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The anisotropy of cosmic ray arrival directions around 10^{18} eV

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Abstract

Anisotropy in the arrival directions of cosmic rays with energies above 10^{17} eV is studied using data from the Akeno 20 km^2 array and the Akeno Giant Air Shower Array (AGASA), using a total of about 114 000 showers observed over 11 years. In the first harmonic analysis, we have found a strong anisotropy of $\sim$ 4% around 10^{18} eV, corresponding to a chance probability of $\sim$ 0.2% after taking the number of independent trials into account. With two-dimensional analysis in right ascension and declination, this anisotropy is interpreted as an excess of showers near the directions of the Galactic Center and the Cygnus region. © 1999 Elsevier Science B.V.

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1. Introduction

Searches for anisotropy in the arrival directions of high energy cosmic rays have been made by many experiments so far and the arrival direction distribution of cosmic rays is found to be quite isotropic over

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a broad energy range. In most experiments harmonic analysis in right ascension (RA) has been applied to find a wide-angle cosmic ray flow. Results of various experiments up to 1980 are summarized in Linsley and Watson [1], up to 1983 in Lloyd-Evans and Watson [2], and to 1991 in Watson [3]. Above 10^{15} eV, most amplitudes published so far are upper limits and increase with energy as $E^{0.5}$ up to a few $\times 10^{19}$ eV, due to the number of events decreasing with energy like E^{-2}.

One possibly significant signal of wide-angle cosmic ray flow claimed so far is from the Haverah Park experiment in the energy region near 10^{17} eV, which shows an amplitude $(1.52 \pm 0.44)\%$ at RA = $212° \pm 17°$ with chance probability of 0.3% [2]. The interpretation of significant anisotropy in a narrow energy range may be very difficult and their result should be confirmed with much larger statistics. The Yakutsk group claimed a significant anisotropy with an amplitude $(1.2 \pm 0.3)\%$ and chance probability 0.17% in the energy region $10^{16.5} \sim 10^{17.5}$ eV [4]. The phase, however, is 124° in the right ascension so the direction is 90° different from the Haverah Park result.

The Haverah Park group also claimed evidence for an enhancement from southern latitudes in the range 5×10^{17} eV to 10^{19} eV and for the tendency of primary cosmic rays to arrive from high northern galactic latitude above 10^{19} eV [5].

The Fly's Eye group investigated the anisotropy by dividing the sky into six lobes of equal solid angle and comparing the number of detected cosmic rays in each lobe with the number expected from an isotropic intensity [6]. The lobes investigated are the directions of the north Galactic pole, the south Galactic pole, the center of the Galaxy, the anti-center of the Galaxy, forward along the solar revolution (the Sun's orbit about the Galaxy's center) and backward along that revolution. They could not find any statistically significant anisotropy above 10^{17} eV, but detected some excess from the Galactic north sky lobe above $10^{19.5}$ eV consistent with the Haverah Park indication of a northern excess at the highest energies.

In this report we present the anisotropy in arrival directions of cosmic rays around 10^{18} eV observed by AGASA. That beyond 10^{19} eV will be reported in a separate paper.

2. Experiment

The Akeno Giant Air Shower Array (AGASA) consists of 111 scintillation detectors of 2.2 m^2 area each, which are arranged with inter-detector spacing of about 1 km over a 100 km^2 area. Akeno is located at latitude 35° 47'N and longitude 138° 30'E at an average altitude of 900 m above sea level. Details of the AGASA array are described in Chiba et al. [7].

The whole area is divided into 4 branches, called the Akeno Branch (AB), the Sudama Branch (SB), the Takane Branch (TB), and the Nagasaka Branch (NB). The data acquisition started independently in each branch, and the four branches were unified in December of 1995. The present result includes data up to July 1995 before the unification. Data from the 20 km^2 array [8] are included in this analysis. Data acquisition from that array started in 1984, and it became part of the AB branch of AGASA in February 1990. The triggering requirement is a coincidence of more than five adjacent detectors, each with a signal greater than 20% of that produced by a muon traversing vertically the scintillator of 5 cm thickness. About 99% of triggered events are accidentally coincident and only 1% are real air showers, which are selected in the procedures of fitting the particle densities of all detectors within 2.5 km from the core to the empirical lateral distribution and their arrival times to the empirical shower front structure. About 230 000 events are identified as extensive air showers over the total observation period of 11 years. The typical angular resolution is 3 degrees and 1.5 degrees for 10^{18} eV and 10^{19} eV showers, respectively.

3. Results

The data sets used in the present analysis are listed in Table 1. The column marked Sel. 1 (Selection 1) in Table 1 shows the number of events selected based on the following conditions: the core is inside the array, the number of hit detectors is ≥ 6, and the reduced χ^2 in determining the arrival direction and the core position is less than 5.0. All events with zenith angles $\leq 60°$ are used in the present analysis. About 114 000 events remain after this Selection 1.

One of the conventional methods to search for any global anisotropy in the arrival directions of cosmic

Table 1
The data sets used in the present analysis. "Akeno I" is a data set taken by the 20 km^2 array from 1984 to 1990; Sel. 1 is obtained after the usual AGASA data selection, Sel. 2 is after the good day cut

Branch	Period	Period (yr)	Showers	Sel. 1	Sel. 2
Akeno I	840909–900216	3.5	12323	9310	6857
Akeno II	900217–930419	3.2	34493	14153	9283
Akeno III	930623–941215	1.7	26432	12304	8348
Akeno-Sudama	941226–950630	0.7	18681	11827	7517
Nagasaka I	910308–930709	2.4	21379	9581	6037
Nagasaka II	930811–950630	1.10	18670	8862	6031
Sudama I	900731–930512	2.10	27769	11858	7852
Sudama II	930821–941214	1.5	15408	7129	5033
Takane I	901115–930914	2.10	34882	17149	11762
Takane II	930924–950630	1.9	22640	11811	8418
total			232677	113984	77138

rays is to apply harmonic analysis to the right ascension distribution of events. That is, the method is to fit the distribution to a sine wave with period $2\pi/m$ (mth harmonic) to determine the amplitude and phase of the anisotropy. The mth harmonic amplitude, r, and phase of maximum, θ, are obtained for a sample of N measurements of phase, $\phi_1, \phi_2, \dots, \phi_n$ ($0 \le \phi_i \le 2\pi$) from

$$r = (a^2 + b^2)^{1/2}\,, \tag{1}$$

$$\theta = \tan^{-1}(b/a)\,, \tag{2}$$

where $a = (2/n)\sum_{i=1}^{n} \cos m\phi_i$ and $b = (2/n)\times \sum_{i=1}^{n} \sin m\phi_i$.

The following k represents the statistical significance. If events with total number N are uniformly distributed in right ascension, the chance probability of observing the amplitude $\ge r$ is given by

$$P = \exp(-k)\,, \tag{3}$$

where

$$k = Nr^2/4\,. \tag{4}$$

Results of first harmonic analysis in right ascension using the events after Selection 1 are shown in Fig. 1. The amplitude (top), the phase (middle), and the significance k (bottom) are shown as a function of primary energy threshold. Each point is obtained by summing over events with more than the corresponding energy. Clearly, $k \sim 10$ around 10^{18} eV is surprisingly high, corresponding to a chance probability of 0.005%. We have searched for the energy bin width which gives the maximum k-value, and find that the region $10^{17.9}$ eV–$10^{18.3}$ eV gives the maximum k-value of 11.1. This means the showers which contribute to the anisotropy are distributed in the energy range of 0.4 decade. In Fig. 2, the right ascension distributions of events are shown in the energy ranges $<10^{17.9}$ eV (top), $10^{17.9}$ eV$\sim$$10^{18.3}$ eV (middle), and $>10^{18.3}$ eV (bottom). A clear excess is found around 300° in the right ascension distribution of events in the energy region $10^{17.9}$ eV$\sim$$10^{18.3}$ eV (middle) and is not found in the other energy ranges (top and bottom).

In Table 2, the results of harmonic analysis are listed as a function of threshold energy in each 0.5 decade. We also listed the results in the differential bins with energy ranges of a factor of two from $\frac{1}{8}$ EeV to 8 EeV in Table 3, for the comparison with the world data. According to these tables, the chance probability is estimated to be $\sim$ 0.21% by taking the number of independent trials into account.

In searching for anisotropy, rates from different regions on the celestial sphere are compared. Therefore, uniform observation time in right ascension is quite important in this analysis. There are various effects which can produce spurious anisotropies, such as a temporary detector inefficiency, or communication trouble, or spurious events due to lightning, or change of observed rates due to temperature and pressure variation.

In the following we try to exclude data that might include spurious events by checking the data set in

Table 2
The results of the first and second harmonic in right ascension as a function of energy

	Log (energy)	number of events	Amplitude[%]	Phase	P_{prob}
First harmonic	$\geq$ 17.5 eV	81904	1.4	301	0.014
	$\geq$ 18.0 eV	27600	3.6	293	0.00009
	$\geq$ 18.5 eV	4096	3.5	268	0.26
	$\geq$ 19.0 eV	495	4.4	28	0.77
Second harmonic	$\geq$ 17.5 eV	81904	0.4	207	0.67
	$\geq$ 18.0 eV	27600	0.6	215	0.71
	$\geq$ 18.5 eV	4096	1.4	7	0.80
	$\geq$ 19.0 eV	495	12	109	0.13

Table 3
The differential results of the first harmonic analysis in right ascension as a function of energy

Bin	Energy range/*E*eV	#	Amplitude[%]	Phase	k	P_{prob}
E2	1/8–1/4	19146	1.6	211	1.37	0.25
E3	1/4–1/2	32921	1.2	35	1.32	0.26
E4	1/2–1.0	31657	1.0	298	0.87	0.41
E5	1.0–2.0	18274	4.1	300	7.95	0.00035
E6	2.0–4.0	6691	3.1	269	1.62	0.19
E7	4.0–8.0	1913	2.9	278	0.41	0.66

each day and each branch.

(i) If the detection efficiency of each day were constant and there was no lack of observations during any day, the daily number of events should follow a Gaussian distribution centered on the average value. We selected only those days for which the number of events is within $\pm 2\sigma$ of the average.

(ii) If the event distribution were random in each day, the distribution of daily k-values (Eq. (3)) should follow $\exp(-k)$ (Rayleigh test). Days which have k greater than 2 are excluded.

(iii) To find days which include a sudden increase or decrease of events for a short time, we have applied the Kolmogorov–Smirnov test (K–S test) on the data for each day and selected those days having a maximum deviation less than 90% of the boundary.

With these three criteria, bad days that could cause spurious anisotropy in arrival directions were excluded. The numbers of remaining events after these selections are listed in the column marked Sel. 2 (Selection 2) in Table 1. About 70% of the events were selected.

Using the data set after Sel. 2, the first harmonic analysis has been done and the results are shown in Fig. 3. We can still see clear peaks in the k-plot, $k \sim 7$ around 10^{18} eV, corresponding to a chance probability of 0.06%. The decrease of the value k can be explained by the decrease in the number of events (70%). It should be noted that the anisotropy amplitude and phase did not change after these selections. This means that the observed anisotropy cannot be due to those spurious causes. We have also carried out harmonic analysis on the cut data (30%) and they also show a Rayleigh power with $k \sim 3$ at 10^{18} eV. Considering the difference in the number of selected and cut events, it is concluded that the significance of the observed anisotropy is independent of the above selections.

Any spurious variation would likely arise from diurnal variations (temperature and barometric pressure effects) and should be more evident in solar time than in sidereal time. We checked the solar time variation of the number of air shower events in Sel. 2 using harmonic analysis. That is, the analysis was done using the arrival time of each event in solar time instead of sidereal time. Around 10^{18} eV the amplitude is about

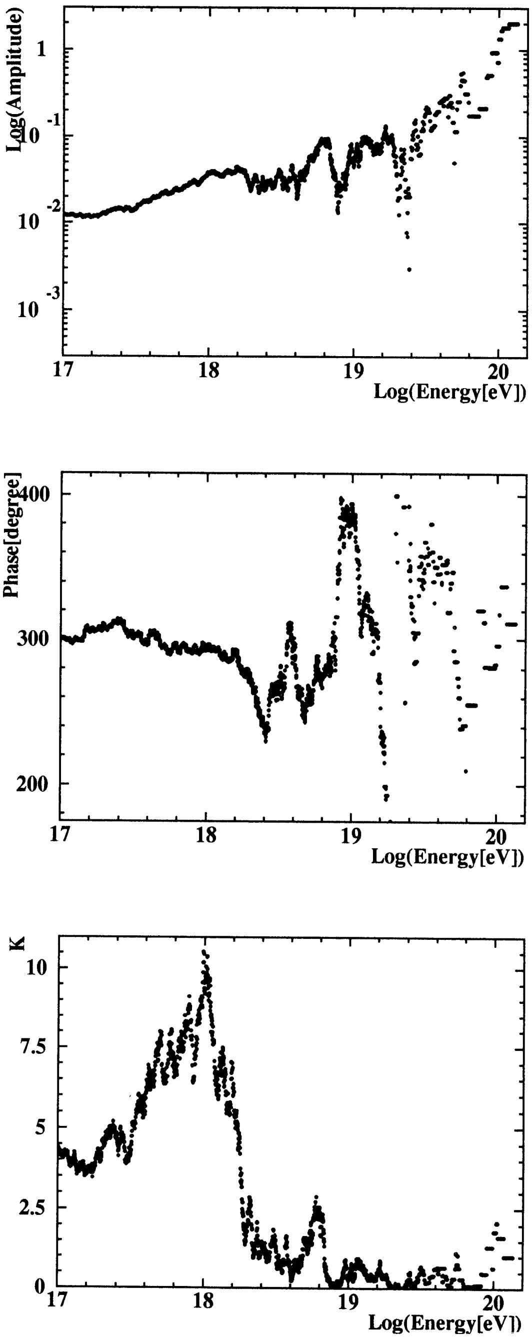

Fig. 1. The result of the first harmonic analysis in right ascension using data after Sel. 1. The amplitude (top), phase (middle), k (bottom) of anisotropy in each energy bin are plotted as a function of the primary energy.

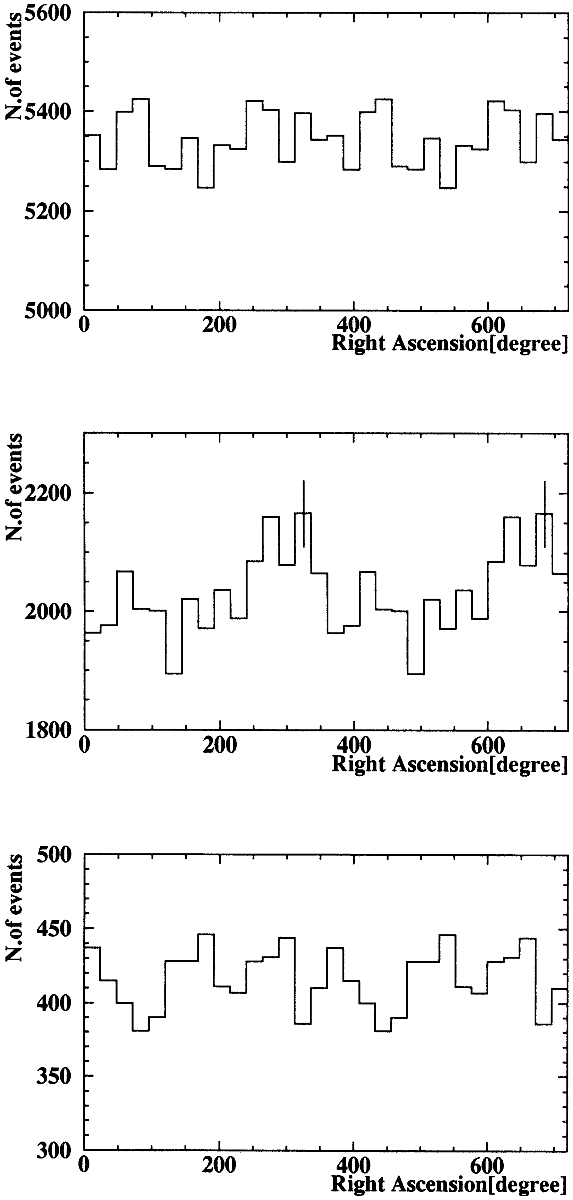

Fig. 2. Right Ascension distribution in the energy range of $<10^{17.9}$ eV (top), $10^{17.9}$–$10^{18.3}$ eV (middle), $>10^{18.3}$ eV (bottom).

1% in solar time and k is less than 1 as shown in Fig. 3 by thin dotted points. At Akeno the amplitudes of first harmonic and second harmonic pressure variation are about 0.5 mb and 0.9 mb in solar time at 3 hour and 9 hour, respectively, throughout a year. The expected amplitude due to the pressure variation is smaller than

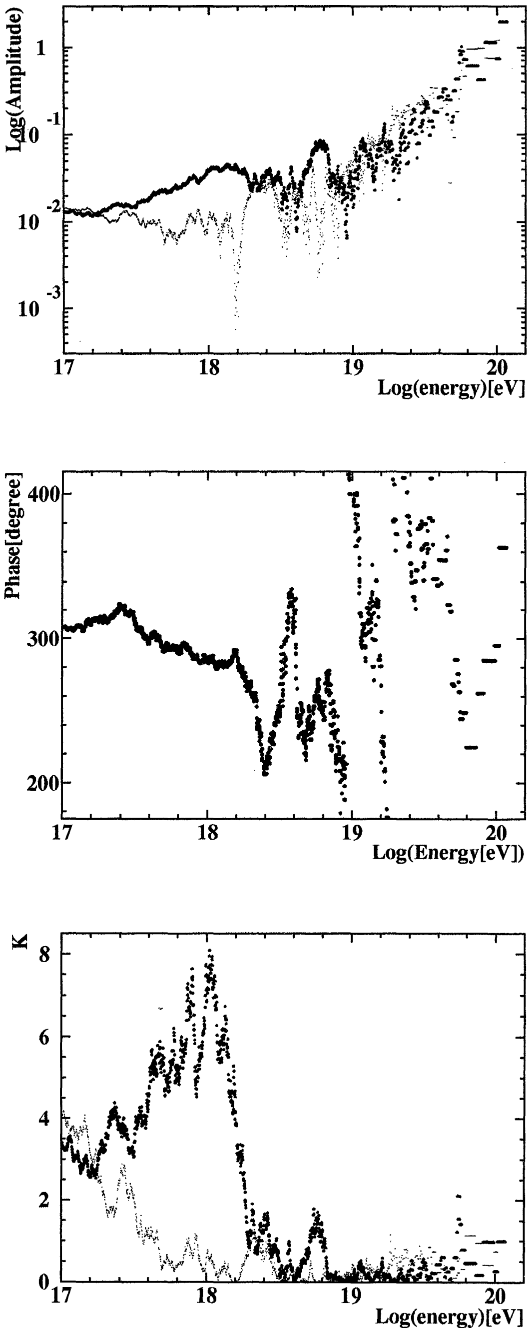

Fig. 3. The result of the first harmonic analysis in right ascension using data after Sel. 2. The amplitude (top), phase (middle), k (bottom) of anisotropy in each energy bin are plotted as a function of the primary energy. The result of the first harmonic analysis in solar time applied to the same data sets is drawn by thin dotted points.

0.4% in solar time [9]. Even if there were significant anisotropy of 1% in the solar time due to other reasons, the amplitude due to the daily variation must be reduced considerably when analyzed in sidereal time. Conversely, if the 4% anisotropy in right ascension seen in the present experiment were due to a daily variation, then the amplitude should be larger in the solar time analysis. We can conclude that the observed anisotropy in sidereal time is not due to a solar effect. These considerations indicate that the observed anisotropy is genuine.

In Figs. 4 and 5, the arrival direction distributions in equatorial coordinates are shown. They show the ratio of the number of observed events to the number expected and the statistical significance of the deviations, respectively. Here, the energy region of $10^{17.9} \sim 10^{18.3}$ eV is selected to maximize the harmonic analysis k-value. Since the geographical latitude of Akeno observatory is 35° 47'N, we cannot observe events with declination less than $-25°$, as long as we use showers with zenith angles less than 60°.

The number of expected events at each right ascension and declination is estimated as follows. The sky is divided into declination bands (width of 1 degree), and the number of events in each declination band is calculated $(f(\delta)d\delta)$. Since non-uniformity of the observation time in right ascension is less than 1% from the data, we estimate the expected event density as $g(\alpha,\delta) = f(\delta)/360$ in each right ascension and declination bin by assuming constancy in right ascension. In these figures, we have chosen a circle of 20° radius to evaluate the excess. We have integrated the expected event density inside this circle $\int_s g(\alpha,\delta)\,d\alpha d\delta$ and then compared with the observed number. We have examined with four different radii of 10°, 15°, 20°, and 30° centered near the Galactic center and obtained significances, 2.6σ, 2.7σ, 4.1σ and 2.8σ, respectively. The radius of 20° gave the maximum deviations.

In the significance map with beam size of 20°, a 4σ excess (obs./exp. = 308/242.5) can be seen near the direction of the Galactic Center. In contrast, near the direction of anti-Galactic Center we can see a deficit in the cosmic ray intensity (-3.7σ). An event excess from the direction of the Cygnus region is also seen in the significance map at the 3 sigma level.

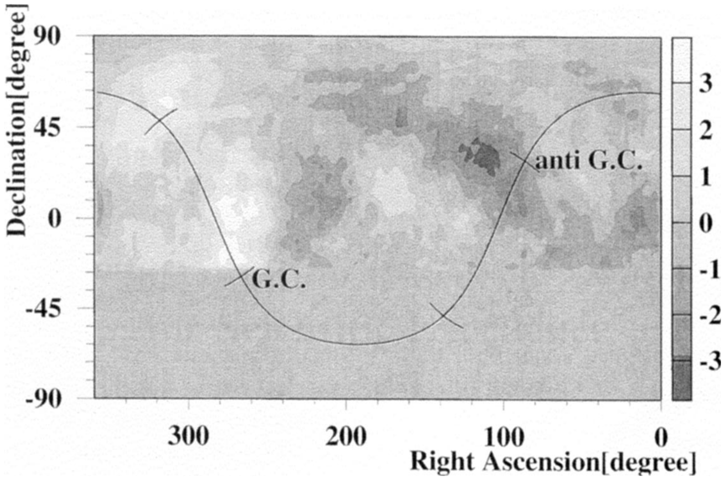

Fig. 4. Map of ratio of the number of observed events to expected ones in equatorial coordinate. Events within a radius of 20° are summed up in each bin. Solid line shows Galactic Plane. G.C. marks the galactic center.

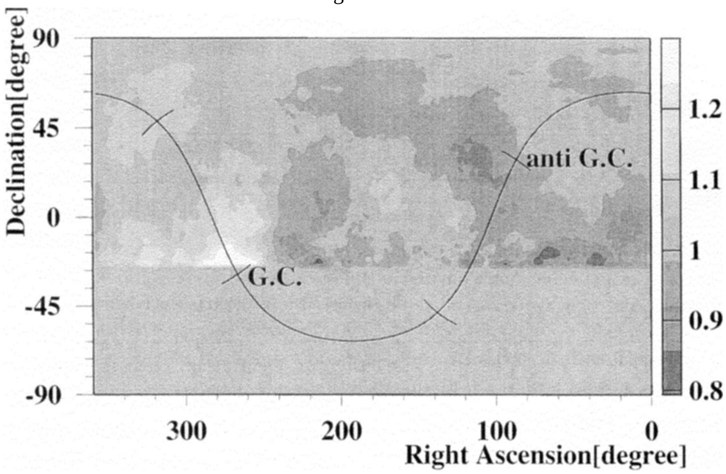

Fig. 5. Significance map of excess or deficit events. Events within radius of 20° are summed up in each bin.

4. Discussion

An anisotropy of amplitude 4% around 10^{18} eV was found in the first harmonic analysis. With a two-dimensional map, we can identify this as being due to event excesses of 4σ and 3σ near the galactic center and the Cygnus region, respectively. The observed anisotropy seems to be correlated with the galactic structure.

As shown in Table 4, such anisotropy has not been observed by previous experiments. Since the latitudes of the Haverah Park and Yakutsk are around 60 degrees, the direction of significant excess in the present experiment near the galactic center cannot be observed by those experiments and hence a significant amplitude in harmonic analysis might be absent in their data. However, the possible enhancement at southern galactic latitudes in $5\times10^{17}\sim10^{19}$ eV claimed by the Haverah Park experiment may be related to the present experiment. Statistics from the Fly's Eye experiment do not appear to be sufficient to support or refute the present result.

One possible explanation of the anisotropy reported here involves cosmic ray protons. In Fig. 6,

Table 4
Comparison of harmonic analysis in right ascension by various experiments in the energy region around 10^{18} eV

Experiment	Latitude	Energy	#	Amplitude [%]	Phase	k	Ref.
present	35.47°N	1–2 EeV	18274	4.1 ± 1.0	300	7.9	
Haverah Park	53.58°N	1–2 EeV	7320	2.1 ± 1.7	70	0.80	[15]
Yakutsk	61.7°N	1–1.8 EeV	14972	1.6 ± 1.2	198	0.97	[4]
Fly's Eye	40.2°N	1–2 EeV	1579	6.6	318	0.09	[6]

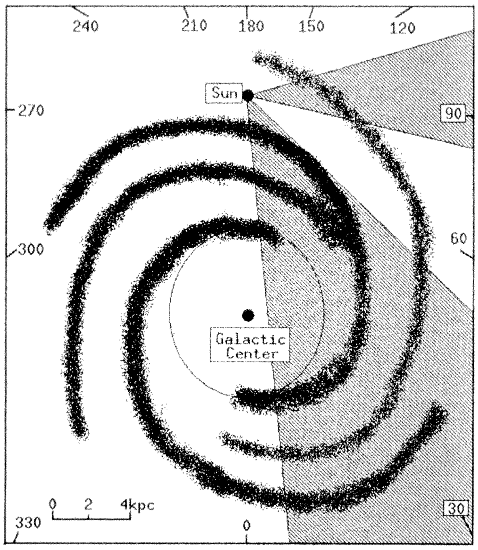

Fig. 6. The spiral structure of our Galaxy [10]. The shaded regions correspond to the excess directions of the present experiment.

a schematic view of the galactic spiral structure is shown [10]. The observed regions of excess are directed toward the galactic plane. Their directions are shown by the hatched region in the figure and seem to be correlated with the nearby spiral arms. The Larmor radius of a proton with energy 10^{18} eV is estimated to be $\sim$300 pc in our galaxy, which is comparable with the scale height of the Galaxy's magnetic field. Near this energy the slope of the cosmic ray energy spectrum changes. It becomes steeper above 10^{18} eV [11,12] as the leakage of cosmic rays from our galaxy seems to become more rapid than at lower energies. In the leaky box model, the amplitude of anisotropy and the energy spectra at the production site and observation site are closely related [13]. If we denote the cosmic ray residence time by $\tau(E)$, the amplitude of the anisotropy is proportional to $1/\tau(E)$. That is, if the observed energy spectrum becomes steeper at around 10^{18} eV, the anisotropy should become stronger at that energy. However, the direction of anisotropy need not point toward the nearby galactic arm, since scattering is diffusive in the leaky box model. According to the Monte Carlo simulation by Lee and Clay [14], a proton anisotropy of 10%$\sim$20% amplitude is expected at RA $\sim$ 300° using an axisymmetric concentric ring model of the galactic magnetic field with interstellar turbulence of a Kolmogorov spectrum. The source distribution is assumed to be uniform within the galactic disk and both a non-random and turbulent magnetic halo with various field strengths are taken into account. If the observed anisotropy is due to protons, we can estimate the proton abundance as to be about 20%$\sim$40% of all cosmic rays, by comparing our result of 4% amplitude with their simulation.

Another possible explanation is that the anisotropy is due to neutron primary particles. Neutrons of 10^{18} eV have a gamma factor of 10^9 and their decay length is about 10 kpc. Therefore they can propagate from the galactic center without decaying or bending by the magnetic field. In the cosmic ray acceleration regions, there may be ambient photons or gases. The accelerated heavy nuclei should interact with these photons or matter, and spill out neutrons. The acceleration region may have enough size and magnetic field strength to confine the charged particles, while the produced neutrons can escape easily from the site. In this scenario, the heavy dominant chemical composition below 10^{18} eV [16] and the lack of anisotropy below $10^{17.9}$ eV (due to the short neutron lifetime) can be naturally explained. Below 10^{18} eV, the neutron energy spectrum strongly depends on the source distance. On the other hand, above 10^{18} eV, it depends on the source energy spectrum. We have tried to fit the observed k distribution with the expected one obtained by assuming the energy spectrum and the source distance, however, we

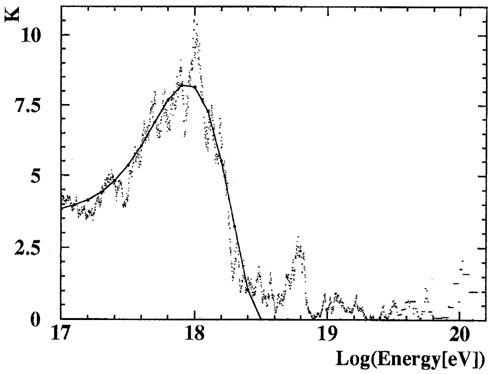

Fig. 7. The experimantal result can be well explained by the neutron source model with parameter, $\gamma = -2.5$, $D = 10$ kpc, $E_{\rm cut} = 10^{18.5}$ eV.

found the neutron energy spectrum with the power law spectrum of E^{-2}–$E^{-2.5}$ which can be expected from the acceleration model does not agree with the k distribution above $10^{18.5}$ eV. We need to use a steeper energy spectrum with an index of $-3 \sim -4$, or we need to introduce the cutoff in the energy spectrum at $10^{18.5}$ eV. For example, we could fit well the observed k distribution with the reasonable parameters $\gamma = -2.5$, $D = 10$ kpc, $E_{\rm cut} = 10^{18.5}$ eV as shown in Fig. 7, where γ is a index of the differential energy spectrum. The cutoff energy of $10^{18.5}$ eV or steeper energy spectrum may be natural, if we consider the maximum energy of galactic cosmic rays.

In this section, we have discussed two possibilities of the anisotropy origin; however, it is difficult to interpret the present data. More accumulation of the data, observation in the southern hemisphere, and the determination of energy spectrum in the excess region are important to confirm the experimental result and to discriminate the two possibilities.

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