Possible Clustering of the Most Energetic Cosmic Rays within a Limited Space Angle Observed by the Akeno Giant Air Shower Array

N. Hayashida,[1] K. Honda,[2] M. Honda,[1] N. Inoue,[3] K. Kadota,[4] F. Kakimoto,[4] K. Kamata,[5] S. Kawaguchi,[6] N. Kawasumi,[2] Y. Matsubara,[7] K. Murakami,[8] M. Nagano,[1] H. Ohoka,[1] N. Sakaki,[1] N. Souma,[3] M. Takeda,[4] M. Teshima,[1] I. Tsushima,[2] Y. Uchihori,[1] S. Yoshida,[1] and H. Yoshii[9]

[1]*Institute for Cosmic Ray Research, University of Tokyo, Tokyo 188, Japan*
[2]*Faculty of Education, Yamanashi University, Kofu 400, Japan*
[3]*Department of Physics, Saitama University, Urawa 338, Japan*
[4]*Department of Physics, Tokyo Institute of Technology, Tokyo 152, Japan*
[5]*Nishina Memorial Foundation, Komagome, Tokyo 188, Japan*
[6]*Faculty of General Education, Hirosaki University, Hirosaki 036, Japan*
[7]*Solar-Terrestrial Environment Laboratory, Nagoya University, Nagoya 464-01, Japan*
[8]*Nagoya University of Foreign Studies, Nissin, Aichi 470-01, Japan*
[9]*Department of Physics, Ehime University, Matsuyama 790, Japan*

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Accumulated data of the Akeno Giant Air Shower Array (AGASA) indicate that arrival directions of a significant fraction of extremely high energy cosmic rays (EHECR) are uniformly distributed over the observable sky. However, three pairs of showers with angular separation of less than 2.5° within the pair are observed among the 36 events above 40 EeV (4×10^{19} eV), corresponding to a chance probability of 2.9% from uniform distribution. It should be noted that two pairs of them are observed to be within 2.0° of the supergalactic plane. [S0031-9007(96)00833-2]

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After the discovery of very energetic cosmic rays with energies up to 100 EeV [1,2], various acceleration mechanisms have been proposed [3] for possible sources in our Galaxy as well as in extragalactic objects. The possibility of cosmic rays being of nonacceleration origin, such as decayed nucleons or gamma rays from topological defects, has also been discussed [4]. Observations of a 120 EeV cosmic ray by the Yakutsk group [5], a 300 EeV one by the Fly's Eye detector [6], and a 200 EeV one by the Akeno Giant Air Shower Array (AGASA) [7], well beyond the expected Greisen-Zatsepin-Kuzmin cutoff energy [8] have enhanced the interest in studies searching for their origin.

One of the clues to their origin can be obtained from correlation of their arrival directions with some astrophysical objects or large scale structure of galaxy distibution. An interesting approach for this study is to search for a possible correlation of events with the supergalactic structure [9]. The supergalactic plane was originally defined by bright nearby galaxies in the northern hemisphere [10]. Later it was shown that extragalactic radio sources also concentrate towards the supergalactic plane, and this concentration extends to at least $z \sim 0.02$ [11], based on the MRC Catalog measured at Molonglo covering the declination band between 18.5° and −85.0°. Stanev *et al.* [9] have claimed that cosmic rays with energies greater than 40 EeV exhibit a good correlation with the direction of the supergalactic plane and the magnitude of the observed excess is $(2.5–2.8)\sigma$, in terms of Gaussian probabilities. They have used the world data available to them at that time with more than half of the events observed with the Haverah Park experiment.

On the other hand, the revised energy spectrum by AGASA [12] supports the previous result [13] which suggests the isotropic distribution of sources in the Universe. In this picture, recoil particles from collisions between the microwave background and extremely high energy cosmic rays (EHECRs) emitted from relatively nearby sources should be accumulated near 40 EeV. Therefore it is quite important to examine the arrival direction distribution of EHECRs above 40 EeV, whether they are uniform or correlate with large scale structure of nearby radio or active galaxies.

In this Letter we examine the arrival directions of EHECRs from the new AGASA data set. In the AGASA, 111 scintillation detectors of 2.2 m^2 area are arranged on the surface with detector separation of approximately 1 km over an area of about 100 km^2. The details of the array are described in Chiba *et al.* [14]. The experiment started in 1990 and showers observed until the end of October, 1995 have been included in the present analysis. The method of determining the primary energy and arrival direction is described in Yoshida *et al.* [13]. The error in arrival direction determination is about 1.6°, and that in energy determination is about ±30% for showers above 40 EeV.

Following the analysis procedure of Stanev *et al.* [9], we have calculated the average of the absolute values of angular distances ($\langle|b|\rangle$) of events from the galactic (G) and supergalactic (SG) planes and their rms ($b_{\rm rms}$) values: $\langle|b^{\rm G(SG)}|\rangle = \sum_i |b_i^{\rm G(SG)}|/N$ and $b_{\rm rms}^{\rm G(SG)} =$

TABLE I. Average ($\langle|b|\rangle$) and rms ($b_{\rm rms}$) angular distances (in degrees) of showers from the galactic (G) and supergalactic (SG) planes for six energy threshold values.

$>E$	No. of	$b^{\rm G}_{\rm RMS}$			$b^{\rm SG}_{\rm RMS}$			$\langle\|b^{\rm G}\|\rangle$			$\langle\|b^{\rm SG}\|\rangle$		
(EeV)	events	Data	MC	Pu	Data	MC	Pu	Data	MC	Pu	Data	MC	Pu
40	36	39.2	38.5	0.67	35.2	36.4	0.47	32.0	31.2	0.69	27.2	29.8	0.30
50	20	42.6	39.0	0.81	35.3	37.0	0.44	34.3	31.3	0.79	26.3	30.1	0.26
63	10	27.8	39.8	0.12	46.1	38.1	0.92	25.3	31.6	0.24	35.3	30.4	0.83

$[\sum_i (b_i^{\rm G(SG)})^2/(N-1)]^{1/2}$. The values expected for a uniform arrival direction distribution have been determined by assuming a uniform distribution in right ascension and the distribution in declination observed experimentally. 10^5 Monte Carlo (MC) sets were simulated for each of three energy thresholds, 40, 50, and 63 EeV. The results obtained from this analysis are tabulated in Table I. P_u is the probability that a uniform arrival direction distribution gives rise to the experimental values. The error in each value of data in the table is almost comparable to that due to the statistical error of events in each bin and hence uncertainty of P_u is dominated by this error and reaches to a comparable value to P_u value itself in each energy bin.

The distributions in the galactic and supergalactic latitudes for showers with energy threshold of 40 EeV are shown in Fig. 1. The expected values for uniform arrival direction distribution in the whole sky are represented by solid lines. These distributions reflect the zenith angle coverage by extensive air showers observed at Akeno with a zenith angle cut at 45°.

From Table I and Fig. 1, AGASA data show that the observed arrival directions of a significant fraction of EHECRs are consistent with a uniform distribution, both in the galactic latitude as well as in the supergalactic latitude. Though there seems to be a concentration of cosmic rays in a band from 0° to 10° in supergalactic latitude, we need further accumulation of data for confirmation.

In the following we examine the arrival direction distribution of EHECR above 40 EeV in some detail. The arrival directions of cosmic rays above 40 EeV in galactic coordinates are plotted in Fig. 2. The supergalactic plane from [9] is drawn by a dashed curve, which intersects with the galactic plane at galactic longitudes around 137° and 317°. It is remarkable that two pairs of showers, with angular separation of less than 2.5° within the pair (nearly consistent with the measurement error $\sqrt{2} \times 1.6°$), are observed within 2° of the supergalactic plane among the 20 showers of energy above 50 EeV, shown as squares in the figure. Another pair (3rd) is observed when 16 showers with energy between 40 and 50 EeV are included. The energies and coordinates of showers of these three pairs are listed in Table II.

The chance probability for observing three or more clusters of more than 2 events within 2.5° for each cluster from among the 36 events above 40 EeV anywhere in the observable sky has been estimated from 10 000 data sets, which were simulated by assuming a uniform arrival direction distribution in right ascension and the observed declination distribution with the zenith angle cut of 45°. The chance probability is 2.9%. If we take into account the probability that two pairs of them correlate with the supergalactic plane, assuming its thickness of $\pm 10°$, the chance probability is about 7×10^{-3}. If we consider two pairs among 20 showers with energies above 50 EeV, the probability is 1.7%, and if we take into account them being within $\pm 10°$ from the supergalactic plane, it is 6×10^{-4}.

As shown in Table I, the present results on $\langle|b^{\rm SG}|\rangle$ and $b^{\rm SG}_{\rm rms}$ do not show any significant deviation from the expectations for uniform distribution in arrival directions. This seems to be inconsistent with the results of Stanev *et*

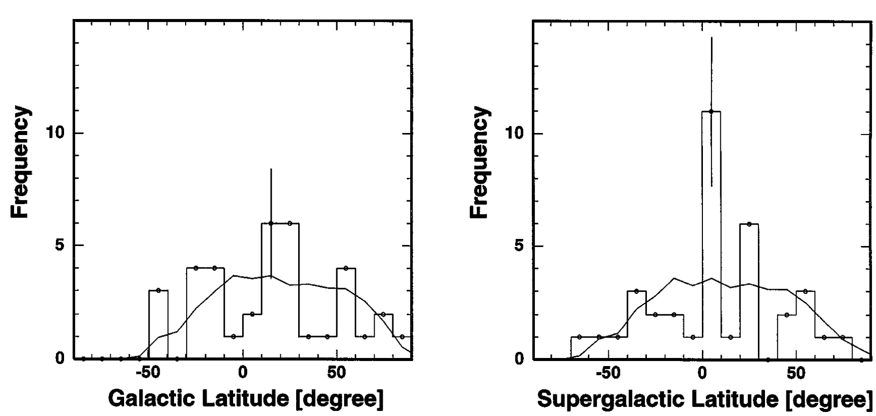

FIG. 1. Galactic (left) and supergalactic (right) latitude distributions of arrival directions of cosmic rays of energies above 40 EeV. Solid lines are expected values for a uniform arrival direction distribution.

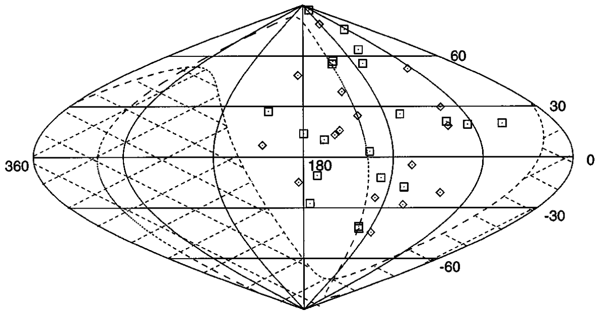

FIG. 2. Arrival direction distribution of 36 cosmic rays above 40 EeV in galactic coordinates. Open squares represent showers with energies above 50 EeV (20 events) and open diamonds between 40 and 50 EeV (16 events). The dashed curve shows the supergalactic plane. Sky not observed by the AGASA due to the zenith angle cut of 45° is shown as cross-hatched area.

al. [9] who have used data mainly from the Haverah Park experiment. The excess from Haverah Park data is mainly from a disk of $\pm 20°$ of the supergalactic plane and very few showers have been observed at high supergalactic latitudes. On the other hand, the AGASA data are spread up to higher supergalactic latitudes as is expected from uniform arrival direction distribution.

It should be noted that the galactic coordinate (l, b) of one Haverah Park event of energy 69 EeV is $(134.1°, -41.0°)$ [15] which is within a 3.0° circle of the highest energy event (1 in Table II) observed by AGASA. The (l, b) of the world highest energy event of Fly's Eye experiment is (163.4°, 9.6°) [6] and almost coincides with our 62 EeV event (165.7°, 10.7°) within experimental errors.

In the following we discuss the implications of the collimated pairs observed on the supergalactic plane and at high supergalactic latitude. It is most likely that there are natural accelerators in the directions of these pairs and the primary particles are neutral.

Though we have looked for active astrophysical objects in the directions within a 3° circle from 1 to 3 in Table II, both in extragalactic space and within our own Galaxy, no candidate has been found.

In order to examine a possibility of gamma-ray primary, the ratio of muon density above 0.5 GeV [$\rho_\mu(1000)$] to charged particle density [S(1000)] at 1000 m from the shower axis was determined. In Table II, the experimental values for this ratio for the pair events are listed. We have estimated the expected values for proton and gamma ray primaries, from simulation results obtained by Dawson [16] using the MOCCA program (developed by A.M. Hillas), to be 0.12 and 0.03, respectively. Though the experimental errors are large, the observed ratios are consistent with the average values expected for proton primaries. The experimental values are within the range of fluctuations around the average value observed for other showers in this energy region. Therefore there is no evidence for the primaries of pair events to be gamma rays.

Since the decay length of a neutron is about 1 Mpc at 100 EeV, neutrons after production and escape from the large magnetic field environment around a source must travel most of their way through intergalactic space as protons.

For proton primaries, there are strong constraints on the scale, strength, and direction of the magnetic field in our galactic disk or halo and intergalactic space. A deflection angle difference ($\delta\theta_0$) between two events in a pair, due to the ordered magnetic field in the space must be less than 2.5°, after taking into account the error in the energy determination and the deflection angle being inversely proportional to energy E. On the other hand, the accumulated deviation angle (θ_t) of protons from their sources through turbulent magnetic fields (δB) is approximately expressed by $\theta_t \sim \sqrt{N}\sigma \sim \sqrt{d\lambda}\, e\delta B/E$, where σ^2 is the variance of the deflection angle for propagation over a scale length λ in a turbulent magnetic field δB and $E/e\delta B$ is the Larmor radius. Here, in the random walk over distance d from the source to the observation point, $N \sim d/\lambda$ is assumed. Then,

$$\theta_t \sim 3.6°\left(\frac{d}{50\ \mathrm{Mpc}}\right)^{1/2}\left(\frac{\lambda}{1\ \mathrm{Mpc}}\right)^{1/2} \times \left(\frac{\delta B}{10^{-9}\ \mathrm{G}}\right)\left(\frac{E}{100\ \mathrm{EeV}}\right)^{-1}.$$

The deviation angle is about 9°, under assumptions of

TABLE II. Details for showers forming the three pairs with energies above 40 EeV. l^{G}, b^{G}, and b^{SG} are galactic longitude, galactic latitude, and supergalactic latitude (in degrees), respectively, and $\rho_\mu(1000)$ and S(1000) are muon density and charged particle density at 1000 m from the core.

No.	Event No.	Date	Energy (EeV)	l^{G}	b^{G}	b^{SG}	$\rho_\mu(1000)/\mathrm{S}(1000)$
1	akn25400-0296	93/12/03	210	131.2	−41.1	0.4	0.08 ± 0.04
	aksd27933-6673	95/10/29	51	130.2	−42.3	1.1	0.14 ± 0.07
2	tkn00897-0545	92/08/01	55	143.5	56.9	2.0	No $\rho_\mu(1000)$ data
	tkn03588-0947	95/01/26	78	145.8	55.3	0.5	No $\rho_\mu(1000)$ data
3	tkn00226-0693	91/04/20	43	77.9	18.6	57.8	No $\rho_\mu(1000)$ data
	akn25790-0886	94/07/06	110	77.6	21.1	57.3	0.13 ± 0.05

$d = 50$ Mpc, $\lambda = 1$ Mpc, $E = 40$ EeV, and $\delta B = 1 \times 10^{-9}$ G. The deflection through the galactic disk or halo may be of a similar magnitude and is not negligible, if d and λ are smaller than the above values by an order of 10^{-3}, whereas δB is larger by 10^3. Therefore, if the primary particles are protons, significant constraints are imposed on the scale, strength, and the direction of the magnetic field configuration and its turbulence in the interstellar and intergalactic space to explain pair events with angular separation of only a few degrees.

In conclusion, the arrival direction distribution of a significant part of EHECR above 40 EeV is uniform over the observable sky at Akeno, in agreement with the expectation from the interpretation of the highest energy part of energy spectrum observed by AGASA. However, three pairs within a limited space angle of the present experimental accuracy are observed with a chance probability of 2.9%, and two of them are within 10.0° of the supergalactic plane corresponding to a chance probability of 0.7%. If such a concentration within a limited space angle is confirmed by further observation, the nature of the source candidates and the direction and the strength of the magnetic field on the path to the sources are severely constrained. Further studies with higher statistics, better arrival direction accuracy, and capability of gamma-ray or proton primary discrimination is anticipated with the Telescope Array Project [17], the HiRes Project [18], and the Pierre Auger Project [19] now under construction or development.

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[1] J. Linsley, *Catalogue of Highest Energy Cosmic Rays, No.1,* edited by M. Wada (Institute of Physical and Chemical Research, Tokyo, 1980), p. 3.
[2] G. Cunningham *et al.,* in Ref. [1], p. 63.
[3] Various acceleration models are discussed in *Astrophysical Aspects of the Most Energetic Cosmic Rays,* edited by M. Nagano and F. Takahara (World Scientific, Singapore, 1990), pp. 252–334.
[4] P. Bhattacharjee, Phys. Rev. D **40**, 3968 (1989); P. Bhattacharjee, C. T. Hill, and D. N. Schramm, Phys. Rev. Lett. **69**, 567 (1992).
[5] N. N. Efimov *et al., Astrophysical Aspects of the Most Energetic Cosmic Rays* (Ref. [3]), p. 20.
[6] D. J. Bird *et al.,* Astrophys. J. **441**, 144 (1995).
[7] N. Hayashida *et al.,* Phys. Rev. Lett. **73**, 3491 (1994).
[8] K. Greisen, Phys. Rev. Lett. **16**, 748 (1966); G. T. Zatsepin and V. A. Kuzmin, Pis'ma Zh. Eksp. Teor. Fiz. **4**, 114 (1966).
[9] T. Stanev *et al.,* Phys. Rev. Lett. **75**, 3056 (1995).
[10] G. de Vancouleurs, Vistas Astron. **2**, 1584 (1956).
[11] P. A. Shaver and M. Pierre, Astron. Astrophys. **220**, 35 (1989).
[12] T. Doi *et al.,* ICRR Report No. 353-96-4, 1996, p. 1.
[13] S. Yoshida *et al.,* Astropart. Phys. **3**, 105 (1995).
[14] N. Chiba *et al.,* Nucl. Instrum. Methods Phys. Res., Sect. A **311**, 338 (1992).
[15] A. A. Watson (private communication).
[16] B. Dawson, in *Proceedings on Techniques for the Study of Extremely High Energy Cosmic Rays,* edited by M. Nagano (Institute for Cosmic Ray Research, University of Tokyo, Tokyo, 1993), p. 125.
[17] M. Teshima *et al.,* Nucl. Phys. B (Proc. Suppl.) **28B**, 169 (1992).
[18] S. C. Corbato *et al.,* Nucl. Phys. B (Proc. Suppl.) **28B**, 36 (1992).
[19] J. W. Cronin, Nucl. Phys. B (Proc. Suppl.) **28B**, 213 (1992).