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Estimation of cosmic ray composition around the knee region from Cherenkov light measurements at the Yakutsk array

A.A. Ivanov[a], S.P. Knurenko[a], Z.E. Petrov[b], I.Ye. Sleptsov[a]
(a) Yu.G. Shafer Institute of Cosmophysical Research & Aeronomy, Yakutsk 678980, Russia
(b) Department of Physics, Yakutsk State University, Yakutsk 677980, Russia
Presenter: A.A. Ivanov (ivanov@ikfia.ysn.ru), rus-ivanov-AA-abs2-he12-poster

Average cascade curve parameters of EAS in the atmosphere give some implications on the mass composition of primaries within a given model of shower development. We use air Cherenkov light measurement data of the Yakutsk array in order to estimate these parameters. As a result, an indication has been found that the average mass of primary particles increases with energy in the region $E_0 \sim 10^{15}$ to $\sim 10^{17}$ eV and decreases at higher energies.

1. Introduction

The measurement of mass composition of the primary cosmic rays (PCR) in the energy range $E_0 = 10^{15} \div 10^{20}$ eV is not possible by the direct methods. It is only possible to apply indirect methods based on simultaneous measurement of different components of extensive air showers (EAS). These can be concerned to the longitudinal and lateral development of shower in atmosphere. The information on the composition of PCR with the energy $E_0 \geq 10^{15}$ eV can be obtained analyzing the Yakutsk array data. It is convenient to analyze the shower components most sensitive to the composition, i.e. which differ from each other by a character of formation and absorption in the atmosphere, for example, the charged particle flux (electrons, muons) and a flux of Cherenkov or ionization light.

2. Analysis method

If fluctuations in the shower development are negligible, then one can express the total number of particles at the observation level X_0 in a shower as $N_e \sim E_0^{\alpha}$, $N_\mu \sim E_0^{v}$, where E_0 is the energy of primary proton, index $\alpha > 1$ behind the shower maximum. Correspondingly, the total flux of EAS Cherenkov light is expressed as $F \sim E^{\beta}$ ($\beta > 1$). In superposition approximation one can consider a shower generated by primary nucleus as a sum of showers from the group of nucleons with energy E_0/A. Then in the framework of this simple model we obtain the following relations of EAS characteristics for the primary nuclei [1]:

$$N_e \sim (E_0/A)^{\alpha} \text{ and } F \sim (E_0/A)^{\beta},$$

or at given N we have the following relations

$$F/N_e \sim (E_0/A)^{\beta-\alpha} \text{ and } F/N_\mu \sim (E_0/A)^{(\beta-v)}. \tag{1}$$

Thus, the mean ratio of the total flux F and charged particle number N_s or the ratio of the total flux and the number of muons with $E_{thr.} \geq 1$ GeV (N_μ that observed at the sea level) depends on the average mass of PCR. Characteristics of the longitudinal EAS development: an average depth of maximum X_{max} and a dispersion $D(X_{max})$ are also sensitive to PCR mass composition. In a binary assumption that the primary flux is a mixture of protons and iron nuclei, and supposing the maximum depth distribution of shower to have exponential form, one can derive X_{max} и $D(X_{max})$ as a function of α (parameter connected to the logarithmic rise of interaction cross section with energy) and η (the fraction of protons in the primary flux) [2]:

$$X_{max} = \eta X_p(\alpha) + (1 - \eta) X_{Fe}(\alpha),$$

$$D(X_{max}) = \beta^2\{\eta\lambda_p^2(\alpha) + \eta(1 - \eta)[X_p(\alpha) - X_{Fe}(\alpha)]^2 + (1 - \eta)\lambda_{Fe}^2(\alpha)\}, \tag{2}$$

where $\lambda_p(\alpha)$ and $\lambda_{Fe}(\alpha)$ are mean free path lengths of proton and iron nucleus in air; $X_p(\alpha)$ and $X_{Fe}(\alpha)$ are the maximum depths of cascades initiated by the primary proton and iron nucleus in a given model of EAS development. Factor β stands for the correction due to fluctuations of the inelasticity coefficient. Using equation (2) and iteration method one can get some hints on a proton fraction of PCR.

Another approach to estimation of the mass composition of PCR is the analysis of X_{max} distribution at fixed E_0 [3]. In this case the comparison is used of the experimental and simulated distribution of X_{max} for different primary nuclei basing on χ^2- criterion. The value of χ^2 is given by

$$\chi^2_{(Xmax)} = \sum(N_{exp.}(X_{max}) - N_{Theor.}(X_{max}))^2 / N_{Theor.}(X_{max}), \tag{3}$$

where $N_{exp.}(X_{max})$ is the number of detected showers with X_{max} in the interval ΔX_{max}; $N_{Theor.}(X_{max}, A_i)$ is the number of fake showers initiated by the nucleus A_i. If $P(A_i)$ is the probability distribution of the primary beam in atomic weight, then

$$N_{Theor}(n) = \sum P(A_i)\cdot N_{Theor}(X_{max},A_i). \tag{4}$$

The solution of linear equations system is possible, for instance, using the simplex algorithm.

3. Results

In Figure1a the ratio N_s/F is shown as a function of energy, in the interval $E_0 = 10^{15} \div 2\times10^{17}$ eV. Figure 1b presents data on EAS maximum depth X_{max} in the energy interval $\Delta E_0 = 2\times10^{14} \div 2\times10^{17}$ eV. It is seen from Figires 1a and 1b that observed dependence of parameters N_s/F and X_{max} on energy cannot be described by simple linear function as in models with primary proton or iron nucleus. The dependence of N_s/F on E_0 takes a fall in the energy range of $(0.3 \div 3)\times10^{16}$ eV, as $X_{max}(E_0)$ does in the range $(0.3 \div 4)\times10^{16}$ eV. Above $E_0=10^{17}$ eV the parameters are monotonically increasing with energy. With suppositions assumed one can explain such a behavior (with regard to simulation results in Figure 1a) by changing mass composition of primaries: below $E_0 \leq 3\times10^{15}$ eV 'light' nuclei predominate in the cosmic ray flux, in the energy range $10^{15} \div 10^{17}$ eV 'heavier' composition does; above $E_0 \geq 10^{17}$ eV the mass composition returns to the normal light one.

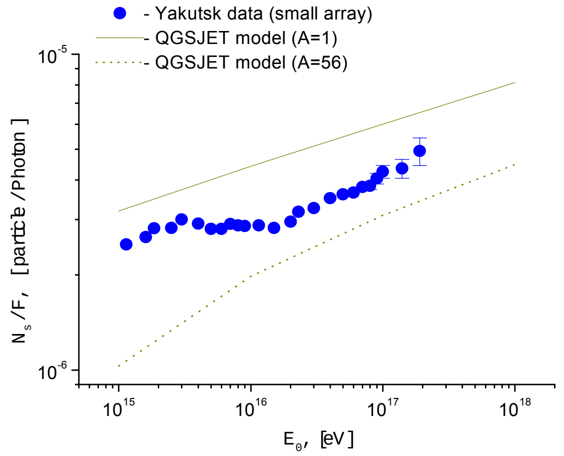

Figure 1a. Ns/F vs. primary energy.

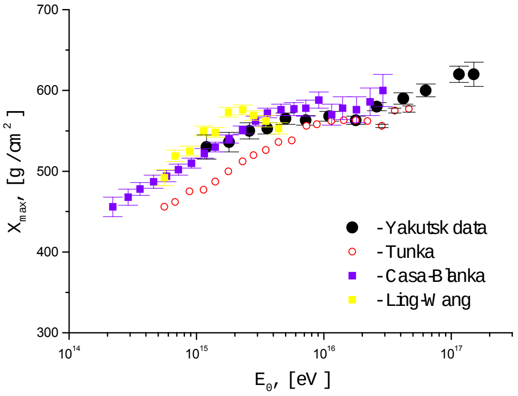

Fig.1b. Xmax vs. primary energy.

In Figure 2a our data are shown in comparison with the calculation results from [4], in which cosmic rays in the range $10^{15}\div3\times10^{17}$ eV are assumed to be of galactic origin. Propagation of cosmic rays in the fractal magnetic field of our Galaxy is simulated according to anomalous diffusion model for charged particles. The results of calculations [4] are given in Table 1.

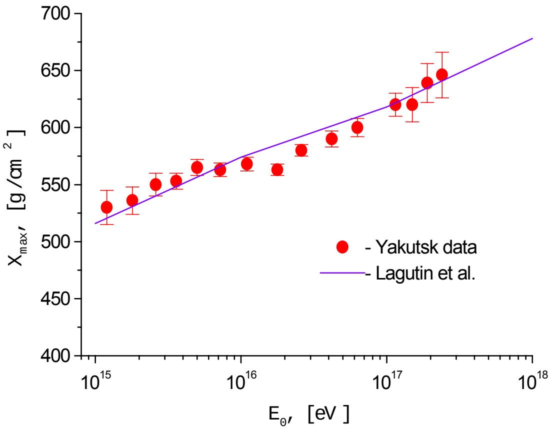

Figure 2a. Dependence of EAS maximum depth on the of primary energy. The curve is calculation results from [4].

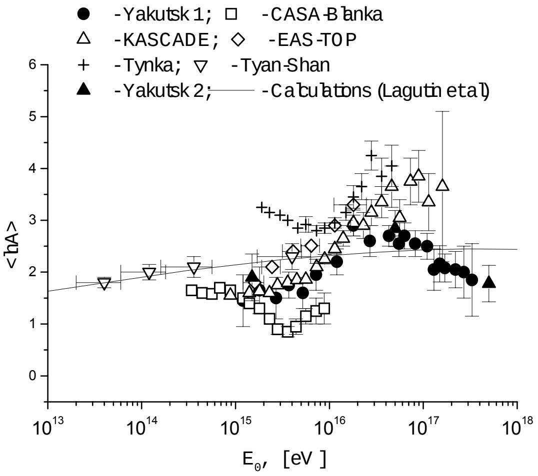

Figure 2b. Average mass of the primaries as a function energy. Experimental data in comparison withe calculations [4].

Table1. Mass composition of CRs by QGSJET model

A $E_{0,}$ (eV)	p, (%)	α, (%)	M, (%)	H, (%)	Fe, (%)	<lnA>
The results by A.A. Lagutin et al. [4] reconstructed from $<X_{Max}>$						
$1\cdot10^{15}$	0.51	0.23	0.09	0.09	0.08	2,14
$3\cdot10^{15}$	0.50	0.26	0.08	0.08	0.08	2,24
$1\cdot10^{16}$	0.41	0.26	0.11	0.11	0.11	2,32
$3\cdot10^{16}$	0.35	0.25	0.13	0.13	0.14	2,38
$1\cdot10^{17}$	0.31	0.23	0.15	0.15	0.16	2,43
$3\cdot10^{17}$	0.30	0.22	0.15	0.16	0.17	2,45

4. Discussion and Conclusions

The fraction of protons in the primary beam within range $E_0=(1\div3)\times10^{15}$ eV is estimated to be (40 ÷50)% using experimental data on $\overline{X}_{max}$, $D(X_{max})$, assuming superposition hypothesis and two-component primary composition. The primary flux is enriched here by protons in comparison with interval $E_0=(1\div5)\times10^{16}$ eV where the proton fraction is ~(30 ÷ 40) % (see full circles in Figure 2b).

In this regard it would be very interesting to analyze the form of X_{Max} distribution. For this case the experimental distributions and calculations with QGSJET model has been used. The calculations take into account the experimental errors in determination of X_{Max} ($\sigma_x \cong 60$ g/cm^2) and they are fitted to the experimental data. The following few components of primary cosmic radiation composition have been considered: a pure proton, pure iron nuclei and CNO at 1.5×10^{15} eV, 10^{16} eV [3]. The comparison of calculations and experimental data combining three-component composition indicates the variation of chemical composition of primary particles in the energy range above $(3 \div 5) \times10^{15}$ eV. The 'lighter' mass composition of PCR in the range of $10^{15}\div 3\times10^{15}$ eV, and the 'harder' one for energies $3\times10^{15}\div5\times10^{16}$ eV are required to fit the data (full triangles in Figure 2b). The model calculations [4] also indicate such a tendency (see Table.1).

Thus, in the framework of QGSJET model, using different methods of estimation of PCR mass composition, we conclude that the average mass of primaries is changing with energy in the range (1÷3)×1015 eV to (3÷50)×1015 eV. At E0≥ 3×1017 eV mass composition is not far from that observed at E0≤ 3×1015 eV. It is seen from Figure 2b where our results and results of other arrays are shown. It also follows from Figures 2a and 2b that experimental results do not contradict within errors the hypothesis of anomalous cosmic ray diffusion in fractal magnetic fields of the Galaxy [4].

5. Acknowledgements

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