Composition of cosmic rays with energy more than 0.1 EeV by long-term optical observations of Cherenkov emission at Yakutsk array

ISCRA 2019
International Symposium on Cosmic Rays and Astrophysics
25 – 28 June 2019, MEPhI, Moscow, Russia

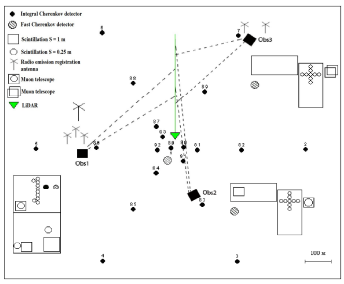
S.P. Knurenko, **I.S. Petrov,**
Yu.G. Shafer Institute of Cosmophysical Research and Aeronomy SB RAS, Yakutsk, Russia
Contact: igor.petrov@ikfia.ysn.ru, id: 2.6

Abstract. The paper presents results on longitudinal development of air showers with ultra-high energies (X_{max}) and mass composition of cosmic rays <ln$A$>. The data is obtained from observations of Cherenkov emission at the Yakutsk array in 1974-2014. Cascade curves of individual showers reconstructed by lateral distribution of Cherenkov light and depth of maximum X_{max} analyzed in energy region 10^{16}-5.7·10^{19} eV. It is shown that elongation rate dX_{max}/dE in the atmosphere has irregular nature and depends on energy. Such behavior indicates change of mass composition and is confirmed by fluctuations σ(X_{max}) in the energy region. Composition of cosmic ray is determined by interpolation of hadronic interaction QGSJetII-04 model.

Yakutsk Array

Location: *61°42' N, 129°24' E;* Height: *110 m*
Area of the array: *~8 km²*; Energy range: *10^{15}≤E≤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.

Air shower parameters reconstruction

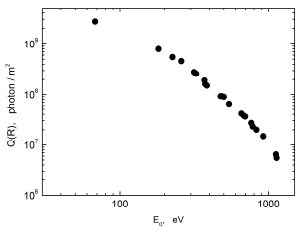
To determine the depth of maximum X_{max} we used cascade curve, which is reconstructed from the experimental function of Cherenkov light LDF.

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

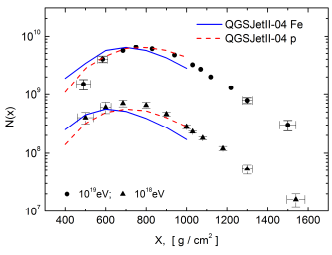
The energy E_0 is estimated by formula:

$E_0 = (1{,}78 \pm 0{,}44) \cdot 10^{17} \cdot (Q(200) / 10^7)^{(1{,}01 \pm 0{,}04)}$

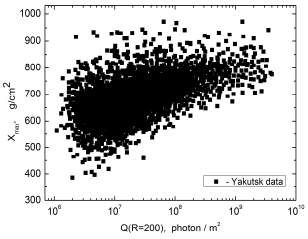
Q(200) – density of the Cherenkov light flux at a distance of 200 m.



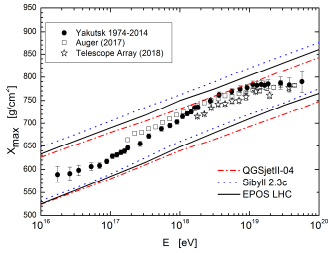
Cascade curve of the individual shower. $E_0 = 1.3 \cdot 10^{19}$ eV, θ = 25°, X_{max} = 738 g/cm²



Average experimental cascade curves and simulations of QGSJetII-04 for proton and iron nucleus.

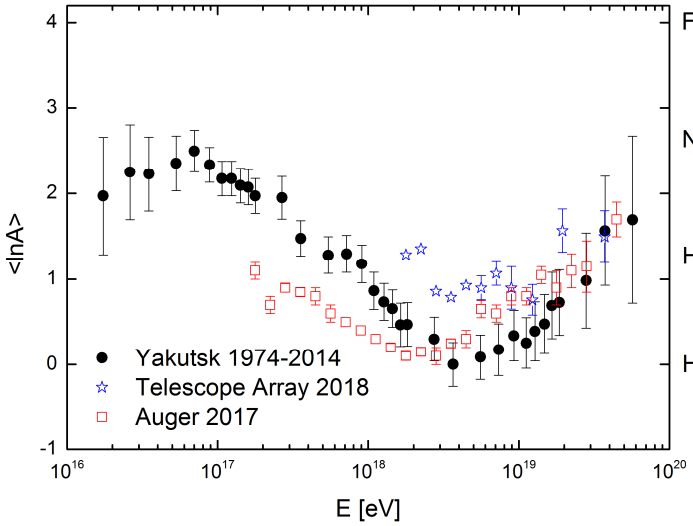


Dependence of X_{max} on classification parameter Q(200).



Comparison of the experimental data obtained for at the Yakutsk array

Mass Composition of Cosmic Rays



Knowing the depth of maximum X_{max} for the proton and iron nucleus from the simulation model QGSJetII-04, the value of <ln$A$> can be determined by interpolation method:

$$<\ln A> = \frac{X^{exp}_{max} - X^{p}_{max}}{X^{Fe}_{max} - X^{p}_{max}} \cdot \ln A_{Fe}$$

Where X^{exp}_{max} – depth of maximum, from the experiment, lnA_{Fe} – logarithm of iron atomic weight.

Summary

The Yakutsk array has been operating more than 45 years continuously, measuring electrons, muons, Cherenkov and radio radiation. With more than 5·10^6 events of air showers in the region above 10^{15} eV were registered. Using a large database of experimental data, we analyzed the Cherenkov component of air showers, namely, the LDF. From LDF longitudinal profile was reconstructed in the energy range of 10^{16}-10^{20} eV and dependence of X_{max} on energy was derived. It is shown that X_{max} advancement has irregular course. The displacement rate of Xmax on decades of energy ER is equal to: 48±6, 78±5, 63±6, 50±7 g/cm². As break points are on energies ~10^{17} eV and ~5·10^{18} eV, i.e. on the regions of "second knee" and "bump - deep" it can be assumed that such advancement of X_{max} is related with MC CR change. As MC estimation in the energy region 10^{16}-10^{20} eV shown: in the lower energies there are more particles with atomic weight of 4–56, at energies 10^{17} – 10^{18} eV proton fraction reaches its maximum and is equal to 60–80 %, further it gradually decreases and in energy range of 10^{19}– 10^{20} эВ CR are consists of He, CNO and heavier nuclei.

Acknowledgment. The reported study was funded by RFBR according to the research project 16-29-13019

References:
[1]V.P. Zrelov. *Vavilov-Cherenkov radiation and it's application in high-energy physics. Part 1*. (Atom, Moscow, 1968); [2] J.V. Jelley. *Cerenkov radiation and its applications* (Pergamon Press, London, 1958); [3] V.P. Artamonov, et al., Bull. of RAoS. Physics. **58**, 92 (1994); [3] S. Knurenko et al., Sci. and Edu. **4**, 46-50 (1998); [4] G.K. Garipov et al., Proc. 27th ICRC, p. 885-887 (2001); [5] A.A. Ivanov et al., NIM A **772**, 34-42 (2015); [6] Y.A. Egorov et al., PoS (ICRC2017), **301**, 462 (2018); [7] M. Dyakonov et al., Atmos. Oceanic. Optic. **12**, 315 (1999); [8] V.E. Zuev. *Atmospheric transparency in the visible and the infrared* (Israel Program for Scientific Translations, Jerusalem, 1970); [9] M.N. Dyakonov et al., Optics of atmosphere **4**, 868–873 (1991); [10] S.P. Knurenko et al., Proc. of SPIE, **6522**, 65221U (2006); [11] S.P. Knurenko et al., Proc. of SPIE. **9292**, 92925B (2014); [12] S.P. Knurenko et al., NIM A, **866**, 230 (2017); [13] S.P. Knurenko et al., Proc. 27-th ICRC, Hamburg (Germany), **1**, 157 (2001); [14] M.N. Dyakonov et al., NIM A **248,** 224 (1986); [15] A. Kochnev. Proc. of "Use of PC in control problems", 62-71 (1985); [16] A.N. Tikhonov and V.Ya. Arsenin, *Methods for Solution of Ill-Posed Problems* (Winston, New York, 1977); [17] S.S. Ostapchenko. Phys. Rev. D. **83**, 014018 (2011); [18] S. Knurenko et al., JETP Lett. **83** (11) (2006) 473-477; [19] J. Bellido et al., Proc. of Science **301**, 506 (2018); [20]S. Ostapchenko, Phys. Rev. D, **83**, 014018 (2011); [21]R. U. Abbasi et al., ApJ, **858**, 76 (2018); [22] R. Ulrich and L. Cazon, Astropart. Phys. **38**, 41-45 (2012); [23]F. Riehn et al., , Proc. of Science, **236**, 558 (2016); [24] T. Pierog et al., Phys. Rev. C, **92**, 034906 (2015) [25]E.G. Berezhko et al., Astropart. Phys. **36**, 31-36 (2012) [26]J. Hörandel. J. Phys.: Conf. Ser. **47**, 41 (2006); [27]R.U. Abbasi et al., Phys. Rev. D, **99**, 02002 (2019).