Extension of the Cosmic-Ray Energy Spectrum beyond the Predicted Greisen-Zatsepin-Kuz'min Cutoff

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The cosmic-ray energy spectrum above $10^{18.5}$ eV is reported using the updated data set of the Akeno Giant Air Shower Array from February 1990 to October 1997. The energy spectrum extends beyond 10^{20} eV and the energy gap between the highest energy event and the others is being filled up with recently observed events. The spectral shape suggests the absence of the 2.7 K cutoff in the energy spectrum or a possible presence of a new component beyond the 2.7 K cutoff. [S0031-9007(98)06893-8]

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How high the maximum energy of cosmic rays reaches is one of the most important problems in cosmic ray research. Detections of cosmic rays with energies above 10^{20} eV [1,2] have given rise to much discussion regarding their origin. Many models have been proposed as source candidates of such high energy cosmic rays: active astrophysical objects [3], decay products of much higher energy particles such as superheavy relic particles [4] or topological defects [5], or cosmological gamma-ray bursts [6] (see Ref. [7] for a recent review). If such high energy cosmic rays come from far outside our Galaxy, they interact with cosmic microwave background photons and cannot travel cosmological distances. This interaction causes a cutoff in the energy spectrum near 5×10^{19} eV which is referred to as the Greisen-Zatsepin-Kuz'min (GZK) cutoff [8]. Furthermore, the cosmic rays which have interacted form a "bump" just below the GZK cutoff energy [9–11]. The change in the spectral slope around 10^{19} eV ("ankle") may arise from a transition from galactic to extragalactic sources. The investigation of these features in the energy spectrum is one of the most important scientific challenges.

There are two techniques for detecting extensive air showers (EAS): widely spread surface arrays and atmospheric fluorescence detectors. Using these techniques, the energy spectrum of extremely high energy cosmic rays has been measured by many groups such as Volcano Ranch [12], Haverah Park [13], Sugar [14], Yakutsk [15], Fly's Eye [16], and Akeno [17,18] (only the Fly's Eye group has adopted the atmospheric fluorescence detector). While the energy spectra obtained from these experiments coincide within $\pm 15\%$ in energy below $\sim 10^{19}$ eV, the details of energy spectrum in the highest energy range is still inconclusive, mainly because of low statistics of their observed events. In this Letter, we present the energy spectrum above $10^{18.5}$ eV obtained from the Akeno Giant Air Shower Array (AGASA) [19,20], which currently has the largest exposure of any extremely high energy cosmic ray detectors.

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 [20]. 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 [21], 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 [22]. This empirical formula is found to be valid for EAS with energies up to 10^{20} eV [23,24]. The conversion relation from $S(600)$ to the primary energy is evaluated through the Monte Carlo simulation [25] up to 10^{19} eV by

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

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 more atmospheric depth 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.* [22].

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 $10^{19.5}$ eV (left) and 10^{20} eV (right) showers with zenith angles less than 45°. The primary energy is determined with an accuracy of about ±30% and the proportion of events with a 50%-or-more overestimation in energy is about 2.4%.

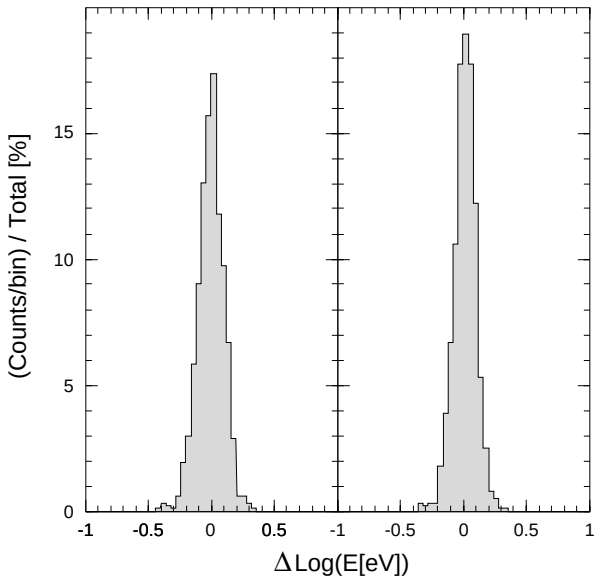

FIG. 1. Fluctuation of energy determination for $10^{19.5}$ eV (left) and 10^{20} eV (right) showers with zenith angles less than 45°.

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 μs and discriminated at a certain level (see [19] for the details of the AGASA instruments). 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 ±20%, even if both factors shift the estimated energy in the same direction [22]. The third is uncertainty in the conversion formula of $S(600)$ into primary energy. Although this formula is not sensitive to interaction models or primary composition in each of simulation codes [25], the systematic errors due to the differences in simulation codes are not quantitatively clear.

In order to evaluate the systematic errors *experimentally,* we compare the AGASA spectrum derived below with the Akeno spectrum which was accurately determined between $10^{14.5}$ and 10^{19} eV using the arrays with different detector spacing [17]. The Akeno spectrum fits very well with extrapolation of those obtained from direct measurement on balloons and satellites, and with the Tibet result [26] 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 $10^{18.5}$ 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 estimation 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.

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 2.6×10^{16} m^2 sr s, which is about 5 times as large as that in our

previous paper [18] (cf. $\sim 0.5 \times 10^{16}$ m^2 sr s of the stereo Fly's Eye exposure [16] and $\sim 0.7 \times 10^{16}$ m^2 sr s of the Haverah Park exposure [13]). However, the exposure below $10^{18.5}$ eV depends strongly on the primary energy. Since this energy dependence causes systematic errors in the energy spectrum derivation, only events with energies above $10^{18.5}$ eV are used for the energy spectrum in this Letter. From February 1990 to October 1997, 3847, 461, and 6 events were observed with energies above $10^{18.5}$, 10^{19}, and 10^{20} eV, respectively.

The energy spectrum observed with AGASA is shown in Fig. 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 [11].

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 the same as described in Yoshida *et al.* [18]. The maximum likelihood procedure for a single power law spectrum results in $\gamma_1 = 3.08^{+0.08}_{-0.15}$; the likelihood significance of γ_1 is only 0.051. If only events with energies below 10^{19} eV are considered, $\gamma_1(E \leq 10^{19}\ \text{eV}) = 3.23^{+0.10}_{-0.12}$ is obtained which is consistent with the spectral index, 3.16 ± 0.08, determined from the Akeno experiment [17].

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

$$\frac{dJ}{dE} = \begin{cases} \kappa(E/E_a)^{-\gamma_0} & 10^{18.5}\ \text{eV} \leq E < E_a\,, \\ \kappa(E/E_a)^{-\gamma_2} & E_a \leq E\,, \end{cases}$$

where γ_0 and γ_2 are indexes below and above a bending (ankle) energy E_a, and γ_0 is fixed to be $\gamma_1(E \leq 10^{19}\ \text{eV}) = 3.16$ determined from the Akeno experiment [17]. The most probable parameters are obtained at $E_a = 10^{19.01}$ eV and $\gamma_2 = 2.78^{+0.25}_{-0.33}$, where the likelihood significance is found to be 0.903. This is also consistent with the results of 2.8 ± 0.3 at energies above $10^{18.8}$ eV determined from the Akeno experiment [17] and of $2.3^{+0.5}_{-0.3}$ above $10^{19.0}$ eV in the previous paper [18].

Furthermore, the energy spectrum presented here extends up to higher energies than the previous results [17,18]; six events were observed above 10^{20} eV. If the real energy spectrum is that shown in Fig. 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 [11]. The arrival directions of six 10^{20} eV events are shown in Fig. 3. 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 Energetic Gamma Ray Experiment Telescope sources [27] or the extragalactic radio sources with redshift $z \leq 0.02$ [28]. Our previous result for cosmic-ray arrival directions has been reported in Hayashida *et al.* [29] and the new results are under preparation.

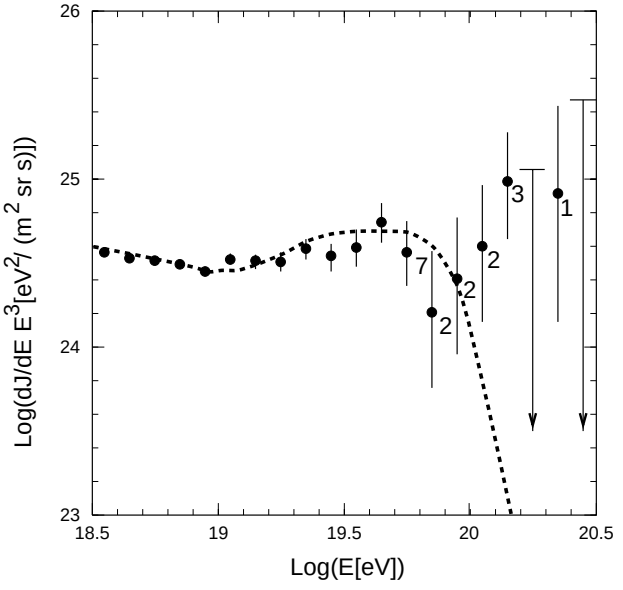

FIG. 2. Energy spectrum observed with AGASA. The vertical axis is multiplied by E^3. Error bars represent the Poisson upper and lower limits at 68% and arrows are 90% C.L. upper limits. Numbers attached to points show the number of events in each energy bin. The dashed curve represents the spectrum expected for extragalactic sources distributed uniformly in the Universe, taking account of the energy determination error [11].

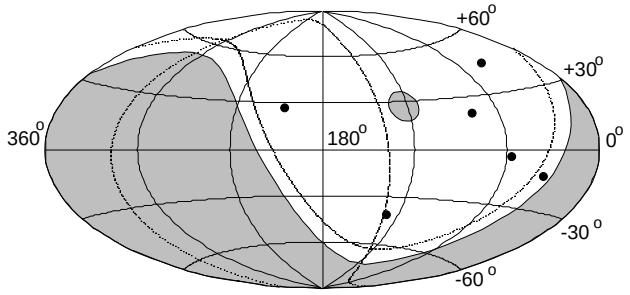

FIG. 3. Arrival directions of six 10^{20} eV events on the Galactic coordinates. The shaded regions indicate the nonobservable celestial regions due to the zenith angle cut of ≤45°. The equatorial and supergalactic planes are also shown.

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. The next generation experiments such as the Telescope Array [30,31], High Resolution Fly's Eye [32,33], and Auger [34,35] projects will solve the puzzle of the highest energy cosmic rays.

In conclusion, the cosmic-ray energy spectrum extends beyond 10^{20} eV. No candidate sources are found in the directions of six 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 the origin of the highest energy cosmic rays. A detailed discussion with the AGASA data will be published elsewhere.

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