Energy Spectrum Above 3×10^{18}eV observed with AGASA

The AGASA Collaboration

Abstract

The cosmic-ray energy spectrum above 3×10^{18}eV is reported using the updated data set of the Akeno Giant Air Shower Array (AGASA) from February 1990 to March 1999. The energy spectrum extends beyond 10^{20}eV and shows the absence of the 2.7 K cutoff in the energy spectrum. The cosmic rays above 10^{20}eV isotropically distribute on the celestial sphere.

1 Introduction

After our PRL publication (Takeda et al., 1998), we added seventeen-months observation and the seventh 10^{20}eV event was detected. The energy and arrival direction are listed in Table 1, with other six 10^{20}eV events. For these most energetic cosmic rays, the Space is opaque. This arises from the GZK effect (Greisen 1966; Zatsepin and Kuz'min, 1966) – a series of energy loss through interaction with the cosmic microwave background photons. The spectral features around these energies reflect origin, acceleration mechanism and propagation process of extremely high energy cosmic rays.

Table 1: AGASA 10^{20}eV events.

Date	Energy	Coordinates			
		α	δ	l^G	b^G
93/01/12	1.01×10^{20}eV	$8^h\ 17^m$	16.8°	206.7°	26.4°
93/12/03	2.13	$1^h\ 15^m$	21.1°	130.5°	−41.4°
94/07/06	1.06	$18^h\ 45^m$	48.3°	77.6°	20.9°
96/01/11	1.44	$16^h\ 06^m$	23.0°	38.9°	45.8°
96/10/22	1.05	$19^h\ 54^m$	18.7°	56.8°	−4.8°
97/03/30	1.50	$19^h\ 38^m$	−5.8°	33.1°	−13.1°
98/06/12	1.20	$23^h\ 16^m$	12.3°	89.5°	−44.3°

2 Experiment

The AGASA array is the largest operating surface array, covering an area of about 100 km^2 and consisting of 111 surface detectors of 2.2 m^2 area. Each surface detector is placed with a nearest-neighbor separation of about 1 km and the detectors are sequentially connected with pairs of optical fibers. All the detectors are controlled at detector sites through rapid communication with a central computer. The data acquisition system of AGASA was improved in December 1995 (Ohoka et al., 1997). In a widely spread surface array like AGASA, the local density of charged shower particles at a specific distance from the shower axis is well established as an energy estimator (Hillas et al., 1971), since this depends weakly on variation in the interaction model, fluctuation in shower development and the primary mass. In the AGASA experiment, we adopt local density $S(600)$ at 600 m which is determined from fitting the lateral distribution of observed particle densities to an empirical formula (Yoshida et al., 1994). This empirical formula is found to be valid for EAS with energies up to $10^{20} eV$ (Doi et al., 1995; Sakaki et al 1999). The conversion relation from $S(600)$ to the primary energy is evaluated through the Monte Carlo simulation (Dai et al., 1988) up to $10^{19} eV$ by

$$E = 2.03 \times 10^{17}\, S_0(600) \quad eV,$$

where $S_0(600)$ is the $S(600)$ value in units of m^{-2} for a vertically incident shower. Since an inclined air shower traverses atmosphere deeper than a vertical shower, $S_\theta(600)$ observed with zenith angle θ must be transformed into $S_0(600)$ at the vertical. This attenuation curve of $S(600)$ has been formulated by Yoshida et al (1994).

The accuracy of event reconstruction has been evaluated through the analysis of a large number of artificial air shower events. These artificial events were simulated over a larger area than the AGASA area with directions sampled from an isotropic distribution. In this air shower simulation, the fluctuation on the longitudinal development of air showers, the resolution of the scintillation detectors, and statistical fluctuation of observed shower particles at each surface detector were taken into account. Only events with zenith angles smaller than 45° and with core locations inside the array area are used in the following analysis. Figure 1 shows the fluctuation of energy determination for 3×10^{19}eV (left) and 10^{20}eV (right) showers with zenith angles less than 45°. The primary energy is determined with an accuracy of about $\pm 30\%$ and the proportion of events with a 50%-or-more overestimation in energy is about 2.4%.

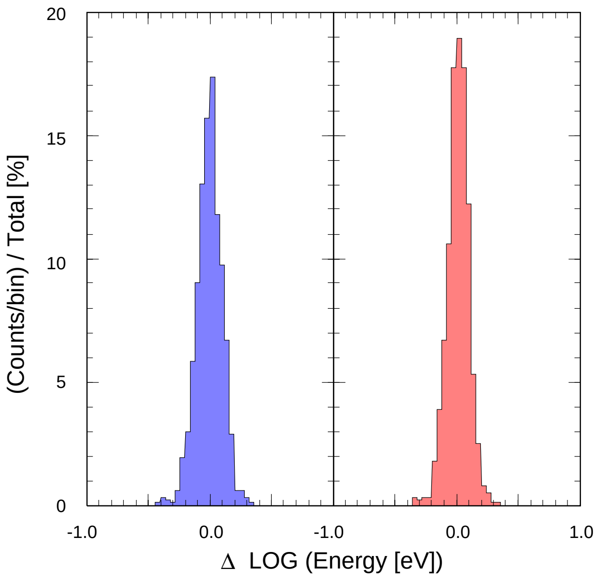

Figure 1: Accuracy of event reconstruction. Fluctuation of energy determination for 3×10^{19} eV (left) and 10^{20} eV (right) showers with zenith angles less than 45°.

Energy uncertainty also arises from the following systematic errors. The first is uncertainty in measuring the particle density incident upon each detector. The number of incident particles is determined from the time width of a pulse, which is generated by decaying an anode signal of a photomultiplier tube exponentially with a time constant of about 10 μ s and discriminated at a certain level. The variation in the amplifier gain and the decay constant are monitored in every run for detector calibration and their seasonal variations are within 2%. The second is uncertainty in the empirical formula of the lateral distribution function and in the attenuation curve of $S(600)$. The energy uncertainty due to the limited accuracy on both of these is estimated to be $\pm 20\%$, even if both factors shift the estimated energy in the same direction. The third is uncertainty in the conversion formula of $S(600)$ into primary energy. If we estimate this conversion factor using CORSIKA codes, the energy convered by the above Equation shows the upperlimits, irrespective of interaction models and composition tested by Nagano et al. (1998).

In order to evaluate the systematic errors *experimentally*, we compare the AGASA spectrum derived below with the Akeno spectrum which was determined between 3×10^{14}eV and 10^{19}eV using the arrays with different detector spacing (Nagano et al., 1992). The Akeno spectrum fits very well with extrapolation of those obtained from direct measurement on balloons and satellites, and with the Tibet result (Amenomori et al., 1996) obtained through the observation of the shower at the height of its maximum development. The difference between the present AGASA and Akeno spectra is about 10% in energy at 3×10^{18}eV. In addition, the difference among spectra obtained from the Fly's Eye, Yakutsk, Haverah Park, and AGASA experiments is within 30% in energy in spite of quite different methods for determining the primary energy. Therefore, the total systematic error in the AGASA energy determination is estimated to be within 30%, and the primary energy of the highest energy event of AGASA, for example, is estimated to be in the range (1.7 – 2.0) $\times$ 10^{20}eV.

3 Results

The effective area of AGASA has been calculated from the simulation of artificial air shower events. The energy spectrum in this simulation was assumed to be E^{-3}, and the reconstruction uncertainty in energy estimation was also taken into account. Although the effective area depends weakly on the spectral index, this dependence is negligible when compared with other ambiguities like energy resolution. The total exposure of AGASA is obtained by multiplying the effective area and the observation time of each branch for each epoch. Above 10^{19}eV, this exposure is constant and is 3.3×10^{16} m^2 sr s, which is about 1.3 times as large as that in our previous paper (Takeda et al., 1998) (cf. $\sim 0.5 \times 10^{16}\, m^2\, sr\, s$ of the stereo Fly's Eye exposure (Bird et al., 1994) and $\sim 0.7 \times 10^{16}\, m^2\, sr\, s$ of the Haverah Park exposure (Lawrence, Reid, and Watson, 1991)). However, the exposure below 3×10^{18}eV depends strongly on the primary energy. Since this energy dependence causes systematic errors in the energy spectrum derivation, only events with energies above 3×10^{18}eV are used for the energy spectrum. From February 1990 to March 1999, 571 and 7 events were observed with energies above 10^{19}eV and 10^{20}eV, respectively.

The energy spectrum observed with AGASA is shown in Figure 2, multiplied by E^3 in order to emphasize details of the steeply falling spectrum. Error bars represent the Poisson upper and lower limits at 68% and arrows are 90% C.L. upper limits. Numbers attached to points show the number of events in each energy bin. The dashed curve represents the spectrum expected for extragalactic sources distributed uniformly in the Universe, taking account of the energy determination error (Yoshida and Teshima, 1993).

First, we examine whether the observed energy spectrum could be represented by a single power law spectrum ($\propto E^{-\gamma_1}$). The optimum spectral index γ_1 is derived from the maximum likelihood procedure comparing the observed and expected number of events in each energy bin. This procedure is same as described in Yoshida et al. (1995). The maximum likelihood procedure for a single power law spectrum results in $\gamma_1 = 3.04 \pm 0.12$; the likelihood significance of γ_1 is only 0.079. If only events with energies below $10^{19}eV$ are considered, $\gamma_1(E \leq 10^{19}eV) = 3.22 \pm 0.11$ is obtained which is consistent with the spectral index, 3.16 ± 0.08, determined from the Akeno experiment (Nagano et al., 1992).

Next, a broken energy spectrum is examined with the same procedure. The broken energy spectrum is assumed to be

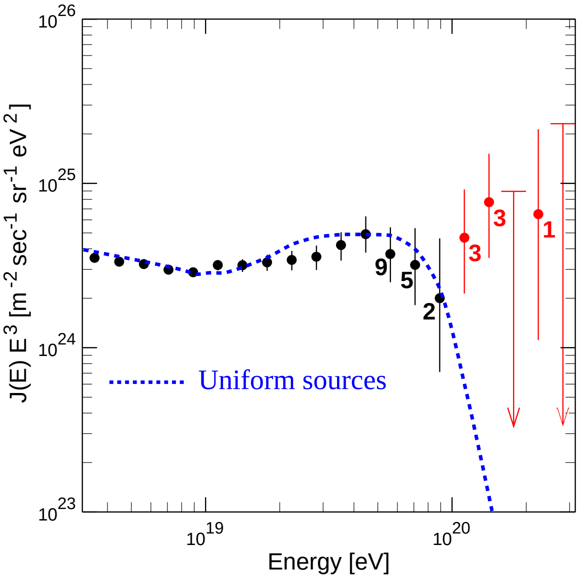

Figure 2: Energy spectrum observed with AGASA. The vertical axis is multiplied by E^3. Error bars represent the Poisson upper and lower limits at 68 % and arrows are 90 % C.L. upper limits. Numbers attached to points show the number of events in each energy bin. The dashed curve represents the spectrum expected for extragalactic sources distributed uniformly in the Universe, taking account of the energy determination error.

$$\frac{dJ}{dE} = \begin{cases} \kappa\,(E/E_a)^{-\gamma_0} & 3 \times 10^{18}eV \leq E < E_a \\ \kappa\,(E/E_a)^{-\gamma_2} & E_a \leq E \end{cases},$$

where γ_0 and γ_2 are indexes below and above a bending (ankle) energy E_a, and γ_0 is fixed to be $\gamma_1(E \leq 10^{19}eV) = 3.16$ determined from the Akeno experiment (Nagano et al., 1992). The most probable parameters are obtained at $E_a = 10^{18.96}eV$ and $\gamma_2 = 2.77^{+0.28}_{-0.25}$, where the likelihood significance is found to be 0.995. This is also consistent with the results of 2.8 ± 0.3 at energies above $10^{18.8}eV$ determined from the Akeno experiment (Nagano et al., 1992) and of $2.3^{+0.5}_{-0.3}$ above $10^{19.0}$ in the previous paper (Yoshida et al., 1995).

Furthermore, the energy spectrum presented here extends up to higher energies than the previous results (Nagano et al., 1992; Yoshida et al. 1995); seven events were observed above 10^{20}eV. If the real energy spectrum is that shown in Figure 2 as the dashed curve, the expected number of events above 10^{20}eV is less than one, taking account of the energy resolution. The energy spectrum is therefore more likely to extend beyond 10^{20}eV without the GZK cutoff. However, it is also worth noting that the observed energy spectrum suggests a small deficit just below 10^{20}eV, whose significance is not compelling because of the uncertainty in γ_2 estimation. This deficit may imply another component above the GZK cutoff energy. In either case, sources of the most energetic cosmic rays must be located within a few tens of Mpc from our Galaxy (Yoshida and Teshima, 1993). Within the accuracy of arrival direction determination (1.6° above 4×10^{19}eV), no 10^{20}eV events coincide with possible candidates from the second EGRET sources (Thompson et al., 1995) or the extragalactic radio sources with redshift $z \leq 0.02$ (Veron-Cetty and Veron 1983). The detailed study on arrival directions is reported in Takeda et al. (1999). The fact that the energy spectrum extends beyond 10^{20}eV and no 10^{20}eV events coincide with nearby active astrophysical objects leads highest energy cosmic-ray physics into a much more exciting stage.

4 Summary

In conclusion, the cosmic-ray energy spectrum extends beyond $10^{20}eV$. No candidate sources are found in the directions of seven $10^{20}eV$ events, while their sources must be closer than $50\,Mpc$. The possible deficit around $10^{20}eV$ is a notable area in which to search for origin of the highest energy cosmic rays.

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