The Cosmic Ray Anisotropy Observed by the Large Area Air Shower Experiments

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The cosmic ray anisotropy, calculated in terms of the harmonic analysis of the EAS arrival local sidereal times(LSTs) observed by Large Area Air Shower (LAAS) group, is presented. The amplitude and phase of the first harmonic obtained are $0.23 \pm 0.04\%$ and 0.4 ± 0.7 hr LST in the energy region from 5×10^{13} to 10^{15} eV respectively. The results have also been compared with the model calculation on the basis of the diffusive propagation model of relativistic charged particles. The rigidity dependence of anisotropy amplitudes($\delta \sim R^\alpha$) is evaluated as $\alpha = 0.339 \pm 0.014$.

1. Introduction

The cosmic ray anisotropy provides us a clue to explore the source distributions of cosmic rays and their diffusive propagations. Recent theoretical calculations[1] based on the diffusive propagation of cosmic rays predicted the longitudinal and latitudinal anisotropy amplitudes in the case of Kolmogorov type spectrum of turbulence ($\alpha = \frac{1}{3}$) and in the case of Kraichnan type one ($\alpha = \frac{1}{2}$). The sidereal anisotropy have been measured by various research groups and the amplitude has been reported to be less than 0.1% at ~ 100 TeV and to increase with primary energies. The phase of the first harmonic is around 0 hr LST at below 100 TeV, however, it scatters over whole LST range at higher energies [2]. The amplitude is so small that a huge number of events is required and care must be taken to correct atmospheric temperature and pressure effects.

The Large Area Air Shower (LAAS) experiment is a joint project organized by 10 Japanese institutions and has 11 compact EAS arrays [3, 4, 5]. Each array have been operated independently with a 1μsec. accuracy in UT by using GPS-synchronized time stamp system(KAIZU KC3051A, Furuno GF-77). There are 4 arrays within 1km baseline in Okayama city area, and others are located at several hundred km baselines. The data sets from multiple observatories by using compact EAS arrays enable us to analyze the cosmic ray anisotropy with higher statistics and with less systematic effect of atmospheres.

In this paper, results on the basis of a harmonic analysis of the LAAS data are reported and our results are compared with the theoretical model of diffusive propagation model of relativistic cosmic rays to evaluate the primary energy dependence of the amplitude of the first harmonics.

Table 1. The list of the LAAS stations.

Station Name	Abbrev.	Latitude (N)	Longitude (E)	# of counters All	# of counters Trig.	Data period
Hirosaki Univ.	HU	40°35'	140°29'	5	5	11/1998-5/2002
Nara Univ. of Industry	NUI	34°35'	135°41'	7	7	8/1996-5/2002
Kinki Univ.	KU	34°39'	135°36'	5	5	9/1996-5/2002
Okayama Univ. of Sci. 1	OUS1	34°42'	133°56'	8	2	9/1996-6/2004
Okayama Univ. of Sci. 2	OUS2	34°42'	133°56'	8	2	3/2002-6/2004
Okayama Univ. of Sci. 3	OUS3	34°42'	133°56'	5	2	12/2002-6/2004
Okayama Univ.	OU	34°41'	133°55'	8	2	9/1996-6/2004

2. Experiments

LAAS group have been operating 9 compact EAS array at 6 observatories in Japan, that is typically composed of five to eight sets of 0.25 m^2 scintillation counter arranged over a few hundreds of square meters [3, 4, 5]. EAS data used in this analysis, are collected at seven stations of the LAAS group. Some profiles of those stations are summarized in table 1.

The energy response functions of the typical LAAS array were numerically calculated by using the parameterized formulae of the longitudinal development and the lateral distribution of EAS [6, 7], of which FWHM ranges from 50 TeV to 1 PeV.

The event rates of EASs registered at each EAS array have been corrected by the effect of varying both barometric and temperature. To calculate these coefficients, data sets are analyzed within 5 hPa and 5 degree interval. These coefficients were used to correct the atmospheric effects in the harmonic analysis described in the next section.

3. Results and Discussions

The conventional harmonic analysis method were applied on LAAS data sets. The data of HU, KU and NUI were combined in the analysis due to their small statistics. The analyzed data sets were assembled so that the exposure is uniform over the entire LST range. The amplitude δ of the cosmic ray anisotropy is very small such as $\delta \sim 10^{-4}$ to 10^{-3} and the statistical significances of estimates from the harmonic analysis should be tested by using the Z_2^2 statistic [8],

The amplitudes and phases of the first and second harmonics obtained from the harmonic analysis of the LAAS data are summarized in table 2 as well as the chance probabilities calculated from Z_2^2 statistics. For the first harmonics, the amplitude obtained is shown in Fig. 1 with other results reported by various experiments.

Three-dimensional models of diffusive propagation of relativistic charged particles in the Galaxy have been proposed to explain cosmic ray anisotropy. Our results obtained by the harmonic analysis were compared with the analytical solution proposed by Shibata [1]. Taking account of primary energy dependence of effective area of EAS arrays numerically, we simulated the following equations,

$$E(\delta_r(E,\alpha)) = \frac{\int_0^\infty \delta_r(E,\alpha)\frac{dN(E)}{dE}A(E)dE}{\int_0^\infty \frac{dN(E)}{dE}A(E)dE}$$

where $\delta_r(E,\alpha), N(E)$ and $A(E)$ correspond to longitudinal anisotropies, primary cosmic ray flux and effec-

Table 2. Anisotropy results for the LAAS arrays. The result from the HU, KU and NUI combined data is shown in the row labeled "others".

Station	First Harmonic		Second Harmonic		analyzed events	chance probability
	Amplitude (%)	Phase (hour)	Amplitude (%)	Phase (hour)		
OU	0.25 ± 0.076	3.2 ± 1.2	0.12 ± 0.076	4.7 ± 2.4	3487676	1.1×10^{-2}
OUS1	0.24 ± 0.077	0.3 ± 1.2	0.15 ± 0.077	8.3 ± 2.0	3348469	1.0×10^{-2}
OUS2	0.26 ± 0.093	22.0 ± 1.4	0.08 ± 0.093	17.5 ± 4.4	2317034	7.2×10^{-2}
OUS3	0.54 ± 0.12	1.0 ± 0.8	0.12 ± 0.12	14.3 ± 3.7	1506367	1.3×10^{-4}
others	0.21 ± 0.10	20.6 ± 1.9	0.07 ± 0.10	9.4 ± 5.6	1835664	3.5×10^{-1}
Total	0.23 ± 0.040	0.4 ± 0.7	0.06 ± 0.040	7.5 ± 2.6	12494910	2.7×10^{-8}

tive area of LAAS arrays with primary energy E and exponent α of rigidity dependent diffusion coefficient ($D(R) = D_0 v R^{\alpha}$), respectively. The numerical results for LAAS arrays are also shown in Fig. 1, and the exponent value of rigidity dependent diffusion coefficient was obtained as $\alpha = 0.339 \pm 0.014$.
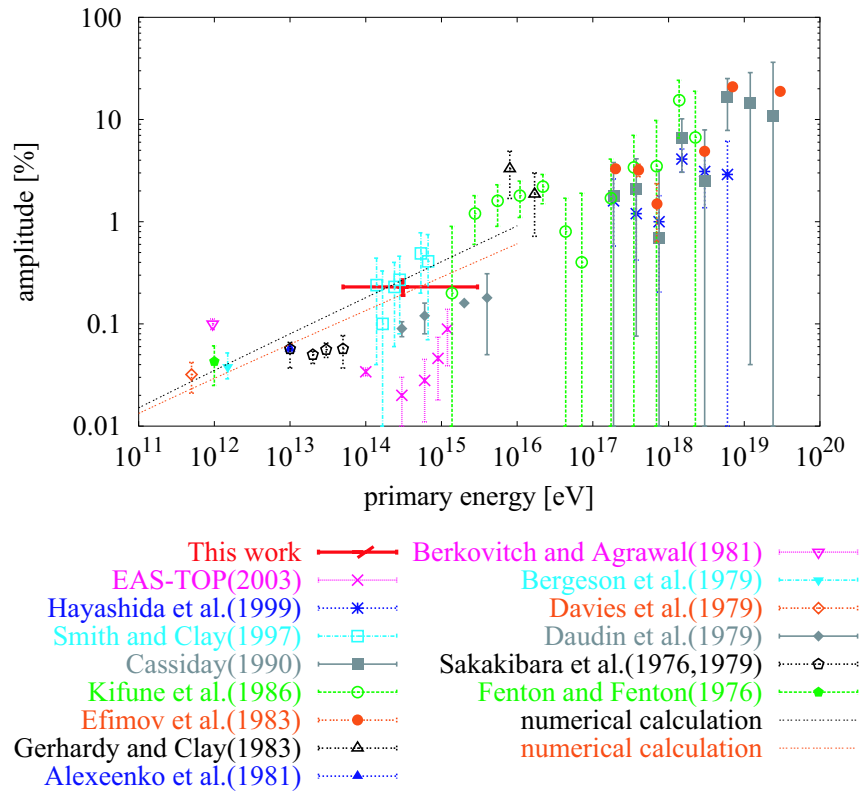
Figure 1. First harmonics amplitude and phase dependence of primary energy.

4. Conclusion

The harmonic analysis is performed for the 1.2×10^7 of EAS data obtained at latitudes between 34°41' and 40°35'. The FWHM energy range of the analyzed EAS is from 50 TeV to 1 PeV. The obtained amplitude (phase) of the first and second harmonics are $0.23 \pm 0.04\%$ (0.4 ± 0.7 hr) and $0.06 \pm 0.04\%$ (7.5 ± 2.6 hr) respectively. The chance probability of our result is estimated as 2.7×10^{-8}.

The amplitude and phase of the first harmonic are compared with those obtained by other groups [9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19] in Fig. 1. It can be seen that the amplitudes reported by other groups for less (larger) than 1 PeV are somewhat smaller (larger) than our result and the phase of our result is consistent with other results for less than 100 TeV. The exponent value of rigidity dependent diffusion coefficient are estimated as $\alpha = 0.339 \pm 0.014$.

Acknowledgements

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