Estimating primary mass composition at energies $10^{17} - 10^{18}$ eV from EAS radio emission lateral distribution

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Abstract. Distribution of maximum depths of extensive air showers (EAS) with energies of $10^{17} - 10^{18}$ eV is restored from the lateral distribution of EAS radio emission measured by the LOPES experiment (40–80 MHz). Dependence of the EAS maximum depth on its energy is constructed and mass composition of cosmic rays is estimated. It follows from the obtained dependencies that the fraction of light cosmic ray’s nuclei increases in the energy range under consideration.

1. Introduction
Registration of the coherent (at wavelengths greater than $\sim 1$ m) radio emission from extensive air showers (EAS) is a youngest method of cosmic ray (CR) detection [1, 2], among other methods based on the measurement of electromagnetic radiation produced by charged shower particles (Cherenkov light and fluorescence). Presently, there are two experiments realizing such type of radio detecting of EAS: CODALEMA (20–80 MHz) [3] and LOPES (40–80 MHz) [4]. In the near future, it is also planned to launch the AERA experiment [5] at the Pierre Auger array and a radio antenna system as a part of the Tunka array [6].

As early as in the beginning of 1970th Allan [7] and Hough [8] found that the shape of the lateral distribution function (LDF) of EAS radio emission is influenced strongly by the shower longitudinal profile and can therefore be used to provide the information on the shower maximum depth $X_{\text{max}}$. This fundamental for the radio method result, obtained in the framework of simplified models of radio emission generation and confirmed in experimental studies [9], has been proved in modern theoretical works based on Monte-Carlo shower simulations [10, 11].

In this paper, the distribution of EAS maximum depths at the $10^{17} - 10^{18}$ eV energy range is reconstructed by using recent LOPES experimental data [12] on the LDF of EAS radio emission. CR mass composition is then also estimated. The reconstruction is based on calculations of EAS radio emission, which are performed in the framework of microscopic approach [11] and founded on the Monte-Carlo simulation of EAS (the CORSIKA code [13]).

2. LDF’s parameter for EAS maximum reconstruction and events selection
The experimental data on the LDF of radio emission are taken from [12] and consist of 121 individual LDF with known energy and arrival direction of EAS (reconstructed from the data...
of the KASCADE-Grande array [14] for each event). The average values of the EAS parameters for this group of events are: $\langle E_0 \rangle = 4.7 \cdot 10^{17} \text{ eV (energy)}$ and $\langle \theta_0 \rangle = 28^\circ$ (zenith angle).

In obtaining the shower maximum depth $X_{\text{max}}$ from the LDF of radio emission it is more preferable to deal with “natural” (directly measured or given in measurements) quantities rather than with the parameters of the function used to approximate the experimental LDF (see below). We then use the following quantity

$$
\eta = \frac{E_\nu(R_\perp + \delta R_\perp)}{\delta R_\perp} - \frac{E_\nu(R_\perp)}{\delta R_\perp}
$$

being an integral characteristics of the LDF, where $E_\nu(R_\perp)$ is the radio emission field strength observed at the frequency $\nu$ and the shower-antenna distance $R_\perp$. The values $R_\perp = 50 \text{ m}$ and $\delta R_\perp = 100 \text{ m}$ have been adopted in our calculations.

To reduce an uncertainty of the solution of an inverse problem for $X_{\text{max}}$ it is necessary to regularize experimental data on the LDF, so that the trial function

$$
f(R_\perp; \mathbf{a}) = a_1 \exp (a_2 R_\perp + a_3 R_\perp^2)
$$

is employed in order to fit the data by the adjustment of suitable parameters $\mathbf{a} = (a_1, \ldots, a_n)$ (see Figure 1).

Further, two types of criteria are used to select the events from the LOPES experimental data on the LDF. The first one concerns the reconstructed shower parameters, namely: the selected events are those for which $10^{17} \text{ eV} \leq E_0 \leq 10^{18} \text{ eV}$, $\theta_0 \leq 50^\circ$ and all $\varphi_0$ (shower azimuth angle) except $180^\circ \pm 45^\circ$ (the southern quadrant of the celestial hemisphere). The second set of criteria relates to the LDF themselves. The main requirements are as follows: the points of experimental LDF must cover the selected range of distances (50–150 m), whereas the value of $\chi^2$-parameter for the approximation (2) can not exceed $n_f$, where $n_f$ equals to the number of experimental points. In total, 42 events have been discarded and the other 79 events are processed. As an example, in Figure 1 the typical selected LDF is shown. The average energy of the showers in the selected events equals to $\approx 3.2 \cdot 10^{17} \text{ eV}$. 

Figure 1. The typical selected LDF of EAS radio emission measured by the LOPES array.

Figure 2. The resulting theoretical diagram $\eta(X_{\text{max}})$ for showers with zenith angle $\theta_0 = 25^\circ$ and coming from the North.
3. Shower maximum depth reconstruction

The radio emission from EAS is calculated at the frequency 60 MHz in the framework of the scheme described in [11]. Monte Carlo simulations are carried out with CORSIKA 6.960 [13] for showers developing at the LOPES experiment location. The simulated energies $E_0$ are 100 PeV, 500 PeV and 1 EeV. The number of showers for the corresponding energies is 1300, 700 and 1200 respectively. This statistics includes the simulations for the four following types of primaries: hydrogen (proton), carbon (represents CNO-group), silicon (intermediate elements) and iron (heavy component). For each primary the simulated zenith angles $\theta_0$ are 25°, 35° and 45°, whereas the azimuth angles $\varphi_0$ are 0° (North), 90° (East) and 270° (West) for each $\theta_0$.

As it turns out, the slope of the LDF, described by the parameter $\eta$, is a function of only two variables ($\theta_0$ and $\varphi_0$), so that the showers having different $E_0$ and $A$ (where $A$ is the mass number of a primary particle) are grouped together. As an example, the resultant diagram for $(\theta_0, \varphi_0) = (25^\circ, 0^\circ)$ is shown in Figure 2. In order to obtain an analytical expression for $\eta(X_{\text{max}})$ a simple linear regression analysis is employed [15]. In the framework of this analysis the result is presented in the following form

$$\eta(X_{\text{max}}) = \hat{\eta}(X_{\text{max}}) \pm \hat{\eta}_\pm(X_{\text{max}}, p),$$

where $\hat{\eta}$ is the regression line and $\hat{\eta}_\pm$ are the branches of the hyperbola, which define the confidence bands corresponding to the $p$-significance level. In Figure 2 the function $\eta(X_{\text{max}})$ is shown against the simulated data for a particular shower arrival direction (in our analysis the 70%-significance level has been chosen). At the non-simulated values of $\theta_0$ and $\varphi_0$ the function $\eta(X_{\text{max}})$ is found by using an interpolation.

The experimental value $\eta = \bar{\eta} \pm \Delta \eta_\pm$ is calculated by employing the formula (1). The uncertainties $\Delta \eta_\pm$ are determined by the uncertainties $\Delta a_2$ and $\Delta a_3$ in reconstructing the parameters $a_2$ and $a_3$. To find $X_{\text{max}} = \bar{X}_{\text{max}} \pm \Delta X_{\text{max}}^\pm$ the following equations are solved:

$$\eta(\bar{X}_{\text{max}}) = \bar{\eta},$$

$$\eta(\bar{X}_{\text{max}} \pm \Delta X_{\text{max}}^\pm) = \bar{\eta} \pm \Delta \eta_\pm.$$
The obtained distribution of $X_{\text{max}}^{\text{rec}}$ has the following parameters: the average value $\langle X_{\text{max}}^{\text{rec}} \rangle = 645 \pm 14 \text{ g/cm}^2$ and the standard deviation $\sigma(X_{\text{max}}^{\text{rec}}) = 120 \pm 8 \text{ g/cm}^2$. The reconstructed function $X_{\text{max}}^{\text{rec}}(E_0)$ is shown in Figure 3. The general conclusion is that in the $10^{17} - 10^{18}$ eV range CR composition tends to be more light. The increase in the fraction of light CR nuclei at the energy range under consideration is consistent with the results of Fly's Eye, HiRes-MIA [17] and Yakutsk [18] measurements.

Knowing (from simulations) the function $X_{\text{max}}^{\text{sim}}(A, E_0)$ one may also estimate roughly the quantity $A = A \pm \Delta A^\pm$ for each individual event by solving the following system:

\[
X_{\text{max}}^{\text{sim}}(\tilde{A}, E_0) = \tilde{X}_{\text{rec}}^{\text{max}},
\]

\[
X_{\text{max}}^{\text{sim}}(\tilde{A} \pm \Delta A^\pm, E_0) = \tilde{X}_{\text{rec}}^{\text{max}} \pm \Delta X_{\text{max}}^{\text{rec}}.
\]

In Figure 4 the result of such a reconstruction is shown. The values of an average logarithm of CR mass number obtained within simulations with QGSJET 01 [16] and SIBYLL 2.1 [19] high-energy hadronic interaction models $\langle \ln A^{\text{rec}} \rangle = 1.9^{+0.7}_{-0.9}$ (QGSJET 01) and $\langle \ln A^{\text{rec}} \rangle = 2.0^{+0.7}_{-0.9}$ (SIBYLL 2.1) do not differ essentially from each other.

4. Conclusions

The distribution of EAS maximum depth at the $10^{17} - 10^{18}$ eV energy range has been reconstructed within a reliable scheme of calculating the radio signals from EAS [11, 20] and by using experimental radio data only. For doing this, the correlation between the shape of the LDF of EAS radio emission and the shower longitudinal profile has been used. In according to the current (free-available) LOPES data on the LDF of radio emission [12] the cosmic ray composition tends to be more light at the $10^{17} - 10^{18}$ eV range. This result is consistent with data of other experiments [17, 18], in which different methods of EAS registration were used.

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