Characteristics of Giant Air Showers with Energy larger than 10^{19}eV Observed by AGASA

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Abstract

Since 1990 the Akeno Giant Air Shower Array (AGASA) has been operated in a stable mode and more than 500 showers of energies larger than 10^{19}eV have been observed. For these giant air showers, we have determined the average lateral distributions for charged particles, detected by scintillation counters. Our study shows that the empirical formula determined earlier from a study of showers of energies below 10^{19}eV can also be applied to showers with energies up to $10^{19.8}$eV, and with core distances up to 3 km for particles detected with scintillation counters.

1 Introduction:

Very energetic cosmic rays above 200EeV were observed by AGASA (Takeda et al., 1998). To solve the mystery of these ultra high energy events, it is very important to determine the energy spectrum of the primary cosmic rays precisely. On the other hand, three pairs of cosmic rays coming from the same direction within the experimental angular resolution is observed by AGASA, including the highest energy event in one of three pairs (Hayashida et al., 1997). They may be neutral particles, possibly gamma-rays, however, shower characteristics of these showers are similar to the average characteristics of other showers and they seem not to be subjected to Landau-Pomeranchk-Migdal effects (Landau & Pomeranchk, 1953a, 1953b; Migdal, 1956).

The study of shower characteristics of giant air showers in the ultra high energy region is very important for estimating not only their primary energies, their species and their arrival directions, but also for finding any different group of their characteristics.

In order to estimate the primary energy, the density observed at a distance 600m ($S(600)$) is used. Since AGASA consists of 111 scintillation detectors spread over the area 100km^2 with separation of 1km (Chiba et al., 1992, Ohoka et al., 1997), the density of each detector is fitted by the lateral distribution formula to obtain

$S(600)$. $S_\theta(600)$, the density at 600m of the shower with the zenith angle θ is converted to the primary energy taking account of the attenuation.

2 Results:

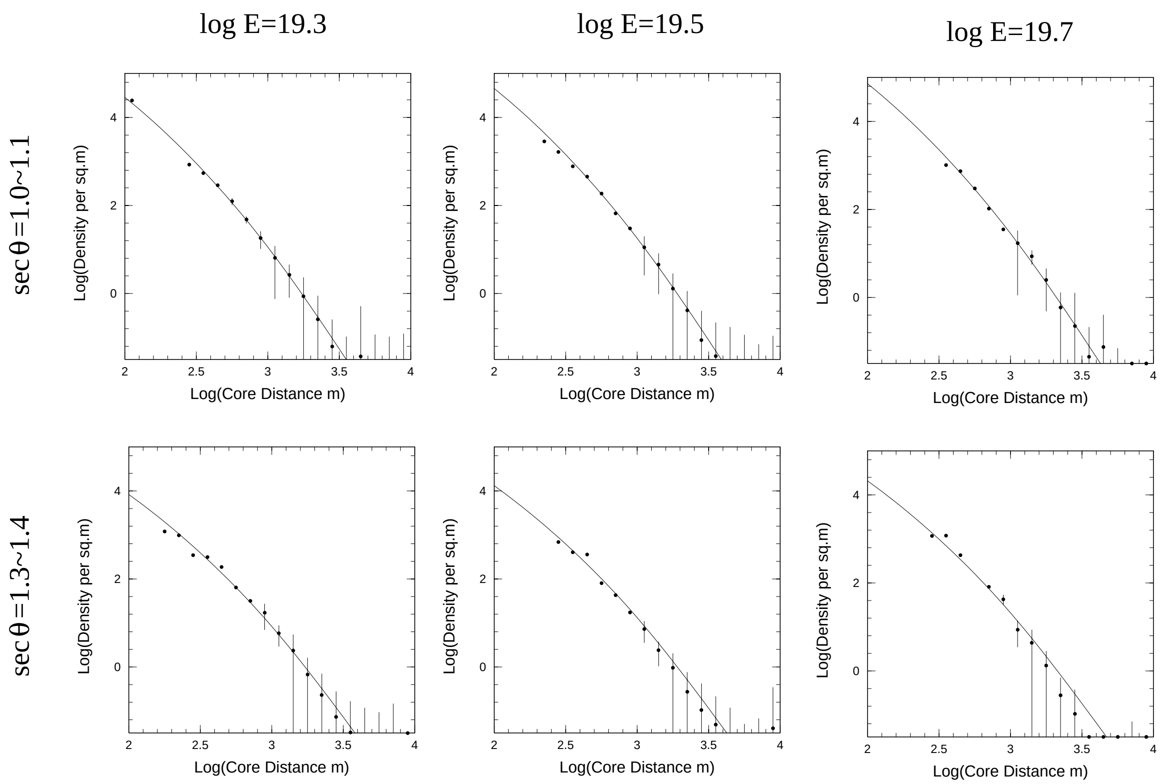

Figure 1: average lateral distribution for charged particles in three energy bins and two zenith angle bins.

As described in Yoshida et al. (1994), we have determined the following function for charged particles on the surface.

$$\rho(R) = C\left(\frac{R}{R_M}\right)^{-\alpha}\left(1+\frac{R}{R_M}\right)^{-(\eta-\alpha)}\left(1+\left(\frac{R}{1km}\right)^2\right)^{-\delta} \tag{1}$$

where R is distance in meter from the core, R_M is a Moliere unit at two radiation lengths above the observation level and is 91.6m at Akeno. C is a normalization factor. α and δ are 1.2 and 0.6, respectively. η is a function of the zenith angle of the arrival direction and is expressed by

$$\eta = 3.97 - 1.79(\sec\theta - 1.0) \tag{2}$$

The average lateral distribution of charged particles measured with scintillators on the surface are plotted in figure 1 in each energy($\log E = 19.3, 19.5, 19.7$,$\Delta(\log E) = 0.2$) and zenith angle ($\theta$) bins ($\sec\theta = 1.05, 1.35$, $\Delta(\sec\theta) = 0.1$). Solid lines are the function 1, which was determined with showers below 10EeV. It is seen that the function 1 agrees with data in the present energy region as well.

In order to see the fluctuation of η of an individual air shower, densities of each counter were fitted with varying core position and η value to search for the minimum χ^2 value. The showers are selected as follows after the fitting; the period from Feb.1990 to Dec.1998, the number of hit detectors is more than or equal to 8, the reduced χ^2 in determining arrival direction and core position is less than 1.0, and the core is within

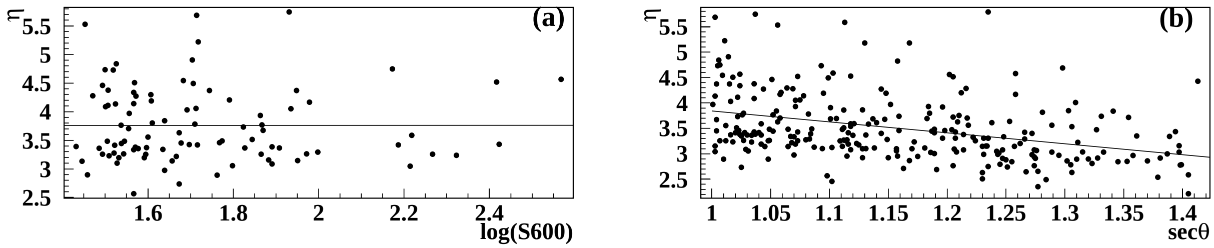

Figure 2: dependence of η on S(600) (a) and on zenith angle (b). The solid lines shows the best-fit lines.

$< \log E >$	1.05	1.15	1.25	1.35
19.1	3.72±0.52	3.57±0.69	3.03±0.33	3.00±0.20
19.2	3.27±0.69	3.50±0.69	3.32±0.35	2.96±—
19.3	4.12±0.94	3.72±0.26	3.37±0.29	2.90±0.13
19.4	3.29±—	3.76±0.72	3.56±0.53	2.91±0.02

Table 1: The average η value and its fluctuation around the average in each energy and zenith angle bins(experiment). The column is $\sec\theta$ and the row is $\log E$.

the array. 258 events are used in total. The best fitted η is plotted in figure 2(a) as a function of $S(600)$ for $\cos(\theta) < 1.1$. The fitting function of η value is given by the following equation,

$$\eta = (3.76 \pm 0.16) + (0.01 \pm 0.43) \log \left(\frac{S(600)}{100[m^{-2}]} \right) \tag{3}$$

The average η values and their deviations around the averages are listed in Table 1. It is found the average value is almost independent from primary energy and from $S(600)$, and depends on zenith angle.

Assuming no dependence of η on $S(600)$, η is approximated as

$$\eta = (3.84 \pm 0.11) - (2.15 \pm 0.56)(\sec\theta - 1.0) \tag{4}$$

for zenith angle $\theta < 45^o$ and $\log(E[eV]) > 18.8$. (figure2(b))

In order to examine whether these deviations are due to real fluctuations of showers or experimental ones, the same analysis was performed for artificial showers. The artificial showers were simulated with the average lateral distribution expressed by the formula 1 and 2. The statistical fluctuation and the response of the detector are taken into account, however, fluctuation of longitudinal development or others are not included. Figure 3 shows the deviation of η value for $\log(E[eV]) = 19.0$ and $\sec\theta < 1.1^o$. The mean value and the standard deviation of it is 3.75 ± 0.47 and are comparable with the experimental ones. That is, most of the fluctuation of the η value is not due to the shower development fluctuation, but due to the experimental one.

3 Conclusion:

The average lateral distributions for charged particles detected by scintillation detectors on the surface has been well represented by the empirical formula derived earlier for showers in the energy region below 10EeV. This study shows that the empirical formula for charged particles is valid up to $10^{19.8}$eV for energies and 3km for core distances. The fluctuation of eta of real showers is within the present experimental fitting error and hence we had better use the average lateral distribution (1) to estimate $S(600)$ of each event without changing

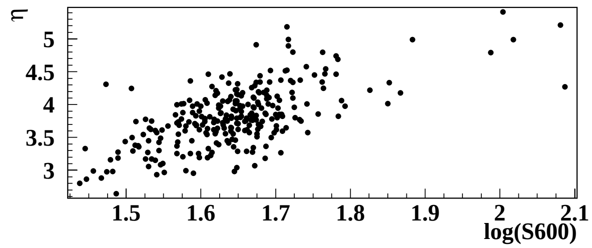

Figure 3: dependence of η for nearly vertical artificial showers.

eta value, as being done so far to derive the primary energy spectrum (Takeda et al., 1998). The zenith angle dependence (4) is better determined than Eq.(2) for $\log E \geq 18.8$eV.

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