OG.1.3.04

The Anisotropy of Cosmic Ray Arrival Direction around 10^{18}eV

(AGASA Collaboration)

N. Hayashida[1], K. Honda[2], N. Inoue[3], K. Kadota[4], F. Kakimoto[4], S. Kakizawa[5], K. Kamata[6], S. Kawaguchi[7], Y. Kawasaki[8], N. Kawasumi[9], E. Kusano[10], Y. Matsubara[11], K. Mase[1], T. Minagawa[1], K. Murakami[12], M. Nagano[13], D. Nishikawa[1], H. Ohoka[1], S. Osone[1], N. Sakaki[1], M. Sasaki[1], K. Shinozaki[3], M. Takeda[1], M. Teshima[1], R. Torii[1], I. Tsushima[9], Y. Uchihori[14], T. Yamamoto[1], S. Yoshida[1], and H. Yoshii[15]

[1]*Institute for Cosmic Ray Research, University of Tokyo, Tokyo 188-8502, Japan*
[2]*Faculty of Engineering, Yamanashi University, Kofu 400-8511, Japan*
[3]*Department of Physics, Saitama University, Urawa 338-8570, Japan*
[4]*Department of Physics, Tokyo Institute of Technology, Tokyo 152-8551, Japan*
[5]*Department of Physics, Shinshu University, Matsumoto, Japan*
[5]*Nishina Memorial Foundation, Komagome, Tokyo 113-0021, Japan*
[6]*Faculty of General Education, Hirosaki University, Hirosaki 036-8560, Japan*
[7]*Department of Physics, Osaka City University, Osaka 558-8585, Japan*
[8]*Faculty of Education, Yamanashi University, Kofu 400-8510, Japan*
[9]*KEK, High Energy Accelerator Organization, Tsukuba 305-0801, Japan*
[10]*Solar-Terrestrial Environment Laboratory, Nagoya University, Nagoya 464-8601, Japan*
[11]*Nagoya University of Foreign Studies, Nissin, Aichi 470-0131, Japan*
[12]*Department of Applied Physics and Chemistry, Fukui University of Technology, Fukui 910-8505, Japan*
[13]*National Institute of Radiological Sciences, Chiba 263-8555, Japan*
[14]*Department of Physics, Ehime University, Matsuyama 790-8577, Japan*

Abstract

Anisotropy in the arrival directions of cosmic rays around 10^{18}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 216,000 showers observed over 15 years above $10^{17}eV$. In the first harmonic analysis, we have found significant anisotropy of ~ 4 % around 10^{18}eV, corresponding to a chance probability of $\sim 10^{-5}$ 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. This is a clear evidence for the existence of the galactic cosmic ray up to the energy of $10^{18}eV$. Primary particle which contribute this anisotropy may be proton or neutron.

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 a broad energy range. In the previous report (Hayashida et al. 1998), we have reported the evidence of the anisotropy correlated with our galaxy at 10^{18}eV. This result means the existence of galactic cosmic rays up to the energy of $10^{18}eV$ and can be interpreted by two models, one is the proton diffision model and the other, the superposition of neutron emission from the galactic sources. It is worthwhile to note that the neutron's life time become comparable with the scale of the galaxy at this energy range. Here, we obtained more significant results by adding data upto April 1999.

The Akeno Giant Air Shower Array (AGASA) consists of 111 scintillation detectors of 2.2 m^2 area each, which are arranged with 1km spacing over 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 Ohoka et al. 1997. Data from the 20 km^2 array (Teshima 1986) are included in this analysis. The typical angular resolution is 3 degrees for 10^{18}eV cosmic rays.

2 Results:

The showers are selected with 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 216,000 events remain after these Selection. Results of first harmonic analysis in right ascension are shown in Figure 1. The amplitude, the phase (peak direction in right ascension), and the significance k are shown as a function of primary energy threshold. Each point is obtained by summing over events with more than the corresponding energy. The parameter k follows the probability distribution of exp(-k), if we assume the random sample. $k \sim 14$ around 10^{18}eV can be seen in the bottom plot. It is surprisingly high, corresponding to a chance probability of 10^{-6}. We have searched for the energy bin width which gives the maximum k -value, and find that the region $10^{18.0}$eV - $10^{18.4}$eV gives the maximum k-value of 15.1. This means the showers which contribute to the anisotropy are distributed in the energy range of 0.4 decade.

We also listed the results in the differential bins with energy ranges of a factor of two from 1/2EeV to 8EeV in Table 1, for the comparison with the world data. According to this table, the chance probability is estimated to be $\sim 10^{-5}$ 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. We have carried out several tests on the systematic effect(see Hayashida et al. 1998), however, we found the observation is quit uniform and the systematics are negligeble small for the present $\sim 4\%$ amplitude.

In Figures 2, the arrival direction distributions in equatorial coordinates are shown. They show the ratio of the number of observed event to the expected one, and the statistical significance of the deviations from the expectation. Here, the energy region of $10^{18.0} \sim 10^{18.4}$eV is selected which maximize the harmonic analysis k-value. We can not observe events with declination less than -25°, as long as we use showers with zenith angles less than 60°. In this figure, we have chosen a circle of 20° radius to evaluate the excess. The expected event density inside this circle are evaluated using the average of event rate at the same decli-

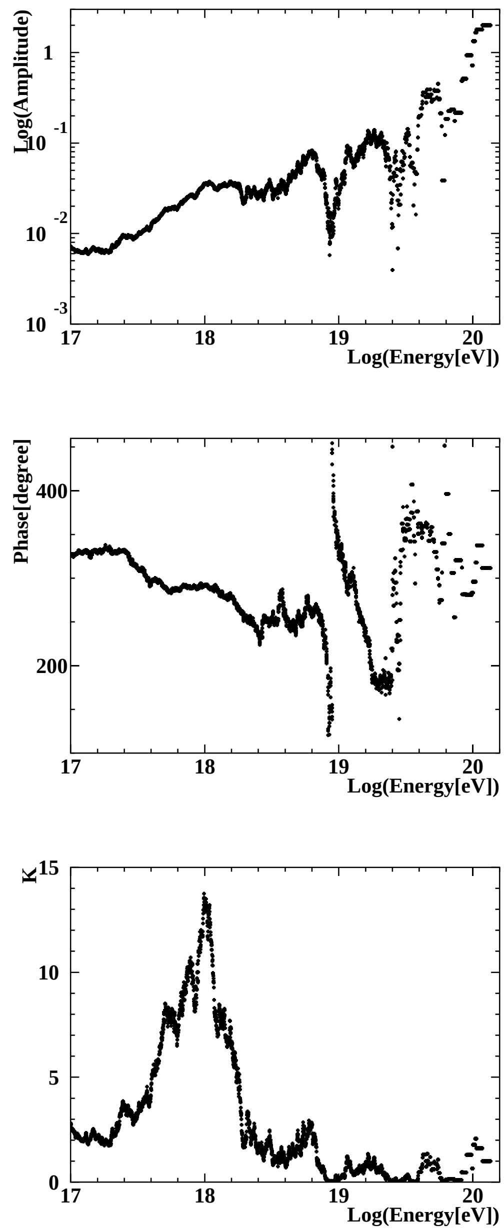

Figure 1: The first harmonic analysis. The amplitude, the phase, peak direction in right ascension, and the significance k are shown as a function of primary energy threshold, respectively. Each point is obtained by summing over events with more than the corresponding energy.

Table 1: The first harmonic analysis in right ascension.

Bin	Energy Range/EeV	#	Amplitude[%]	Phase	k	P_{prob}
E4	1/2 - 1.0	56658	0.5	272	0.42	0.65
E5	1.0 - 2.0	29207	4.2	297	12.9	2.5E-6
E6	2.0 - 4.0	10129	2.0	256	1.10	0.33
E7	4.0 - 8.0	2769	3.3	256	0.76	0.46

nation band.

In the significance map with beam size of 20°, a 4.5σ excess (obs./exp. = 506/413.6) near the Galactic Center region can be seen. In contrast, near the direction of anti-Galactic Center we can see a deficit in the cosmic ray intensity (-4.0σ). An event excess from the direction of the Cygnus region is also seen in the significance map with 3.9 σ (obs./exp. = 3401/3148).

3 Discussion

An anisotropy of amplitude 4% around 10^{18}eV was found in first harmonic analysis. With a two dimensional map, we can identify this as being due to event excesses of 4.5σ and 3.9σ near the galactic center and the Cygnus region, respectively. The observed anisotropy seems to be correlated with the galactic structure.

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 can not be observed by those experiments and hence a significant amplitude in harmonic analysis might be absent in their data. Fly's Eye data show the enhancement at similar energy range(Bird et al.1999).

One possible explanation of the anisotropy reported here is due to the propagation of cosmic ray protons. The observed regions of excess are directed toward the galactic plane and seem to be correlated with the nearby spiral arms. 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 1995, a proton anisotropy of 10% $\sim$ 20% amplitude is expected at RA $\sim 300^\circ$ 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 linearly from the galactic center without decaying. The accelerated heavy nuclei should interact with the ambient photons or gases in the acceleration region, and spill out neutrons. The produced neutrons can escape freely from the acceleration site. In this scenario, the heavy dominant chemical composition below 10^{18}eV (Gaisser et al. 1993) and the lack of anisotropy below 10^{18}eV (due to the short neutron lifetime) can be naturally explained.

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 two possibilities.

Acknowledgment

We are grateful to Akeno-mura, Nirasaki-shi, Sudama-cho, Nagasaka-cho, Takane-cho and Ohoizumi-mura for their kind cooperation. The authors also wish to acknowledge the valuable help by other members of the Akeno Group in the maintenance of the array.

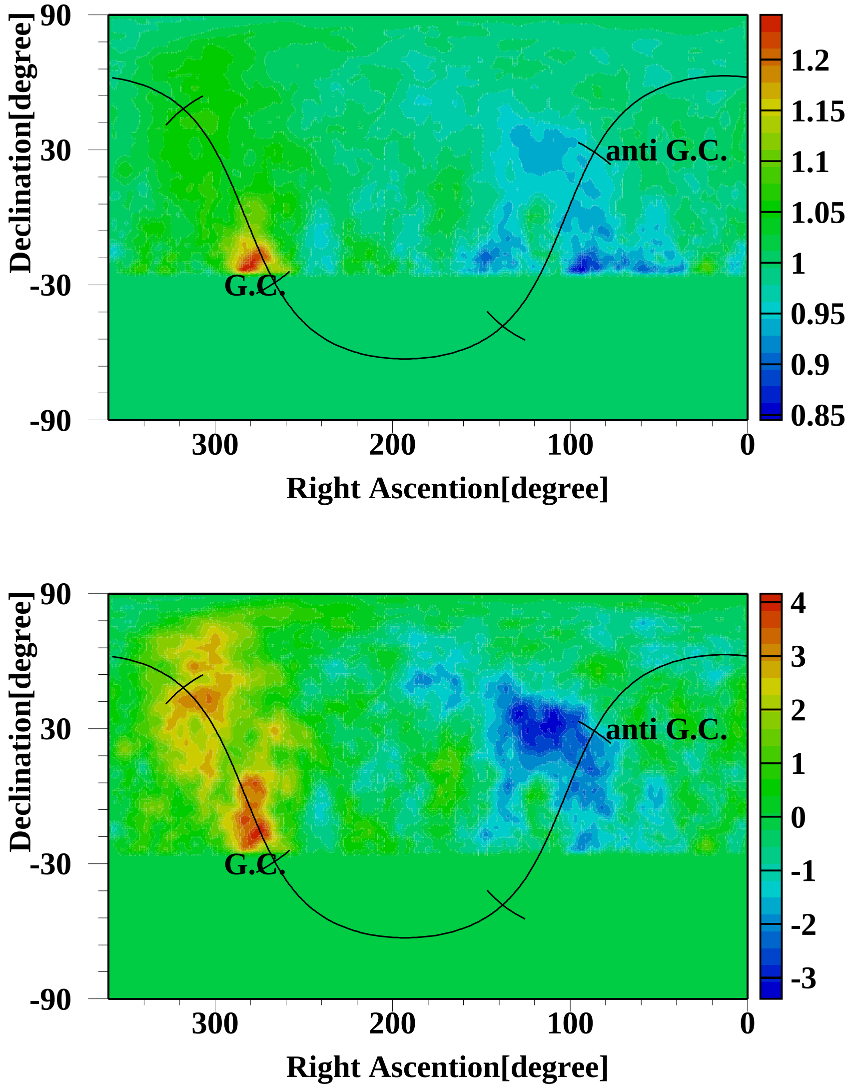

Figure 2: The ratio of the number of observed events to the expected one (top pannel) and the statistical significance of the deviations (bottom pannel) are shown on the equatorial coordinate.

References

Bird, D. et al. 1999, ApJ 551, 739

Gaisser, T.K. et al. 1993, Phys. Rev. D47, 1919.

Hayashida, N. et al. 1998, astro-ph/9807045, Astrop. Phys. 10-4, 303.

Lee, A.A. and Clay, R.W. 1995, J. Phys. G: Nucl. Part. Phys. 21, 1743.

Ohoka, H. et al. 1997, Nucl.Istr. Meth. A385, 268.

Teshima, M. et al. 1986, Nucl.Instr.and Meth. A247, 399.