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Radio emission of air showers with energy E$\geq 10^{19}$ eV registration results at frequency 30-35 MHz by the Yakutsk Array data.

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The paper presents results obtained from radio emission measurements at frequency 30-35 MHz from air shower particles with energy E$\geq 10^{19}$ eV. The data obtained at the Yakutsk array, for 1986-1989 and 2009-2014 years. The generalized formula for the description of the lateral distribution of radio emission was derived with use of fundamental characteristics of air showers: energy E_0 and air shower depth of maximum development X_{max}.

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1. Introduction

The method of registration of radio emission of ultrahigh energy particles is based on the motion of charged particles in the geomagnetic field [1, 2] and Askaryan effect [3]. Both generation mechanisms are effective in passing air shower particles through the atmosphere. Their contribution to the generation of radio emission depends on the conditions of the shower development in the atmosphere: height of the shower maximum, zenith angle of the incoming shower and energy. Influence from both mechanisms affects the symmetry of the lateral distribution of air showers radio emission as shown from the experiments. This is especially noticeable at small distances from the shower axis, where the radio emission intensity decreases significantly.

This method allows not only to estimate the energy, but also to reconstruct the track of the longitudinal development of the shower, namely, the depth of the maximum development of the EAS X_{max} [4, 5]. In this sense, the radio emission of EAS can be used for mutual calibration with respect to the energy of large ground arrays [6, 7, 8].

2. The Yakutsk array

The Yakutsk array registers showers with an energy of 10^{15}-10^{20} eV on an area of 12 km^2. The time resolution of the coincidence circuit is 2 μs. Selection of air shower events is carried out with the simultaneous triggering of three neighboring stations forming a triangle. When the trigger signal is produced, the data from all stations and detectors connected to the central station sent to the central station. Information from stations and commands from the center at the station is transmitted over the fiber optic link. A muon component, a charged component, Cherenkov radiation [9, 10] and radio emission [11] are measured at the Yakutsk array.

2.1 Methods and techniques of measurements

In early 2009, at the Yakutsk array, the radio array was reconstructed [12]. It consists 12 crossed at 90 ° receiving antennas (6 pillars with 2 antennas each) oriented in directions W - E (West - East), N - S (North - South), the peripheral recording device (PRD) and data storage on a personal computer. PRD was located directly at the antenna field. The antenna field is located close to the main center of Yakutsk array and consists two independent clusters, synchronized by GPS system. The spacing between antennas was 50 m, 100 m and 500 m. Antennas located at a distance of 50-100 m from ground stations with scintillation detectors.

Antennas that used to register high-frequency signals are shown in Fig. 2.

The bandwidth of the bandwidth at the level of 0.7 was ±4 MHz, the sensitivity was ∼10 μV (2 $\mu V \cdot m^{-1} MHz^{-1}$), the dynamic range of the amplifier was 50 dB. Receiving channels are based on the principle of direct signal amplification and subsequent detection. The main paths are based on the cascade amplification circuit with mismatched contours. As a recorder computer, IBM PC / AT type was employed. We used fast 8-bit LA n10M8PCI as an ADC with sampling frequency 100 MHz. The location of antenna sets is shown in Fig. 1.

Registration of radio emission is triggered by one of two event triggers from the Yakutsk array. The first of the two possible triggers is the main Yakutsk array trigger, which registers in an area of

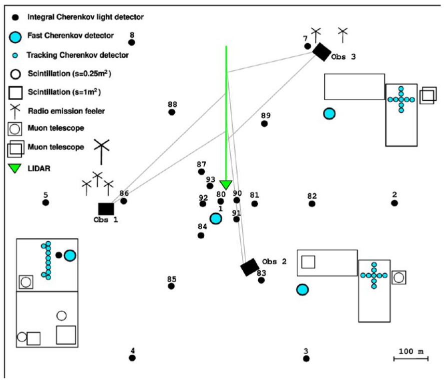

Figure 1: Arrangement of observation stations at the Small Cherenkov array

Figure 2: Radio antenna at the Yakutsk array.

12 km^2 showers with energy more than 10^{17} eV. The Small Cherenkov array (Fig. 1) registers in an area of 1 km^2 showers with energy 10^{15}-5·10^{17} eV [13].

Calibration of radio channels is performed by applying the calibration of radio pulses at the input of antenna amplifiers. signal duration was 200 ns, 32 MHz frequency filling. Calibration pulses are passed through the entire path and recorded in digital form on the hard disk along with the experimental data.

3. Air showers with energy higher than 10^{19} eV

Fig. 3 shows an example of the radio pulse of one of the strongly inclined showers with an energy of $\sim 3 \cdot 10^{19}$ eV [14]. Fig. 4 shows the spatial distribution of radio signals recorded in several showers with energies above 10^{19} eV. Most of the showers have energies of 10^{19}-3.5·10^{19} eV, and two showers with energies above 10^{20} eV [15]. The points are normalized to the mean energy $< E_0 >$ = 1.54 · 10^{19} eV, to the mean zenith angle $< \theta >$ = 43.1 ° and are presented on a logarithmic scale. Approximation is given by formula (1). In Fig. 4, some showers (triangles) are significantly higher than other points. These are signals of two showers with maximum energy.

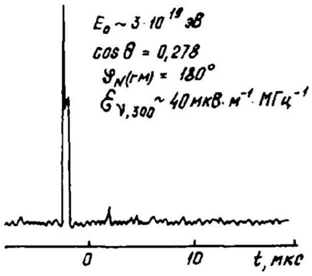

Figure 3: Radio pulse shape with energy $E_0 \sim 3 \cdot 10^{19}$ eV, arrived at zenith angle $\theta \geq 73.9°$.

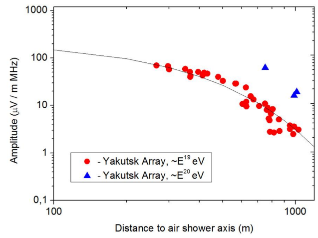

Figure 4: LDF showers with an energy E $\geq 10^{19}$ eV. The points are normalized to the mean energy $< E_0 >$ = 1.54·10^{19} eV, to the mean zenith angle $< \theta >$= 43.1° and are presented in a logarithmic scale

Table 1: List of air showers with energy 10^{19} eV registered by Yakutsk array antennas. Date - is a date of shower registration, θ - zenith angle (degree), ψ - azimuth angle (degree), E_0 âĂŞ energy of primary particle (eV), A_ν âĂŞ radio emission amplitude (μV·m^{-1}·MHz^{-1}), R - distance from air shower axis to antenna (m)

date	θ,deg	ψ, deg	E_0, eV	A_ν	R, m
16.11.86	74	180	3.1·10^{19}	58.0	300
16.12.87	71	178	3·10^{19}	40	367
21.02.88	70	210	10^{19}	3.1, 3.8	1030, 950
09.03.88	36	125	9·10^{18}	6.2	792
07.05.89	59	168	2·10^{20}	62.5	750
10.03.11	51	239	1.1·10^{19}	89, 43, 5.8	350, 413, 604
16.05.11	69	99	1.6·10^{19}	33, 29, 40	501, 564, 479
31.12.11	15	165	1.1·10^{19}	1.2, 1.0, 2.9	950, 980, 860
12.04.12	8	222	1.3·10^{19}	4.1, 2.8, 6.0	762, 785, 626
04.05.13	46	295	1.1·10^{19}	5.3, 6.0, 12	776, 768, 368
12.12.13	15	297	1.2·10^{19}	5.1, 8.4, 3.6	855, 806, 988
03.10.13	21	21	1.1·10^{19}	9.1, 11, 2.7	419, 396, 815
22.03.13	46	4	1.8·10^{19}	41, 48, 78	418, 432, 366
02.01.14	48	207	1.0·10^{20}	16.3, 19.4	1013, 988
22.01.14	47	189	1.1·10^{19}	107.6, 119.6	297, 266
05.02.14	26	343	3.5·10^{19}	3.4, 5.6	671, 627
02.03.14	30	217	1.2·10^{19}	4.9, 6.0, 7.8	782, 749, 708

Table 1 lists the showers with highest energies registered at the Yakutsk array with radio emission. These observations have shown that radio emission generated at 30-35 MHz by particles of cosmic rays with energies above 10^{19} eV exists and is recorded at large distances from the shower axis, up to 1000 m.

$$A = \varepsilon \cdot exp\left(-\frac{R}{R_0}\right) \tag{3.1}$$

where A - radio emission amplitude, ε - the fit parameter(depends on the energy), R - the distance from shower axis to the antenna, R_0 - the slope parameter.

As seen from Fig. 4, the shape of LDF is fitted well by formula (1) only in the range of 50-350 m from the shower axis at greater distances for its approximation, we probably need another exponent.

Fig. 4 shows that slope of LDF increases with energy. Possibly, this change in the slope of LDF is related to the development of X_{max} in the atmosphere. This fact we used to estimate X_{max} by ratio P1 = A1(80)/A2(200) in showers with energy $E \geq 3 \cdot 10^{17}$ eV and P2 = A1(175)/A2(725) in showers with energy $E \geq 3 \cdot 10^{18}$ eV. From long-term data, we found the dependence of radio emission amplitude on zenith angle θ, energy E and depth of maximum development X_{max} [16]. The approximation was chosen by maximum likelihood estimation:

$$\varepsilon = (188.8 \pm 1.6) \left(\frac{E}{5 \cdot 10^{17}}\right)^{0.83 \pm 0.03} \cdot (1.16 - \cos\alpha) \cdot \cos\theta \cdot \exp\left\{-\frac{R}{162 \pm 8 + (84 \pm 3)\left[\frac{X - 675}{100}\right]}\right\} \tag{3.2}$$

From equation (3.2) it follows that radio emission LDF depends on energy E and depth of maximum X_{max}.

4. Conclusion

Long-term observations of the radio emission of EAS at the Yakutsk array proved the existence of radio emission at an energy $E \geq 10^{19}$ eV and this allowed obtaining some characteristics of radio emission at such energies:

- The attenuation function of the EAS radio signal from the distance at an energy of $1.54 \cdot 10^{19}$ eV and its gradient;
- The presence of radio emission of EAS at energies of 10^{20} eV, i.e. in the largest showers recorded at the Yakutsk array [14];
- Significant signal in strongly inclined showers and the influence of the magnetic field on the shape of the LDF, which once again confirms the role of the geomagnetic mechanism in the generation of radio emission [17].

Acknowledgments

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