Extensive air showers of highest energies registered at the Yakutsk array

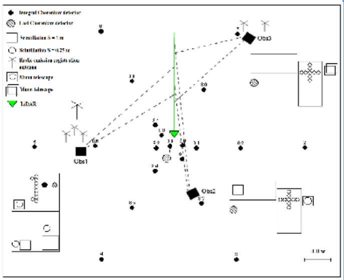
S.P. Knurenko, I.S. Petrov
Yu.G. Shafer Institute of Cosmophysical Research and Aeronomy SB RAS, Yakutsk, Russia
Contact: knurenko@ikfia.ysn.ru

Abstract. The article considers showers produced by primary particles with energies $E_0 \geq 100$ EeV. The showers were registered in the course of continuous long-term observations at the Yakutsk array of extensive air showers. In the present work, the mathematical processing of showers was repeated and the phenomenology of the charged component, muons with threshold $\varepsilon_{thr} \geq 1$ GeV and radio emission in the region of highest energies was refined. The characteristics of cosmic rays are analyzed: the energy spectrum and mass composition determined from the Cherenkov, muon components and radio emission in the energy range 50–200 EeV.

Yakutsk Array

Location: *61°42' N, 129°24' E*; Height: *110 m*
Area of the array: ~*8 km²*; Energy range: $10^{15} \leq E \leq 10^{20}$ eV
58 stations with 120 scintillation detectors $\varepsilon_{thr} \geq 10$ MeV
Spacing: *500 m*
Yakutsk array measures: charged component; muon component; Cherenkov light. radio emission

Small Cherenkov array



Area of array ~1 km². Spacing 50-250 m, 3 tracking Cherenkov detectors at 250, 300 & 500 m from center.

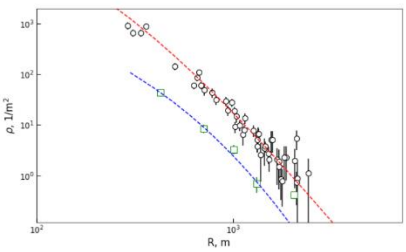
Energy estimation and depth of maximum determination

At the Yakutsk array with detectors spacing 500 and 1000 m, the energy in the shower can also be measured by the muon flux density at distances 600 m from the shower axis. The relationship between the energy E_0 and $\rho_\mu(R=600)$ was found empirically, based on the correlation of energy and muon density at a distance of 600 m from the shower axis

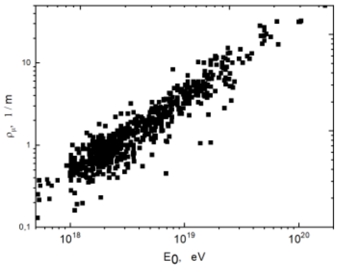
$$\lg E_0 = 18{,}33 + 1{,}12 \cdot \lg(\rho_\mu(R=600))$$

X_{max} determinated by empirical formula:

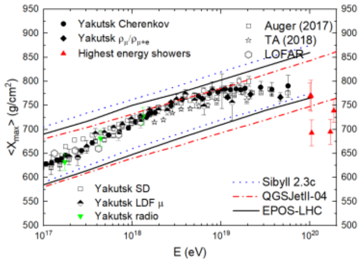
$$X_{max} = (430 + 357 \cdot (\sec\theta - 1)) \cdot \exp\left(-\left(\frac{\rho_\mu}{\rho_{\mu+e}}\right)_\theta / (0.526 + 0.374 \cdot (\sec\theta - 1))\right) + (454 - 75(\sec\theta - 1))$$



Average LDF of charged particles and muons. $\langle E_0 \rangle = 1 \cdot 10^{20}$ eV, $\langle\theta\rangle = 18.5°$,



Correlation of E_0 and classification parameter $\rho_\mu(R=600)$.

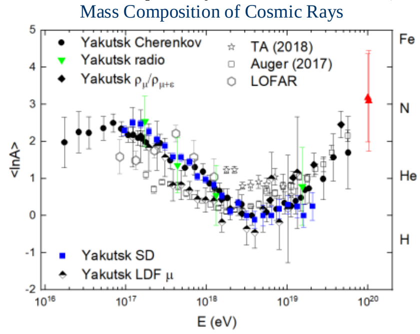


Dependence of X_{max} from air shower energy. Red triangles – air showers with highest energies.

№	Date	$\lg E^\mu_0$	$\rho_s(600)$	$\rho_\mu(600)$	$\rho_\mu / \rho_{\mu+e}$	θ, °	X_{max}	$\lg N_s$	$\lg N_\mu$
1	21.12.77	20,02	56,8	32,3	0,56	49,5	693±27	9,43	8,23
2	15.02.78	20,01	168,3	31,6	0,19	9,6	770±32	10,41	8,38
3	07.05.89	20,28	73,6	54,0	0,73	59,3	739±24	8,52	8,69
4	13.01.95	20,00	120,1	31,5	0,26	27,4	768±28	10,16	8,33
5	18.02.04	20,23	85,8	49,9	0,58	49,8	695±26	9,68	8,42

The characteristics of the showers, reconstructed from the analysis of the radial development of particles at sea level, are presented in Table. The date of registration of the showers, the energy determined from the parameter $\rho_\mu(600)$, the zenith angle θ, the depth of maximum development of the shower X_{max}, and the total number of charged particles N_s and muons are indicated N_μ. The classification parameters $\rho_{\mu+e}(600)$, $\rho_\mu(600)$ have been measured most accurately. Their relative errors are 0.15–0.18 and 0.17–0.20, respectively. The errors in N_s and N_μ are 30-35%.

Mass Composition of Cosmic Rays



Within the framework of the selected QGSjetII-04 model we estimated mass composition using interpolation method for cosmic rays of highest energies. According to the QGSjetII-04 model, vertical showers are formed by CNO nuclei. The depth of the maximum of strongly inclined showers lies within the depths of 700–750 g·cm^{-2}, and this corresponds to nuclei of a larger atomic weight than the iron nucleus. If we assume that the models do have a deficit of muons at such energies, then all showers could be formed by CNO-type nuclei or iron nuclei. In this case, it can be argued that the particles behind the break in the spectrum at the energy $E_0 \geq 50$ EeV are heavy nuclei.

Summary

At the Yakutsk array, thanks to long-term observations, it was possible for the first time to register showers with an energy of $E_0 \geq 100$ EeV. In the showers, the electron-photon component, muons with a threshold $\varepsilon_{thr} \geq 1 \cdot \sec\theta$ GeV, Cherenkov and radio emission. Their phenomenological characteristics, radial and longitudinal development, including the spatiotemporal characteristics of signals in scintillation detectors from shower particles of different masses are studied. Vertical and strongly inclined showers are considered, and it is noted that strongly inclined showers consist of high-energy muons. If we ignore all possible inaccuracies in the course of calculation and processing of artificial showers, as well as experimental errors, the model has a lack of high-energy muons, i.e. there is a muon deficit in the QGSjetII-04 model. The estimate of the mass composition obtained from showers with $E_0 \geq 100$ EeV confirms the tendency for an increase in the number of heavy nuclei in the flux of primary cosmic radiation particles at such energies. The characteristics of the largest showers given in Table indicate that the showers are produced by heavy nuclei.

References:
[1] M.N. Dyakonov et al. Bull. of AS USSR ser. Phys. 50, 2168 (1986); [2] N.N. Kalmykov and S. Ostapchenko. Sov. J. Nucl, Phys. **50** (1989) (2) 315; [3] J. Engel, T.K. Gaisser, T. Stanev, and P. Lipari. Phys. Rev. D46 (1992) 5013 – 5025; [4] S. Octapchenko. Phys. Rev. D74 (2006) 014026; [5] E..G. Berezhko, S.P. Knurenko, L.T. Ksenofontov. Composition of cosmic rays at ultra high energies. //Astroparticle Physics **36** (2012) pp. 31-36; [6] M. Takeda et al., Phys. Rev. Lett., **81**, 1163 (1998); [7] Kichigin, G.N. JETP. 2001. V. 119, No. 6. P. 1038–1049; [8] G.I. Rubtsov, S.V. Troitsky, Nature 11, 2011; [9] S.P. Knurenko, I.S. Petrov, JETP Lett. 107, 709-716 (2018); [10] O. E. Kalashev, G. I. Rubtsov, S. V. Troitsky, Phys. Rev. D80, 103006 (2009); [11] Knurenko, S.P., Ivanov, A.A., Sleptsov, I.E. *et al. JETP Lett.* **83**, 473–477 (2006); [12] Иванов А.А., Кнуренко С.П., Слепцов И.Е. ЖЭТФ, 2007, v.131, № 6, c. 1001 – 1017; [13] A.V. Glushkov, M.N. Dyakonov, T.A. Egorov et al. Bull. of RAoS. Ser. Phys. 57, 91-93 (1993); [14] Knurenko S.P., Kolosov V.A. et al. Nuclear Instruments and Meth-s in Phys. Rec. Amst., A48 (1986), v.4, p. 224-226; [15] Knurenko S.P., Kolosov V.A., Petrov Z.E. // Proc. 27-th ICRC, Hamburg (Germany), 2001, v.1, p.157- 160; [16] Garipov, G.K and Khrenov, B.A. // J. Phys. G: Nucl. Part. Phys, 20, 1981 – 1988; [17] G.K. Garipov, V.M. Grigoryev, N.N. Efimov et al. // Proc. 27th ICRC. Hamburg. 2001. V. 3. P. 885; [18] S. P. Knurenko† and I. S. Petrov. PRD **102**, 023036 (2020); [19] S. Knurenko and I. Petrov. EPJ Web of Conference **208**, 08017 (2019); [20] S. Ostapchenko. PRD **83** (2011) 014018; [21] S. Thoudam, J.P. Rachen, A. van Vliet, A. Achterberg, S. Buitink, H. Falcke, J.R. Horandel. A&A, **595**, A33 (2016); [22] H. P Dembinski et al. PoS, ICRC2017:533, 2018; [23] Dennis Soldin for the EAS-MSU, IceCube, KASCADE-Grande, NEVOD-DÉCOR, Pierre Auger, SUGAR, Telescope Array, and Yakutsk Array Collaborations. PoS 395, 349 (2022); [24] A.A. Watson. EPJ Web of Conferences **283**, 02014 (2023)