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Lateral distribution of charged particles in giant air showers above 1 EeV observed by AGASA

S Yoshida†, N Hayashida‡, K Honda§, M Honda‡, S Imaizumi‖, N Inoue‖, K Kadota†, F Kakimoto†, K Kamata¶, S Kawaguchi††, N Kawasumi§, Y Matsubara‡‡, K Murakami§§, M Nagano‡, H Ohoka‡, Y Suzuki†, M Teshima‡, I Tsushima§ and H Yoshii‖‖

† Department of Physics, Tokyo Institute of Technology, Tokyo 152, Japan
‡ Institute for Cosmic Ray Research, University of Tokyo, Tokyo 188, Japan
§ Faculty of Education, Yamanashi University, Kofu 400, Japan
‖ Department of Physics, Saitama University, Urawa 338, Japan
¶ Nishina Memorial Foundation, Tokyo 188, Japan
†† Faculty of General Education, Hirosaki University, Hirosaki 036, Japan
‡‡ Solar-Terrestrial Environment Laboratory, Nagoya University, Nagoya 464-01, Japan
§§ Nagoya University of Foreign Studies, Aichi 470-01, Japan
‖‖ Faculty of General Education, Ehime University, Matsuyama 790, Japan

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Abstract. We have studied the lateral distribution of charged particles associated with giant air showers and the attenuation of the local particle density at 600 m from the core, S600, with atmospheric depth using data collected with the Akeno Giant Air Shower Array (AGASA). The lateral distribution at distances of more than 1 km from the core has been observed to be much steeper than that suggested by some of the earlier measurements. The shape of the lateral distribution function has been observed to depend on the zenith angle of showers but there is no significant evidence for the dependence on the primary energy, within the resolution of the array. The systematic errors in energy estimation due to the uncertainties in the lateral distribution and the attenuation length of S600 are smaller than statistical errors. These errors have been estimated to be $\sim 5\%$ and $\sim 3\%$ respectively for near vertical showers with $\sec\theta = 1.1$, and $\sim 10\%$ and $\sim 12\%$ respectively for showers with $\sec\theta = 1.4$.

1. Introduction

An accurate determination of the energy spectrum of primary cosmic rays is of fundamental importance for understanding the origin of the highest-energy cosmic rays and their propagation in galactic and/or intergalactic space. In order to estimate the energy of a primary particle with energy above 1 EeV (10^{18} eV), which initiates a giant air shower (GAS) in the atmosphere, the particle density observed at a distance of 600 m from the shower axis, S600, has been widely used as a good energy estimator (Hillas *et al* 1971, Dai *et al* 1988). In the AGASA (Akeno Giant Air Shower Array) experiment, particle density detectors consisting of plastic scintillators of 2.2 m^2 area are spread over 100 km^2 area with inter-detector separation of about 1 km (Chiba *et al* 1992). Therefore observed particle densities are fitted to an empirical formula for the lateral distribution function (referred to as the LDF hereafter) for determining $S600$. Since most detectors in the AGASA are located at distances $R \geqslant 1$ km from the core, the estimated value of $S600$ depends sensitively on the shape of the LDF at large distances. Further, the estimated $S_\theta 600$ for a shower arriving

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at a zenith angle θ is first transformed to the equivalent value in the vertical direction, S_0600, using the attenuation curve for $S600$. S_0600 is then converted to the primary energy of the GAS. Therefore, a detailed understanding of the LDF for GASs and the attenuation of $S600$ with atmospheric depth is indispensable for accurately estimating the primary energy of the GAS. This information is also needed for designing the detector configuration for the proposed giant surface array (Cronin 1993).

In this paper, we present our measurements on the lateral distribution of charged particles in a GAS observed with AGASA and the attenuation of $S600$ with atmospheric depth. In section 2, we describe the experiments performed at the Akeno Cosmic Ray Observatory to study the LDF for a GAS. In section 3, we present the observational results on the LDF for distances beyond 1 km from the shower core in some detail. In section 4, the results obtained for the energy and the zenith angle dependence of the LDF of the GAS are discussed in detail. In section 5 the results of our study on the attenuation of $S600$ using the equi-intensity cuts on integral $S_\theta 600$ spectra are presented. Finally, in section 6, present results are compared with results obtained by other experiments and simulations. Based on results obtained from our study, we present a discussion on the systematic error in the estimation of $S600$, mainly due to uncertainties in the LDF and the attenuation length of $S600$. We also discuss the relevance of the LDF derived from Akeno observations for estimation of primary energies of showers observed with AGASA. At the end of this section we make a comment on the relevance of our results for possible detector configurations for the proposed giant surface array (Cronin 1993).

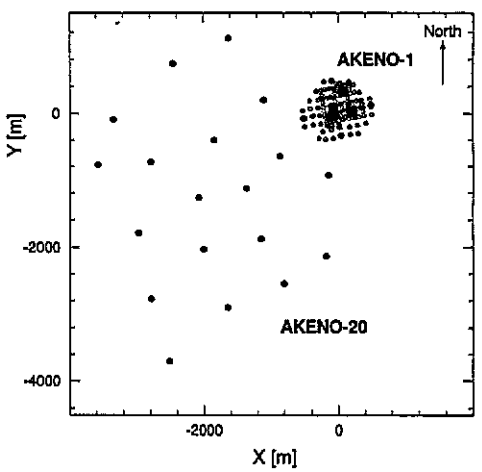


Figure 1. Schematic layout of the Akeno 20 km^2 array (AKENO-20) and the Akeno 1 km^2 array (AKENO-1). The full circles show the density detectors, each of 2.2 m^2 area, in AKENO-20 and the open circles correspond to those of 1 m^2 area in AKENO-1.

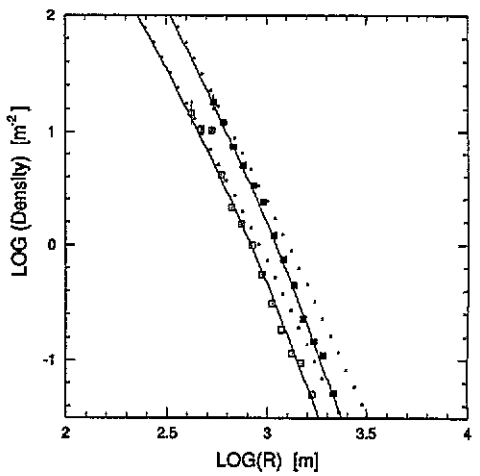


Figure 2. Lateral distribution observed by AKENO-1 for showers hitting inside the boundary of AKENO-20. The open squares show the distribution for near vertical showers with $S600 = 3$ m^{-2} and the full squares for near vertical showers with $S600 = 10$ m^{-2}. The dotted curves represent the Linsley function given by equation (1). The full lines represent the new lateral distribution function with an additional term as given in equation (2).

2. Experiments

The very large surface array covering an area of about 100 km^2, AGASA, became operational in 1990 for studies on the highest-energy cosmic rays, with energies above EeV. The details of the array have been described in Chiba *et al* (1992). One hundred and eleven density detectors are arranged with inter-detector separation of about 1 km and they are sequentially connected by a pair of optical fibres. The schematic view of the array is shown in figure 4. Each surface detector consists of plastic scintillators of total area of 2.2 m^2, which are viewed by a 125 mm diameter Hamamatsu R1512 photomultiplier. To measure the muons associated with the GAS, shielded proportional counters are deployed near 27 of the 111 surface detectors. The absorber shield consists of either a thick iron plate and a thin lead plate or concrete. The threshold energy of muons is about 0.5 GeV. AGASA is divided into four branches, the 'Akeno Branch (AB)', the 'Sudama Branch (SB)', the 'Takane Branch (TB)', and the 'Nagasaka Branch (NB)'. The 20 km^2 array (AKENO-20), operational since December, 1984, forms part of the AB branch (Teshima *et al* 1986). A data processing and storing station, called a 'branch centre', is placed at the centre of each of the four branches. A new data acquisition system has been developed and installed for AGASA which makes it possible to control and operate all the surface detectors through a set of commands transmitted from the central computer at the branch centre.

As a part of AKENO-20, we have a more densely arranged sub-array (AKENO-1), a 1 km^2 array where 156 scintillators, each 1 m^2 in area, are arranged over an area of about 1 km^2, to observe primary cosmic rays with energies of $10^{15} \sim 10^{18}$ eV (Hara *et al* 1979). This sub-array, located in the AB branch, has been operational since 1981. The schematic layout for the AKENO-20 and AKENO-1 arrays is shown in figure 1. For each of the detectors in both arrays, the photomultiplier anode signal is shaped in an exponential form with a decay constant of 10 μs which is then discriminated to give a square pulse. The width of this pulse is proportional to the logarithm of the number of particles incident over the detector. The resultant wide dynamic range, up to $\sim 5 \times 10^4$ particles, is essential for the study of the lateral distribution of GASs.

3. LDF at $R > 1$ km from the core

To determine the LDF at distances far from the core, we have used data from detectors of AKENO-1 with total detection area of 156 m^2 for showers whose core positions have been determined using data from detectors of AKENO-20. Particle densities observed in AKENO-1 detectors have been recorded using the trigger signal from AKENO-20. Since the accuracy in determining the core position by AKENO-20 is ~ 50 m (Nagano *et al* 1992), this uncertainty has a negligible effect on the determination of the LDF at distances $R \geqslant 1$ km from the core. In order to ensure the use of only good quality data for determination of LDF, we have used only those showers whose cores are located well inside the boundary of AKENO-20 and for which more than eight detectors gave a measurable signal.

Figure 2 shows the average lateral distributions of particles, observed using detectors of both AKENO-1 and AKENO-20 arrays, for near vertical showers ($\sec\theta \leqslant 1.2$), for two values of $S600$, namely 3 and 10 m^{-2}. These $S600$ values correspond to primary energies of 6×10^{17} and 2×10^{18} eV respectively (Dai *et al* 1988). The dotted lines shown in figure 2 represent the function given by Linsley *et al* (1962):

$$\rho(R) = C \left(\frac{R}{R_M}\right)^{-1.2} \left(1 + \frac{R}{R_M}\right)^{-(\eta-1.2)} \tag{1}$$

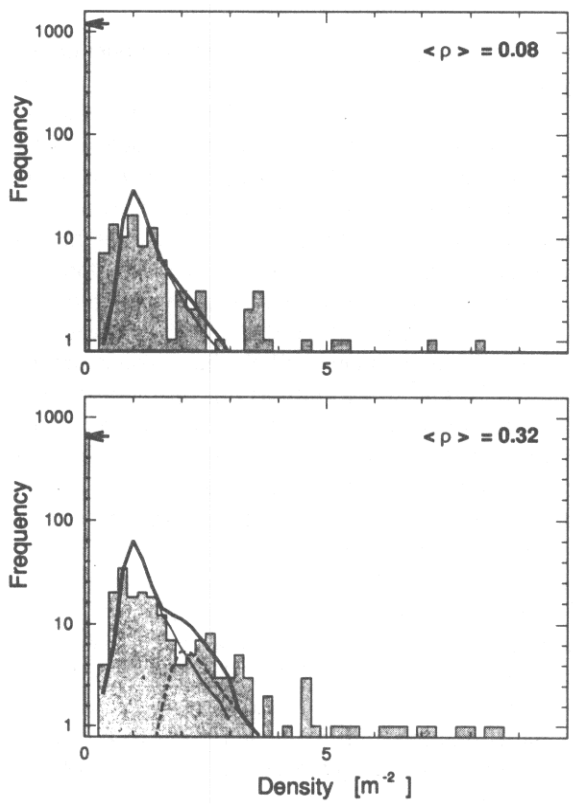


Figure 3. Density distributions for near vertical showers at distances of around 15–20 km from the core for two values of particle densities, 0.08 and 0.32 m^{-2} respectively. The total number of triggered detectors are 1270 (0.03 m^{-2}) and 891 (0.32 m^{-2}). Also shown by arrows in the figure are the expected number of detectors recording zero particles estimated from Poisson probability. The pulse height distributions expected for one and two particles are also shown for comparison by the thin full line and the broken curve. The bold full curve shows the expected pulse height distribution taking into account the contributions of both one and two particles.

where R_M is the Moliere unit (91.6 m at Akeno), C is a normalization factor and η is the parameter which determines the power of the LDF at $R > R_M$. η has been taken to be 3.8 for the curves shown in figure 2 as this was the value obtained by us from an earlier analysis (Teshima *et al* 1986). Note that the observed lateral distribution is much steeper than that expected from equation (1) at distances $R > 1$ km, using $\eta = 3.8$. We have examined in detail the density distributions observed at $R > 1$ km to understand this discrepancy, in particular, whether we fail to record the densities because of inappropriate recording of particle number. In figure 3, we show density distributions recorded in individual detectors at distances around 1.5–2 km from the core, where the densities expected using the LDF given by equation (1) are 0.08 and 0.32 m^{-2} respectively. The expected distributions from Poisson statistics are also shown in figure 3 for comparison. It is seen that the observed distributions are consistent with Poisson statistics for average densities of 0.08 and 0.32 m^{-2} taking detector resolution into account.

The observation of densities above 3 m^{-2} may be related to the incidence of delayed neutrons (Teshima *et al* 1986) and will be discussed in some detail elsewhere. It is necessary to introduce an additional term in equation (1) to represent the steepness of the observed lateral distribution at large core distances. The best-fit empirical LDF is

$$\rho(R) = C\left(\frac{R}{R_M}\right)^{-1.2}\left(1+\frac{R}{R_M}\right)^{-(\eta-1.2)}\left(1.0+\left(\frac{R}{1\text{ km}}\right)^2\right)^{-\delta} \qquad (2)$$

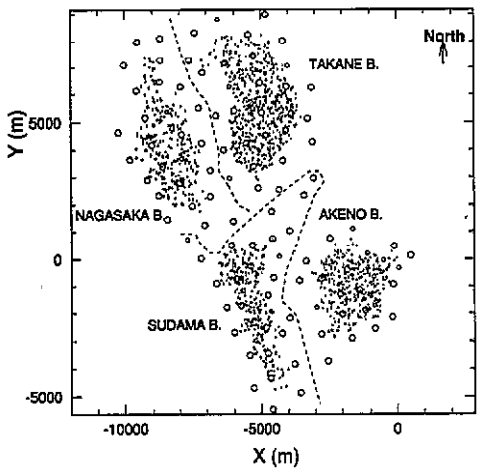


Figure 4. The core location distribution for GAS events used for the present analysis. The open circles represent the density detectors of AGASA.

where $\eta = 3.8$ and $\delta = 0.6 \pm 0.1$ for near vertical showers with $\sec\theta \leqslant 1.2$ and energies between 6×10^{17} and 2×10^{18} eV.

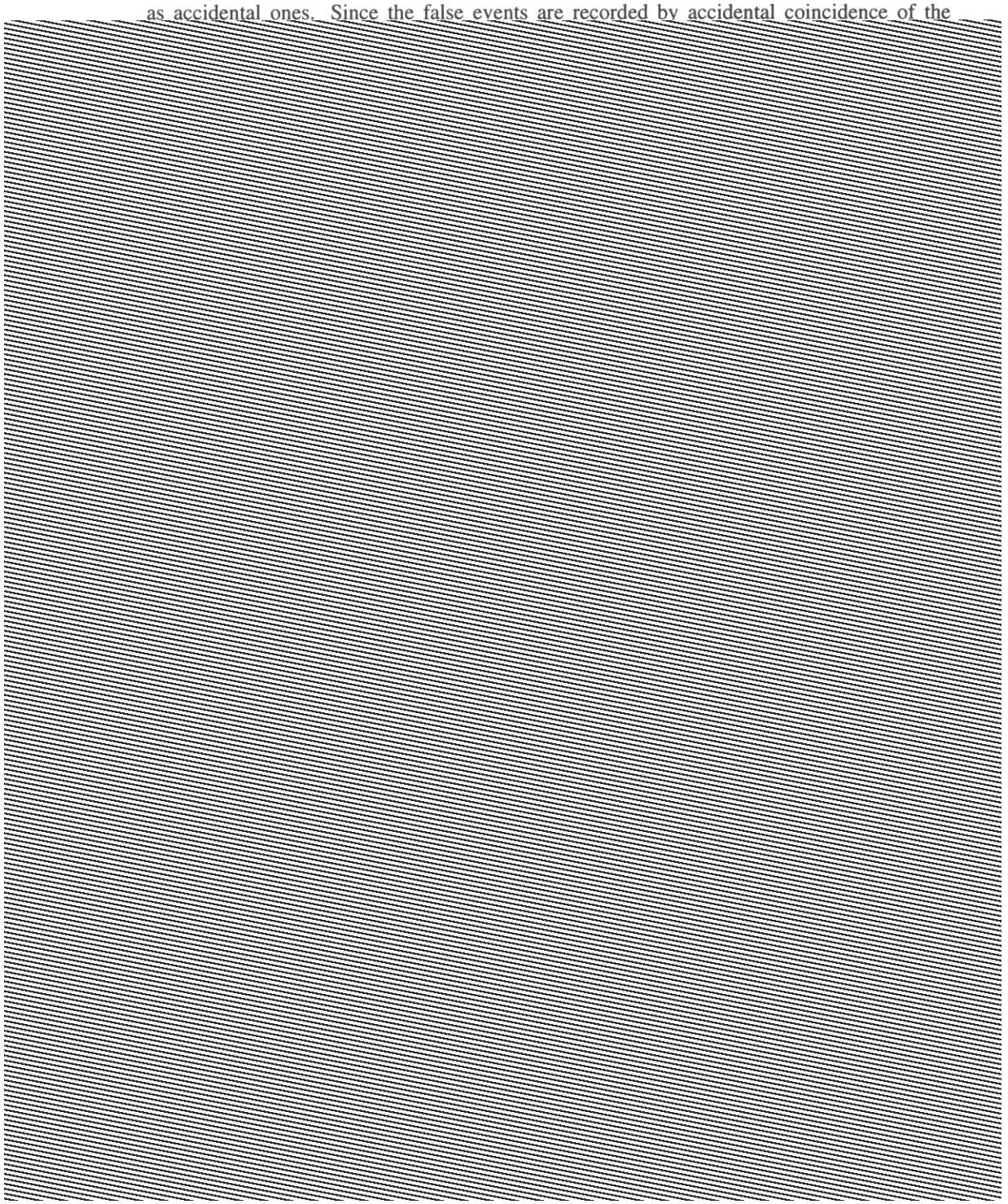
4. Lateral distribution for energies above 1 EeV

We have made a detailed study of the lateral distribution of particles in showers initiated by primary cosmic rays of energies above 1 EeV. We have also studied its dependence on the primary energy and zenith angle. For an individual shower, the new LDF given by equation (2) has been used to fit the observed densities by searching for the location of the shower core which gives the best fit. In the fitting procedure, η and C have been treated as free parameters and the value of δ has been taken as 0.6.

Generally, in arrays designed to have a large collecting area such as AGASA (figure 4), the number of detectors with measurable particle density is not large enough to treat both the core location and η as free parameters for most of the observed showers. In addition, triggering bias tends to favour selection of showers with flatter LDFs. Therefore, care should be taken in choosing the sample of a good GAS so as to minimize the systematic errors during analysis. In order to achieve this objective for our analysis, we have used only those showers which have density information from a minimum of eight detectors and whose cores are located well within the boundary of the array. We also require that $S600 \geqslant 3$ m^{-2}. Figure 4 shows the core location distribution for these selected showers. It may be seen that this procedure excludes all showers whose cores are located in the boundary regions of different branches. It has been observed that showers with cores in the boundary region tend to give the best fit with a steeper lateral distribution.

Next, we exclude events which possibly could suffer from large systematic errors, using a new parameter λ. This parameter λ represents the degree of goodness in locating the core position which is estimated by the maximum likelihood method. This parameter helps in selecting good GASs and discriminates against false events which occur by accidental coincidence between nearby detectors.

The likelihood function $\mathcal{L}(\rho_{\mathrm{LDF}})$, computed for estimating the deviation from the expected LDF, is obtained by assuming that the observed densities follow the normal distribution around the densities expected from the LDF, ρ_{LDF}, taking into account the

expected fluctuations in density, due to both fluctuations in the cascade development and the detector resolution. This fluctuation has been determined experimentally (Teshima *et al* 1986). The search for $S600$ and core position in the fitting procedure is carried out by maximizing $\mathcal{L}(\rho_{\rm LDF})$, based on the maximum likelihood estimation (MLE).

We also calculate the similar likelihood function $\mathcal{L}(\rho_{\rm BG})$ taking the (background) events as accidental ones. Since the false events are recorded by accidental coincidence of the