjet-01, QGSjetII-04) and iron nuclei. Comparison also with the data of Auger [18] and HiRes [19, 20]

5 Fluctuation of $\sigma(X_{max})$. Comparison with calculations for different nuclei

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 shower statistics allowed, the data array was divided into small energy intervals in 1.5 steps and in each interval the value of $\sigma(X_{max})$ was found. The results of the Yakutsk array are shown in Fig. 3. In the same place, the data of other arrays and calculations on modern models of hadronic interactions (Fig. 3) for the primary proton, CNO nuclei and iron nucleus are plotted. The experimental data of all arrays within the limits of statistical errors are consistent, therefore, it can be said that the obtained dependence of the fluctuations X_{max} is due to the mass composition of the primary particles that is likely to vary with the energy. In the energy range 10^{16}-10^{17} eV, the fluctuations of X_{max} are (50-60) g$\cdot$cm^{-2} and tend to increase. In the energy range 10^{17}-10^{18} eV, they are almost constant and above 10^{18} eV noticeably decrease, reaching values (40-50) g$\cdot$ cm^{-2}. Comparing the experimental data, $\sigma(X_{max})$, with model calculations for different nuclei, we can say that the experiment indicates a change in the mass composition. Qualitatively, it looks like this: in the region of lower energies, a noticeably larger number of 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 helium nuclei, CNO and heavier elements.

6 Complex measurements example

As an example of complex measurement the LDF and signals of surface and underground detectors of the Yakutsk array are shown in Fig. 4. Also shown in Fig. 5 are the radio emission pulses of the air shower event registered on 5 January, 2018 00:12 (+9 UTC). The zenith, θ, and

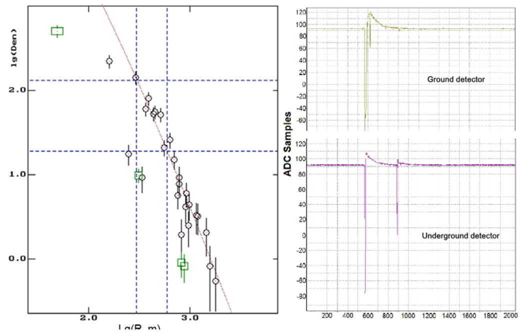

Figure 4. Air shower with energy $E_0 \geq 10^{19}$ eV registered at the Yakutsk array on January 2018

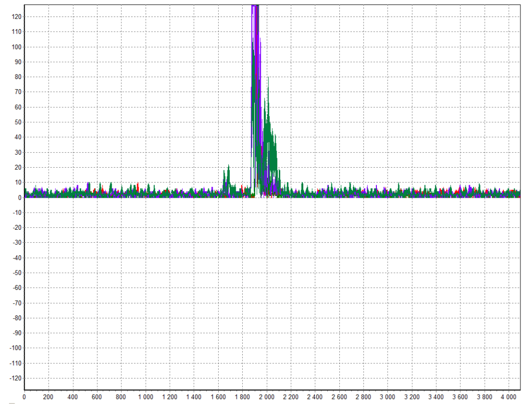

Figure 5. Air shower radio emission pulses detected by radio antennas with different radiation pattern

azimuth, ϕ, angles are 45° and 303° respectively. The energy estimated by the surface detectors is $E_0 = 1.81{\cdot}10^{19}$, with an uncertainty of ~20%. The energy estimated by radio emission data is $E_{rad} = (1.440{\pm}0.42){\cdot}10^{19}$ eV, which within experimental uncertainty is in agreement with each other. The depth of the maximum X_{max} estimated by formula (2) is equal to 848±35 g/cm^2.

7 Conclusion

The Yakutsk complex array has been operating continuously for more than 45 years, measuring electrons, muons and the Cherenkov light of the EAS. At the same time, more than $5{\cdot}10^6$ showers were recorded in the energy region above 10^{15} eV. Since 2009, in a continuous mode, the unit records radio emission from EAS particles at a frequency of 30-35 MHz. The obtained data on radio emission expands the possibilities of an experimental study of the characteristics of showers and compares them with the characteristics obtained for other components of the EAS, as can be seen from Fig. 2 and Fig. 3, these results are in good agreement with the data of other experiments.

Using a large database of experimental data, we analyzed the Cherenkov component of the EAS, namely, the LDF. According to the LDF of the Cherenkov light, the longitudinal development of showers in the energy range 10^{16}-10^{20} eV was reconstructed and the dependence of

X_{max} and $\sigma(X_{max})$ on energy was shown. It is shown that the development of X_{max} with an increase in energy has an irregular course. The rate of displacement of X_{max} per decade for energy ER takes the values 48±6, 78±5, 63±6, 50±7 $g \cdot cm^{-2}$ in the intervals indicated above in the text.

As can be seen, the inflection points fall on the energy of $\sim 10^{17}$ and $\sim 8 \cdot 10^{18}$ eV, i.e. on the "second knee" and "bump-deep".

From this it can be assumed that such a nature of the advancement of X_{max} to sea level is associated with a change in the mass composition of cosmic rays. Comparing the experimental data $\sigma(X_{max})$ with model calculations for different nuclei, we can say that the experiment in Yakutsk indicates a change in the mass composition. Quantitatively, it looks like this: in the region of lower energies, a noticeably larger number of 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.

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