The depth of maximum shower development and its fluctuations: cosmic ray mass composition at $E_0 \geq 10^{17}$ eV

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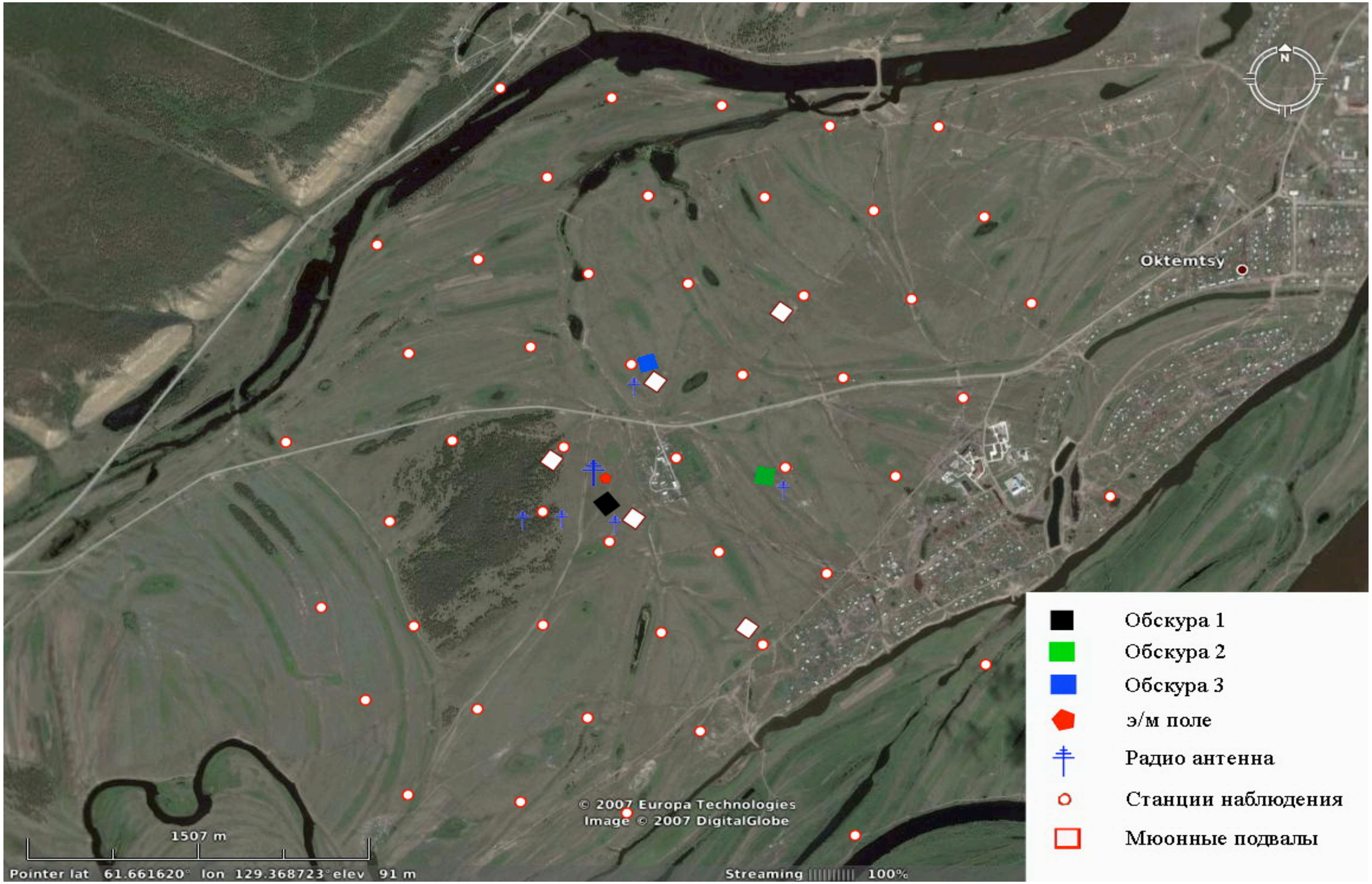
Abstract. We present new data on Cherenkov light observations obtained during 1994-2009 period, after a modernization of the Yakutsk EAS array. A complex analysis of $x_{\max}$ and its fluctuations $\sigma(x_{\max})$ was performed in a wide energy range. With the new data, according to QGSJet II model, an estimation was made of cosmic rays mass composition for $E_0 \sim 10^{17} - 3 \times 10^{19}$ eV. The result points towards a mixed composition with a large portion of heavy nuclei at $E_0 \sim 10^{17}$ eV and the dominance of light nuclei at $E_0 \sim 10^{19}$ eV. The analysis of $\sigma(x_{\max})$ energy dependence for the same energies qualitatively confirms this result. A shape of $x_{\max}$ distribution at fixed energy 10^{18} eV is analysed to make more precise conclusion on cosmic ray mass composition.

Plan of the Yakutsk Array



Technical aspects of longitudinal EAS development characteristics estimation

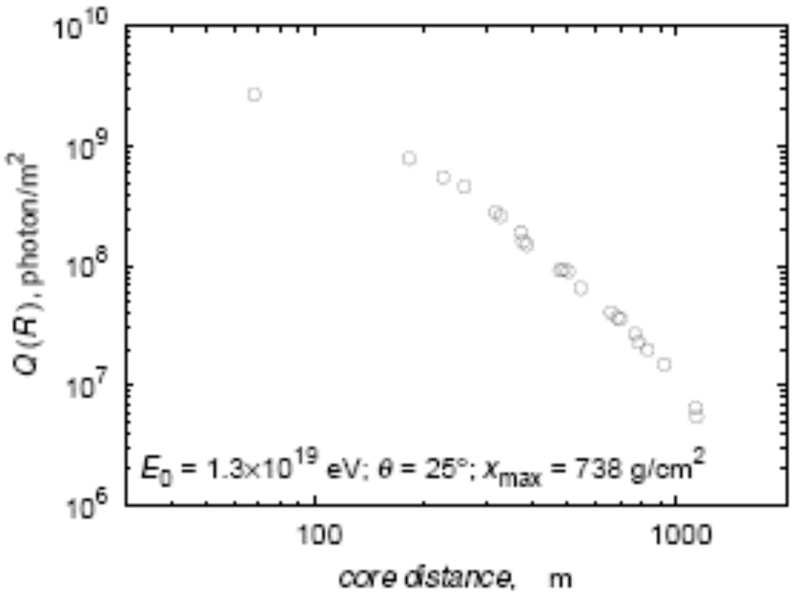


Fig. 1. Estimation of $x_{\max}$ by parameter $p = \lg Q_{200}/Q_{550}$

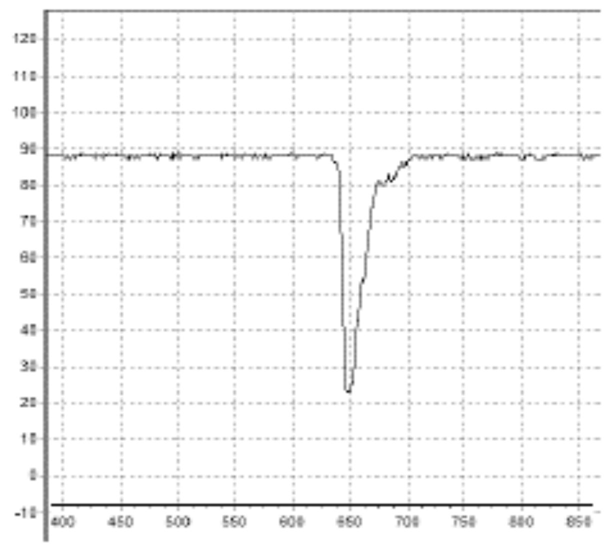


Fig. 2. Estimation of $x_{\max}$ by half-width and half-height of Cherenkov pulse $\tau_{1/2}$

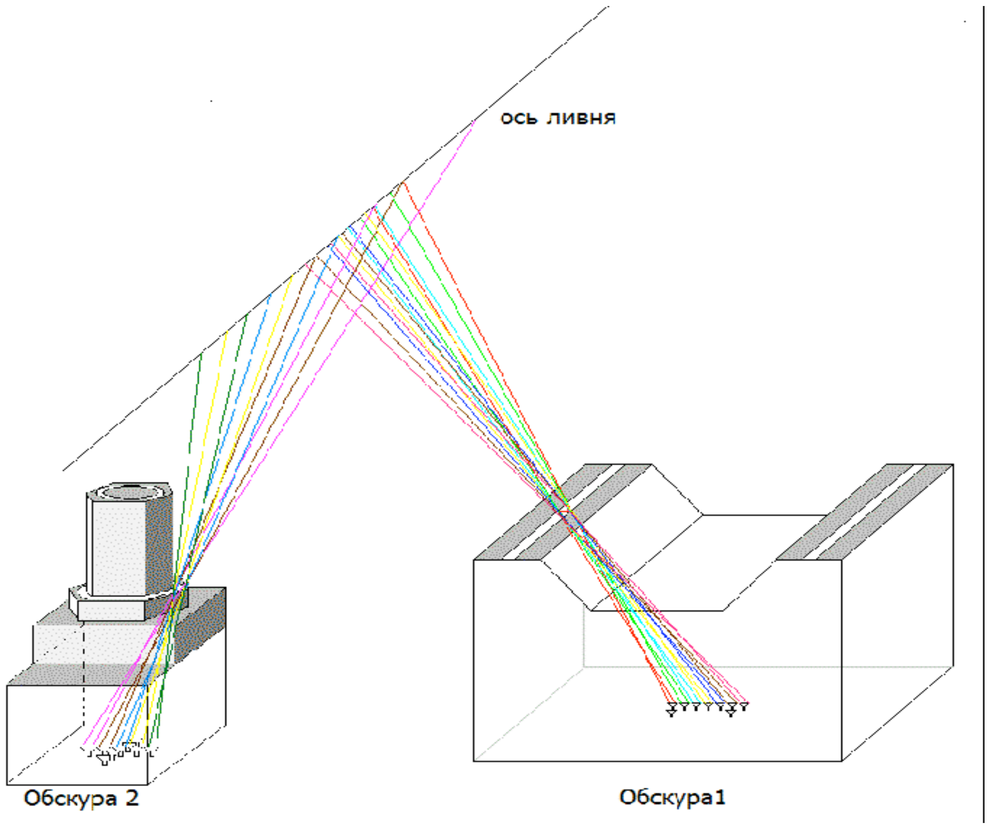


Fig. 3. x_{max} estimation by signals from different atmospheric depths recorded with tracking Cherenkov detectors

Mean depth of maximal shower development

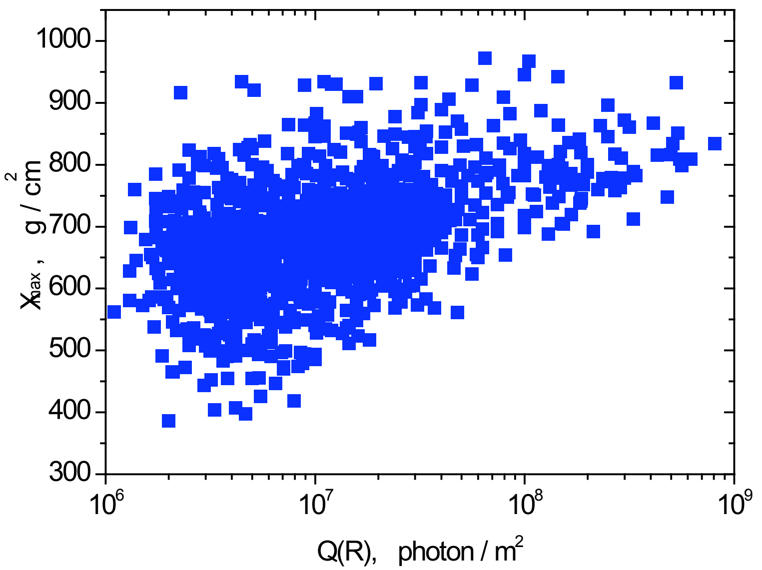


Fig. 4. Individual EAS events detected in Yakutsk experiment during 1994 – 2009.

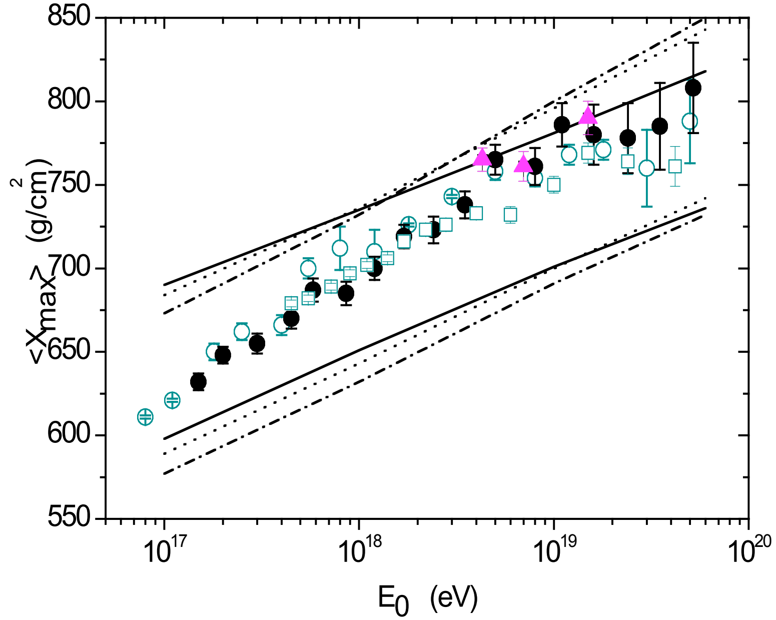


Fig. 5. Energy dependence of x_{max}. Filled circles represent Yakutsk data open circles — CASA-MIA, squares — AUGER data. Solid lines — results obtained with QGSJet II, dashed — EPOS 1.6, point line — SIBYLL 1.62

Fluctuations of x_{max}

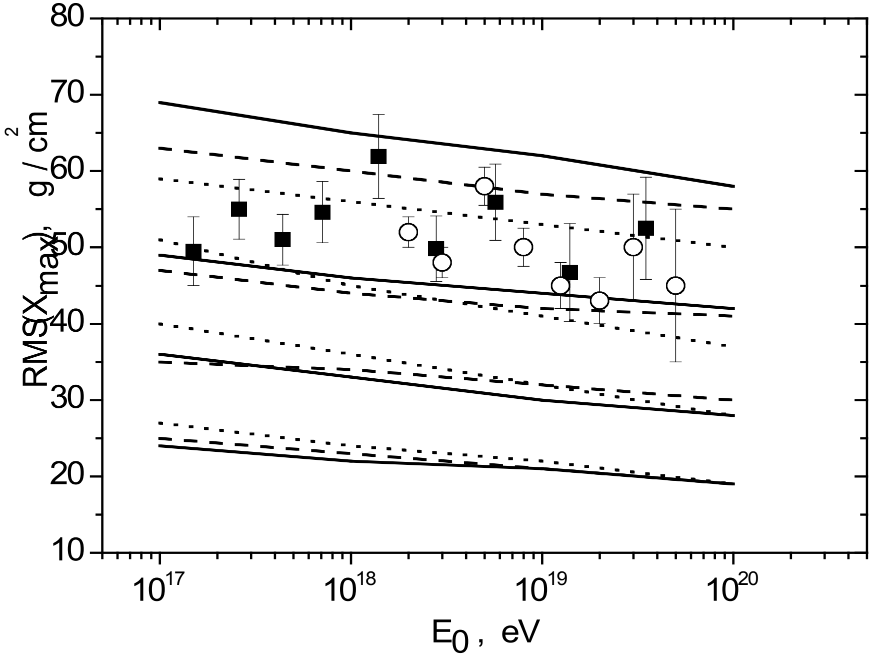


Fig. 6. Fluctuations of the depth of maximum EAS development: filled squares — Yakutsk data, open circles — HiRes data. Straight line — results obtained with QGSJet01, dashed line — QGSJet II, dotted line — SIBYLL 1.62 for various primary nuclei (see Abbasi et al (2009))

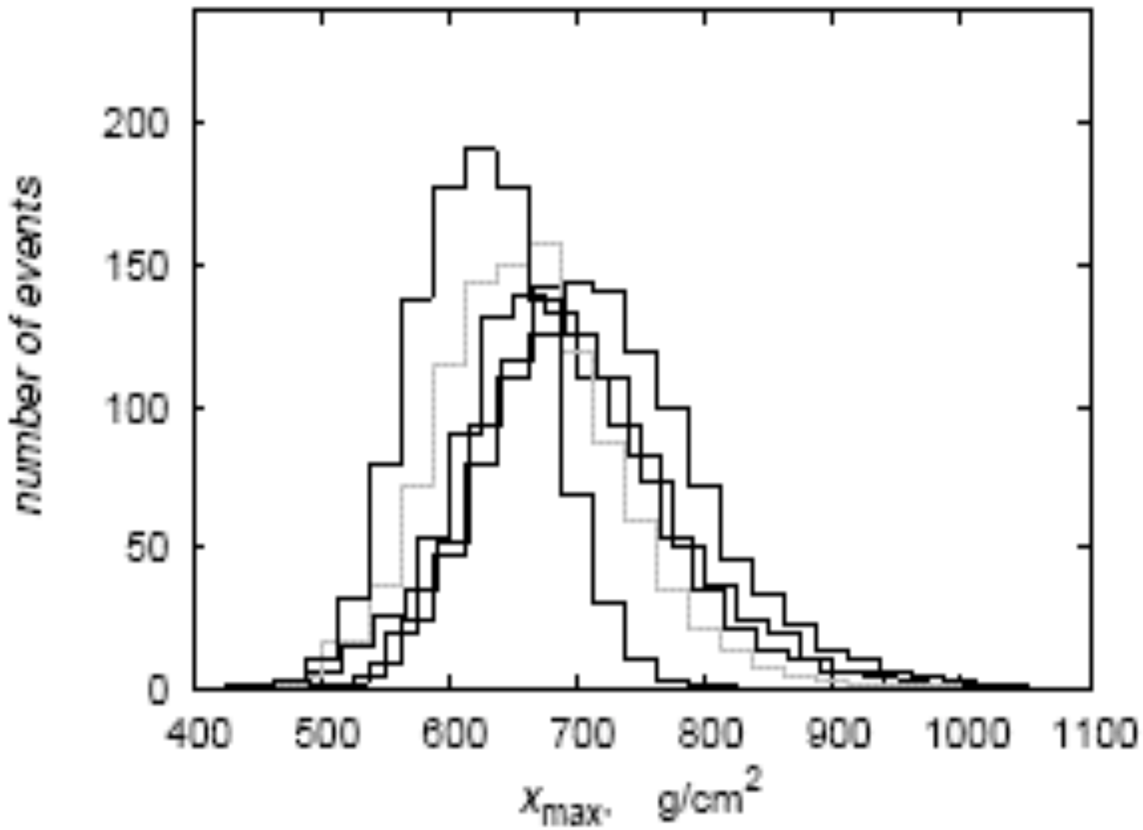


Fig. 7. $x_{\max}$ distribution at fixed energy 10^{18} eV. Solid line represents Yakutsk data ($8 \times 10^{17} < E_0 < 2 \times 10^{18}$ eV, $\langle E_0 \rangle = 1.0 \times 10^{18}$ eV, 857 events); dotted line — QGSJet01 for mixed composition (70 % p, 30 % Fe); dashed line — QGSJet01 for primary protons, solid grey line — QGSJet01 for CNO group nuclei, dash-dotted line — QGSJet01 for iron nuclei (see Knurenko et al (2005))

Cosmic ray mass composition

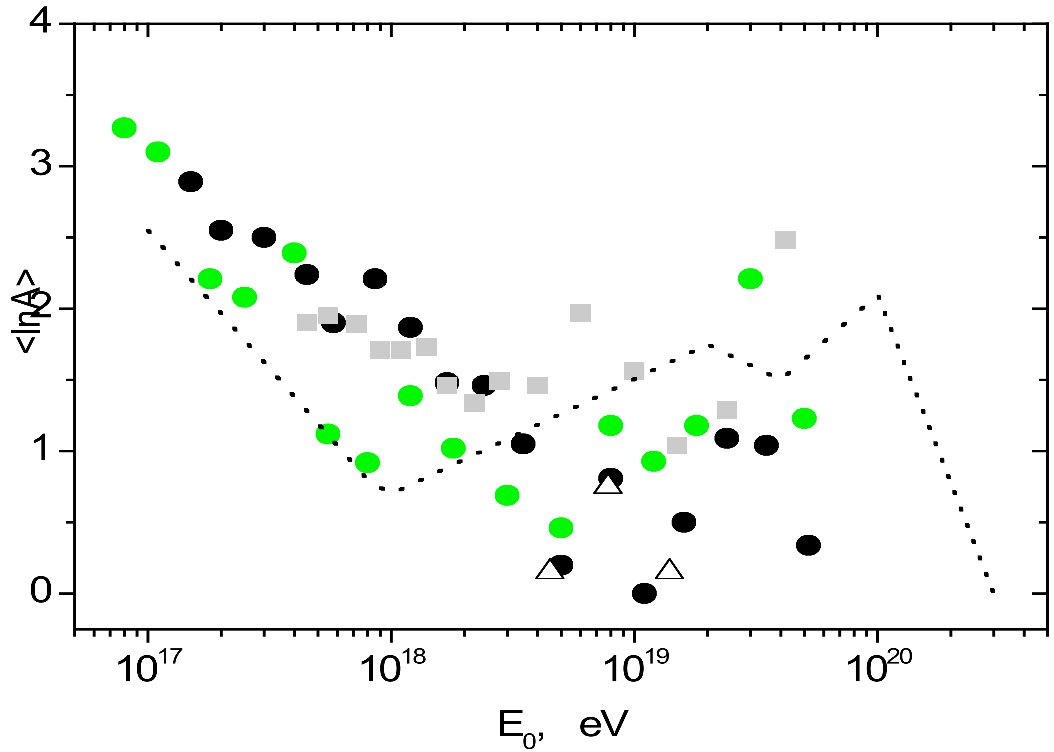


Fig. 8. Mean mass number of primary particle as a function of energy. Circles represent Yakutsk data, triangles — HiRes data, squares — results obtained at Auger observatory

Conclusions

Thus, according to all the data reviewed above, within the framework of QGSJet hadron interaction model it is reasonable to speculate that primary cosmic ray mass composition alters during energy transition from 10^{17} eV to 5×10^{18} eV. At $E_0 \geq 5 \times 10^{18}$ eV cosmic rays by $\sim 70\,\%$ consists of protons and helium nuclei. The content of other nuclei in the region of ankle of the spectrum does not exceed $\sim 30\,\%$. Large portion of protons and helium nuclei in primary CR near the ankle is most likely associated with significant contribution from particles arriving outside our Galaxy. In such a case the region of transition from galactic to extragalactic component might be the energy interval $10^{17} - 10^{19}$ eV. The problem of mass composition altering above 10^{19} eV remains unresolved due to poor event statistics.