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Enhancement of primary cosmic rays > 6 TeV observed with an Air Shower Array at Mt. Chacaltaya

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Abstract. We present a study of the distribution of air shower arrival directions observed at Mount Chacaltaya. The anisotropy is examined in galactic coordinates. The present result shows that there is a galactic plane enhancement of cosmic rays, which is due to nuclear components of primary cosmic rays rather than gamma-ray primaries.

1 Introduction

Measurements of the cosmic ray anisotropy are very important for the study of the origin of cosmic rays and their propagation in the galaxy. BASJE group have reported an enhancement of cosmic rays in the galactic plane at l from $220°$ to $340°$ band (Kakimoto et al. (1999)). Here we present a high statistical investigation of cosmic ray anisotropy using updated data. The distribution of observed air shower arrival directions and a deviation from the expected distribution on the assumption of the isotropic sky is examined in the galactic coordinate system.

2 BASJE MAS Array and the Observed Data

We have installed the MAS (Minimum Air Shower) array at Mount Chacaltaya ($16°20'52''$S, $68°07'57''$W) in Bolivia. Since the array is located at high altitude (5200 m above sea level, $550 \mathrm{g/cm^2}$ atmospheric depth), it is possible to detect air showers at early stages in their longitudinal developments. This results in achievement of a lower threshold primary energy of cosmic rays and a high statistical experiment. We also stress that an observable area of the galaxy in the southern hemisphere is larger than that in the northern hemisphere.

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The MAS array is comprised of 58 fast-timing detectors and 59 particle density detectors arranged in $30\mathrm{m} \times 30\mathrm{m}$ area (Fig.1). A muon detector of $60\mathrm{m}^2$ area is installed at the center of the array (not shown in Fig.1). This is a matrix of 3×5 shielded scintillation detectors of $4\mathrm{m}^2$. The threshold energy of the muon detector is ~ 600 MeV for vertically incident muons. Details of these detectors are described in Kakimoto et al. (1996). The array is triggered with the four-fold coincidence of the L4, L5, L8, L9 detectors. The threshold level of each detector is set to be one particle hit. The threshold primary energy of cosmic ray showers under this condition is ~ 6 TeV and the median energy is ~ 30 TeV. The triggering frequency is ~ 8 Hz. The accuracy in the arrival direction determination is $\sim 2.5°$ and $1.1°$ for cosmic rays of 6 and 30 TeV, respectively.

The MAS array has been operated from May 1998 to Mar. 2001. There are some interruptions in this period because of the detector calibrations and improvements of the data acquisition system.

For further analysis the data are selected as follows. First, we check the uniformity of observation time, and 335 sidereal days without dead time and trigger frequency variation are sampled. Second, events of zenith angles $\theta < 60°$ and $\chi^2 < 3.0$ for arrival direction and shower size fitting are selected. The total number of selected events amounts to 1.4×10^8 (Table 1). Anisotropy analyses are carried out for

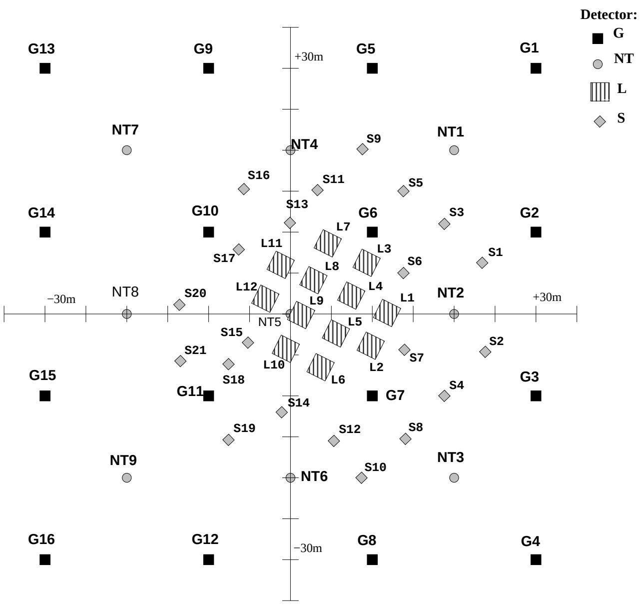

Fig. 1. The BASJE MAS array at Mount Chacaltaya

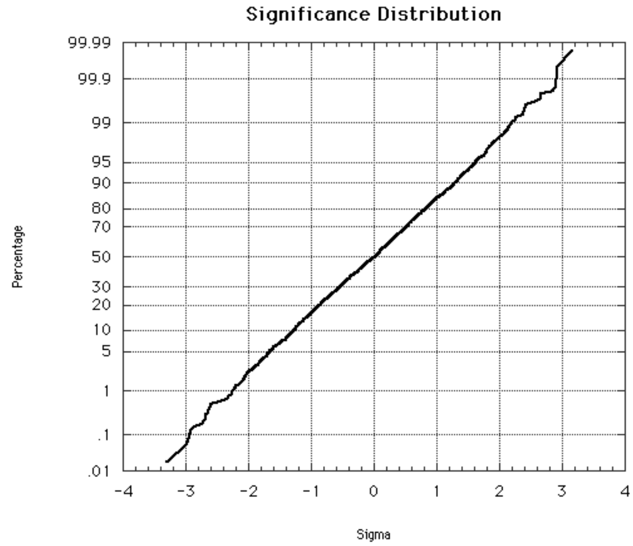

Fig. 2. Significance distribution of estimated isotropic background

four data groups: (a) all events, (b) $\log E[\mathrm{eV}] < 14.5$, (c) $\log E[\mathrm{eV}] \geq 14.5$, (d) muon-poor events.

3 Determination of the Expected Background

The distribution of arrival directions of observed air showers is analyzed in comparison with an expected distribution from an isotropic intensity of cosmic rays. It is crucial to estimate the expected background accurately.

First, we make a map of the number of events $N(h, \delta)$ of each $2^\circ \times 2^\circ$ cell using the all observed data. Where δ is declination and h is hour angle, that is local sidereal time (LST)$-$ right ascension α. Second, the number of observed events N_i is counted for each 2° LST interval. The map $N(h, \delta)$ reflects the geometrical bias of our array, while the number of events N_i reflects the daily effects on the triggering frequency. The expected number of events $N_i(\alpha, \delta)$ from the direction of the (α, δ) cell of $4^\circ \times 4^\circ$ in the time interval of LST bin i is calculated using $N(h, \delta)$ and N_i. This procedure is carried out for all the LST bins, and the distribution $N_{\mathrm{exp}}(\alpha, \delta) = \sum_i N_i(\alpha, \delta)$ gives the expected number of events from the direction of (α, δ).

We examine the following significance distribution to check the validity of our background estimation,

$$\mathrm{Significance}(\alpha, \delta) = \frac{N_{\mathrm{obs}}(\alpha, \delta) - N_{\mathrm{exp}}(\alpha, \delta)}{\sqrt{N_{\mathrm{exp}}(\alpha, \delta)}} \tag{1}$$

If the expected background is estimated properly, the significance distribution should be coincide with Gaussian distribution. Fig.2 shows the probability distribution of the significance defined by the equation (1). The result shows that the expected background is determined in accuracy of 0.1%.

Table 1. Observed data

Observation period	Good Sidereal Days	Selected Events
1998 - 1999	214	9.5×10^7
2000 - 2001	121	4.3×10^7
Total	335	1.4×10^8

4 Results

4.1 Analysis for Whole Sky

The cosmic ray anisotropy is studied in the galactic coordinate system (l, b). In Fig.3 the ratio of the number of observed events to that of expected events $N_{\mathrm{obs}}/N_{\mathrm{exp}}$ is plotted as a function of the galactic latitude b. It is found that at low latitude region the observed numbers of events are more than the expected numbers on the assumption of isotropic background.Our result is analyzed with the model given by Wdowczyk and Wolfendale (1984) and Chi et al. (1992), that is

$$\frac{N_{\mathrm{obs}}(b)}{N_{\mathrm{exp}}(b)} = (1 - f_{\mathrm{e}}) + 1.402 f_{\mathrm{e}} \exp(-b^2) \tag{2}$$

where f_{e} is so called as the galactic plane enhancement factor. For an isotropic distribution of cosmic rays, $f_{\mathrm{e}} = 0$. Our data is well fitted with the equation (2) of $f_{\mathrm{e}} = 1.59 \times 10^{-3}$. Positive value of f_{e} suggests an enhancement of cosmic rays coming from the direction of the galactic plane.

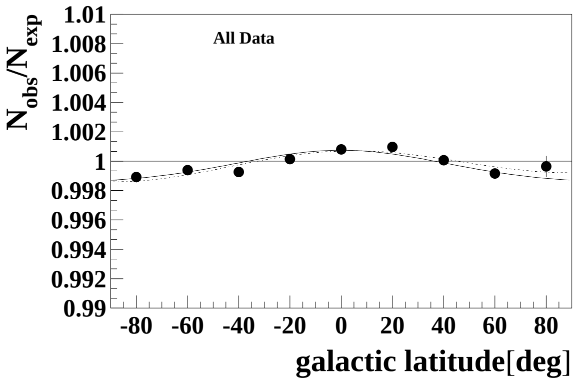

Fig. 3. $N_{\rm obs}/N_{\rm exp}$ variation with galactic latitude b. The solid curve shown is the best fit to the equation (2). The dashed curve corresponds to the equation (3).

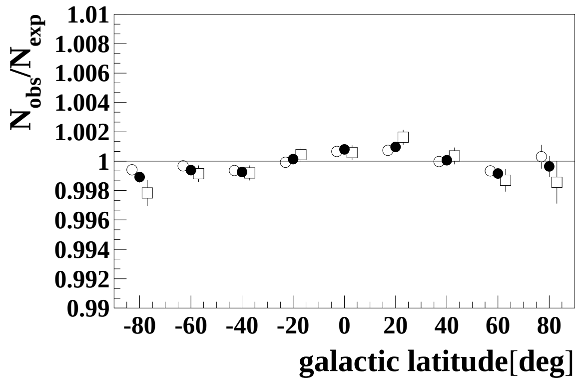

Fig. 4. $N_{\rm obs}/N_{\rm exp}$ plots for different energy bins; Closed circle: (a) all data, Open circle: (b) $\log E_{\rm eV} < 14.5$, Open square: (c) $\log E_{\rm eV} \geq 14.5$. The points of the data groups (b) and (c) are slightly shifted in horizontal axis b for visual purpose.

Another method suggested by Bird et al. (1993) is also employed. This can be written in the form,

$$\frac{N_{\rm obs}(b)}{N_{\rm exp}(b)} = c_0 + c_1 P_1(x) + c_2 P_2(x) \qquad (3)$$

where $x \equiv \sin b$ and P_1 and P_2 are the Legendre functions of order 1 and 2. In this analysis, a negative value of $c_2 = -1.19 \times 10^{-3}$ is found. This also supports the galactic plane enhancement. A non-zero value of $c_1 = 3.10 \times 10^{-4}$ suggests that there is a small south-north gradient in galactic latitude. Obviously, in Fig.3 one can see an asymmetry with respect to the galactic plane, $b = 0$. The values of model fits are listed in Table 2.

In Fig.4 we plot $N_{\rm obs}/N_{\rm exp}$ for the two energy bins. $N_{\rm exp}$ is determined independently for each data groups. Although no strong dependence of the anisotropy on primary energies is found, $f_{\rm e}$ value for the data group of higher energies is larger than that of the lower energies (see Table 2).

4.2 Analysis in Galactic Longitude Band

The sky is divided into four parts of $90°$ band of the galactic longitude, centered at (I) $l = 0°$, (II) $90°$, (III) $180°$ and (IV) $270°$. Fig.5 shows the results for each longitude band. All the f_e values fitted to the equation (2) are positive (see Table 3), but those of the region (II) and (III) might not be significant.

4.3 Muon-Poor Events

Since air showers initiated by primary gamma-rays contain less muons compared to those produced by primary nuclei, the muon-poor selection relatively enhances gamma-ray events in observed air showers. Muon-poor condition is taken to be a event with no signals in 15 shielded detectors. Fig.6 shows the result for the muon-poor group. No significant excess is found. The fitted values to the equations (2) and (3) are also listed in Table 2.

5 Conclusion and Discussion

Our result shows that the arrival direction distribution of cosmic rays is highly isotropic, however, the positive values of $f_{\rm e}$ or the negative values of c_2 indicate a galactic plane enhancement of cosmic rays with primary energies > 6 TeV. This is the first result of a significant anisotropy in this energy range. No significant excess is found in analysis for muon-poor showers. Thus, at present we cannot conclude that the enhancement is due to primary gamma-rays.

There is an excess in $|b| < 30°$ at the longitude band (I), and a deficit in the opposite direction (III). One tempting explanation is that there is a gradient of cosmic ray distribution. Webber et al. (1992) calculated the radial distribution of cos-

Table 2. Results of model fits in galactic latitude anisotropy

Data Group	$f_{\rm e}$ $(\times 10^3)$	$c_1(\times 10^4)$	$c_2(\times 10^3)$
(a) all	1.59 ± 0.22	3.10 ± 1.48	-1.19 ± 0.19
(b) $\log E < 14.5$	0.95 ± 0.25	1.52 ± 1.71	-0.80 ± 0.21
(c) $\log E \geq 14.5$	2.39 ± 0.54	6.14 ± 3.38	-1.75 ± 0.44
(d) muon-poor	0.35 ± 0.64	-2.12 ± 4.12	-0.28 ± 0.53

Table 3. The values of model fits for each galactic longitude region

Region	$f_{\rm e}$ $(\times 10^3)$	$c_1(\times 10^4)$	$c_2(\times 10^3)$
(I) $l = 0°$	2.17 ± 0.39	5.04 ± 2.54	-1.70 ± 0.33
(II) $l = 90°$	0.76 ± 0.65	-3.14 ± 8.64	-0.83 ± 0.73
(III) $l = 180°$	1.18 ± 0.48	1.42 ± 4.48	-0.89 ± 0.47
(IV) $l = 270°$	1.36 ± 0.41	1.60 ± 2.65	-1.12 ± 0.34

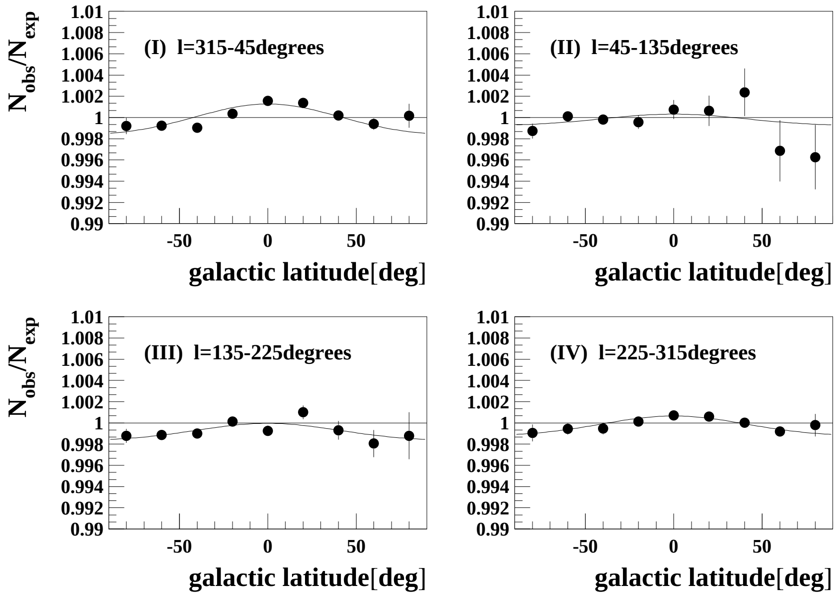

Fig. 5. $N_{\rm obs}/N_{\rm exp}$ plot for four galactic longitude region. The curves shown are the best fits to the equation (2).

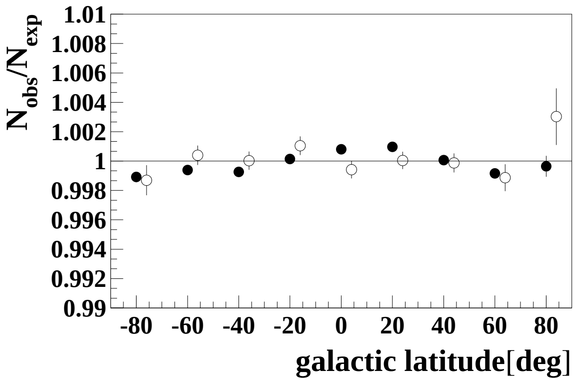

Fig. 6. $N_{\rm obs}/N_{\rm exp}$ plots for muon-poor events (open circle). The result for all data is also shown (closed circle).

mic rays derived from some models of supernova distribution. Such a radial gradient in cosmic ray distribution might yield this type of anisotropy.

An enhancement is also found in the longitude band (IV). This region contains some candidates of cosmic ray sources. Johnson (1993) discussed the cosmic ray intensity from the Geminga and predicted the amplitude of anisotropy of order of 10^{-3}. Senda (1997) calculated cosmic ray flux from the Vela SNR and predicted an anisotropy of 10^{-3}. Our result is in agreement with these predictions, but discussion is still open.

It is expected that the Compton-Getting effect may cause 10^{-3} anisotropy toward $l = 90°$ due to the rotation of the solar system with the velocity of 200 km/s around the galactic center. Our results for the longitude bands (II) and (IV) don't support this picture. The "stationary frame" of the cosmic rays might be corotating with the galaxy.

Ptuskin et al. (1993) predicted 10^{-3} anisotropy directed along the local magnetic field in view of diffusive propagation of cosmic rays in the galactic magnetic field. It has been believed that the cross-field diffusion of cosmic rays is suppressed by $\sim 10^{-1}$ compared to the parallel diffusion. Our result shows an excess in both directions (I) and (IV), and gives some constraints on models of cosmic ray propagation in the galaxy. This work is still in progress.

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