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РЕЗУЛЬТАТЫ ИЗМЕРЕНИЯ РАДИОИЗЛУЧЕНИЯ ЯКУТСКОЙ УСТАНОВКИ В ИНТЕРВАЛЕ ЭНЕРГИЙ $3 \cdot 10^{16}$–$5 \cdot 10^{18}$ эВ

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REGISTRATION RESULTS OF YAKUTSK ARRAY RADIO EMISSION IN THE ENERGY RANGE OF $3 \cdot 10^{16}$–$5 \cdot 10^{18}$ eV

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В работе представлена серия измерений радиоизлучения от ШАЛ сверхвысоких энергий на частоте 32 МГц за период 2008–2012 гг. Ливни отобраны по геомагнитному и азимутальному углам и сгруппированы по энергии в три интервала $3 \cdot 10^{16}$–$3 \cdot 10^{17}$ $3 \cdot 10^{17}$–$6 \cdot 10^{17}$ и $6 \cdot 10^{17}$–$6 \cdot 10^{18}$ эВ. В каждом энергетическом интервале построена средняя функция пространственного распределения по математически усредненным данным с антенн разной направленности.

По экспериментальным данным построены зависимости усредненной амплитуды радиосигнала от геомагнитного угла, расстояния до оси ливня и энергии ШАЛ. Используя расчеты по модели QGSJET и форму средних функций пространственного распределения радиосигнала, найдена оценка глубины максимума развития ШАЛ $X_{\max}$ для рассматриваемого интервала энергий.

This paper presents the set of measurements of ultra-high energy air shower radio emission at frequency of 32 MHz in 2008–2012. The showers are selected by geomagnetic and azimuth angles, and then they are grouped by the energy into three intervals: $3 \cdot 10^{16}$–$3 \cdot 10^{17}$ eV, $3 \cdot 10^{17}$–$6 \cdot 10^{17}$ eV and $6 \cdot 10^{17}$–$6 \cdot 10^{18}$ eV. In each energy interval, average space distribution function is plotted with the use of mathematically averaged data from antennas of different directions. Using experimental data the dependences of averaged radio signal amplitude on geomagnetic angle, the shower axis distance and shower energy are determined. From QGSJET model and the shape of average space distribution functions of radio signal, the depth of maximum ($X_{\max}$) of shower evolution for the given energy range is evaluated.

Introduction

One of the techniques to register ultra-high energy extensive air showers (EAS) is measuring strength of radio pulse by antennas. Unlike traditional techniques, including optic measurements of air shower propagation radio technique can operate in any atmospheric condition except during thunderstorm conditions for whole observation period, which dramatically increases effective time of air showers registration. It is easier to use and much cheaper than other ground detectors in existing air showers array.

The Yakutsk array measured three components of air shower: the total charged component, the muon component and Cherenkov radiation. From these components using average lateral distribution function (LDF) the integral characteristics of air shower, the total number of charged particles, the total number of muons and full flux of Cherenkov light at the sea level are recovered. All these shower characteristics are used for further model-free air shower energy estimation as shown in [Кнуренко и др., 2006]. Cherenkov light registered at the sea level moreover is used to recover air shower longitudinal distribution and it characteristics, cascade curve and depth of maximum $X_{\max}$ [Knurenko et al., 2001; Knurenko, Sabourov, 2011]. Using this, in future is possible to find a relation between the characteristics of the radio emission and characteristics of the EAS, including slope of the radio emission LDF with depth of maximum, as shown in [Huege et al.; http://arxiv.org/pdf/0806.1161.pdf].

Radio event selection for analysis

For the season 2009–2012 were recorded 600 air shower events with radio emission. Showers energy were above $3 \cdot 10^{16}$ eV, and zenith angle $\theta \leq 70°$. For further analysis were selected only 421 showers, appropriate selection criteria of this paper. Therefore, for analysis at Yakutsk array we use following criteria:

1. The shower selected if ADC prehistory contains radio pulse with amplitude 5 times more than noise level and pulse is localized within time gate equal to delay of "master" from small or large arrays.
2. Extensive air shower axis must be within perimeter of central array with radius 600 m. Zenith angle $\theta \leq 35°$. Azimuth angle φ chosen such a way as to exclude influence of polarization effect. That is, the amplitude of the crossed antennas were equal or weren't go beyond limit (3–5) %.

With selected events, we plotted dependence of maximum amplitude of radio pulse from zenith angle (Fig. 1). Approximation curve is given by power function:

$$\varepsilon_{EW}=(0.81\pm0.25)(1-\cos\theta)^{(1.16\pm0.05)}\ [\mu V/m/MHz]. \quad (1)$$

In Fig. 2 is shown dependence of maximum amplitude of radio signal from shower energy.

Approximation is given by:

$$\varepsilon_{EW}=(1.3\pm0.3)(E_0/10^{17}\ eV)^{(0.99\pm0.04)}\ [\mu V/m/MHz] \quad (2)$$

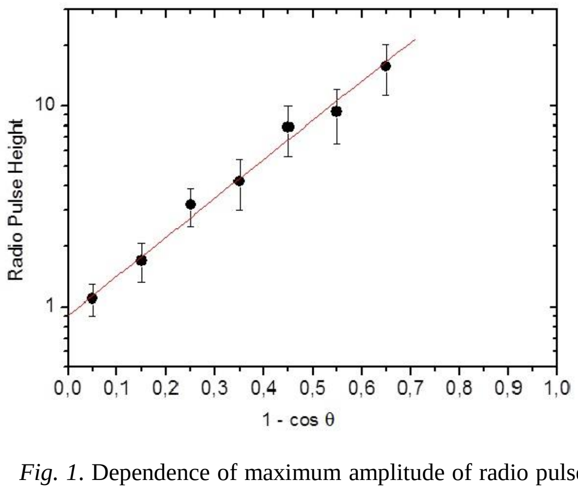

Fig. 1. Dependence of maximum amplitude of radio pulse from zenith angle.

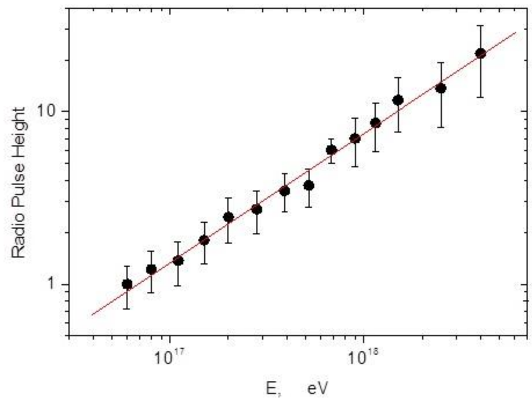

Fig. 2. Dependence of maximum amplitude from shower energy.

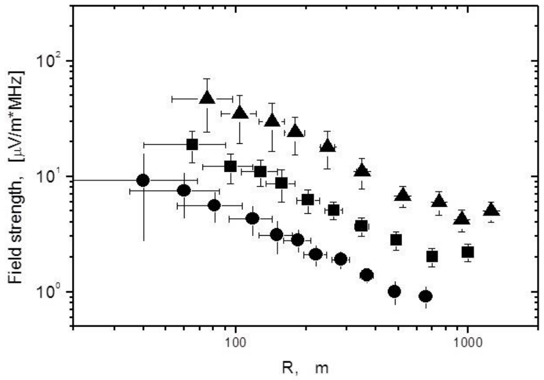

Fig. 3. Average lateral distribution function of radio emission at frequency 32 MHz in showers with energy $1.73 \cdot 10^{17}$, $4.38 \cdot 10^{17}$ and $1.32 \cdot 10^{18}$ eV.

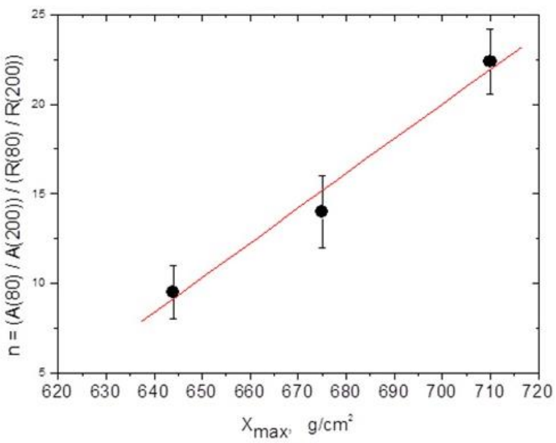

Fig. 4. Dependence of air shower radio emission LDF slope n from depth of air shower maximum X_{max}. The slope was determined from the ratio of the amplitudes, taken at 80 and 200 m using averaged LDF and X_{max} from Cherenkov light measurements.

As seen from Fig. 3, slope of LDF changes with the distance. At large distance signal of radio emission attenuates slowly. From equation (1) and (2) we derived formula for calculating energy in individual showers:

$$\varepsilon=(15\pm1)(1-\cos\theta)^{1.16\pm0.05}\times \exp(-R/(350\pm25.41))(E_p/10^{17})^{0.99\pm0.04}, \quad (3)$$

where θ is the zenith angle, R is the distance of antennas to the shower axis, E_p is the primary particle energy.

In Fig. 4 dependence of radio emission LDF from depth of the air shower maximum. The depth was determined by Cherenkov detectors measurements of Yakutsk array. The slopes were determined from the ratio of the amplitudes, taken at 80 and 200 m (Fig. 3) for three energies $1.73 \cdot 10^{17}$, $4.38 \cdot 10^{17}$ and $1.32 \cdot 10^{18}$ eV.

Conclusion

Yakutsk array measurements are showing: a) there is a correlation between measured maximum amplitude of radio signal and air shower energy determined measurements of the main components at observation level. It follows from the formula (2) derived empirically from the joint consideration of radio signal amplitude and EAS energy; b) the shape of LDF depends on the depth of air shower maximum X_{max} (Fig. 4).

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