Characteristics of Inclined Giant Air Showers Observed by AGASA

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Abstract

Characteristics of inclined giant air showers with $\sec\theta$ of 1.4 – 3.0 have been studied with data taken by AGASA of 100km^2 area. The muon component are predominant in a large $\sec\theta$ region and its proportion in charged particles density at 600m from the core ($S(600)$) reaches to 50 – 70% at $\sec\theta$ of 2.0. The shape of lateral distribution of charged particles is also affected by the increase of muons. A search for deeply developing air showers has been made to examine a possibility of high energy neutrino in the highest energy region. The upper limit on the flux with the energy $\geq 10^{19.5}$eV is 1.9×10^{-16} m^{-2} s^{-1} sr^{-1} at the confidence level of 90%.

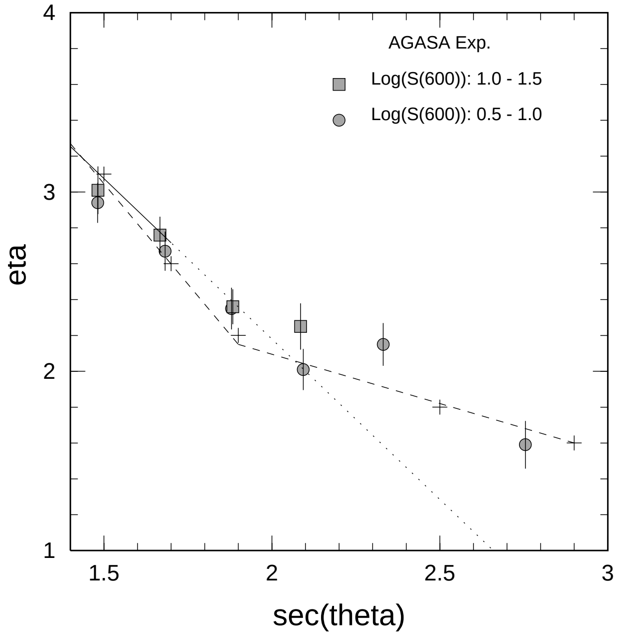
1 Introduction

Giant air showers (GAS) produced by extremely high energy cosmic rays (EHECR) have been observed by Akeno Giant Air Shower Array (AGASA) and their energy spectrum and arrival directions have been studied for vertical showers with $\sec\theta$ less than 1.4 and energies beyond 10^{20}eV. Inclined giant air showers (IGAS) detected by AGASA have not been used for such analysis, so far, since a reliable method of analysis has not been established. In order to estimate their reliable energies, characteristics of electron and muon components in IGAS with $\sec\theta$ of 1.4 – 3.0 have to be studied in detail and be interpreted quantitatively with help of Monte Carlo simulation. Acceptance for EHECR with energy of $\sim 10^{20}$eV can be increased more than 50%, if an evaluation of primary energy can be done for IGAS which have been out of use for analysis, up to now.

A search for deeply developing air showers (DDAS), which start its development deep in the atmosphere, is also important to examine a possibility of high energy neutrino and/or other weakly interacting particles in the highest energy region. Recently there are some speculations of neutrino origin of the highest energy cosmic rays. Barshay and Kreyerhoff (1998) claimed that the highest observed air showers might be initiated by neutrinos (ν_τ) from the decay of dark-matter inflatons. The inflatons proposed by them are heavy massive particles of the order of 10^{10} GeV and a significant part of cold dark matter today. The inflatons can decay specifically into ν_τ and $\bar{\nu_\tau}$ with a lifetime to be several orders of magnitude greater than the present age of the universe. The maximum energy of neutrino is equal to one-half of the inflaton mass. The distinctive signal would be a bump-structure in the energy spectrum which would appear beyond the GZK cutoff energy. Chikashige and Kamoshita (1998) also discussed neutrino or neutralino origin which are decay particles of superheavy particles left over in the Universe, whose origin are not specifically assummed. These models of neutrino origin of extensive air showers are different from a possibility of nucleons or gamma-ray primaries which might be produced by neutrino in extended Galactic halo through Z^0 at resonance in the interactions with the relic neutrino of mass $\sim$eV (Weiler,1982) and their validity can be examined with the present AGASA experiment.

The neutrino-nucleon cross-section is so small for cosmic rays to initiate the extensive air shower in the atmosphere that the expected arrival direction distribution is quite different from those expected from nucleon primaries. That is, if the observed EHECR are from neutrino, we may find DDAS from the direction of large zenith angles in similar rate with GAS from the vertical direction.

2 Experiment and Analysis



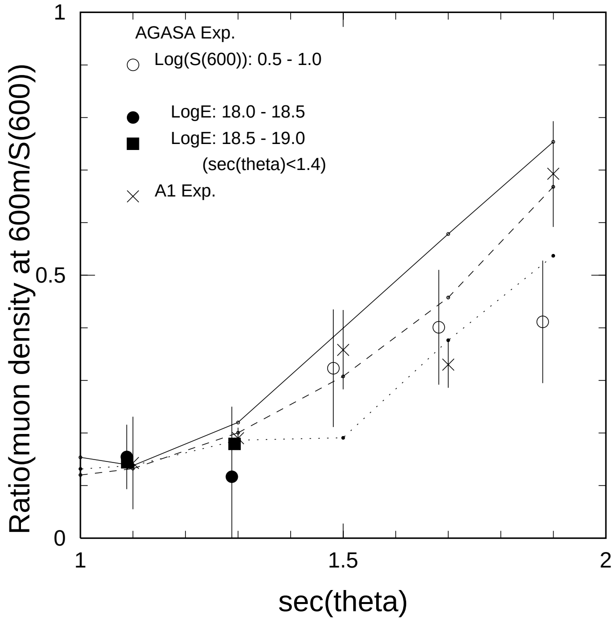


Figure 1: (Left) *The relation between* η *and sec*θ *for showers with sec*$\theta \geq$ *1.4. A solid line is from formula (2) and a dotted line is its extrapolation. A broken line is one expected from CORSIKA-QGSJET proton showers with energy of* 10^{19}*eV*

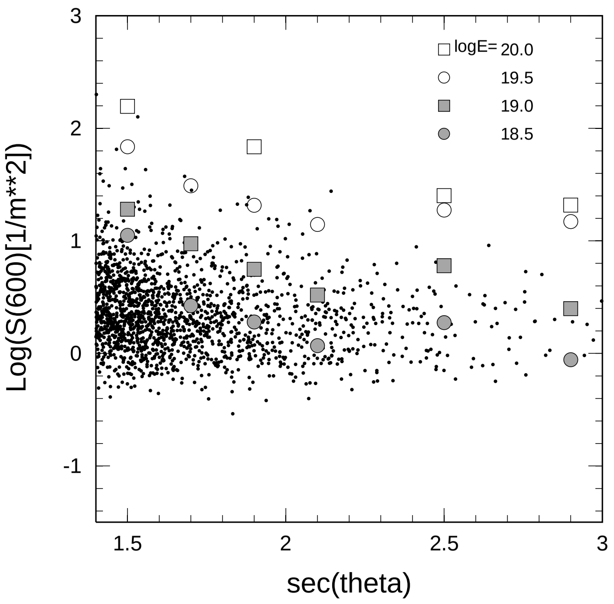
Figure 2: (Right) *The relation between* ρ_μ*(600)/S(600) and sec*θ *for showers with sec*θ *of 1.0 – 2.0. Experimental results from AGASA are shown with circles and squares, and ones from A1 are shown with crosses. The relation from CORSIKA-QGSJET proton simulations are drawn with solid, broken and dotted lines for* E_0*=*10^{18}*,* 10^{19} *and* 10^{20}*eV, respectively.*

AGASA consists of 111 surface detectors of 2.2m^2 area each are deployed over 100km^2 area (A100, Chiba et al., 1992, Ohoka et al., 1997), and 27 muon detectors (threshold energy of muon:$E_\mu \geq 0.5 \sec\theta$ GeV) with area either 2.8m^2 or 10m^2 each are located in the southern half of the full effective area. At Akeno Observatory, the Akeno 1km^2 air shower array (A1) with 156 surface detectors of 1m^2 area each and 8 muon detectors ($E_\mu \geq 1.0 \sec\theta$ GeV) of 25m^2 area each has been operated since October 1981. Present analysis for showers with $\sec\theta \geq 1.4$ has been made with data taken from December 1995 to March 1999, and 5226 showers with $n_{\rm hit} \geq 8$(at least 8 surface detectors within 3.2km from the core detect shower particles) are used in the following analysis.

The lateral distribution of charged particles for showers with $\sec\theta \leq 1.7$ has been reported in Yoshida et al.,1994. The empirical formula is expressed as below.

$$\rho(R) = C\left(\frac{R}{R_{\rm M}}\right)^{-1.2}\left(1+\frac{R}{R_{\rm M}}\right)^{-(\eta-1.2)}\left(1+\left(\frac{R}{1{\rm km}}\right)^2\right)^{-0.6} \qquad , R_{\rm M} = 91.6{\rm m} \tag{1}$$

$$\eta = 3.97 - 1.79(\sec\theta - 1) \tag{2}$$



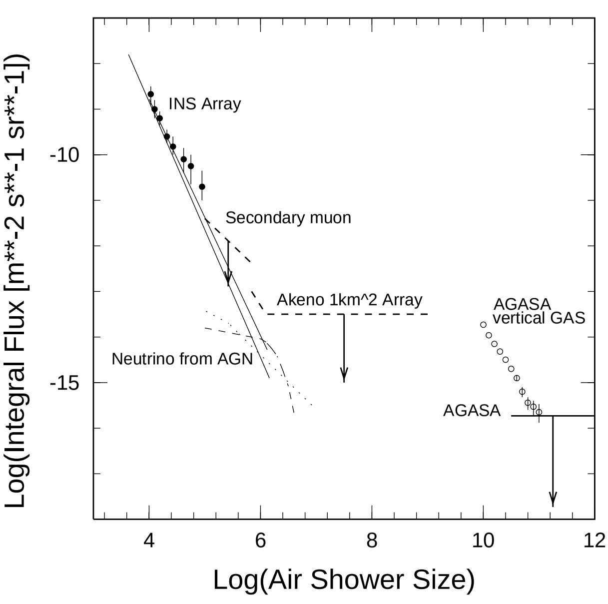


Figure 3: (Left) *The relation between S(600) and secθ. Small dots are observed values and large squares and circles are average values from CORSIKA-QGSJET proton showers for four different primary energies.*

Figure 4: (Right) *The present upper limit of DDAS and integral energy spectrum of AGASA EHECR are shown in integral shower size spectrum of horizontal air showers (HAS). Closed circles are from Mikamo et al. (1982) and upper limit of 1 km^2 array is from Nagano et al. (1986). Expected HAS from AGN neutrino expressed by thin and thick dashed lines are from Halzen and Zas (1992).*

where C is a normalization factor and R_{M} is the Moliere unit at Akeno. η is the parameter which indicates the slope of the lateral distribution at $R \geq R_{\mathrm{M}}$.

Primary energy E_0 in eV is determined with the formula, $E_0 = 2.0 \times 10^{17} S_0(600)$, where $S_0(600)$ is the charged particle density in $1/\mathrm{m}^2$ at 600m from the core for vertical equivalent shower. $S_0(600)$ is evaluated from the observed local density at 600m ($S(600)$) with a relation of attenuation curve of $S(600)$ which is expressed as

$$S_0(600) = S(600)\mathrm{exp}\left[-\frac{X_0}{\Lambda_1}(\sec\theta - 1) - \frac{X_0}{\Lambda_2}(\sec\theta - 1)^2\right]$$

where $X_0 = 920\mathrm{g/cm}^2, \Lambda_1 = 500\mathrm{g/cm}^2, \Lambda_2 = 594^{+268}_{-120}\mathrm{g/cm}^2$. The lateral distribution of IGAS has to be determined carefully since $\sec\theta$ dependence of average η in the formula (2) may not be applied for showers with $\sec\theta \geq 1.7$. In this analysis, IGAS with $\sec\theta$ of $\geq$1.4 have been re-fitted with the formula (1) by changing η and core location to be the minimum χ^2 and then the most probable core location, $S(600)$ and a value of η were determined for each shower.

3 Results and Discussions

The relation between η defined in the formula (1) and $\sec\theta$ is shown in figure 1. The values of averaged η in two different S (600) regions are presented with symbols of circles and squares. The results from simulation: CORSIKA-QGSJET model, which is developed and provided by Heck et al. (1998), are shown in the same figure for proton initiated air showers with energy of 10^{19}eV. The relation of formula (2) is drawn with a solid line. The present result for inclined air showers is almost consistent with a formula (2) and its extrapolation up to $\sec\theta$ of 2.0, however, the slope of this relation becomes flatter for $\sec\theta \geq 2.0$. The change of the slope in the η-$\sec\theta$ relation is due to the increase of the proportion of muon in charged particles in a large $\sec\theta$ region. This tendency is also obtained from the result of simulation as shown by a broken line in the figure.

The method of primary energy estimation for GAS cannot be applied to IGAS, since the muon component are predominant in a large $\sec\theta$ region. The proportion of muon in charged particles may depend on the interaction model. In figure 2, the ratio of muon density at 600m from the core ($\rho_\mu(600)$) to $S(600)$ is shown as a function of $\sec\theta$. The ratios from Akeno 1km^2 array(A1) and simulation results of proton primary are also plotted in the same figure with crosses and lines (solid:10^{18}eV, broken:10^{19}eV and dotted:10^{20}eV). The ratio increases with $\sec\theta$ and reaches to 50% – 70% at $\sec\theta$ of 2.0, which is easily explained by the difference in attenuation length between muon and electron components in an air shower. Ratios from A100 and A1 are almost consistent with ones expected from simulation within error. Uncertainty due to the statistics and/or experimental bias in the present results, is still too large to derive muon proportion in observed $S(600)$ at large zenith angles. We also need to study this ratio with other interaction models to compare with experiment.

Under the assumption of QGSJET model, the search for the EHECR in the large zenith angle region has been made. Plots of $S(600)$ for individual showers are shown in figure 3 together with simulation results for primary energies of $10^{18.5}$, $10^{19.0}$, $10^{19.5}$ and $10^{20.0}$eV. There are some candidate events which show large $S(600)$ and may be above $10^{19.5}$ eV in large zenith angles and the figure suggests the increase of EHECR events after further study of IGAS.

We searched for DDAS in large zenith angles whose lateral distributions are similar to GAS. This search has been made in the showers with core locations inside of the whole array and $n_{\rm hit} \geq 10$ within 3.2km from the core. The selection criterion of DDAS is η of 4 – 6, which indicates steeper lateral distribution than those of the average GAS. For $\sec\theta = 1.4 - 3.5$, triggering efficiency is found to be almost 100% over the whole array for DDAS of $\geq 10^{19.5}$ eV by analyzing artificial showers. During the observation time (live) of 9.7×10^7s, no candidate DDAS was found. This implies the upper limit on the flux of DDAS with the energy $\geq 10^{19.5}$eV is 1.9×10^{-16} m^{-2} s^{-1} sr^{-1} at the confidence level of 90%. In figure 4, the upper limit of the DDAS is plotted with those of lower region by converting from energy to shower size with 1 particle=1 GeV. The models of neutrino origin of EHECR above 10^{20} eV seem to be excluded from this result.

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