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Cosmic Ray Energy spectrum above 3×10^{18} eV observed with AGASA

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Abstract. We report the energy spectrum of primary cosmic rays above 3×10^{18} eV using the updated data set (May, 2001) of the Akeno Giant Air Shower Array (AGASA). In order to increase statistics and cover a larger area of the sky, events up to 60° in zenith angle are used, so that the exposure used for the analysis is increased by 50% above 10^{19} eV compared with that so far used. A new conversion relation from $S_0(600)$ to E_0 is used in the energy estimation. The energy spectrum extends up to a few times 10^{20}eV without a cutoff and the total number of candidates above 10^{20}eV is 17.

1 Introduction

We have reported the extension of the energy spectrum well beyond the GZK energy (Takeda *et al.*, 1998), 4×10^{19}eV, where the cutoff is theoretically expected due to photopion production on 2.7K photons. Many models explaining these super-GZK particles have been proposed so far since the discovery of cosmic rays far beyond 10^{20}eV by AGASA (Hayashida *et al.*, 1994) and Fly's Eye (Bird *et al.*, 1995).

There are two categories of models, Bottom-Up and Top-Down. The first category, Bottom-Up models are based on acceleration around astronomical objects, however, there are difficulties in attaining the maximum energy of cosmic rays above 10^{20}eV. In the acceleration by the statistical mechanism or by the unipolar induction mechanism, the maximum attainable energy is constrained by the object size and the magnetic field strength as discussed by A.M.Hillas (Hillas , 1984).

On the other hand, the Top-Down model explains the super-GZK particles as secondary particles from the decay of massive particles($M_x \geq 10^{21}$eV) which are considered to be formed in the early universe. The maximum energy is governed by that particle mass and the energy spectrum follows that of a hadron jet($\propto E^{-1.5}$) (Bhattacharjee and Sigl , 2000). Therefore the maximum energy of the cosmic rays and their spectral shape are important parameters in investigating their origin.

The intensity of super-GZK particles is very low: a few events per square km per century. Following the discovery of super-GZK particles and in order to solve their origin of super-GZK particles, several next generation projects, Auger, Telescope Array, OWL, and EUSO have been proposed. They have typically 30 times or 1000 times larger aperture than AGASA. R&D study and an engineering array construction are ongoing in these projects. However, we need to wait for some more years until the new results will be presented.

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In order to increase candidates of super-GZK events with the current AGASA detector, we tried to extend the aperture. The analysis of the AGASA energy spectrum was so far limited to 45° in zenith angle, because the employed attenuation curve was only valid up to $\sim 50°$. In this paper, we have obtained new attenuation curves with a larg amount (∼1000 events above 10^{19}eV) of experimental data. The new attenuation curve is now extended up to 60°. An analysis program independent of that used by Takeda *et al.* (1998) is used in this analysis. Though there are some differences in energy and arrival direction determination in each event, they are within experimental errors. The energy spectrum above 3×10^{18}eV is derived with data up to May 2001, for about 16 years of events within 60° including the 20km^2 array data before the AGASA. With this analysis, we found 17 candidates above 10^{20}eV.

2 Experiment

AGASA consists of 111 plastic scintillation detectors over an area of 100km^2 with a separation of about 1km. The detectors are connected by optical fiber cable, which enables fast data transfer and good time resolution of 20nsec. Each detector records the arrival time of shower particles and the number of incident particles (Chiba *et al.*, 1992; Ohoka *et al.*, 1997). The arrival direction of the cosmic rays is determined from the relative arrival times of signals at detectors and the primary energy is estimated from the local density at 600m ($S(600)$) from the shower axis.

A parameter $\rho(600)$, particle density at 600m from the core, was originally proposed by A.M.Hillas (Hillas *et al.*, 1971) to estimate the primary energies of showers observed in the Haverah Park experiment (an array of water Čerenkov detectors). AGASA uses different type of detectors, scintillation detectors, which are sensitive to the electro-magnetic components in the showers. We employed a similar parameter ($S(600)$), and found using a Monte Carlo simulation that $S(600)$ is also a good energy estimator for the AGASA experiment (Dai *et al.*, 1988).

In the experiment, we observe showers with various zenith angles. As inclined showers pass through more atmosphere than vertical showers, the density $S(600)$ is attenuated with zenith angle. The attenuation of the density $S(600)$ is corrected to that of the vertical direction using a experimentally derived formula. The attenuation of $S(600)$ and the conversion relation from $S(600)$ to the primary energy are described in sections 3 and 4.

3 Attenuation of $\mathbf{S}(600)$

So far we have used the following equation up to $\theta = 45°$.

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

where X_0 is the atmospheric depth at Akeno, 920g/cm^2, $\Lambda_1 =$ 500g/cm^2 and $\Lambda_2 = 594$g/cm^2 (Yoshida *et al.*, 1994). As this equation and the experimental data agree well up to $\sec\theta < 1.6$, we have used events with $\theta < 45°$. The empirical formula for attenuation of $S(600)$ is obtained using the method of equi-intensity cuts on integral $S_\theta(600)$ spectra at various zenith angles. In this method, the observed energy spectrum of cosmic rays is assumed to be independent of the zenith angle and hence the plots of $S(600)$ at certain intensity as a function of zenith angle lead to the atmospheric attenuation curve for cosmic rays with a certain energy.

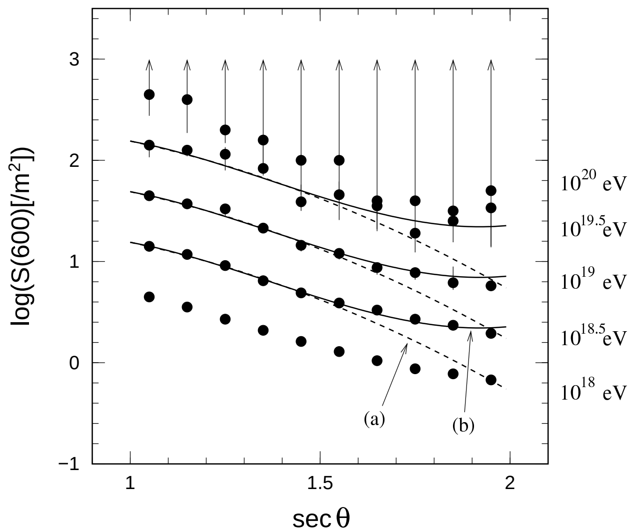

Fig. 1. Attenuation of $S(600)$ with zenith angle using the equi-intensity method. The closed circles are experimental data. The dashed lines (a) represent Equation(1) which has been used for AGASA experiment so far, and the solid lines (b) represent the newly obtained function (Equation(2)), which agrees well with experimental data up to 60°.

Fig.1 shows the variation of $S(600)$ with zenith angle derived with the equi-intensity cut method. The energies in the plots correspond to $10^{18.0}$eV to $10^{20.0}$eV with a step of half decade.

In order to obtain a formula valid up to 60° in zenith angle, Equation(1) is revised as follows.

$$S_\theta(600) = S_0(600)\exp\left[-\left\{\frac{X_0'}{\Lambda_1'}(\sec\theta-1)\right\} - \left\{\frac{X_0'}{\Lambda_2'}(\sec\theta-1)\right\}^2 + \left\{\frac{X_0'}{\Lambda_3'}(\sec\theta-1)\right\}^3\right], \quad (2)$$

where X_0' =957g/cm^2 is the average atmospheric depth at AGASA, $\Lambda_1' = 605$g/cm^2, $\Lambda_2' = 514$g/cm^2 and $\Lambda_3' =$ 654g/cm^2. This function agrees with the experimental data even at the higher energy than 10^{19}eV, although the error increases with the primary energy. This relation is almost independent of primary species and the hadronic interaction models at ultra-high energy. It was confirmed using a detailed Monte Carlo simulation with AIRES, as reported in another paper in this conference (Sakaki *et al.*, 2001).

4 Energy Conversion

So far we have used the following function

$$E\,[\mathrm{eV}] = 2.03 \times 10^{17} \cdot S_0(600)^{1.0}\,[/\mathrm{m}^2] \quad (3)$$

to estimate the primary energy of AGASA events from $S(600)$ (Dai *et al.*, 1988). A new conversion relation is obtained using the air shower simulation AIRES (Sciutto, 1999), taking into account the response of the AGASA detector which includes its detailed structure(Sakaki *et al.*, 2001). The average relation for primary protons and irons using the hadron interaction models, QGSJET and SIBYLL is expressed by the following equation.

$$E\,[\mathrm{eV}] = 2.23 \times 10^{17} \cdot S_0(600)^{1.02}\,[/\mathrm{m}^2] \quad (4)$$

The difference in the energy conversion factor is at 10^{20}eV about 10% between proton and iron, and about 10% between QGSJET and SIBYLL.

5 Energy Spectrum

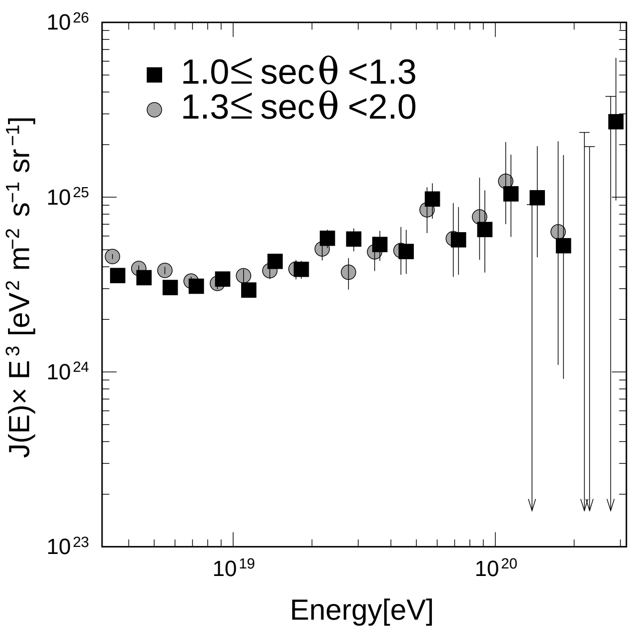

Fig. 2. Energy spectrum for inclined showers (shaded circles) is compared with that for vertical showers (filled squares). The differential flux is multiplied by E^3. The arrows are Poisson upper limits of 90% C.L.

To check the consistency of the energy spectrum of the inclined showers with that of vertical showers, the spectra of inclined showers ($1.3 < \sec\theta \leq 2.0$) and of vertical showers ($\sec\theta \leq 1.3$) are plotted separately in Fig.2. The two spectra are consistent with each other although there is a small discrepancy below 10^{19}eV. In this energy region some systematic error remains, because the exposure decreases rapidly with decreasing energy.

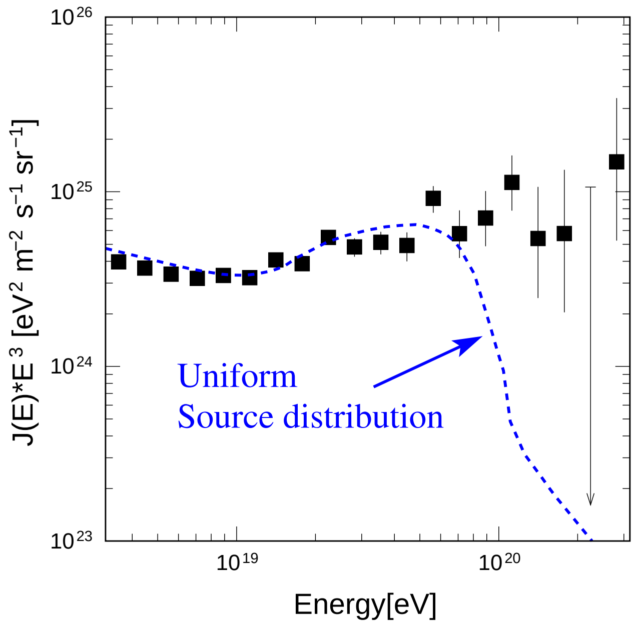

Fig. 3. The energy spectrum of cosmic rays with events up to 60°. The arrows are Poisson upper limits of 90% C.L. The dashed curve is the expected energy spectrum for sources uniformly distributed in the universe taking account of the energy resolution of the AGASA experiment.

The energy spectrum observed by AGASA using events with zenith angles up to 60° is shown in Fig.3, multiplied by E^3 in order to emphasize the detailed structure of the steeply falling spectrum. Error bars represent the Poisson upper and lower limits at 68% and arrows are 90% confidence level (C.L.) upper limits. There is no cutoff around GZK energy ($\sim 4 \times 10^{19}$eV) and the spectrum extends up to a few times 10^{20}eV. The updated spectrum is consistent with that by Takeda *et al.* (1998).

6 The Highest Energy event

We have newly recorded the highest energy event so far at 2:05 UTC, on 10 May, 2001. The energy was assigned to be 2.8×10^{20}eV and is probably higher than the highest event reported by Hayashida *et al.* (1994). The zenith angle was 37°, and the arrival direction was $(\alpha, \delta) = (358.5°, 22.3°)$ in equatorial coordinates. The left panel of Fig.4 shows the lateral distribution of all charged particle densities and muon densities. The right panel shows the map of density distribution. For this event, the lateral distribution seems to be

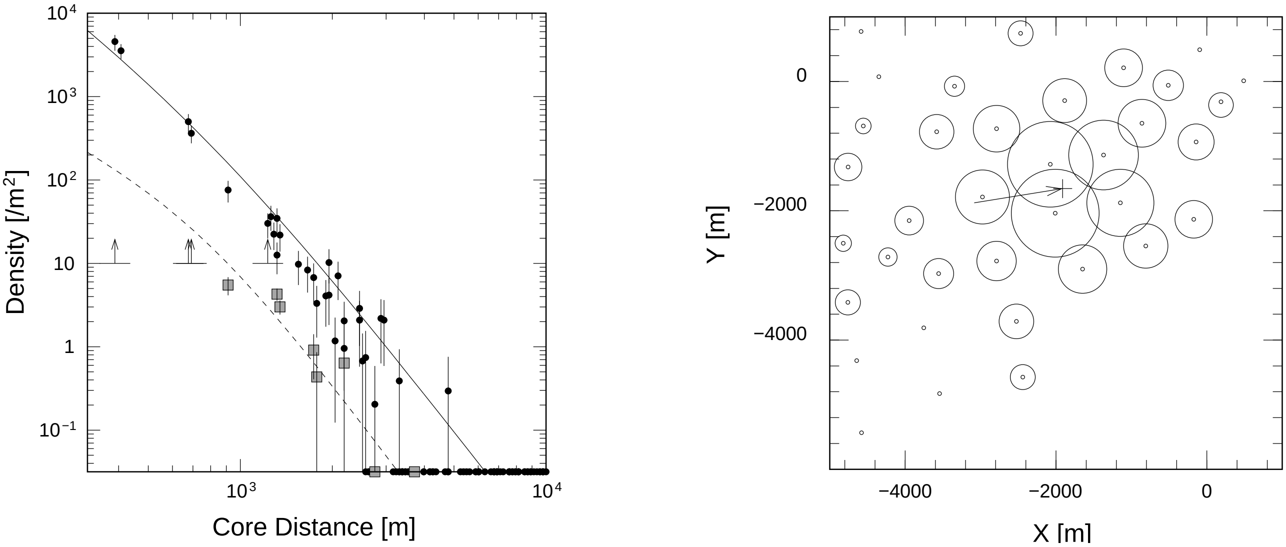

Fig. 4. Candidate for the highest energy event so far observed by the AGASA. The left panel shows the lateral distribution of charged particles (filled dots) and of muons (shaded squares). The solid line is the empirical formula of lateral distribution for charged particles and the dashed line is the lateral distribution for muons by the AGASA. In the right panel, dots are the positions of the scintillation detectors and open circles are the particle densities observed by the detectors. The radius is proportional to the logarithm of the density. The shower core is located at the cross and the arrival direction is shown by the arrow.

steeper than the average one in the lower energy region, and the ratio of muon to electron densities gives a smaller value than the average of other highest energy events. We have analyzed air shower data with fixed slope (η parameter) of the lateral distribution, because the η parameter is almost independent of the primary energy and it gives a more stable estimate on the primary energy (Hayashida *et al.*, 1999). If we analyze this event with variable η, the estimated energy becomes higher, 3.3×10^{20}eV, which is almost the same energy as the Fly's Eye highest event, 3.2×10^{20}eV. The detailed analysis of this event is going on and the results will be reported at this conference.

7 Summary

We have successfully developed a method to obtain the primary energy of cosmic rays up to 60°. As a consequence, the exposure is increased by 50 % compared to that within 45°. The energy spectrum of inclined showers is consistent with that of vertical showers. The combined spectrum using events within 60° extends up to a few times 10^{20}eV without showing the GZK cutoff and the total number of candidates above 10^{20}eV is 17. The highest energy event of $\sim 3 \times 10^{20}$eV was observed in May 2001.

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