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Primary energy determination of UHE events from published Volcano Ranch, Yakutsk and AGASA data

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Abstract. We have compared the lateral analytical structure functions coming from cascade theory to the numerical distributions generated by EAS Monte Carlo simulations and to the empirical functions used in Giant Air Showers experiments. Analysis of published data contained in the catalogues of Volcano Ranch and Yakutsk, and the most energetic event of AGASA is presented. We discuss effects of axis position, profile function, method of localization on the accuracy of energy estimation. Results might have important implications for detector configuration of the future Giant Air Shower arrays.

1 Introduction

At altitudes around 1000 m above sea level, near vertical showers of energy 10^{10-11} GeV are close to the maximum of their longitudinal development; this favourable circumstance reduces dependence on the interaction model, and as far as the cascade curve is more flat around the maximum, the fluctuations are reduced as well as the discrepancies between primary protons and heavy nuclei. However, determination of the size or any other estimator related to the primary energy E_0, such as density around 600 m from shower axis, remains a difficult task. For arrays where detectors are separated by 1 km or more a small number of detectors are hit (for statistical reasons, far from axis, with small densities). What is more, the interpolation of densities at significant distances, or the integration performed to obtain the total size, depends on the axis determination and a shape of lateral distribution function.

2 New function of lateral distribution in EAS

In our previous paper (Capdevielle et al., 2001) we had proposed a new form of function describing lateral distribution of charged particle densities in Extensive Air Showers, which fitted very well results of our simulations. The function (called hereafter JNC function) has the following form:

$$\varrho(r) = N_e \cdot C \cdot x^{-\alpha} \cdot (1+x)^{(\alpha-\eta)} \cdot (1+d\cdot x)^{-\beta} \quad (1)$$

and is exactly normalized in terms of the hypergeometric formalism. (See Capdevielle et al. (2001) for details). We have used this form of function to fit simulated distributions of all charged particles in EAS and also for distribution of electrons only. The relevant sets of parameter values can be found in Capdevielle et al. (2001). Obtained fits were then used in localization procedure of published highest energy events.

3 Treatment of Volcano Ranch, Yakutsk and Akeno data

3.1 Method of localization

The core position has been obtained by minimization with Minuit program between different formulas available for lateral densities written versus the coordinates X, Y as

$$\varrho(r) = \varrho(\sqrt{(X-X_c)^2 + (Y-Y_c)^2}) \quad (2)$$

where the core coordinates X_c and Y_c are taken as two additive parameters in the minimization. We pointed out from the simulation that the barycenter was separated in average by about 180 m from the actual core (for a sparse array with a grid of 1.5 km (Capdevielle et al., 2000). We use the barycenter position as initial values for the parameters X_c and Y_c. The procedure has been tested on simulated showers, as well as on the catalogues of Volcano Ranch and Yakutsk experiments, by the optimization on size, core position and other free parameters (i.e. age s).

We assume that the directions of registered showers were determined sufficiently accurate by analyzing timing from many detectors. However estimation of $\varrho(600)$ or N_e depends on the form of lateral distribution function used to fit the registered number of particles and on localization method (i.e. the form of function chosen for minimization).

We have used following fits to charged particle lateral distribution:

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– JNC function for all charged particles (denoted as JNC01);

– the sum of JNC function for e^+e^- and Greisen function for muons (JNC03);

– empirical functions used in experiments: Yakutsk function (Efimov et al., 1988), Linsley's function (Linsley, 1980), AGASA 1 (Nagano et al., 1992) and AGASA 2 (Yoshida et al., 1995) functions.

The localizations were performed with MINUIT, taking the minimization of the function:

$$\chi^2 = \sum_i \mathcal{W}(D_i, E_i, F_i, K_i, S_i) \qquad (3)$$

where D_i is the number of particles in the $i-th$ detector for the registered event, and $F_i = \varrho(r_i) \cdot A_i$ is the density evaluated from the fit formula multiplied by the A_i – the area of the $i-th$ detector multiplied by $cos\theta$, θ is the EAS zenith angle, E_i is the estimated accuracy of determination of number of particles, K_i the density level when cascading processes might significantly increase estimated particle number and S_i is the particle density corresponding to the phototube–ADC saturation level.

When D_i is greater than $K_i \cdot A_i$ and F_i is less than D_i then $\mathcal{W} = 0$ (possible cascading process might produce larger signal);

when $\varrho(r_i)$ is larger than S_i then $\mathcal{W} = 0$ (expected density is larger than saturation level);

otherwise

$$\mathcal{W}(D_i, E_i, F_i, K_i, S_i) = \frac{(D_i - F_i)^2}{E_i^2}$$

$$E_i = max. \left(\kappa \cdot D_i, \sqrt{D_i}\right)$$

where κ is equal to 0.15 for Volcano Ranch and Yakutsk arrays and 0.10 for AGASA. We put cascading level K_i equal to 200 particles/m^2.

In this way we introduce a special treatment of high density registration. Detectors registering high particle density are very important for estimation of the shape of lateral distribution of particles, as they are relatively near to the EAS core.

3.2 Comparison between different lateral distribution functions and experimental data.

The localization procedure for a given event might give different coordinates of the shower core when different lateral distribution functions were used. The differences are in most cases within 50 m when the number of hit detectors is greater than 10. To compare different lateral distribution functions with the data we use one function (we call it *principal function*) to determine (X_c, Y_c) and corresponding size (N_e) and $\varrho(600)$ for this function. Then we fit another lateral distribution function for already determined (and now fixed) (X_c, Y_c). In this way we can present the difference between shapes of different functions.

Table 1. Comparison of results of localization performed for Yakutsk event 7810061014 (see Fig. 1) for 4 different lateral distribution functions. 'The principal functions' are written in bold characters.

Left Fig. 1:

function	X_c(m)	Y_c(m)	N_e	$\varrho(600)$	χ^2/n
Yakutsk	**1743.8**	**-21.0**	**$1.75\cdot10^9$**	**47.5**	**1.43**
AGASA#2			$3.30\cdot10^{10}$	90.0	2.29
JNC01			$4.70\cdot10^9$	62.5	1.26
JNC03			$3.66\cdot10^9$	63.8	1.33

Right Fig. 1:

function	X_c(m)	Y_c(m)	N_e	$\varrho(600)$	χ^2/n
Yakutsk			$1.76\cdot10^9$	47.8	1.59
AGASA#2			$3.25\cdot10^{10}$	88.6	2.10
JNC01			$4.65\cdot10^9$	61.8	1.10
JNC03	**1719.3**	**-0.8**	**$3.64\cdot10^9$**	**63.4**	**1.16**

3.2.1 Example 1: Yakutsk event 7810061014.

We compare the Yakutsk event 7810061014 (Efimov et al., 1988) with density distributions for 4 lateral distribution functions. Two cases are presented in the Fig. 1 for Yakutsk and JNC03 functions as the *principal functions* for the localization. Some related numerical values are shown in the Table 1.

3.2.2 Example 2: AGASA event #akn25400–0296.

For the very large AGASA event #akn25400–0296 (Yoshida et al., 1995) density distributions for 4 lateral distribution functions are presented in the Fig. 2 and the related numbers in the table 2. *The principal functions* are AGASA#2 and JNC03.

3.3 Volcano Ranch data

The data contained in the catalogue of Volcano Ranch registration (Linsley, 1980) was analyzed event per event: the same localization procedure was first carried with the orig-

Table 2. Comparison of results of localization performed for AGASA event #akn25400–0296 (see Fig. 2) for 4 different lateral distribution functions. 'The principal functions' are written in bold characters.

Left Fig. 2:

function	X_c(m)	Y_c(m)	N_e	$\varrho(600)$	χ^2/n
Yakutsk			$1.57\cdot10^{10}$	310.3	9.09
AGASA#2	**-1209.7**	**-1320.1**	**$9.23\cdot10^{10}$**	**632.4**	**5.24**
JNC01			$1.99\cdot10^{11}$	603.1	5.02
JNC03			$5.04\cdot10^{10}$	487.3	5.27

Right Fig. 2:

function	X_c(m)	Y_c(m)	N_e	$\varrho(600)$	χ^2/n
Yakutsk			$1.59\cdot10^{10}$	312.4	8.43
AGASA#2			$8.66\cdot10^{10}$	593.1	5.76
JNC01			$9.60\cdot10^{10}$	518.1	5.15
JNC03	**-1233.8**	**-1349.6**	**$5.05\cdot10^{10}$**	**473.5**	**5.03**

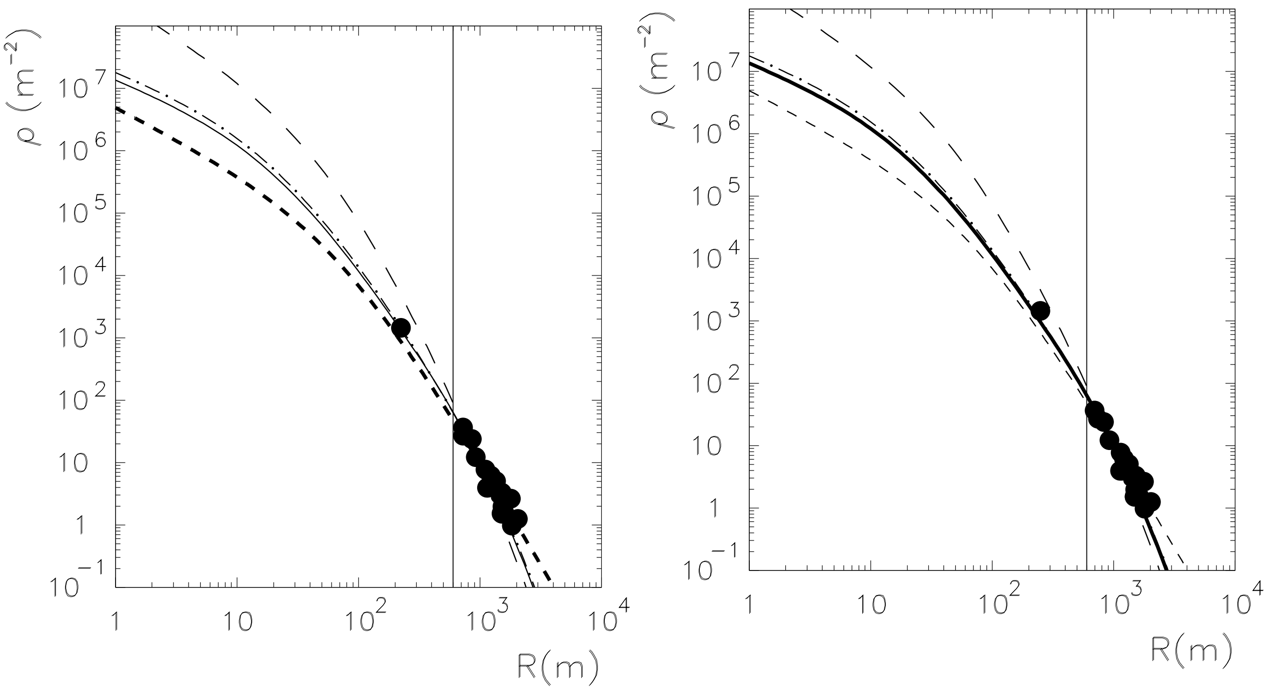

Fig. 1. Yakutsk event 7810061014. Density distributions for 4 lateral distribution functions. Short dashed line represents Yakutsk function, long dashed line AGASA#2, dashed–dotted line JNC01 (all charged), and solid line JNC03 ($e^+e^- +$ muons, N_μ/N_e = 0.05). Vertical line at R = 600 m. *'Principal functions'* are Yakutsk in the left Figure and JNC03 in the right one (corresponding lines are thicker). Values of related N_e and $\varrho(600)$ are in the table 1.

inal function used in the experiment and then repeated with JNC01 and JNC03 functions, and the functions used in another experiments. The results of our localization procedure have been compared with the original results as given in experimental paper or recalculated by us using the Linsley's function of lateral distribution. The optimization of the localization and the employment of the new functions turns to one general improvement of the minimization; a better control of the convergence is obtained for JNC functions for all charged particles and for Yakutsk function. From the sizes resulting or from the densities interpolated at 600 m, it can be seen that the primary energy originally estimated is reduced in case of Yakutsk function by factor ~ 3 and enlarged in the case of JNC01 function. The very large sizes obtained correspond to hopeless situations where the information is too poor for a rigorous adjustment, i.e. 5 or less detectors hit and axis not contained in the array. In the case of the event 19 (considered originally as the first event above 10^{20} eV), the previous estimation of energy would be reduced by about a factor of 2 for both approaches via $\varrho(600)$ or N_e and JNC functions.

3.4 Yakutsk data

The same treatment has been applied to the showers reported in the catalogue of Yakutsk (Efimov et al., 1988). The original minimization was here carried with Yakutsk function. Also for Yakutsk data better minimization is obtained and we observe here that $\varrho(600)$ is generally the same for JNC01 and Yakutsk functions, but size estimations differ by more than order of magnitude. Still the Yakutsk function provides the smallest sizes, in which case a satisfying agreement with GZK cutoff is also ascertained.

3.5 AGASA data

In the absence of catalogue published for AGASA data, we were constrained to apply our procedure to the unique and most energetic event of AGASA for which densities and respective detectors positions are available (Yoshida et al., 1995). The results are given in the Figure 2 and the table 2. The $\varrho(600)$ is reduced by 25% from 630 to about 470 particles per m^2. This is mainly due to shift of GAS core position in similar direction for all functions used. However the estimated N_e is varying within an order of magnitude, leaving discomfort in energy estimation.

4 Discussion

Although the GAS of energies above 10^{19} eV are being registered near to the maximum of their development the estimation of their energy with accuracy better than 30% is still problematic. In most experimental cases detectors are separated by hundreds of meters, whereas the maximum contribution to the total number of particles is in the range 20 – 200 m, therefore not measured directly. We have shown that the conversion factor $E_0/\varrho(600)$ following from modern simulations can vary within 10% for 'perfect' EAS case

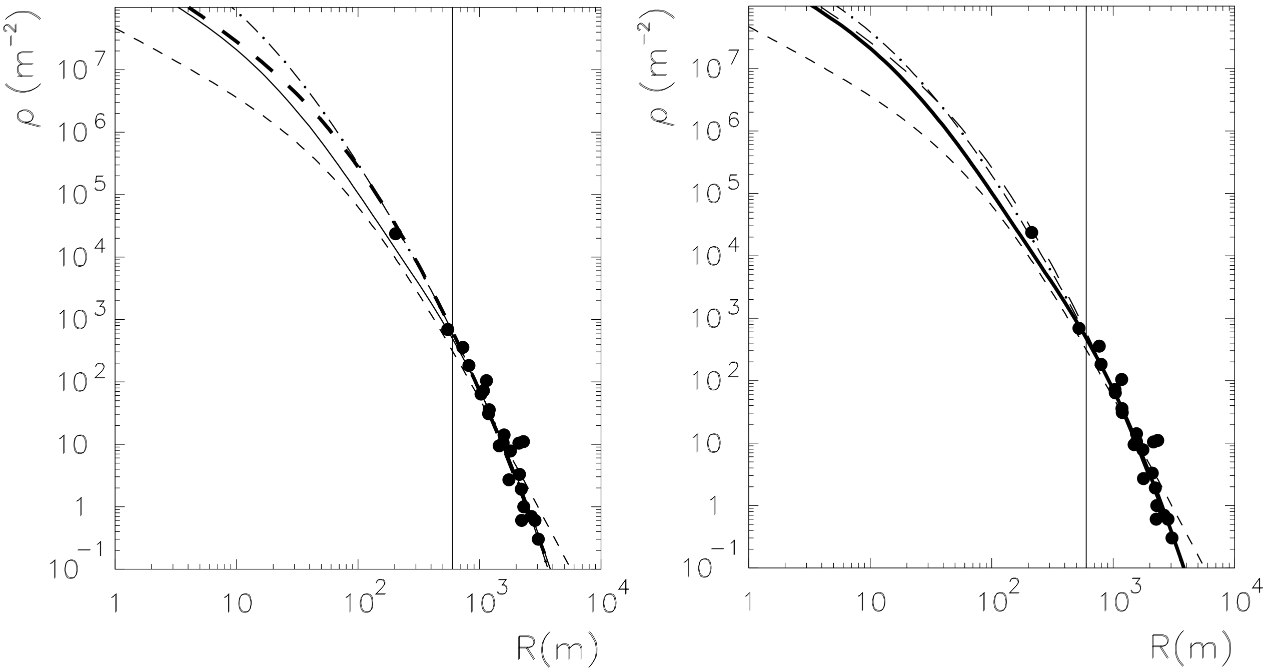

Fig. 2. AGASA event #akn25400–0296. Density distributions for 4 lateral distribution functions. Line description as in the Fig. 1 *'Principal functions'* are AGASA#2 in the left Figure and JNC03 in the right one. See table 2 for comparison of numerical values.

and $\varrho(600)$ determination. Estimation of N_e from $\varrho(600)$ depends on the lateral distribution function used and is uncertain within 50%.

In the more realistic situation localization procedures are not perfect, mostly due to low number of detectors hit, and also due to fluctuations in lateral distribution not correctly included in the form of the used function. We noticed that 60 m error in the core position determination might change normalization up to 40%. It is also worth noticing that determination of $\varrho(600)$ from data registered in arrays having clusters of more closely separated detectors is more 'stable' (e.g. Yakutsk) than in $\sim$ 800 m separated detectors (e.g. Volcano Ranch).

Similarly, there are large discrepancies between localization results when using experimentally derived lateral distribution functions. The GAS core positions are generally localized within 300 m (between themselves) for Volcano Ranch (i.e. large, regular detector separation of about 800 m) or within 60 m for Yakutsk and AGASA events. The axis localization is largely responsible for differences in $\varrho(600)$ estimation in case of Volcano Ranch events. The estimated sizes (N_e) can be different by order of magnitude (or more) due to different shapes of functions at distances smaller than 200 m not covered by experimental measurements.

This should be examined in details, especially taking into consideration different energy thresholds of registered particles (we have used 3 MeV threshold for charged electromagnetic component), contribution from energetic photons and contribution from muons. As recently underlined by Kutter (1998) and Nagano et al. (2000) the ratio of energy loss of electrons and photons in the scintillator (ϱ_{sc}) to the density of charged particles ($R = \varrho_{sc}/\varrho_{ch}$) depends on the distance to the core of GAS. As registrations are taken at large distances the ratio R can be about 1.4. For the primary energy estimations discussed in this paper this would lead to reduction of obtained values of ϱ_{600} and N_e (and energy) by $\sim$40%.

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