

SMALL-SCALE ANISOTROPY OF COSMIC RAYS ABOVE 10^{19} eV OBSERVED WITH THE AKENO GIANT AIR SHOWER ARRAY

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ABSTRACT

With the Akeno Giant Air Shower Array, 581 cosmic rays above 10^{19} eV, 47 above 4×10^{19} eV, and seven above 10^{20} eV were observed until 1998 August. The arrival direction distribution of these extremely high energy cosmic rays has been studied. While no significant large-scale anisotropy is found on the celestial sphere, some interesting clusters of cosmic rays are observed. Above 4×10^{19} eV, there are one triplet and three doublets within a separation angle of 2.5° , and the probability of observing these clusters by a chance coincidence under an isotropic distribution is smaller than 1%. The triplet is especially observed against expected 0.05 events. The $\cos(\theta_{GC})$ distribution expected from the dark matter halo model fits the data as well as an isotropic distribution above 2×10^{19} and 4×10^{19} eV, but the fit with the dark matter halo model is poorer than the isotropic distribution above 10^{19} eV. The arrival direction distribution of seven 10^{20} eV cosmic rays is consistent with that of lower energy cosmic rays and is uniform. Three of the seven are members of doublets above about 4×10^{19} eV.

Subject headings: cosmic rays — galaxies: general — Galaxy: halo — large-scale structure of universe

1. INTRODUCTION

Investigation on anisotropy of extremely high energy cosmic rays is one of the most important aspects for revealing their origin. In energies $\gtrsim 10^{19}$ eV, cosmic rays slightly deflect in the galactic magnetic field if they are protons of galactic origin, so that one could observe the correlation of their arrival directions with the galactic structure. Especially in the highest observed energy range, correlation of cosmic rays with the local structure of galaxies may be expected if their origins are nearby astrophysical objects and the intergalactic magnetic field is less than 10^{-9} G.

In the 1980s, J. Wdowczyk, A. W. Wolfendale, and their collaborators (Wdowczyk & Wolfendale 1984; Szabelski, Wdowczyk, & Wolfendale 1986) have shown that excess of cosmic rays from the direction of the Galactic plane increases systematically with energy until a little above 10^{19} eV, although the available data were not statistically enough at that time. Gillman & Watson (1993) have sum-

marized anisotropies in right ascension and Galactic latitude combining the Haverah Park data set with the data sets from the arrays at Volcano Ranch (Linsley 1980), Sydney (Winn et al. 1986), and Yakutsk (Efimov et al. 1986). No convincing anisotropies were observed, but a large amplitude of the second harmonics at $(4-8) \times 10^{18}$ eV was reported. Ivanov (1998) showed, with the Yakutsk data set, a north-south asymmetry in the Galactic latitude distribution, which is the southern excess with 3.5σ deviation from an isotropic distribution in $(5-20) \times 10^{18}$ eV.

Recently, we have shown a significant anisotropy with a first harmonic amplitude of $\simeq 4\%$ in $(0.8-2.0) \times 10^{18}$ eV, which corresponds to the chance probability of 0.2% due to fluctuation of an isotropic distribution (Hayashida et al. 1999). This anisotropy shows broad cosmic-ray flow from the directions of the Galactic center and the Cygnus regions. In the higher energies, no significant large-scale anisotropy was found. Bird et al. (1999) have shown the Galactic plane enhancement in the similar energy range. These experiments show that a significant fraction of cosmic rays around 10^{18} eV come from Galactic sources.

In the much higher energy range of $\geq 4 \times 10^{19}$ eV, Stanev et al. (1995) have claimed that cosmic rays exhibit a 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. Their result was mainly based on the Haverah Park data set. In the same energy range, such large-scale correlation with the supergalactic plane was not observed in the data sets of the Akeno Giant Air Shower Array (AGASA; Hayashida et al. 1996), the Sydney University Giant Air Shower Recorder (Kewley, Clay, & Dawson 1996), and Fly's Eye (Bird et al. 1999) experiments. However, AGASA observed three pairs of cosmic rays above 4×10^{19} eV within a limited solid angle of the experimental accuracy, and the chance probability is 2.9% if cosmic rays distribute uniformly in the AGASA field of view. Two out of three are located nearly on the supergalactic plane. If cosmic rays in each of these pairs come

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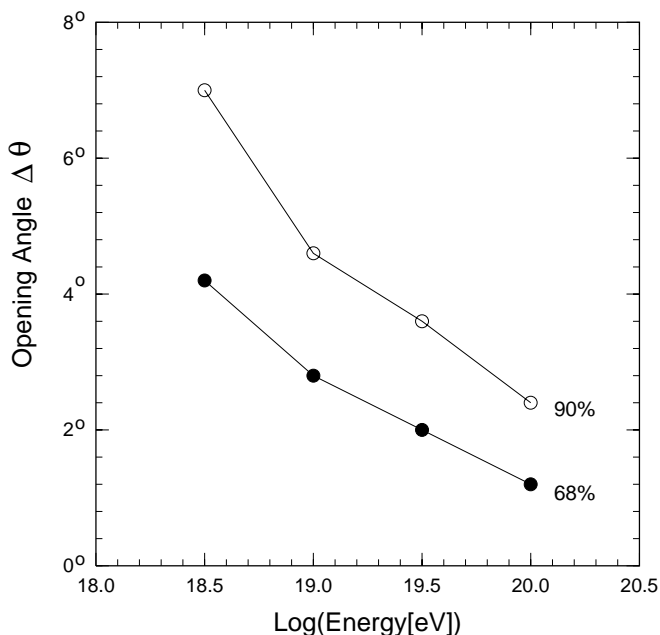


FIG. 1.—Accuracy on arrival direction determination. Closed and open circles are the opening angles encompassing 68% and 90% data, respectively.

from the same source, a detailed study on the energy, arrival time, and direction distribution of these clusters may bring information on their source and the intergalactic magnetic field (Sigl & Lemoine 1998; Medina Tanco 1998).

In the observed energy spectrum, there are two distinctive energies: $E \simeq 10^{19}$ and 4×10^{19} eV. The former is the energy where the spectral slope changes (Lawrence, Reid, & Watson 1991; Efimov et al. 1991; Bird et al. 1994; Yoshida et al. 1995; Takeda et al. 1998). This is interpreted as transition from Galactic to extragalactic origin. The latter is the energy where the Greisen-Zatsepin-Kuzmin (GZK) effect (Greisen 1966; Zatsepin & Kuzmin 1966), which is a series of energy loss through interaction with the cosmic microwave background photons, becomes important on their propagation from sources. It is important to study whether the arrival direction distribution of cosmic rays changes at these energies.

A recent result of the AGASA energy spectrum shows the extension beyond the expected GZK cutoff (Takeda et al. 1998). Since the distance to sources of cosmic rays above the expected GZK cutoff is limited to 50 Mpc (Hill & Schramm 1985; Berezhinsky & Grigor'eva 1988; Yoshida & Teshima 1993), their arrival directions may be correlated with luminous matter distribution if they are of astrophysical source origin, such as hot spots of radio galaxies (Biermann & Strittmatter 1987; Takahara 1990; Rachen & Biermann 1993; Ostrowski 1998), active galactic nuclei (Blandford 1976; Lovelace 1976; Rees et al. 1982), accretion flow to a cluster of galaxies (Kang, Rachen, & Biermann 1997), rela-

tivistic shocks in gamma-ray bursts (Vietri 1995; Waxmann 1995), and so on. There is another possibility that most energetic cosmic rays are generated through the decay of supermassive “X” particles related to topological defects (Bhattacharjee & Sigl 1998 and references therein). In this case, arrival directions of most energetic cosmic rays are not necessarily associated with luminous matter. If such particles are part of the dark matter and are concentrated in the Galactic halo, anisotropy associated with our Galactic halo is expected (Kuzmin & Rubakov 1997; Berezhinsky, Kachelriess, & Vilenkin 1997).

In this paper, we first examine large-scale anisotropy in terms of various coordinates using the data set of the AGASA until 1998 August, including the old data set of the Akeno 20 km² array (A20) before 1990. Then we search for the small-scale anisotropy above 10^{19} eV with the AGASA data set.

2. EXPERIMENT

The Akeno Observatory is situated at 138°30' east and 35°47' north. AGASA consists of 111 surface detectors deployed over an area of about 100 km² and has been in operation since 1990 (Chiba et al. 1992; Ohoka et al. 1997). A20 is a prototype detector system of AGASA, operated from 1984 to 1990 (Teshima et al. 1986), and it became a part of AGASA after 1990.

Each surface detector consists of plastic scintillators of 2.2 m² in area. The detectors are placed with a separation of about 1 km. They are controlled and operated from a central computer through an optical fiber network. The relative time difference among the detectors is measured with 40 ns accuracy; all clocks at detector sites are synchronized to the central clock, and the signal-propagation time in cables and electronic devices is regularly measured at start of each run (twice daily). The details of the AGASA instruments have been described in Chiba et al. (1992) and Ohoka et al. (1997).

The accuracy on the determination of the shower parameters is evaluated through the analysis of a large number of artificial events. These artificial events are generated by taking into account the air shower features and fluctuation determined experimentally. Figure 1 shows the accuracy on the arrival direction determination for cosmic-ray-induced air showers as a function of energies. The vertical axis denotes the opening angle $\Delta\theta$ between input (simulated) and output (analyzed) arrival directions. The opening angles, including 68% and 90% of the data, are plotted. By analyzing artificial events with the same algorithm used above, the accuracy on energy determination is estimated to be $\pm 30\%$ above 10^{19} eV (Yoshida et al. 1995).

Table 1 lists the number of selected events, $N(E)$, with zenith angles smaller than 45° and with core locations inside the array area. Events below 10^{19} eV are used only as a reference for analysis in this paper. The difference of $N(E \geq 3.2 \times 10^{19} \text{ eV})/N(E \geq 10^{19} \text{ eV})$ between A20 and AGASA arises from the difference in the detection efficiency of each system. Seven events are observed above 10^{20} eV, including one event after Takeda et al. (1998).

3. RESULTS

Figure 2a shows arrival directions of cosmic rays with energies above 10^{19} eV in equatorial coordinates. Dots, open circles, and open squares represent cosmic rays with

TABLE 1
NUMBER OF EVENTS IN THE DATA SET

Array	$\geq 10^{19}$ eV	$\geq 4 \times 10^{19}$ eV	$\geq 10^{20}$ eV
A20	59	7	0
AGASA	522	40	7
Total	581	47	7

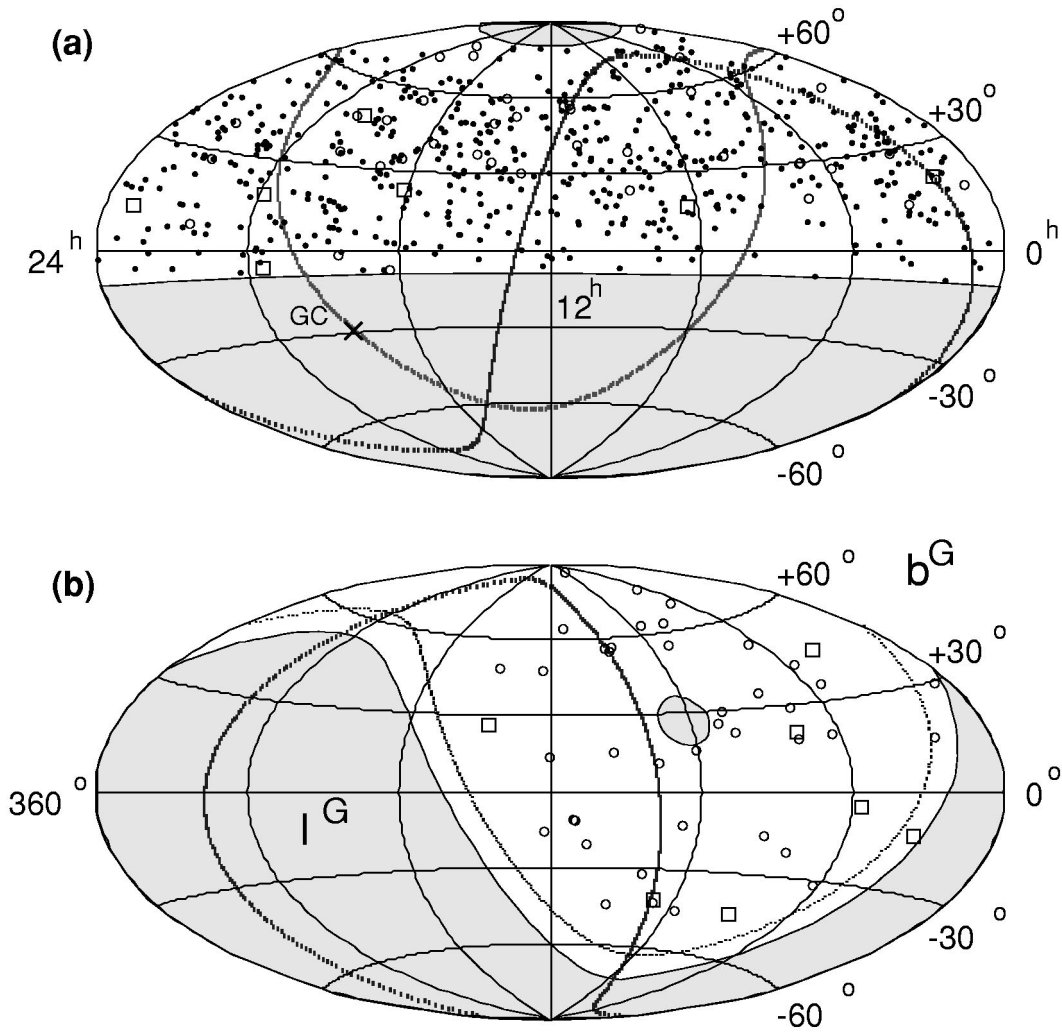


FIG. 2.—Arrival directions of cosmic rays with energies above $10^{19.0}$ eV in (a) equatorial and (b) Galactic coordinates. Dots, open circles, and open squares represent cosmic rays with energies of $(1-4) \times 10^{19}$, $(4-10) \times 10^{19}$, and $\geq 10^{20}$ eV, respectively. The Galactic and supergalactic planes are shown by the dotted curves. “GC” designates the Galactic center.

energies of $(1-4) \times 10^{19}$, $(4-10) \times 10^{19}$, and $\geq 10^{20}$ eV, respectively. The shaded regions indicate the celestial regions excluded in this paper due to the zenith angle cut of $\leq 45^\circ$. The Galactic and supergalactic planes are drawn by the dashed lines. “GC” designates the Galactic center. Figure 2b shows arrival directions of cosmic rays only above 4×10^{19} eV in Galactic coordinates. Details of the cosmic rays above 4×10^{19} eV are listed in Table 2.

3.1. Analysis in the Equatorial Coordinates

3.1.1. Harmonic Analysis

In order to search for cosmic-ray anisotropy, it is required that we compare the observed and expected event frequencies at each region. An expected frequency is easily estimated in so far as the exposure in each direction can be obtained; the uniformity of observation time on solar time for several years, which results in the uniform observation in right ascension, is expected for a surface array detection system operating in stable conditions like AGASA. The fluctuation of the observation time on the local sidereal time is $(0.2 \pm 0.1)\%$, which is small enough compared with anisotropy in this energy range, so that the exposure (the

observation time times the collection area) in right ascension is quite uniform.

Figure 3 shows results of the first (*left*) and second (*right*) harmonics in right ascension. The amplitude (*top*), the phase (*middle*), and the chance probability (*bottom*) are shown in each energy bin. In the top panels of the harmonic amplitude, the shaded region is expected from the statistical fluctuation of an isotropic distribution with the chance probability larger than 10%. Error bars in the middle panels represent statistical uncertainties in the phase. No significant anisotropy above this level is found above 3.2×10^{18} eV. This is consistent with our previous paper (Hayashida et al. 1999), in which zenith angles up to 60° were used.

3.1.2. Declination Distribution

Figure 4 shows the declination distribution of events above 10^{19} eV (*light histogram*) and 10^{20} eV (*dark histogram*). A solid curve is a third-order polynomial function fitted to the light histogram. This curve is consistent with the zenith angle dependence of the AGASA exposure and is considered to be the expected distribution if cosmic rays distribute isotropically on the celestial sphere. Since

TABLE 2
AGASA EVENTS ABOVE 4×10^{19} eV

DATE (1)	TIME (JST) (2)	ENERGY ¹ ($\times 10^{19}$ eV) (3)	COORDINATES ²				NOTE (8)
			α (4)	δ (5)	l^G (6)	b^G (7)	
1984 Dec 12	14:18:02	6.81	22 21	38.4	93.3	-15.7	
1984 Dec 17	10:28:16	9.79	18 29	35.3	63.5	19.4	
1986 Jan 5	19:31:03	5.47	4 38	30.1	170.4	-11.2	C4
1986 Oct 23	14:25:15	6.22	14 02	49.9	96.8	63.4	
1987 Nov 26	17:49:20	4.82	21 57	27.6	82.1	-21.1	
1989 Mar 14	02:45:39	5.27	13 48	34.7	68.3	75.6	
1989 Aug 16	08:32:01	4.07	5 51	58.5	154.5	15.6	
1990 Nov 25	11:05:39	4.51	16 17	-7.2	6.1	29.6	
1991 Apr 3	00:32:40	5.09	15 47	41.0	65.7	51.5	
1991 Apr 20	08:24:49	4.35	18 59	47.8	77.9	18.4	C3
1991 May 31	13:07:04	5.53	3 37	69.5	136.6	11.2	
1991 Nov 29	14:53:03	9.10	19 06	77.2	108.8	25.6	
1991 Dec 10	18:59:10	4.24	0 12	78.6	121.0	15.9	
1992 Jan 7	03:16:49	4.51	9 36	38.6	184.3	48.0	
1992 Jan 24	12:26:17	4.88	17 52	47.9	74.8	29.4	
1992 Feb 1	17:20:52	5.53	0 34	17.7	117.2	-45.0	
1992 Mar 30	03:05:30	4.47	17 03	31.4	53.6	35.6	
1992 Aug 1	13:00:47	5.50	11 29	57.1	143.2	56.6	C2
1992 Sep 13	08:59:44	9.25	6 44	34.9	180.5	13.9	
1993 Jan 12	02:41:13	10.1	8 17	16.8	206.7	26.4	
1993 Jan 21	07:58:06	4.46	13 55	59.8	108.8	55.5	
1993 Apr 22	09:39:56	4.42	1 56	29.0	139.8	-31.7	
1993 Jun 12	06:14:27	6.49	1 16	50.0	127.0	-12.7	
1993 Dec 3	21:32:47	21.3	1 15	21.1	130.5	-41.4	C1
1994 Jul 6	20:34:54	10.6	18 45	48.3	77.6	20.9	C3
1994 Jul 28	08:23:37	4.08	4 56	18.0	182.8	-15.5	
1995 Jan 26	03:27:16	7.76	11 14	57.6	145.5	55.1	C2
1995 Mar 29	06:12:27	4.27	17 37	-1.6	22.8	15.7	
1995 Apr 4	23:15:09	5.79	12 52	30.6	117.5	86.5	
1995 Oct 29	00:32:16	5.07	1 14	20.0	130.2	-42.5	C1
1995 Nov 15	04:27:45	4.89	4 41	29.9	171.1	-10.8	C4
1996 Jan 11	09:01:21	14.4	16 06	23.0	38.9	45.8	C5
1996 Jan 19	21:46:12	4.80	3 52	27.1	165.4	-20.4	
1996 May 13	00:07:48	4.78	17 56	74.1	105.1	29.8	
1996 Oct 6	13:36:43	5.68	13 18	52.9	113.8	63.7	
1996 Oct 22	15:24:10	10.5	19 54	18.7	56.8	-4.8	
1996 Nov 12	16:58:42	7.46	21 37	8.1	62.7	-31.3	
1996 Dec 8	12:08:39	4.30	16 31	34.6	56.2	42.8	
1996 Dec 24	07:36:36	4.97	14 17	37.7	68.5	69.1	
1997 Mar 3	07:17:44	4.39	19 37	71.1	103.0	21.9	
1997 Mar 30	07:58:21	15.0	19 38	-5.8	33.1	-13.1	
1997 Apr 28	13:46:18	4.20	2 18	13.8	152.9	-43.9	
1997 Nov 20	07:23:25	7.21	11 09	41.8	171.2	64.6	
1998 Feb 6	00:12:26	4.11	9 47	23.7	207.2	48.6	
1998 Mar 30	08:17:26	6.93	17 16	56.3	84.5	35.3	
1998 Apr 4	20:07:03	5.35	11 13	56.0	147.5	56.2	C2
1998 Jun 12	06:43:49	12.0	23 16	12.3	89.5	-44.3	
1997 Apr 10	02:48:48	3.89	15 58	23.7	39.1	47.8	C5

NOTE.—Units of right ascension are hours and minutes, and units of declination are degrees.

¹ The energies are reevaluated after the system response have been checked in 1997 October.

² The celestial coordinates are based on the J2000.0 coordinates.

the trigger efficiency is independent of energy above 10^{19} eV and a zenith angle less than 45° , this distribution is applicable in higher energies. Excess with 2.5σ deviation is found in $\delta = [30^\circ, 40^\circ]$, and this will be discussed later.

3.2. Analysis in the Galactic and Supergalactic Coordinates

3.2.1. Galactic and Supergalactic Plane Enhancement

If cosmic rays have their origin associated with nearby astrophysical objects, we should expect cosmic-ray aniso-

tropy correlated with the Galactic or supergalactic plane. Figure 5 shows the latitude distribution on the Galactic (*left*) and supergalactic (*right*) coordinates in three energy ranges of $(1-2) \times 10^{19}$ (*top*), $(2-4) \times 10^{19}$ (*middle*), and $\geq 4 \times 10^{19}$ eV (*bottom*). A solid line in each panel indicates the cosmic-ray intensity expected from an isotropic distribution. In order to examine any preference for arrival directions along the Galactic and supergalactic planes, the plane enhancement parameter f_E introduced by Wdowczyk

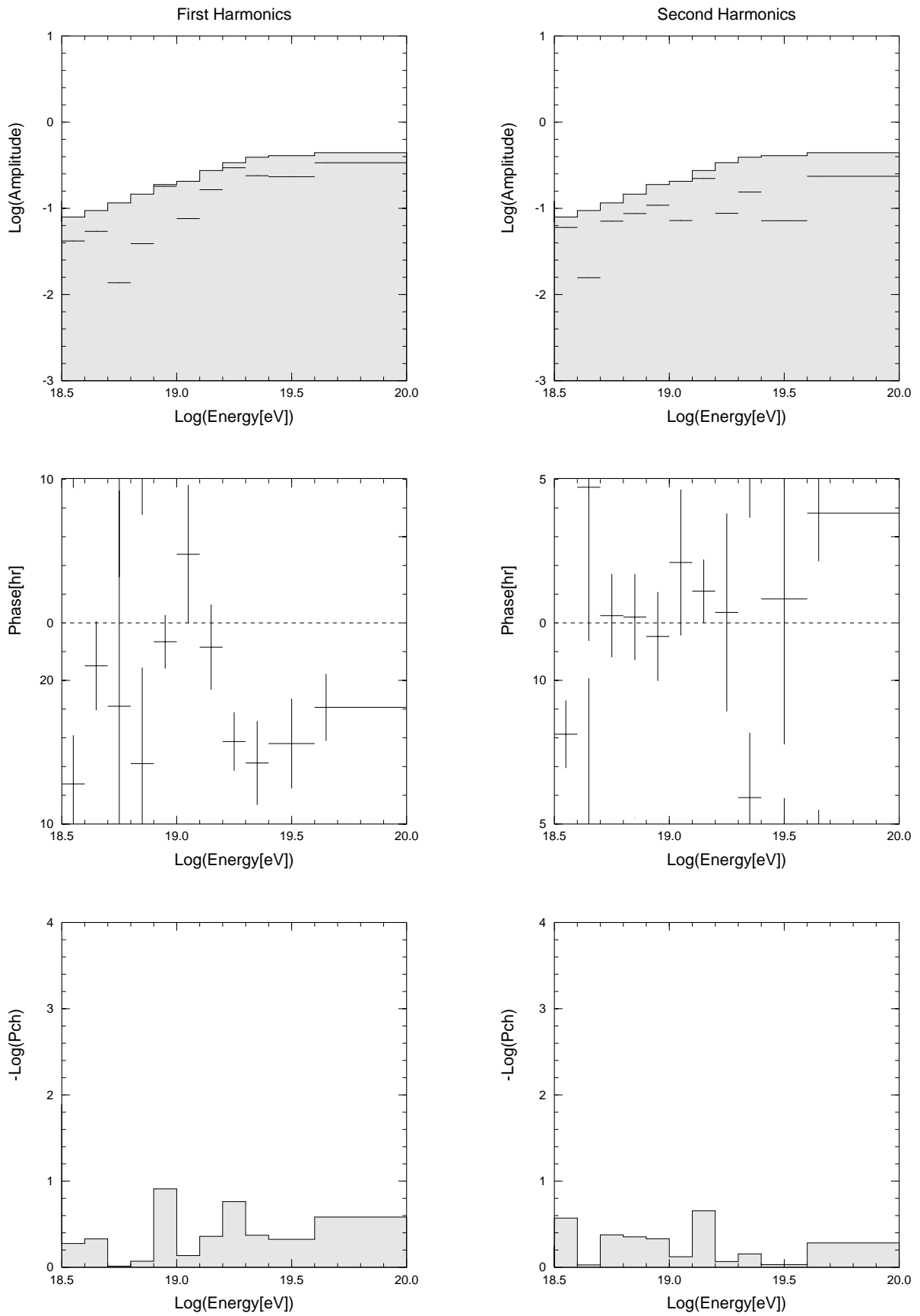


FIG. 3.—Results of the harmonic analysis. *Top to bottom*: amplitude, the phases, and the chance probabilities of the first (*left*) and second (*right*) harmonics.

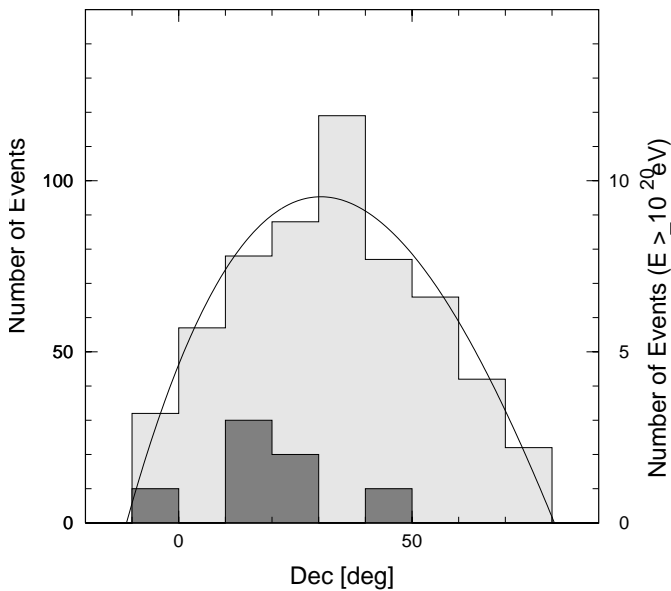


FIG. 4.—Declination distribution of the observed cosmic rays: $\geq 10^{19}$ (light histogram) and $\geq 10^{20}$ eV (dark histogram)

& Wolfendale (1984) was used. The f_E value characterizes the anisotropy expressed by

$$I_{\text{obs}}(b)/I_{\text{exp}}(b) = (1 - f_E) + 1.402f_E \exp(-b^2), \quad (1)$$

where b is the Galactic or supergalactic latitude in radians, and $I_{\text{obs}}(b)$ and $I_{\text{exp}}(b)$ are the observed and expected intensities at latitude b . A positive f_E value suggests a Galactic or supergalactic plane enhancement, $f_E = 0$ indicates that the arrival direction distribution is isotropic, and a negative f_E shows depression around the plane.

Figure 6 shows the dependence of f_E on the primary energy for the Galactic (*left*) and supergalactic (*right*) coordinates. Error bars represent fitting uncertainties. Some excess can be seen around the supergalactic plane in the seventh energy bin $\{\log(E[\text{eV}]) = [19.1, 19.2]\}$, where $f_E^{\text{SG}} = 0.36 \pm 0.15$. In other energies, the arrival direction distribution is consistent with an isotropic distribution.

3.2.2. The θ_{GC} Distribution

Figure 7 shows the $\cos(\theta_{\text{GC}})$ distribution, where θ_{GC} is the opening angle between the cosmic-ray arrival direction and the Galactic center direction, with energies above 10^{19} (*top*), 2×10^{19} (*middle*), and 4×10^{19} eV (*bottom*). Histograms are the observed distribution, and the solid curves are expected from an isotropic distribution. The observed distribution is consistent with the solid curve in all energy ranges. The dashed and dotted curves are expected from the dark matter halo model (Berezinsky & Mikhailov 1999) and will be discussed in § 4.2.

3.3. Significance Map of Cosmic-Ray Excess/Deficit

There is no statistically significant large-scale anisotropy in the above one-dimensional analyses. Here we search for two-dimensional anisotropy while taking account of the angular resolution event by event. Figures 8 and 9 show the contour maps of the cosmic-ray excess or deficit with respect to an isotropic distribution above 10^{19} and 4×10^{19} eV, respectively. A bright region indicates that the observed

cosmic-ray intensity is larger than the expected intensity, and a dark region shows a deficit region. For each observed event, we calculate a point-spread function that is assumed to be a normalized Gaussian probability distribution with a standard deviation of the angular resolution $\Delta\theta$ obtained from Figure 1. The probability densities of all events are folded into cells of $1^\circ \times 1^\circ$ in the equatorial coordinates. At each cell, we sum up densities within a 4° radius for Figure 8 and $2^\circ.5$ for Figure 9. These radii are obtained from $2^{1/2} \times \Delta\theta$, and they would make excess regions clearer. The reference distribution is obtained from an isotropic distribution. In these figures, small statistics of observed and expected events result in bright regions at the lower and higher declination, and hence bright spots below $\delta = 0^\circ$ are not significant. Two distinctive bright regions are found in Figure 8 that are broader than the angular resolution. They are referred to as broad clusters, such as the BC1 ($20^{\text{h}}50^{\text{m}}, 32^\circ$) and BC2 ($1^{\text{h}}40^{\text{m}}, 35^\circ$). The member events within a 4° radius of BC1 are listed in Table 3. Four brighter regions in the middle declination are found in Figure 9: the C1–C4 clusters, which are noted in column (8) of Table 2. The C1–C3 clusters follow the notation used in our previous analysis (Hayashida et al. 1996). The C2 cluster is observed in both energy ranges.

In Figure 8, the contour map has eight steps in $[-3\sigma, +3\sigma]$; two steps below -1.5σ are absent. The significance of deviation from an isotropic distribution is estimated to be 2.4σ at the C2 cluster, 2.7σ at the BC1 cluster, and 2.8σ at the BC2 cluster. The arrival directions of cosmic rays around the BC1 cluster are shown in Figure 10a, and the radius of each circle corresponds to the logarithm of its energy. Shaded circles have energies above 10^{19} eV, and open circles have energies below 10^{19} eV. Figure 10b shows the arrival time–energy relation, and open circles denote members of the BC1 cluster. The members of the BC1 cluster have energies between 10^{19} and 2.5×10^{19} eV, and no excess of cosmic rays is observed below 10^{19} eV around this direction. Five members of the BC1 cluster are observed around MJD 50,000. This cluster is in the direction of a famous supernova remnant: the Cygnus Loop, which extends about 3° around ($20^{\text{h}}50^{\text{m}}, 30^\circ34'$). The BC2 cluster is the broader cluster without a clear boundary. The BC1 and BC2 clusters contribute the excess around $\delta = 35^\circ$ shown in Figure 4. The C2 and BC2 clusters are located

TABLE 3
MEMBERS OF THE CLUSTERING EVENTS ABOVE 10^{19} eV

NAME	DATE	ENERGY ($\times 10^{19}$ eV)	COORDINATES ^a			
			α	δ	l^G	b^G
BC1.....	1995 Oct 09	1.47	20 50	30.8	73.9	−8.2
	1995 Nov 23	1.68	20 54	34.2	77.1	−6.8
	1995 Jul 18	1.31	20 42	33.2	74.8	−5.5
	1995 Sep 24	1.33	20 41	34.1	75.4	−4.8
	1991 Jul 02	1.10	20 55	35.1	77.9	−6.4
	1996 Aug 02	2.29	20 55	32.4	75.9	−8.1
	1997 May 28	1.06	20 50	34.7	77.1	−5.9
	1997 Jun 20	1.11	21 02	33.7	77.8	−8.4
BC2.....	1 40	35	134	−27

NOTE.—Units of right ascension are hours and minutes, and units of declination are degrees.

^a The celestial coordinates are based on the J2000.0 coordinates.

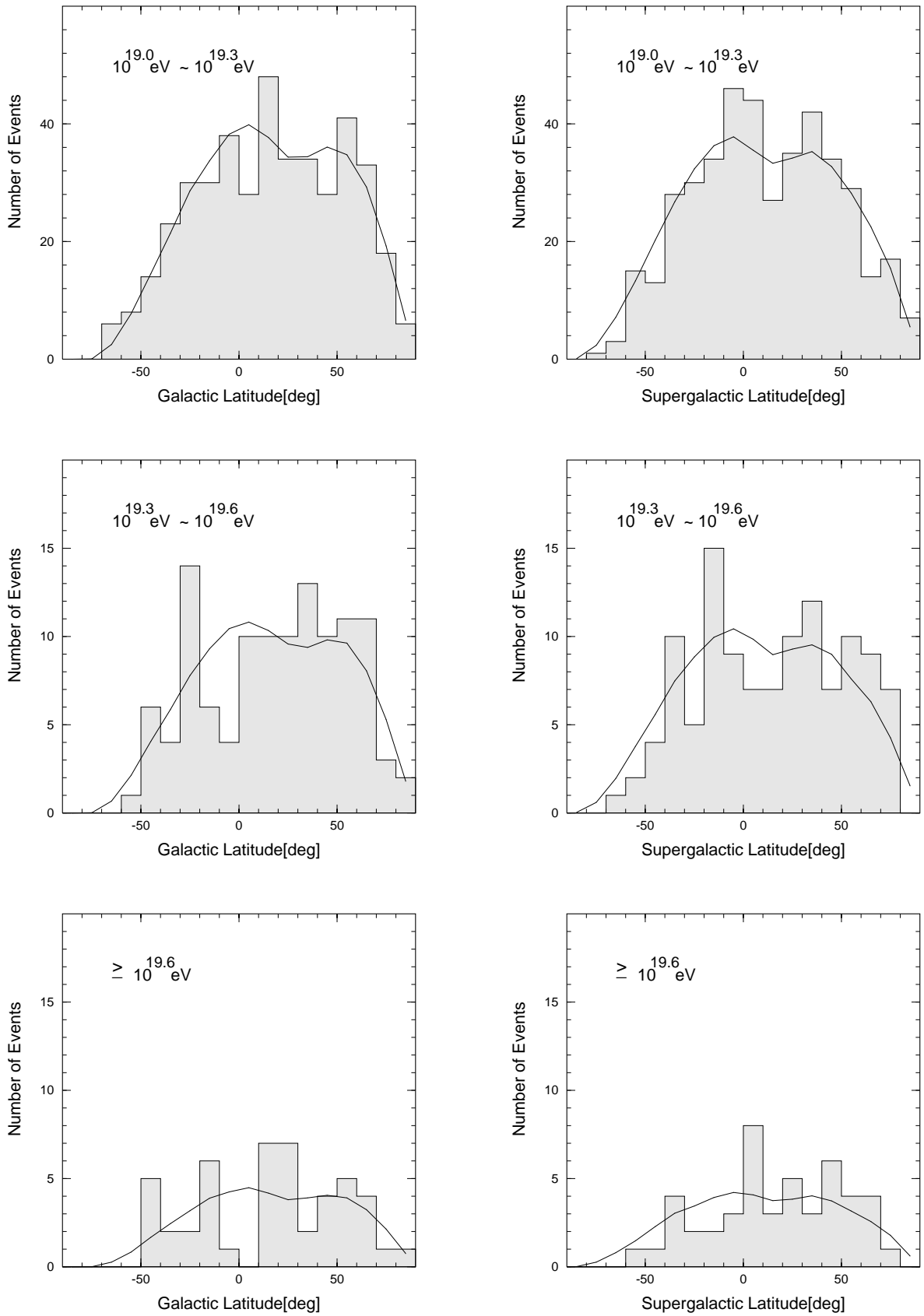


FIG. 5.—Galactic (*left*) and supergalactic (*right*) latitude distribution: $(1-2) \times 10^{19}$ (*top*), $(2-4) \times 10^{19}$ (*middle*), and $\geq 4 \times 10^{19}$ eV (*bottom*)

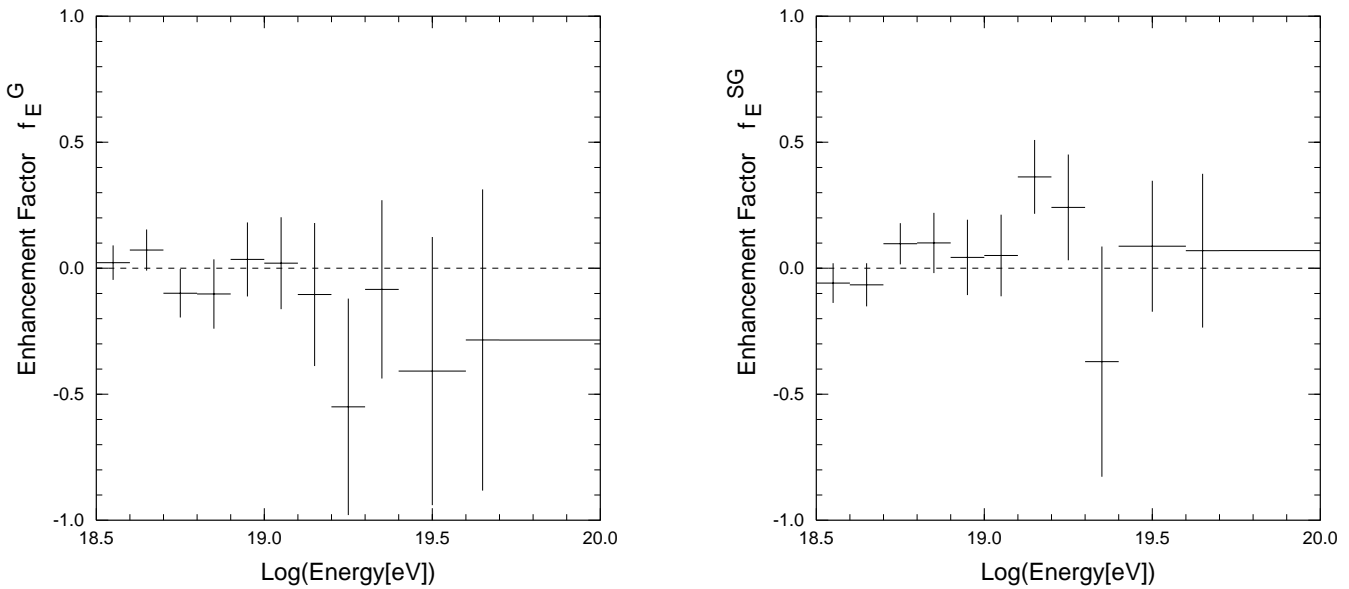


FIG. 6.—Dependence of the plane enhancement factor on the energy for the Galactic coordinates (*left*) and for the supergalactic coordinates (*right*)

near the supergalactic plane and lead the largest f_E^{SG} value in § 3.2.1.

For small statistics of observed events, Figure 9 reflects the arrival directions of individual events (Fig. 2, *open squares and open circles*). The brightest peak is at the C2 cluster, where three cosmic rays are observed against expected 0.05 events. It is possible that some of these clusters are observed by a chance coincidence. It should be noted, however, that two of these clusters—the doublet (C1) including the AGASA highest energy event and the triplet (C2)—lie near the supergalactic plane, as pointed out in our previous analysis (Hayashida et al. 1996). The arrival directions (*left*) and arrival time–energy relation (*right*) for the C1 (*top*) and C2 (*bottom*) clusters are shown in Figure 11. A radius of each circle in the left panels corresponds to the logarithm of its energy, and the open circles in the right panels denote members of the C1 and C2 clusters. Around the C2 cluster, several lower energy cosmic rays are observed very close to the C2 cluster.

3.4. Cluster Analysis

The threshold energy of 4×10^{19} eV is one distinctive energy where the GZK effect becomes large, as mentioned in § 1. It is, however, quite important to examine what kind of dependence on threshold energy is operating.

TABLE 4
KS TEST FOR CELESTIAL COORDINATES

Coordinates	KS Probability
Azimuth angle (ϕ)	0.268
Zenith angle (θ)	0.867
Right ascension (α)	0.202
Declination (δ)	0.025
Ecliptic longitude	0.085
Ecliptic latitude	0.449
Galactic longitude (l^G)	0.182
Galactic latitude (b^G)	0.540
Supergalactic longitude (l^{SG})	0.654
Supergalactic latitude (b^{SG})	0.167

To begin with, we estimate the chance probability of observing one triplet and three doublets from 47 cosmic rays above 4×10^{19} eV. A cluster of cosmic rays is defined as follows:

1. Define the i th event;
2. Count the number of events within a circle of radius 2.5 centered on the arrival direction of the i th event;
3. If this number of events exceeds a certain threshold value N_{th} , the i th event is counted as a cluster.

This procedure was repeated for a total of 47 events, and then the total number of clusters with N_{th} was determined. The chance probability P_{ch} of observing this number of clusters under an isotropic distribution is obtained from the distribution of the number of clusters using 10,000 simulated data sets. These simulated data sets were also analyzed by the same procedure described above. Out of 10,000 simulations, 32 trials had the same amount of or more doublets ($N_{th} = 2$) than the observed data set, so that $P_{ch} = 0.32\%$; $P_{ch} = 0.87\%$ for triplets ($N_{th} = 3$).

Then the energy dependence for observing (a) doublets and (b) triplets are estimated, and the results are shown in Figure 12. When a new cluster is added above a threshold energy, a histogram changes discontinuously at that energy. At the maximum threshold energy where the triplet is detected, we find $P_{ch} = 0.16\%$ in Figure 12b. The narrow peaks of $P_{ch} \simeq 0.1\%$ above 4×10^{19} eV in Figure 12a result from the C1, C3, and C4 doublets, and another doublet, C5, is found just below 4×10^{19} eV. Here these chance probabilities are estimated without taking the degree of freedom on the threshold energy into account. However, the chance probabilities are smaller than 1% and do not vary abruptly with energies above 4×10^{19} eV. This means that the threshold energy of 4×10^{19} eV for doublets and triplets in Figure 9 may indicate any critical energy, and it suggests that their sources are not very far from being different from those below this energy.

3.5. The 10^{20} eV Events

Seven events have been observed with energies above 10^{20} eV, and their energies and coordinates are also listed in

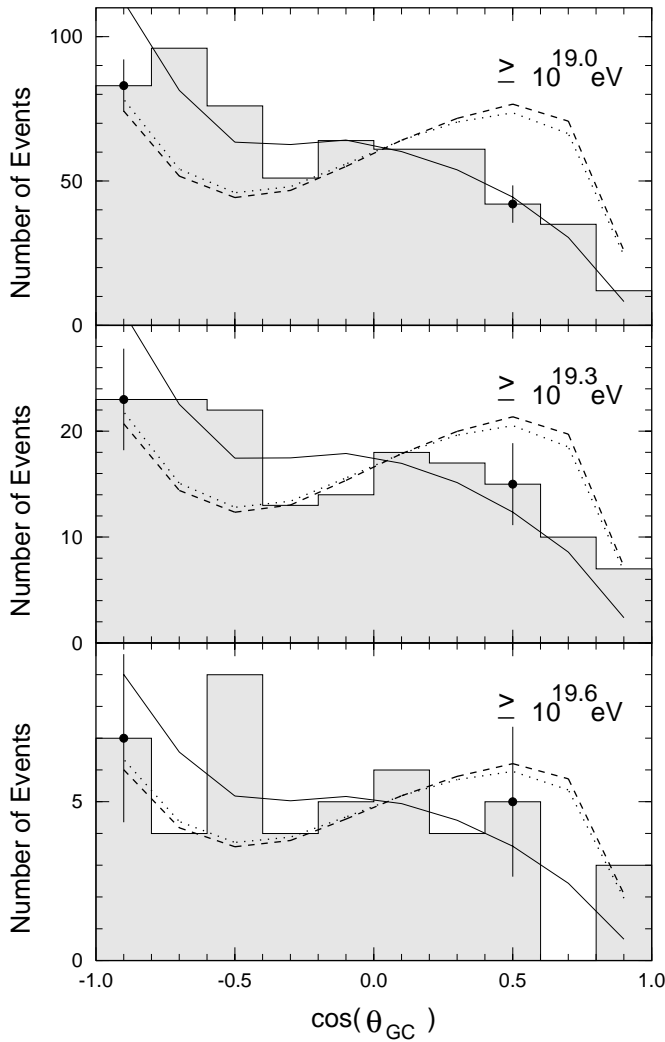


FIG. 7.—The $\cos(\theta_{GC})$ distribution: $\geq 10^{19}$ (top), $\geq 2 \times 10^{19}$ (middle), and $\geq 4 \times 10^{19}$ eV (bottom). Here θ_{GC} is the opening angle between the cosmic-ray direction and the Galactic center direction, with energies $\geq 10^{19}$ (top), 2×10^{19} (middle), and 4×10^{19} eV (bottom). The solid, dashed, and dotted curves indicate the distribution expected for the isotropic, ISO, and NFW models, respectively.

Table 2. Their declinations are near $\delta \simeq 20^\circ$, while an isotropic distribution is shown by the solid curve in Figure 4. To check whether these seven events distribute isotropically or not, we compare the celestial distribution of seven 10^{20}

eV events with that for events between 10^{19} and 10^{20} eV in 10 different coordinates. The Kolmogorov-Smirnov (KS) test (Press et al. 1988) was used for avoiding any binning effect. The results are summarized in Table 4. The smallest KS probability in Table 4 is 2.5% for the declination distribution, but this probability becomes larger when using a data set above 6.3×10^{19} eV. One interesting feature is that five 10^{20} eV cosmic rays come from southwest of the AGASA array, where the strength of the geomagnetic field component that is perpendicular to an air shower axis is larger than the other directions (Stanev & Vankov 1997).

4. DISCUSSION

4.1. Comparison with Other Experiments

Above 3×10^{18} eV, no large-scale anisotropy has been found with the harmonic analysis and the f_E^G fit. Gillman & Watson (1993) summarized the f_E^G values using the data sets obtained mainly from the Haverah Park experiment. They obtained no significant deviation from $f_E^G = 0$. The result from the Fly’s Eye experiment (Bird et al. 1999) is consistent with an isotropic distribution of cosmic rays with $E \gtrsim 10^{19}$ eV. The analysis with the Yakutsk data set (Ivanov et al. 1997) shows no significant Galactic plane enhancement above 10^{18} eV. The results from all experiments are consistent with this work on the noncorrelation of cosmic rays above 10^{19} eV with the Galactic plane. This may implicate an extragalactic origin of cosmic rays above 10^{19} eV if they are mostly protons.

The BC1, BC2, and C1–C5 clusters are found with energies $\geq 10^{19}$ or $\gtrsim 4 \times 10^{19}$ eV. The C2 and BC2 clusters dominate the small preference along the supergalactic plane in the energy range of $\log(E[\text{eV}]) = [19.1, 19.2]$. With the data sets of Haverah Park, Yakutsk, Volcano Ranch (Uchihori et al. 1996), and AGASA, another triplet is found at the position of the C1 cluster within the experimental error box on the arrival direction determination. This triplet at the C1 cluster position includes the AGASA highest energy event and a 10^{20} eV Haverah Park event. It should be noted that these triplets at the C1 and C2 positions are close to the supergalactic plane.

4.2. Correlation with Galactic Halo

Kuzmin & Rubakov (1998) and Berezhinsky et al. (1997) have suggested that the production of most energetic cosmic rays from the decay of supermassive particles, which are trapped in the Galactic halo, distribute symmetrically around the Galactic center and are possibly associated with

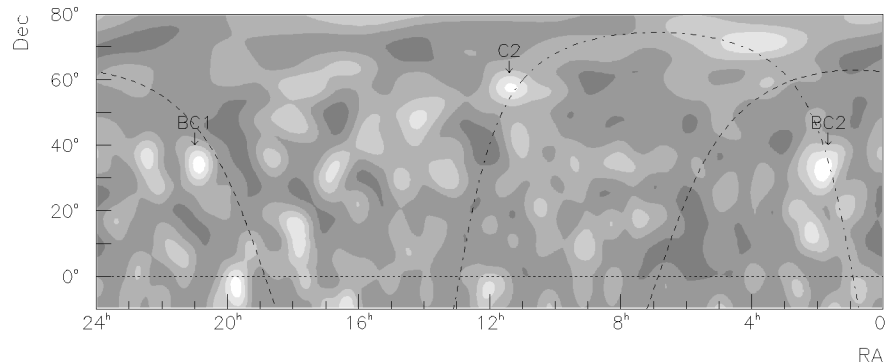


FIG. 8.—Significance map of cosmic-ray excess/deficit above 10^{19} eV. The dashed and dash-dotted curve indicate the Galactic and supergalactic plane, respectively.

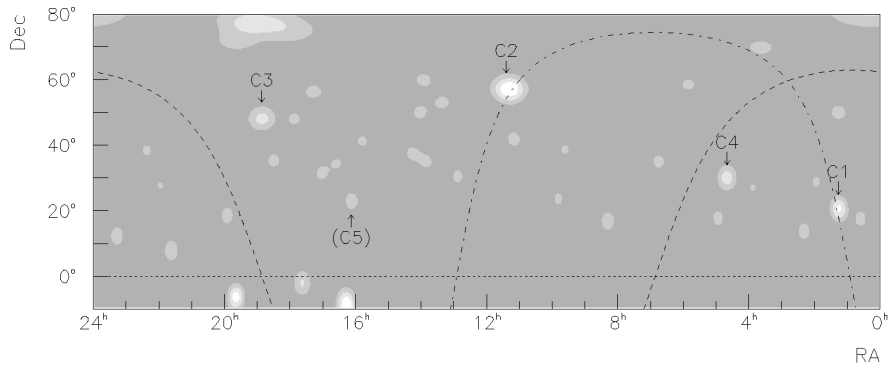


FIG. 9.—Significance map of cosmic-ray excess/deficit above 4×10^{19} eV. The dashed and dash-dotted curve indicate the Galactic and supergalactic plane, respectively.

dark matter. The arrival directions of most energetic cosmic rays, therefore, exhibit anisotropy at the Earth (Berezinsky 1998). From recent studies by Berezinsky & Mikhailov (1999) and Medina Tanco & Watson (1999), a significant anisotropy would be expected in the first harmonics of right ascension distribution, the amplitude of 40% at phase about 250° , which is independent of the *Infrared Space Observatory* (*ISO*) and Navarro-Frenk-White (NFW) models of dark matter distribution in the Galactic halo. The

ISO and NFW models are described in Kravtsov et al. (1997) and Navarro, Frenk, & White (1996), respectively. This expected anisotropy is consistent with the results of the harmonic analysis above 4×10^{19} eV, as shown in Figure 3. However, this amplitude is explained with the statistical fluctuation of an isotropic distribution.

As shown by the dashed and dotted curves in Figure 7, the *ISO* and NFW models of dark matter distribution in the Galactic halo lead to an excess toward the Galactic center.

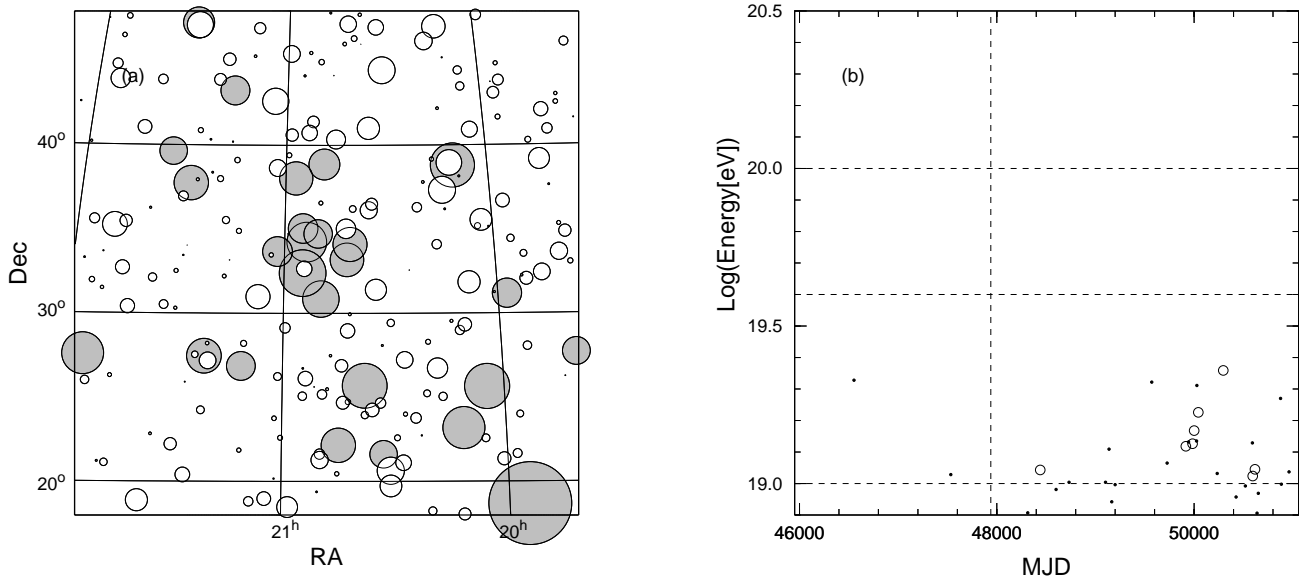


FIG. 10.—BC1 cluster: (a) Arrival directions of cosmic rays around the BC1 cluster. The radius of each circle corresponds to $\log [E(\text{eV})]$, and the shaded and open circles have energies above 10^{19} eV and between 3×10^{18} and 10^{19} eV, respectively. (b) Arrival time–energy relation. Open circles denote members of the BC1 cluster, and dots are cosmic rays near the BC1 cluster. After the vertical dotted line, A20 is combined with AGASA.

TABLE 5
REDUCED- χ^2 VALUES OF THE $\cos(\theta_{GC})$ DISTRIBUTION WITH THREE MODELS

DM Model	$\geq 10^{19}$ eV	$\geq 2 \times 10^{19}$ eV	$\geq 4 \times 10^{19}$ eV
Isotropic distribution	2.0	1.7	1.8
<i>ISO</i> model	11.8	2.2	1.7
NFW model	10.0	1.9	1.6

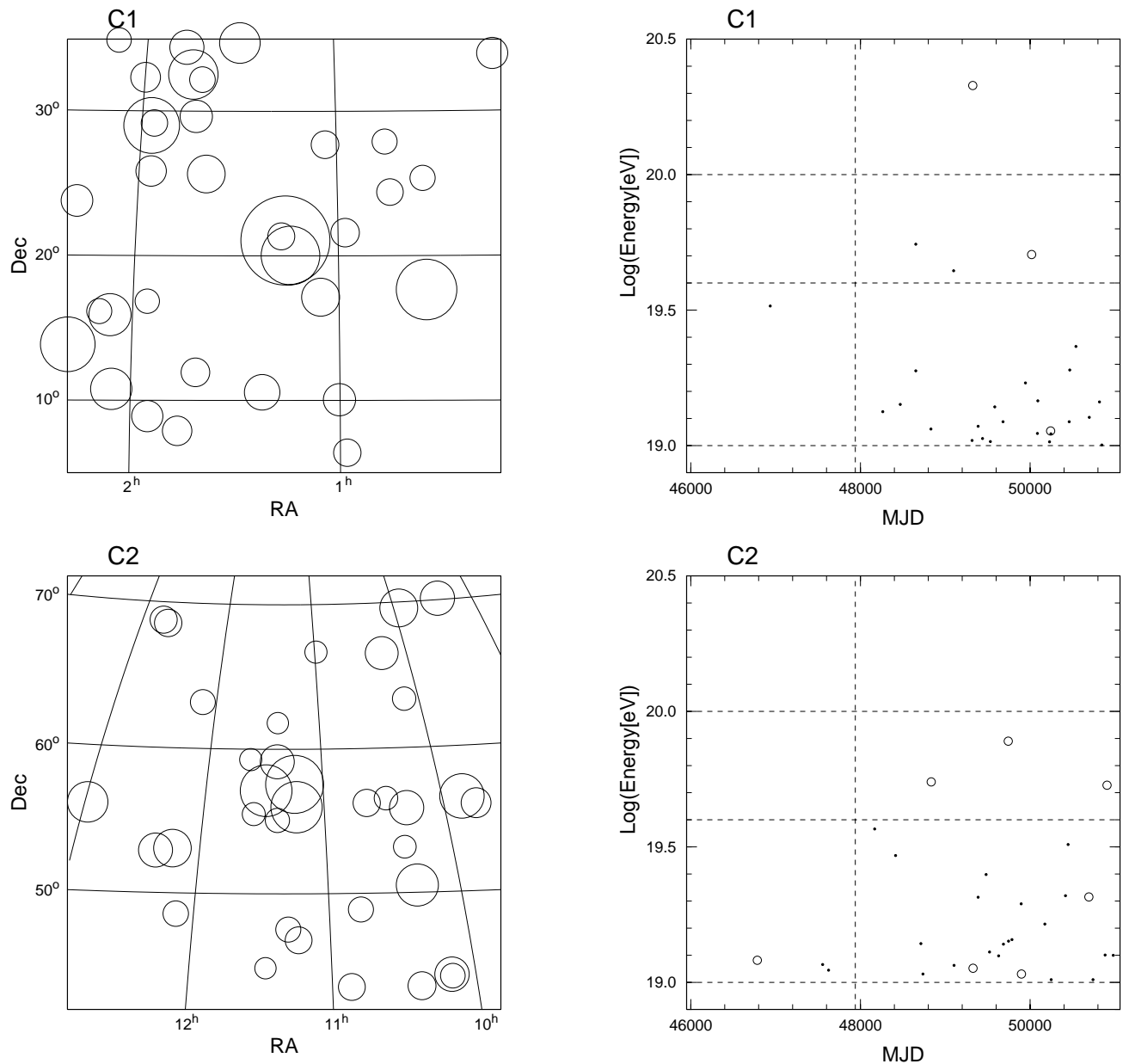


FIG. 11.—Arrival directions and arrival time–energy relation for the C1 and C2 clusters. Here cosmic rays above 10^{19} eV are plotted (see also Fig. 10).

Table 5 shows the reduced χ^2 values of the observed $\cos(\theta_{GC})$ distribution with the isotropic, *ISO*, and NFW models. Although the distribution expected from the *ISO* and NFW models is quite different from the observed distribution in energies above 10^{19} eV, the reduced χ^2 values are close to one another above 2×10^{19} and 4×10^{19} eV. Above 2×10^{19} eV, all three models are acceptable, and it is hard to distinguish one from another.

4.3. Correlation with Nearby Galaxies

In § 3.4, we calculated the chance probability of observing clusters under an isotropic distribution. If cosmic rays have an astrophysical source origin, the nonuniform distribution of galaxies or luminous matter should be taken into account, as claimed by Medina Tanco (1998). He calculated trajectories of cosmic rays above 4×10^{19} eV in the inter-

galactic magnetic field under the assumption that the flux of cosmic rays is proportional to the local density of galaxies. The expected distribution of cosmic-ray intensity is no more uniform, and this may result in a strong anisotropy. This is different from the results in this paper, so our estimation of the chance probability of observing clusters under an isotropic distribution is experimentally reliable. However, his calculation shows important results: the C2 cluster is on top of a maximum of the arrival probability for sources located between 20 and 50 Mpc, the C1 and BC2 clusters locate on a high arrival probability region for sources at more than 50 Mpc, and the C4 and C5 clusters locate at the foot of high arrival probability regions for distant (≥ 50 Mpc) sources. This suggests the possibility that the members of these clusters are generated at different sources. One needs to accumulate further statistics to make the arrival direction, time,

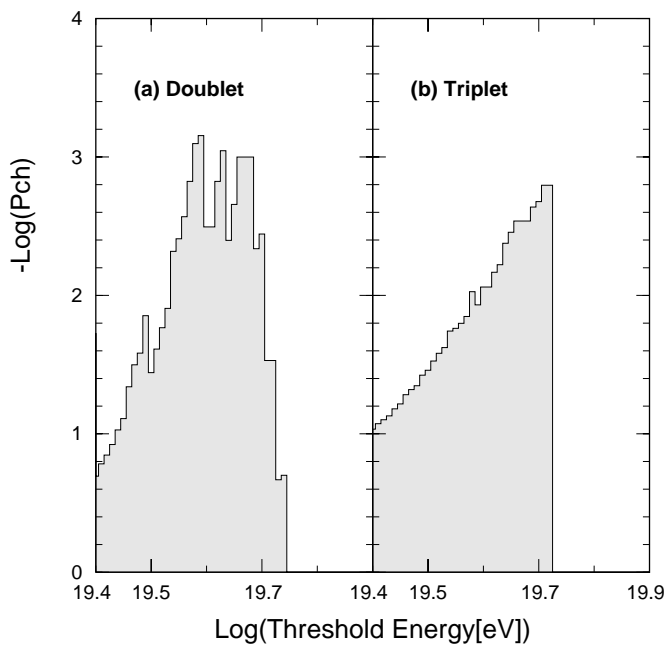


FIG. 12.—Energy dependence of the chance probability of observing (a) doublets and (b) triplets

and energy relation clear (Medina Tanco 1998; Sigl & Lemoine 1998) in order to distinguish whether the members of clusters come from a single source or unrelated sources.

4.4. Correlation with the Known Astrophysical Objects

As mentioned in § 3.4, the BC1 cluster is in the direction of the Cygnus Loop (NGC 6992/95). From the Hillas confinement condition (magnetic field times size) for cosmic-ray acceleration (Hillas 1984), the magnetic field in the shock of the Cygnus Loop is too small to accelerate cosmic rays up to 10^{19} eV. And the observed energy distribution and a bunch of the arrival times of the cluster members do not favor the diffusive shock acceleration. Another possible candidate is PSR 2053+36 with a period of 0.2215 s and a magnetic field of about 3×10^{11} G (Manchester & Taylor 1981). It may be plausible that such a highly magnetized pulsar has accelerated cosmic rays up to 10^{19} eV within a short time (Gunn & Ostriker 1969; Goldreich & Julian 1969). It is highly desirable to search for any signals from this direction in other energy ranges around MJD 50,000. If this is not the real coincidence, the spectrometer effect of the regular/irregular Galactic magnetic field is another interesting subject.

For the C1–C5 clusters and 10^{20} eV cosmic rays, a coincidence with known astrophysical objects is searched for from three catalogs: the second EGRET catalog (Thompson et al. 1995, 1996), the CfA redshift catalog

(Huchra et al. 1995), and the eighth extragalactic redshift catalog (Veron-Cetty & Veron 1998). The selection criteria are the following: (1) a separation angle within 4° from a member of each cluster and 2.5° for the 10^{20} eV cosmic ray, and (2) a redshift within 0.02. In the CfA catalog, only quasi-stellar objects/active galactic nuclei are selected. Candidate objects are listed in Table 6. Out of these objects, Mrk 40 (VV 141, Arp 151) is an interacting galaxy and may be the most interesting. It should be noted that Al-Dargazelli et al. (1996) claimed that nearby colliding galaxies are most favored as the sources of clusters (regions of excess events) defined by them using the world data available before 1996.

5. SUMMARY

In conclusion, there is no statistically significant large-scale anisotropy related to the Galactic nor supergalactic plane. The slight supergalactic plane enhancement is observed just above 10^{19} eV and arises mainly from the BC2 and C2 clusters. Above 4×10^{19} eV, one triplet and three doublets are found, and the probability of observing these clusters by a chance coincidence is smaller than 1%. The triplet is especially observed against expected 0.05 events. Out of these clusters, the C2 (AGASA triplet) and C1 (doublet, including the AGASA highest energy event, or triplet together with the Haverah Park 10^{20} eV event) clusters are the most interesting: they are triplets found in the world data sets and are located near the supergalactic plane. One should wait for further high-rate observations to distinguish whether the members of clusters come from a single source or from different sources. The $\cos(\theta_{GC})$ distribution expected from the dark matter halo model fits the data as well as an isotropic distribution above 2×10^{19} and 4×10^{19} eV, but the fit with the dark matter halo model is poorer than the isotropic distribution above 10^{19} eV. The arrival direction distribution of the 10^{20} eV cosmic rays is consistent with that of cosmic rays with lower energies and is uniform. It is noteworthy that three of seven 10^{20} eV cosmic rays are members of doublets. The BC1 cluster is in the direction of the Cygnus Loop or PSR 2053+36 region. It is desirable to examine any signals from this direction in other energy band around MJD 50,000. We hope other experiments in TeV–PeV regions explore the C1–C5 clusters and 10^{20} eV cosmic-ray directions.

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TABLE 6
ASTROPHYSICAL OBJECTS NEAR THE AGASA EVENTS

Event ID	Astrophysical Object
C1.....	Mrk 359 (0.017)
C2.....	NGC 3642 (0.005), Mrk 40 (0.02), Mrk 171 (0.01)
970330 (1.5×10^{20} eV).....	H 1934–063 (0.011)

NOTE.—Redshift values for each object are given in parentheses.

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