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Observation of a Very Energetic Cosmic Ray well beyond the Predicted 2.7K Cutoff in the Primary Energy Spectrum

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ABSTRACT

A very energetic cosmic ray of energy about $(1.7\sim2.6)\times10^{20}$eV was observed by the Akeno Giant Air Shower Array (AGASA) on December 3, 1993 from the direction of galactic longitude $l=131°$ and galactic latitude $b=-41°$ within an error circle of 1.0° radius. Shower characteristics such as lateral distribution and arrival time spread of charged particles, and lateral distribution of muons ($\geq$0.5GeV) are well fitted to values extrapolated from lower energy showers. If this cosmic ray were a proton, its origin could be extragalactic. However, the distance of the source cannot be much more than a few times 10 Mpc due to the energy loss during its travel from interactions with universal background radiation. There is no known active object within 50 Mpc near the arrival direction of this shower.

It has been suggested that there might be a cutoff in the energy spectrum of primary cosmic rays around 10^{20}eV, if they are of extragalactic origin, since those cosmic rays lose their energy during traveling in the intergalactic space as a result of their interaction with universal background radiation. This cutoff is called the '*GZK cutoff*' after predictions by Greisen [1] and Zatsepin and Kuźmin [2].

By combining all data accumulated for more than 30 years by the experiments at Volcano Ranch [3], at Haverah Park [4], at Sydney [5], at Yakutsk [6], at Dugway [7] and at Akeno [8], the significance of evidence for the *GZK cutoff* has increased. That is, only several cosmic rays exceeding 10^{20}eV have been observed, compared with an expectation of more than 25 if there is no cutoff and the spectrum extends beyond 10^{20}eV with the same slope [9]. The extragalactic origin of the highest energy cosmic rays is supported by their uniform distribution over the celestial sphere and the flattening of the primary energy spectrum around 10^{19}eV.

Modifications of the injected energy spectrum of extragalactic cosmic rays in intergalactic space have been studied in detail by many authors [10-13]. It is now generally accepted by these calculations that there will be a cutoff in the energy spectrum below 10^{20}eV, unless the sources are relatively near to our Galaxy (within a few times 10 Mpc).

Therefore detection by the Fly's Eye detector [7] of a 3×10^{20}eV cosmic ray, well beyond the expected cutoff energy, has posed a puzzle concerning its origin. We report here another big extensive air shower (EAS) produced by a cosmic ray exceeding 10^{20}eV which was observed at Akeno on December 3, 1993, in some detail. This event is a factor of 3 larger than the second highest energy event so far observed at Akeno. Every characteristic of this shower, such as its lateral distribution, the arrival time spread of charged particles, and the lateral distribution of low energy muons can be fitted to the forms extrapolated from showers observed at lower energies. Therefore the primary species of this EAS may not be different from those in the lower energy region and we may extend our energy conversion relation up to this energy. The estimated energy is $(1.7\sim2.6)\times10^{20}$eV.

In the Akeno Giant Air Shower Array (AGASA), 111 scintillation detectors of 2.2m^2 area are arranged on the surface with detector separation of approximately 1 km. Proportional counters shielded by concrete or iron/lead plates are also deployed at 27 positions of the 111 surface detectors. The threshold energy of muons is about 0.5GeV. The AGASA is divided into 4 branches, the "Akeno Branch", the "Sudama Branch", the "Takane Branch" and the "Nagasaka Branch". The largest event reported here hit near the

Table 1: Details of the most energetic event.

Event Number	#akn25400-0296	
Date	December 3, 1993	
Incident Time	12:32:47	UT
Modified Julian Day	2449324.52277	day
Zenith Angle	22.9	degrees
Error circle in arrival direction determination	1.0°	radius
Determined $S_{23}(600)$	892	m^{-2}
Error in $S_{23}(600)$ determination	+21 and -6.6	%
$S_0(600)$	892~1065	m^{-2}
Primary Energy	$(1.7\sim2.6)\times 10^{20}$	eV
Right Ascension	18.9	degrees
Declination	21.1	degrees
Galactic Longitude	131	degrees
Galactic Latitude	-41	degrees
Exposure for the event	5.0×10^{15}	m^2 sec sr

center of the "Akeno Branch" with a zenith angle of 22.9 degrees. The details of the array are described in Chiba et al. [14]. In the east-south corner of the AGASA, there is an array called the "*1km² array*" [15], where 156 scintillation detectors of $1m^2$ area each and 9 muon detectors of $25m^2$ area each are deployed, and the data are stored by an independent recording system. Since an EAS of about 10^{16}eV hit this array less than 1 second prior to the giant EAS, the signals from the giant EAS were unfortunately not recorded in the *1km² array* data due to the dead time of the recording system.

The details of the event are summarized in Table 1. In Figure 1 is shown a map of the particle density distribution at each detector position, where the radii of the circles represent the logarithm of the particle densities (per m^2). It is seen that the shower core hits near the center of the Akeno Branch. Figure 2 is a lateral distribution of charged particles, whose core is determined by fitting particle densities to the following function.

$$S(R) = C(\frac{R}{R_M})^{-1.2}(1 + \frac{R}{R_M})^{-(\eta-1.2)}(1.0 + (\frac{R}{1000})^2)^{-0.6}, \qquad (1)$$

where R is distance from the core in m, R_M is 91.6 m at Akeno and C is a normalization factor. η is a function of the arrival direction's zenith angle θ and is expressed by $\eta = 3.97 - 1.79(sec\theta - 1)$. This function was determined previously for showers between 10^{18}eV and 10^{19}eV [16]. No energy dependence of η is observed in that energy range. It is found that the lateral distribution of this giant EAS can be well fitted to Eq.(1) up to 2.5km from the core with η determined from the 10^{19}eV energy region.

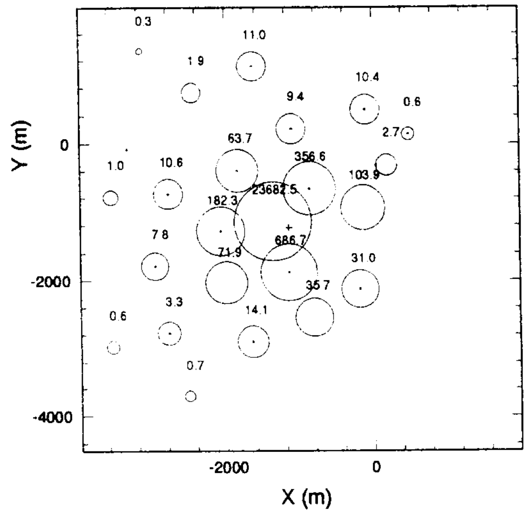

Figure 1: Map of the the density distribution of the giant EAS. The radius of each circle represents the logarithm of the density at each detector location. A cross shows the estimated position of the shower core.

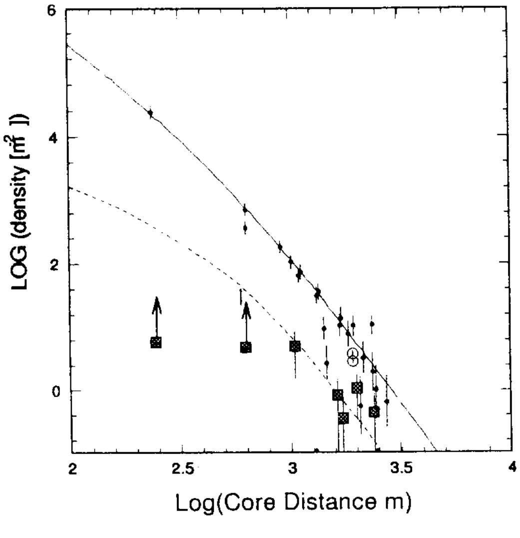

Figure 2: The lateral distribution of charged particle (LDF, closed circles) and muons (LDM, shadowed squares). The large open circle is that measured by a detector for arrival time distribution. The expected LDF is shown by a solid line and that of muons by a dotted line.

As will be described later, we use the particle density at 600m from the core $S_0(600)$ [suffix represents zenith angle] as an energy estimator. The $S_{23}(600)$ of this event at the zenith angle 23° is determined to be 892 m^{-2}. If we convert this density to the vertical $S_0(600)$ by using the attenuation length determined in the 10^{19}eV region [16], we find $S_0(600)$ = 1065 m^{-2}. If this shower is at maximum shower development, the attenuation correction may be inappropriate. Therefore $S_0(600)$ should be between 892 and 1065 m^{-2}.

The muon densities observed in each detector at different core distances are also plotted in Figure 2. Each detector in this event consists of 11~18 proportional counters of (0.2~0.5)m^2 area each. Muon densities ρ_μ were determined by

$$\rho_\mu = -\frac{N_{prop}}{Area} ln(1 - \frac{N_{hit}}{N_{prop}}), \tag{2}$$

where N_{prop} and N_{hit} are total and hit number of counters respectively, and Area is a total area of counters at each detector. Within 1000m from the core, most proportional counters exceeded their dynamic ranges and hence the number of particles can not be determined unambiguously. Only lower limits are plotted with arrows for points within 1000m from the core. (Since there are punch through electromagnetic particles within 600m from the core for showers of 10^{18}eV [17], it may be unsafe to use muon counter information within 1000m from the core for this energetic shower.)

The lateral distribution of muons ($\geq$0.5GeV) drawn by a dotted line in the figure is obtained by fitting the experimental points beyond 1000m from the core to our recent function [18] determined at Akeno for energies between $10^{16.5}$ and $10^{19.5}$ eV:

$$\rho_\mu(R) = N_\mu(\frac{C_\mu}{R_0^2})(\frac{R}{R_0})^{-0.75}(1+\frac{R}{R_0})^{-2.52}\{(1+(\frac{R}{800})^3\}^{-0.6} \tag{3}$$

where C_μ is a normalization constant. The characteristic distance R_0 is given by $\log R_0 = 0.58(\sec\theta - 1) + 2.39$ as a function of zenith angle.

The estimated $\rho_\mu(600)$ for this event is plotted by an open circle in Figure 3. The filled circles in that figure are average values in each bin for the $\rho_\mu(600)$ vs. S(600) relation observed by the AGASA. The solid line is a fit for $0.8 < \log S_0(600) < 2.4$ and the dashed line is its extrapolation. A dotted bar at log(S600)=2.95 indicates an extrapolated uncertainty. It is found that $\rho_\mu(600)$ is consistent with the extrapolated line and hence the muon component agrees with the expectation extrapolated from lower energies.

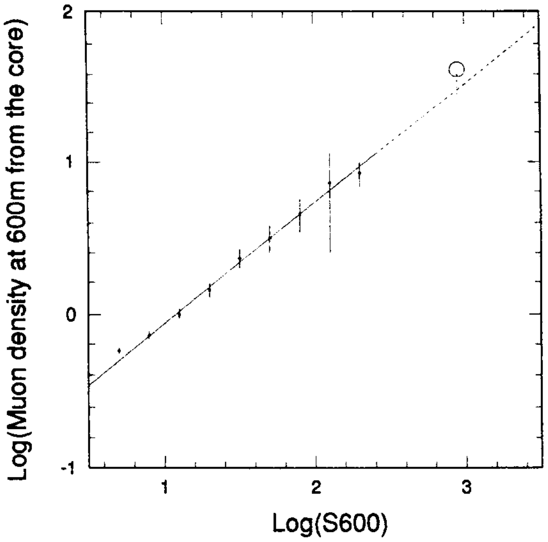

Figure 3: $\rho_\mu(600)$ vs $S_0(600)$ relation. An open circle is the estimated value of the present event and filled circles are average values for each bin determined by the AGASA experiment.

Table 2: Time response of the recording system for a muon traversing vertically on the scintillator

pulse height	11.8 ±20%	mV
FWHM	92.4 ±15%	nsec
integrated area	1152±15%	mV·nsec

The distribution of arrival times for the incident particles over the scintillation detectors of $30m^2$ area have been measured at the east corner of the Akeno Branch [20] by adding the signals from all 15 scintillation detectors of $2m^2$ area each. Since the trigger pulse is issued at the center of the Akeno Branch and delivered to the east corner through an optical fiber, the trigger pulse is delayed from the time signal by an interval which depends on the core position and arrival direction. The time signal is recorded by a wave form recorder in an interval of 102μsec before the trigger pulse. The arrival time distribution of this event started from 67μsec before the trigger pulse, consistent with the expected delay time. The distance of the detector from the core is 1920m and the recorded signal shape is shown in Figure 4. The time resolution for recording is 50nsec and the average time response of whole experimental system for a muon traversing vertically on the scintillator is listed in Table 2.

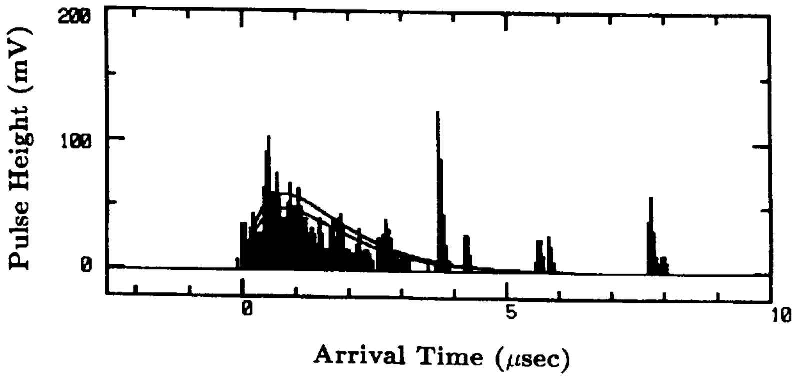

Figure 4: The arrival time distribution of charged particles measured by a wave form recorder at 1920m from the core. Solid curves are expected ones at this core distance determined by showers of 10^{19}eV energy [21]. The areas are normalized to the number of particles: 87 and 115.

The observed number of particles in 30m^2 are 87 and 115 particles within time intervals up to 3.5μsec and 8.1μsec from the start, respectively. These densities, $(2.9\pm0.3)/\mathrm{m}^2$ excluding delayed pulses and $(3.8\pm0.36)/\mathrm{m}^2$ including delayed pulses, are plotted by open circles in Figure 2. Both circles are in good agreement with measurements of other detectors in the Akeno Branch, but lie below the expected lateral distribution curve derived from lower energy showers. A curve in Figure 4 is an expected empirical function from the lower energy showers and is expressed [21] as

$$f(t,R) = \frac{t}{t_0(R)} \times exp(\frac{-t}{t_0(R)}), \tag{4}$$

where t is the time from the start signal in μsec. For this event, $t_0(2000)=0.8\mu$sec is used, which is estimated by extrapolating the $t_0(R)$ vs R relation determined for distances between 600m and 1500m from the core and for showers between 10^{18}eV and 10^{19}eV. The pulse shape within 3.5μsec is well fitted to the extrapolation of the standard pulse shape in the lower energy region. There are 5 signals after 3.5μsec, the pulses corresponding to 12.2, 2.8, 2.8, 2.3 and 7.7 particles, respectively. The probabilities of these delayed pulses to be accidental can be determined experimentally by artificial triggering and are approximately 5.0×10^{-5}, 1.3×10^{-3}, 1.3×10^{-3}, 2.1×10^{-3} and 1.4×10^{-4}. Therefore these particles are surely associated with the giant EAS. This kind of delayed pulse is observed frequently in large air showers at large core distances.

The arrival time dispersion of shower particles of this event is shown in Figure 5 by a large open circle. Small open circles are other events

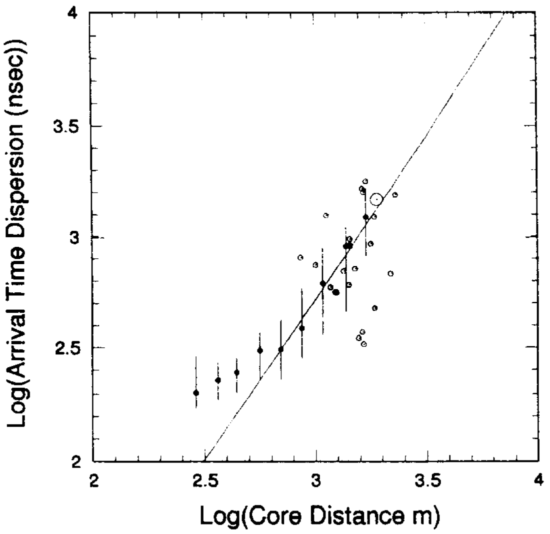

Figure 5: The arrival time dispersion of charged particles as a function of core distance. Dots with bars are the average values in each bin for showers of energy greater than 10^{18}eV, and small open circles are individual events above 10^{19}eV. The big open circle is the giant EAS.

of energies greater than 10^{19}eV and secθ of 1.0~1.2 in the corresponding distance range. Closed circles are average values in each distance bin for showers with energies greater than 10^{18}eV, and bars show the RMS spread of events in each bin [21]. The solid line is an empirical formula for arrival time dispersion determined by Linsley [22] and used in the arrival direction determination of the present experiment. Agreement of this big event with the formula is quite good.

Hillas et al. [23] showed that local particle density at 600 m from the shower axis $S_0(600)$ is proportional to the primary energy and is a good energy estimator, since this value depends only weakly on the primary mass or fluctuations in the cascade development. The conversion relation from $S_0(600)$ to primary energy at Akeno level is evaluated by the Monte Carlo simulation up to 10^{19}eV by Dai et al. [24] to be

$$E = 2.0 \times 10^{17} S_0(600) \quad eV. \tag{5}$$

Uncertainty in the the energy determination arises from possible systematic error in the calibration of each detector, unusual detector response,

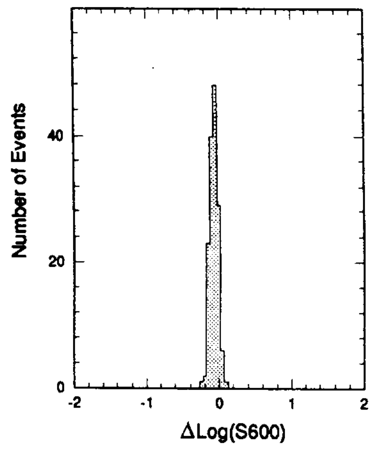

Figure 6: The fluctuation of S600 determination for the highest energy event. This distribution has been obtained by Monte Carlo simulation taking into account the fluctuations in the cascade development, detector resolution and statistical errors.

the resolution of the detector, uncertainty in the LDF, statistical fluctuation in the number of observed particles in each detector, and fluctuation of $S_0(600)$ due to cascade development. The details of these uncertainties are discussed in Hayashida et al. [25]. The gain of each detector is continuously monitored and calibrated within ±0.5% at the time of analysis. Since we are using the logarithmic amplifier after discriminating the exponential pulse, the seasonal variation of the decay constant of the exponential pulse is another uncertainty in the density measurement. This decay constant is also monitored by recording the density spectrum in every run. The frequency of accidental signals is about 4×10^{-3} for 10μsec per detector and hence an accidental signal is possibly added to the tail of the exponential pulse to give a big density at a rate of one detector per 10 showers. In order to avoid the overestimation of $S_{23}(600)$ due to this possibility, we estimated $S_{23}(600)$ value, by excluding the highest density detector or the second highest one. The estimated $S_{23}(600)$ does not change more than 4%.

In order to know the possible errors in the $S_{23}(600)$ determination for this giant EAS due to other factors mentioned before, we simulated artificial showers including both fluctuation of shower development and detector response. Here the fluctuation of shower development is assumed to be similar to that in the 10^{19}eV energy region. Artificial showers are analyzed with the same method as for real showers. The resulting output $S_{23}(600)$ distribution is shown in Figure 6. It is found that $S_{23}(600)$ is on average underestimated and its determination error is +21% and -6.6% at 68 % C.L and these values can be applied to the $S_0(600)$ determination.

As was shown before, all observables such as the lateral distribution and the arrival time spread of charged particles, and the lateral distribution of muons can be nicely fitted to those extrapolated from lower energy. Therefore we may use the above conversion relation up to the highest energies in the present analysis. Taking into account both ambiguity of the stage of shower development and possible errors in $S_0(600)$ determination, $S_0(600)$ is within the range 833~1289 m^{-2}, and the primary energy is estimated to be $(1.7 \sim 2.6) \times 10^{20}$eV.

The exposure for this event is 5.0×10^{15} m^2sec steradian and 1.1~2.7 events are expected for $E \geq 1.7 \times 10^{20}$eV, if the primary energy spectrum determined below $10^{19.9}$eV extends further above 10^{20}eV without the *GZK cutoff* [25]. The energy estimated for this event is, however, a factor 3 larger than the second highest energy event, 6.7×10^{19}eV, and no events are observed between them, whereas 2.1~4.2 events would be expected.

Since the spread of arrival times of shower particles agrees with that observed at lower energies and the arrival direction is near vertical, the error in arrival direction determination estimated by the Monte Carlo simulation [14] can be applied to this event, and it gives an error circle of 1.0° radius.

The galactic latitude of this event is -41°, which suggests an extragalactic origin if the primary particle is a proton. We don't have any definite indication of the particle species, however, it should be noted that $\rho_\mu(600)/S(600)$ relation shown in Figure 3 is unchanged from that in the 10^{19}eV energy region, where most primaries are claimed to be protons by the Fly's Eye experiment [26].

The attenuation lengths for protons, nuclei and gamma-rays of energy 2×10^{20}eV are about 27 [13], 30 [10] and 37 [13] Mpc, respectively, in intergalactic space. Therefore a search for the correlation with any active object is very important, in relation to the intergalactic magnetic field. The direction of the present event is on the edge of the Pisces Cluster of Galaxies [27]. There is, however, no known nearby active object ($<$ (30~50)Mpc) such as an active galactic nucleus within a few degrees circle around its arrival direction. Though the exposure is larger in the direction of the outer galaxy for experiments in the northern hemisphere, it is interesting that all three energetic events (Fly's Eye [7], Yakutsk [28] and AGASA) which clearly exceed 10^{20}eV come from within 50° of the anti-galactic center. A detailed discussion of a search for sources of these high energy events beyond the expected 2.7K cutoff energy has been made by Elbert and Sommers [29].

Chi et al. [30] examined the world data on EAS produced by cosmic rays of energies above 10^{19}eV and claimed the presence of specific clusters of cosmic rays both near the galactic plane and a region around l=150° and b=-40°. Their definition of clusters is 5 or more events above 10^{19}eV within a circle of 6° radius centered on an event with energy above 3×10^{19}eV. It should be noted that the directions of the three energetic events are all close to directions of their claimed clusters.

Efimov and Mikhailov [31] have also looked for clusters of cosmic rays above 10^{19}eV using their own data and Akeno data reported before 1990, in addition to the same samples used by Chi et al [30]. Their definition of clusters is 4 or more events above 10^{19}eV within a circle of 3° radius. They claimed four cluster directions with a chance probability of less than 2×10^{-3}. Two of them nearly agree with cluster directions of Chi et al., and one of those is close to the direction of the present event.

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