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Anisotropy of cosmic-ray arrival directions at 10^{18}eV observed by AGASA.

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Abstract. The anisotropy of the arrival directions of cosmic rays at 10^{18}eV was studied using AGASA (Akeno Giant Air Shower Array) data. We have found a significant excess of events from the direction near the galactic center and deficit from near the anti-galactic center. This global anisotropy pattern of cosmic ray arrival direction distribution can be interpreted as cosmic ray diffusive flow from the direction of the galactic center. A search for point sources was also carried out at the same energy range. Though even the most significant direction (the Cygnus region) can be explained by statistical deviation, it should be noted that the direction is nearly coincident with one of the observed clusters of 10^{19}eV events.

1 Introduction

The cosmic rays with energies below the knee ($\sim 5\times10^{15}$eV) can be explained by shock acceleration in super nova remnants, however, above the knee their origin is not clear in spite of considerable experimental efforts. Experimental results and theoretical discussion suggest that the ankle($\sim 5 \times 10^{18}$eV) is the transition from galactic cosmic rays to extra galactic ones. Above the knee, study of anisotropy plays an important role in obtaining information about cosmic ray origin as well as the study of chemical composition.

In previous papers (N.Hayashida et al. , 1999a,b), we have reported significant anisotropy of cosmic ray arrival directions at 10^{18}eV. We found an excess of events toward the Galactic center and a deficit in the anti-galactic center direction. This global anisotropy pattern is correlated with galactic structure and considered as a good evidence for the existence of galactic cosmic rays up to 10^{18}eV. In this report, we have carried out a similar analysis with a new data set (increased in size by 25%) and discuss the nature of this anisotropy.

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2 Experiment

The Akeno Observatory is located about 150km west of Tokyo, its geographical coordinates are $138°30'$E and $35°47'$N. AGASA (Akeno Giant Air Shower Array) consists of 111 scintillation detectors of $2.2m^2$ area each and 27 muon detectors of various sizes and has an effective area of $100km^2$. A20 is a prototype detector system of AGASA, operated from 1984 to 1990, and became a part of AGASA after 1990. A detailed description of AGASA can be found elsewhere (M.Teshima et al. , 1986; N.Chiba et al. , 1992; H.Ohoka et al. , 1997). In this analysis, we have used 284,000 events above 10^{17}eV from A20 and AGASA after the usual event selections; number of hit detectors ($N_{hit} \geq 6$), χ-square cut for arrival direction fit, core location fit($\chi^2/dof \leq 5.0$), and zenith angle of less than 60 degrees.

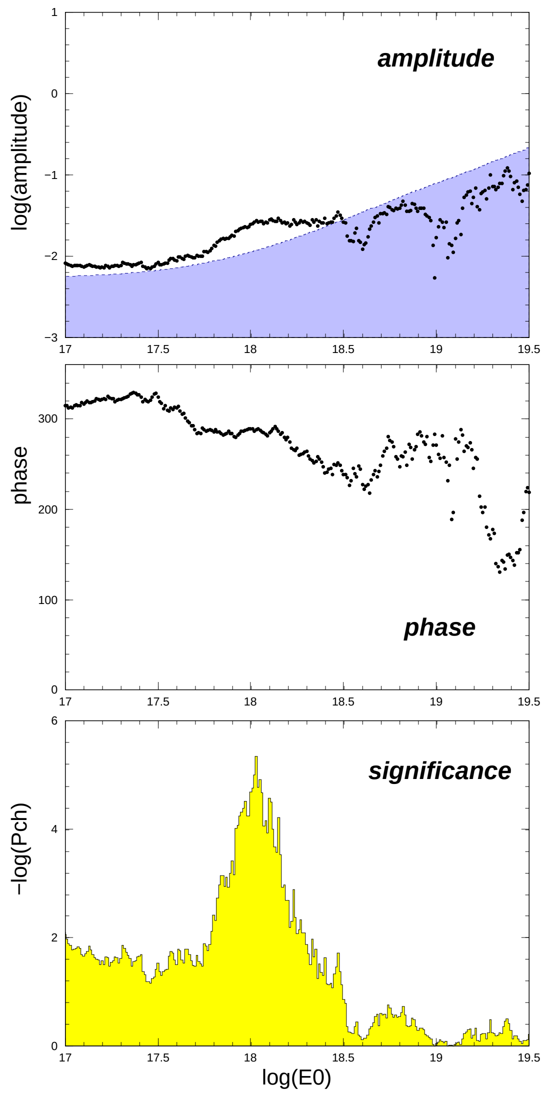

Fig. 1. The first harmonic analysis in the right ascension direction. **Top:** The amplitude of first harmonics is shown as a function of threshold energy. The shaded region represents statistical fluctuation with 90 % C.L.. **Middle:** The direction of maximum amplitude in the right ascension. **Bottom:** The statistical significance of the first harmonic is shown as a function of threshold energy. The chance probability at $10^{18}eV$ threshold energy is 10^{-5}.

The detector has been operated very stably and actual live time is greater than 95% of calendar time. The main dead time is due to power failures, optical fiber cable movement due to road works, and network trouble.

The sky coverage in right ascension is very uniform and the effective variation is less than 0.4%.

3 Results

3.1 Harmonic analysis

The traditional method to find anisotropy in an air shower experiment is a harmonic analysis in the right ascension direction. This is because the exposure in right ascension is essentially very uniform for case of a stable ground air shower detector like AGASA. The anisotropy amplitude of 4.0 ± 0.8 % in the first harmonic at 10^{18}eV is obtained as shown in figure 1. The harmonic analysis was carried out at each energy threshold, using all events above that energy. In the top panel of figure 1, dots represent the amplitude and the shaded region represents the statistical fluctuation with 90% C.L. at each energy threshold. We can see the harmonic amplitude exceeds the statistical fluctuation at 10^{18}eV threshold energy. The chance probability to obtain an amplitude of 4.0% by the random fluctuations from a uniform distribution is evaluated as 10^{-5} as shown in the bottom panel. The phase (the direction of maximum amplitude) is $280°$ in right ascension. This result is essentially the same as previous results (N.Hayashida et al. , 1999a,b).

3.2 Two dimensional analysis at 10^{18}eV

In order to get a clearer view, we have calculated the deviation of event density with 20 degrees radius aperture in the equatorial coordinate as shown in figure 2. The exposure in the right ascension direction is uniform with a level of 0.4% variation, however, the declination exposure depends on the zenith angle distribution of observed events and the viewing solid angle of the sky from Akeno observatory. The expected event density can be calculated in each one degree declination band by simply taking an average in the right ascension direction. Then, the deviation can be derived as $(N_{obs} - N_{exp})/\sqrt{N_{exp}}$ in each 1 degree grid on the equatorial coordinate. Since we have chosen events with zenith angles less than $60°$ in this analysis, we cannot see the region below $-25°$ declination.

The excess near the Galactic center is clearly seen with statistical significance of $\geq 4\sigma$. The deficit near the anti-galactic center is also seen with 4σ. However, the excess at the Spiral-In direction decreases in the present work compared with previous reports.

3.3 Wide-angle cosmic ray flow or Point sources?

Now the most important question is whether the excess from the galactic center direction is due to a wide-angle cosmic ray flow or due to multiple point sources.

The global anisotropy pattern could be interpreted as a cosmic ray flow from the galactic center direction. We have examined the event distribution as a function of $cos(\theta_{G.C.})$ as shown in figure 3. Here $\theta_{G.C.}$ represents the angle from the galactic center. If the cosmic rays follow a diffusion process from a major source, we expect their angular distribution from the source direction will follow $1 + \alpha cos(\theta)$ (see, for example, G.Farrar et al. (2001)).

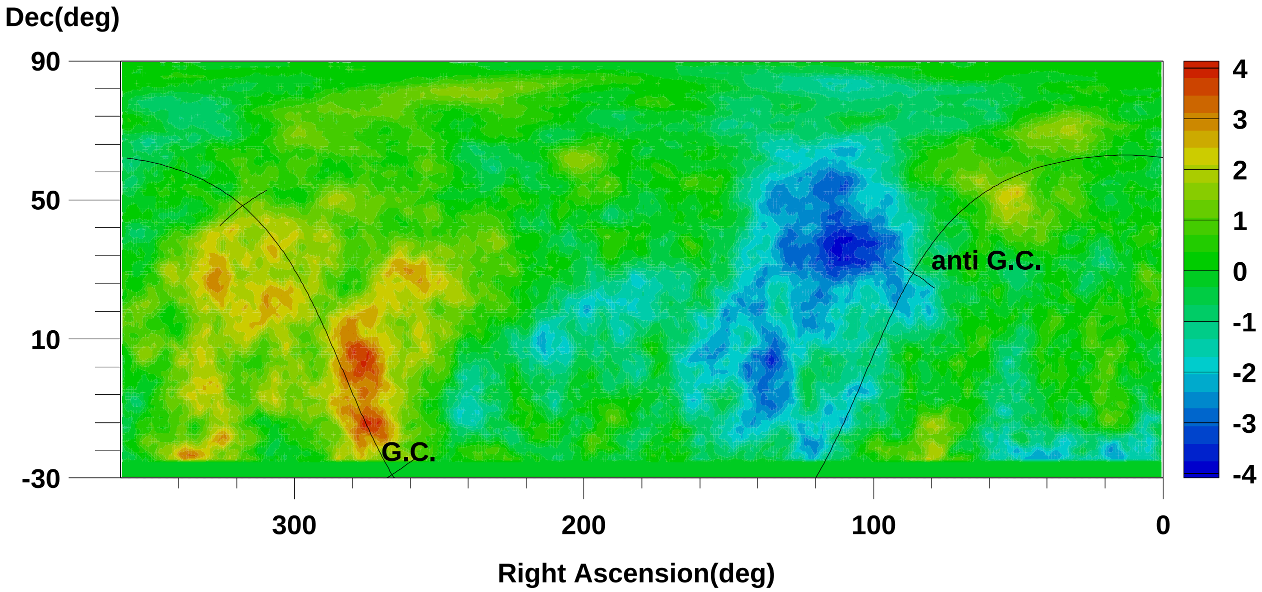

Fig. 2. The significance of event density in equatorial coordinates. The statistical significance of deviation is evaluated for each 1° grid with the aperture of 20 degrees radius. The excess and deficit can be seen with 4 σ statistical significance near the Galactic center and anti-galactic center, respectively.

We can fit this distribution with $\alpha = 0.04$. The event density distribution can be interpreted as cosmic ray flow from the galactic center direction, however, the first bin $cos(\theta_{G.C.}) = 0.9 - 1.0$ shows a large excess but with poor statistics and we cannot exclude the existence of point sources in the direction of the galactic center as reported by J. A. Bellido et al. (2001).

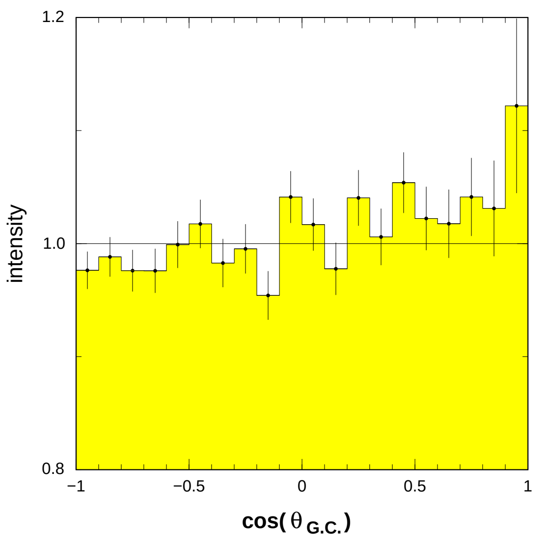

Fig. 3. Event density as a function of $cos(\theta_{G.C.})$. The distribution is consistent with the assumption of cosmic ray diffusive flow from galactic center direction.

We have carried out a search for point sources using a similar procedure, but a smaller aperture of 6 degree radius. This corresponds to the angular resolution of AGASA at 10^{18}eV. Figure 4 shows the deviation of number of events in equatorial coordinates. The significance distribution can be explained statistically. The largest deviation(3.8σ) was observed at the coordinate $\alpha = 313^\circ, \delta = 32$. Note that this position coincides with the direction of the cluster BC1 at an energy of 10^{19}eV reported by M.Takeda et al., (1999). A detailed study is in progress.

In order to test different kinds of source distributions (for example, many weak point sources), the auto-correlation was examined for the arrival direction distribution of cosmic rays between 10^{18}eV and 3×10^{18}eV. As reported by P. G. Tinyakov and I. I. Tkachev (2001), and by M.Takeda et al. (2001), this auto-correlation method was found to be very powerful for many faint point sources at the highest energies. Figure 5 shows the separation angle distribution between two arbitral events. We can not see any significant excess or peak around the AGASA angular resolution of $< 6^\circ$ region at this energy. If we assume the number of point sources N_s, we can estimate the upper bound of the flux from each source as $F_{u.l.} \sim 2.6/\sqrt{N_s} \times 10^{-17} cm^{-2} s^{-1}$ at 10^{18}eV. In case of $N_s = 1$, this flux limit corresponds to the value about three times larger than the flux reported for Cygnux X-3 by M.Teshima et al. (1990); G.L.Cassiday et al. (1988), and the flux reported by J. A. Bellido et al. (2001). In other word, the number of point sources in the northern hemisphere is less than 1, 10, 100 and 1000 for the sources with the intensities of $3\times, 1\times, 0.3\times$ and $0.1\times$ Cygnus X-3 or a G.C. source.

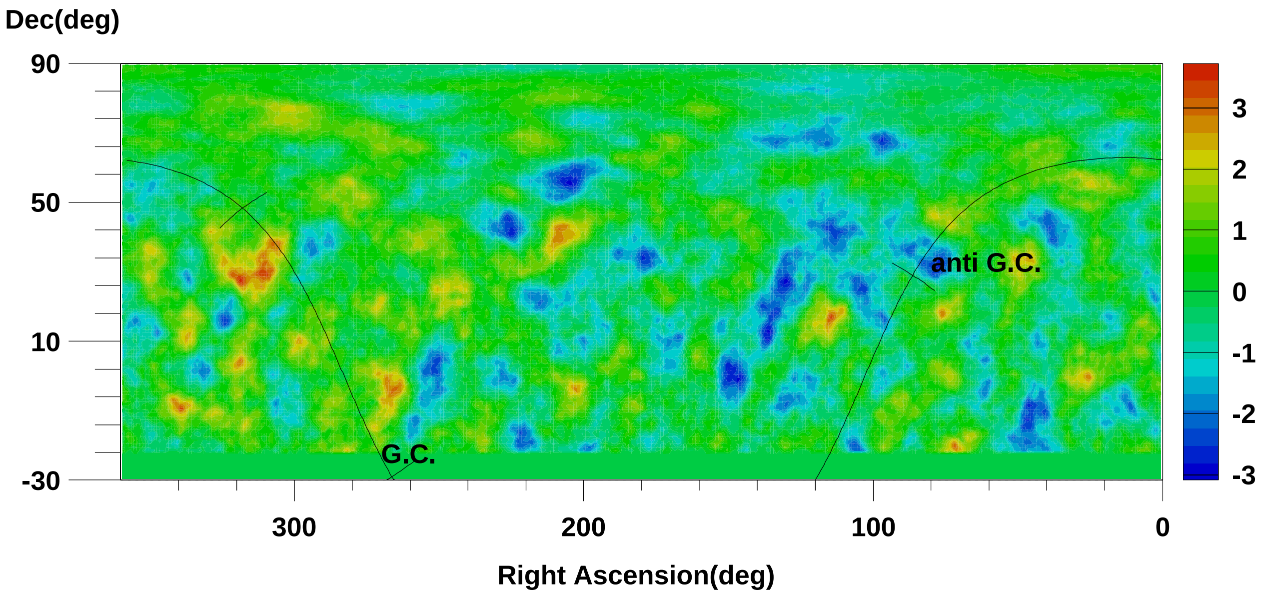

Fig. 4. The deviation of event density in equatorial coordinates with an aperture of 6° radius. This test was carried out to search for point sources at the same energy range as figure 1. There are no significant deviations.

4 Conclusion

A significant anisotropy of $\sim 4\%$ was found at 10^{18}eV. This anisotropy could be interpreted as a diffusive cosmic ray flow from the galactic center direction. The event density as a function of angle from galactic center seems to be fit well with the dipole angular distribution as expected by diffusion model. This is a clear evidence for the existence of galactic cosmic rays up to 10^{18}eV. To explain the anisotropy amplitude, we probably require light components in the chemical composition, for example, protons, heliums with significant portion at this energy.

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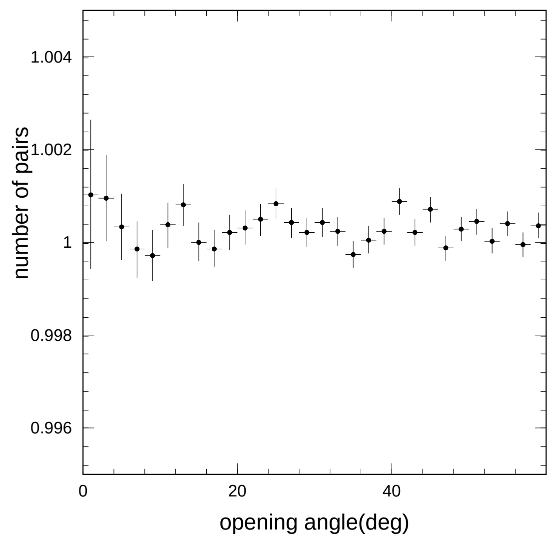

Fig. 5. Auto-correlation of cosmic ray arrival direction at 10^{18}eV. This test is sensitive to source distribution of many weak point sources. We could not see any significant deviation around the AGASA angular resolution of 6° at 10^{18}eV.