Mass Composition of Cosmic Rays at Ultra High Energies by Yakutsk Data

Stanislav Knurenko and Igor Petrov
Yu. G. Shafer Institute of Cosmophysical Research and Aeronomy SB RAS, Lenin ave. 31, Yakutsk, Russia
E-mail: knurenko@ikfia.sbras.ru, igor.petrov@ikfia.sbras.ru

Abstract. The paper describes methods for the analysis of cosmic rays mass composition and results for over a large time span. The data were obtained at Small Cherenkov array over 20 year period of continuous observation and 40 - years of observations at the main Yakutsk array. The experimental data indicates changes in the MC in the energy range 10^{16} - 10^{18} eV which confirmed by results obtained by other EAS arrays.

1. Introduction
In this review, we used Yakutsk group work in which MC at ultra-high energies estimated [1 - 5]. In these studies characteristics of longitudinal and lateral development of EAS were analyzed and reconstructed according observations at the Yakutsk array. This primarily refers to measurements of Cherenkov light of EAS and muons with a threshold energy ≥ 1 GeV. These components considered to be most sensitive air shower characteristics to atomic weight on the basis of obtained results. The results were obtained using different models of hadronic interactions [6 - 8].

One can assume that all presented results on the mass composition are rather indicative, because its are not direct but indirect measurements of the mass composition and depend on many factors: 1) the accuracy of the measurement of the basic characteristics (they are all different for different arrays), 2) the conditions of registration, the techniques used, mathematical processing and selection of events, 3) and, finally, from a large uncertainty in the choice of a single model of hadron interactions to describe the development of extensive air showers at ultrahigh and, especially in the region of huge energies.

However, it is necessary to make the estimation of CR mass composition in the region of ultrahigh energies and compare these results with direct measurements, so called normal composition, which obtained at high energies from satellite and balloon measurements. This leads to a refinement of our knowledge of the nature of cosmic radiation and a better understanding of the physics of EAS development in the field of the highest energies.

2. Mathematical methods of analysis and results.
2.1. The method of joint analysis of the average characteristics of the longitudinal development of EAS and their fluctuations: \(X_{\text{max}}, \sigma(X_{\text{max}}), dE/dX_{\text{max}}\)
In paper [1] was suggested that composition of primary particles consist of a mixture of protons and iron nuclei. The analysis also used the superposition hypothesis, it was assumed that the
collapse of the primary nucleus did not occur on the top of the atmosphere, but at a depth corresponding to a run for the collision of nuclei in the air. Therefore, the average depth of the shower maximum for this superposition is modified by the value of the path is lower than $X_{\text{max}}$ calculated from the diffusion equations of nuclear cascade process. In the method were used the hydrodynamic model with $n_{ch} \sim E_{i}^{1/3}$ [6].

Let the distribution of the maximum depth of showers from primary nuclei has an exponential form with the first moment equal to their run for the nuclear interaction. Then, the average depth of the shower maximum for the sum of two exponential functions will be equal.

$$X_{\text{max}} = \eta \cdot X_p + (1 - \eta) \cdot X_{Fe}$$ (1)

Where $\eta$ - the fraction of protons in the primary cosmic radiation, $X_p$ and $X_{Fe}$ - the depth of maximum development of the primary proton and iron nuclei by the chosen model of the EAS. For the dispersion we have $X_{\text{max}}$ expression

$$D(X_{\text{max}}) = \beta \{ \eta \cdot \lambda_p^2 + \eta(1 - \eta) \cdot (X_p - X_{Fe})^2 + (1 - \eta) \cdot \lambda_{Fe}^2 \}$$ (2)

Here $\lambda_p$ and $\lambda_{Fe}$ respectively the path for the nuclear interaction of the proton and iron nuclei. $\beta$ multiplier takes into account the increase of the dispersion $X_{\text{max}}$ due to fluctuations of the inelasticity coefficient and is taken to be $(1 - <k>)^{-1}$, where $<k>$ - the mean value of the inelasticity coefficient of the leading particle. If we assume that the ratio $\lambda_{Fe}(E) / \lambda_p(E)$ is constant and known, then equations (1) and (2) in the framework of a two-component composition can determine the proportion of protons in the primary radiation and the cross section of the proton - nucleus of an atom from the experimental values $X_{\text{max}}$ and $D(X_{\text{max}})$. Technically, the above simplification can be extended to multi-component composition of the primary particles, but the accuracy of formulas of the type (1) and (2) for $X_{\text{max}}$ and $D(X_{\text{max}})$ will be slightly worse.

We also found an indication of a gradual increase in the energy of the protons in the region of energy $3 \cdot 10^{17} - 3 \cdot 10^{18}$ eV.

2.2. Method of comparing the asymmetry of distribution at different $X_{\text{max}}$ at different fixed energies

This method does not depend from model of air shower development. Since the distribution of $X_{\text{max}}$ at fixed energy is formed by nuclei of different masses, therefore, its shape will reflect their contribution to a statistical contribution of $X_{\text{max}}$, g / cm$^2$. This is understandable, since showers produced by particles of different masses have either rapid development, for example, the iron nucleus or slow development as it happens, if we consider the proton. In paper [2] the ideology of asymmetry of $X_{\text{max}}$ distributions at different energies were used. Its essence is as follows. The value of the effective cross section for inelastic collisions of protons with air nuclei on the distribution of heights of the maxima of the EAS in the energy range of the primary particles $10^{17} - 10^{18}$ eV and $10^{18} - 10^{19}$ eV was studied. Right-hand side of such distributions is determined mainly by the effective cross section for inelastic collisions of protons with air nuclei. Height of the maximum development of the shower was determined by the spatial distribution of the Cherenkov light at the distance range of 100 - 600 m from the shower axis.

Next, assuming that at high energies only protons are presented and rationing distribution at lower energies by the proton (deeper than 700 g / cm$^2$), simply by subtracting the estimated fraction of nuclei in the primary radiation with energy $\sim 10^{17} - 10^{18}$ eV.

Thus the indication that in the energy range $10^{16} - 10^{19}$ eV observed systematic increase in the fraction of protons: $\sim 1.2 \cdot 10^{16}$ eV - (43±5), $\sim 9 \cdot 10^{16}$ eV - (50±6), $\sim 5 \cdot 10^{17}$ eV - (60±10)% and $\sim 5 \cdot 10^{18}$ eV - (90±10)% was obtained.
2.3. Distribution of $X_{\text{max}}$ shape analysis jointly with calculated distribution using QGSJET model by maximum likelihood method.

In this method we used experimental data of $X_{\text{max}}$ at energies $10^{15} - 10^{19}$ eV and simulated showers according to QGSJET 01 model [8]. Joint analysis of showers allowed to obtain quantitative estimates of the mass composition of primary CR, using the distribution of $X_{\text{max}}$ at fixed energy [3]. To do this, we compared the experimental data and theoretical predictions of predictions according QGSJET for different primary nuclei with applied criterion $\chi^2$. The value was determined by the equation $\chi^2$:

$$\chi^2(X_n) = \sum_n (N_e(X_{\text{max}}) - N_T(X_{\text{max}}))^2 / N_T(X_{\text{max}})$$

where $N_e(X_{\text{max}})$ - experimental number of showers in the range $\Delta X_{\text{max}}$, $N_T(X_{\text{max}}, A_i)$ - the same number of showers, calculated under the assumption that the mass number of the nucleus is equal to $A_i$, and $P(A_i)$ - the probability that a storm of energy $E_0$, is formed by the primary particle $A_i$. Then

$$N_T(n) = \sum_i P(A_i) \cdot N_T(X_{\text{max}}, A_i)$$

Analysis of the shape of experimental and calculated distribution of $X_{\text{max}}$ showed that at optimal value of $\chi^2$ obtained result does not conflict with the following relationships for 5 nuclei components:

1. $E_0 = 5 \cdot 10^{17}$ eV - p : (39 ± 11) % , $\alpha$ : (31 ± 13) % , M : (18 ± 10) % , H : (7 ± 6) % , Fe : (5 ± 4) % ;
2. $E_0 = 1 \cdot 10^{18}$ eV - p : (41 ± 8) % , $\alpha$ : (32 ± 11) % , M : (16 ± 9) % , H : (6 ± 4) % , Fe : (5 ± 3) % ;
3. $E_0 = 5 \cdot 10^{18}$ eV - p : (60 ± 14) % , $\alpha$ : (21 ± 13) % , M : (10 ± 8) % , H : (5 ± 4) % , Fe : (3 ± 3) %.

Thus, in the framework of the QGSJET 01 the indication was obtained: mass of the PCR in the transition from the energy $(5 \pm 30) \cdot 10^{17}$ eV to the energy $(3 \pm 10) \cdot 10^{18}$ eV changes. For $E_0 \cdot 3 \cdot 10^{18}$ eV primary cosmic radiation consists on $\sim 70\%$ of protons and helium nuclei, the proportion of other nuclei does not exceed $\sim 30\%$.

2.4. Multicomponent analysis

In order to interpret experimental data of Yakutsk array we used CORSIKA code (v. 6.0. QGSJET model) to generate database of $X_{\text{max}}$ and $\rho_e(600)$ [4]. Simulation were done for five primaries (P, He, C, Si, Fe) and three energies $10^{17}$, $10^{18}$, $10^{19}$ eV. For each energy we simulated 100 showers in the standard atmosphere. In this paper, we used two-dimensional probability density $F(X_{\text{max}}, \rho_e(600))$, preliminary standardized experimental data of the entire array data ($X_{\text{max}}$, $\rho_e(600)$) for a given energy. At numerical implementation of this method instead of ($X_{\text{max}}$, $\rho_e(600)$) and used variables $\tau$ and $\rho_e$:

$$\tau = (X_{\text{max}} / \sigma_x) - \langle (X_{\text{max}} / \sigma_x) \rangle$$

$$\rho = (l \rho(600) / \sigma_l \rho) - \langle l \rho(600) / \sigma_l \rho \rangle$$

Where $\sigma$ standart deviation of the value.

Standardization performed on pooled data ($X_{\text{max}}$, $\rho_e(600)$) for all groups of nuclei and each energy $10^{17}$, $10^{18}$, $10^{19}$ eV. Distribution on $X_{\text{max}}$ and $\rho_e(600)$ separately and joint distributions for $\tau$ and $\rho$ are described respectively by dimensional $F (X_{\text{max}})$ $F (\rho(600))$ and two-dimensional
$f(\tau, \rho)$ logarithmically normal distribution. For each given energy and different types of primary nuclei, including for nuclei, combined in groups P + He, C, Si + Fe, were plotted probability distribution density $f(\tau, \rho)$. The intersection of $f(\tau, \rho)$ layers gives lines m1 and m2, which optimally separates nuclei into 3 groups: (P + He), C and (Si + Fe) respectively.

Fig. 2 shows the result of a multi-component analysis of the data binding ($X_{max} \rho_e (600)$) of Yakutsk array. A cloud of points in such a representation reflects standardized values, and lines represent areas that are directly associated with the mass number of the primary particle. In this case, the line m1 and lines m2 are optimally separates nuclei into groups (P + He), and C (Si + Fe).

Analysis has shown that the proportion of nuclei (p + He) increases from 50% to 53%, and the proportion of carbon nuclei from 23% to 31%. At the same time the proportion of nuclei of heavy chemical elements decreases from 27% to 16% while increasing energy from $2.4 \cdot 10^{17}$ to $4.8 \cdot 10^{18}$ eV.

2.5. Proportion of muons analysis method depending on the length of the track of the particles in the atmosphere

In paper [5] considered the dependence $\rho_\mu / \rho_s$ the length of the track of the particles after the maximum of EAS $\Delta \lambda = X_0 / \cos \theta - X_{max}$ where $X_0 = 1020$ g / cm² for Yakutsk. Here $X_{max}$ determined from measurements of the Cherenkov light and $\rho_\mu$ and $\rho_s$ by measuring a large EAS. Next, the experiment was compared with model calculations of QGSJETII 03 and EPOS. It is known that $X_{max}$ of showers greatly differs depending on primary nucleus, therefore, this fact can be used to analyze the mass composition of cosmic rays, for example, by fixing the parameter $\Delta \lambda$ and analyzing fluctuations in the ratio of $\rho_\mu / \rho_s$. This method is somewhat similar to the method of Christiansen, proposed in 1981 [9]. With sufficient precision of measurements of each parameter (better than 5%) in the distribution allocated single peaks from different nuclei.

Comparison of distribution of muon proportion with calculation results indicates to mixed composition at energies above $10^{18}$ eV. Large fluctuations do not allow allocating separate groups of nuclei with a good precision and evaluating percentage of each group. But, the use of pure response of muon detectors leads to conclusion that MC at energies $10^{18}$ – $10^{19}$ eV is light [10].

![Figure 1. Distribution of $X_{max}$ at fixed energy. Point result - test provided p (70%) and Fe (30%)](image-url)
2.6. Evaluation of the mass composition at average depth of maximum of EAS development.

Interpolation method

In papers [11, 12], dependence of \( X_{\text{max}} \) from energy at range \( \sim 10^{15} \) to \( 5 \cdot 10^{19} \) eV was considered. MC of PCR evaluated by this formula:

\[
< \ln A > \equiv \sum a_i \cdot \ln A_i \quad (7)
\]

Where \( a_i \) the relative proportion of nuclei with mass number \( A_i \).

In each case experimental data compared with QGSJET 03 calculation made for proton and iron in the frame of superposition model:

\[
< \ln A > = \frac{(P_{\text{exp.}} - P_{\text{p}})}{(P_{\text{Fe}} - P_{\text{p}})} \cdot \ln A_{\text{Fe}} \quad (8)
\]

Where \( P_i \) parameter, that characterize longitudinal development of air showers \( X_{\text{max}} \).

In Fig. 4 shows dependence of \( X_{\text{max}} \) from energy (dots) derived from experiment and from simulation (lines) of this characteristics calculated by QGSJET 03 and SIBYLL model for proton and iron nuclei. Fig. 5 shows Yakutsk array results of MC PCR derived by method described above. Data obtained in the frame of QGSJETII 03 model and dual component MC (proton iron). Value \( \ln(A) \) in each case was determined by interpolation method.

Fig. 5 shows that nature of dependence of value \( \ln(A) \) with increase of energy changes reaching maximum at energy range \( (5 - 30) \cdot 10^{16} \) eV. This means, that MC of CR changes after first kink in the spectrum at \( \sim 3 \cdot 10^{15} \) eV, reaching heavier particles \( (3 - 30) \cdot 10^{16} \) eV and then, starting at energies \( 3 \cdot 10^{17} \) eV becomes much lighter.
Figure 4. Dependence of $X_{\text{max}}$ from energy. Lines are calculated values for proton and iron nuclei.

Figure 5. Mass composition of Cosmic rays highest energy are obtained at Yakutsk. Model QGSJETII-03

3. Conclusion

a) For more than 40 years Yakutsk array continuously records air showers with ultrahigh energies. We obtain information about all main components of the shower: electrons, photons, hadrons and muons. All these data at different times were used to estimate the mass composition of cosmic rays involving different methods. This follows from the numerous publications in journals and proceedings of scientific conferences. According to the data shown in Figure 6 [13]. The mass composition is not uniform over a wide energy range, and has a peak at $(0.8 - 2) \times 10^{17}$ eV

Figure 6. Estimation of MC CR with different method by use of different characteristics of air showers

Figure 7 shows the latest results on MC obtained using the interpolation method (see. Section 2.6) and the model QGSJET 04. Also the figure shows results obtained at compact and the large arrays. From Figure 7 it follows that MC is undergoing a change in the energy range $(8 - 20) \times 10^{16}$ eV and $(8 - 20) \times 10^{18}$ eV. And most likely this is due to the nature of the formation of cosmic rays in the sources and their distribution in the galactic and intergalactic space.

b) At the Yakutsk we measured energy spectrum of CR (see. [14, 15]) and evaluated MC over a wide range in energy [11]. If we compare the energy scale with studied spectrum of CR and obtained results of cosmic rays of MC, than we observe matching of energy intervals, where the change in the shape of the spectrum and the change in the value of $A = \langle \ln A \rangle$ are the
same. Most likely, these two results are related and caused by the same astrophysical processes.

c) On the boundary of the transition from galactic to metagalactic cosmic rays. Recently developed nonlinear kinetic theory of CR acceleration in supernova remnants has allowed not only to achieve agreement in shape of CR spectrum up to energies $\sim 10^{17}$ with experimental data, but also to choose a class of SNR, which responsible for MC of particles similar to those observed in the satellite, balloon and ground experiments [11]. This is confirmed by the results of the calculation of work [16], which are shown in Figure 7 (lines). Figure 7 shows a comparison of MC obtained at different arrays, with MC generated in the sources, which are remnants of supernovas. There is not only a satisfactory agreement of experimental data with calculation in the energy range $10^{15}$ - $10^{19}$ eV, but also indicates that the sharp change in the MC at an energy $\sim 2 \times 10^{17}$ eV may be associated with the boundary of the transition from galactic CR to metagalactic CR. In this case mass composition of CRs at energies above $\sim 2 \times 10^{17}$ eV should be presented primarily by protons, which is consistent with mass composition obtained at the Yakutsk EAS.

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