Small-scale Anisotropy of Cosmic Rays above 10^{19}eV observed with AGASA

The AGASA Collaboration

Abstract

Arrival direction distribution of extremely high energy cosmic rays observed with the Akeno Giant Air Shower Array (AGASA) is examined. 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 separation angle of 2.5° and the probability of observing these clusters by a chance coincidence under an isotropic distribution is smaller than 1 %. Especially the triplet is observed against expected 0.05 events. Arrival direction distribution of seven 10^{20}eV cosmic rays is consistent with that of lower energy cosmic rays and is uniform. Three of seven are members of doublets above about 4×10^{19}eV.

1 Introduction

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, their arrival directions may be correlated with nearby luminous matter distribution if they are of astrophysical source origin such as hot spots of radio galaxies, active galactic nuclei, accretion flow to a cluster of galaxies, relativistic shocks in gamma-ray bursts, and so on. There is another possibility that most energetic cosmic rays are generated through decay of supermassive “X” particles related to topological defects. In this case, arrival directions of most energetic cosmic rays are not necessarily associated with luminous matters.

Here, we search for the small-scale anisotropy above 10^{19}eV using the data set of AGASA until March 1999, including the old data set of the Akeno 20 km^2 array (A20) before 1990.

2 Experiment

The Akeno Observatory is situated at 138° 30′ E and 35° 47′ N. AGASA consists of 111 surface detectors deployed over an area of about 100 km^2, 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 become a part of AGASA after 1990. The details of the AGASA instruments have been described in the above references.

The accuracy on determination of shower parameters are evaluated through the analysis of a large number of artificial events. These artificial events are generated by taking into account air shower features and fluctuation determined experimentally. Figure 1 shows the accuracy on 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 data are plotted. By analyzing artificial events with the same algorithm used above, the accuracy on energy determination is estimated to be ± 30 % above 10^{19}eV.

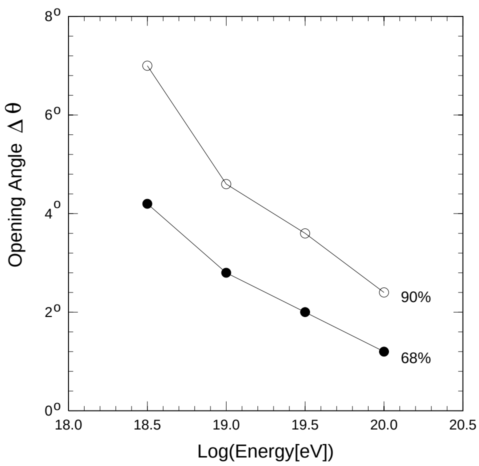

Figure 1: Accuracy on arrival direction determination. Closed and open circles are the opening angles encompassing 68 % and 90 % data, respectively.

3 Results

Figure 2 shows arrival directions of cosmic rays with energies above 10^{19}eV in the equatorial coordinates. Dots, green circles, and red squares represent cosmic rays with energies of $(1 - 4) \times 10^{19}$eV, $(4 - 10) \times 10^{19}$eV, and $\geq 10^{20}$eV, respectively. The shaded regions indicate the celestial regions excluded in this paper due to the zenith angle cut of $\leq 45°$. The galactic and supergalactic planes are drawn by the red and blue curves. "GC" designates the galactic center. The arrival direction distribution exhibits the small-scale anisotropy rather than the large-scale anisotropy. With the harmonic analysis and the galactic/supergalactic plane enhancement analysis, there is no statistically significant anisotropy.

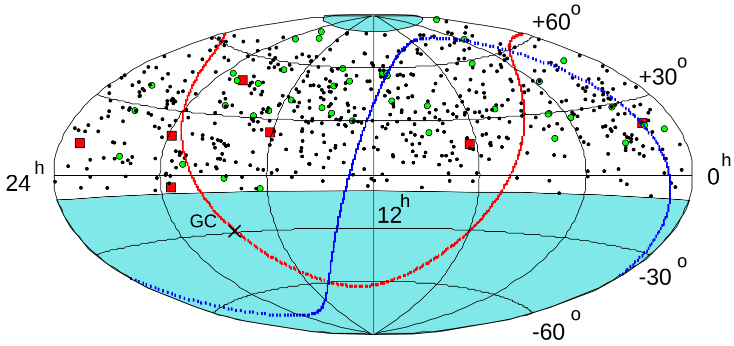

Figure 2: Arrival directions of cosmic rays with energies above 10^{19}eV in the (a) equatorial and (b) galactic coordinates. Dots, green circles, and red squares represent cosmic rays with energies of $(1 - 4) \times 10^{19}$eV, $(4 - 10) \times 10^{19}$eV, and $\geq 10^{20}$eV, respectively. The galactic and supergalactic planes are shown by the red and blue curves. "GC" designates the galactic center.

Figure 3 shows the contour maps of the cosmic-ray excess or deficit with respect to an isotropic distribution above 4×10^{19}eV. A bright (red) region indicates that the observed cosmic-ray intensity is larger than the expected intensity and a dark (blue) region shows a deficit region. For each observed event, we calculate a point spread function which 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 $1° \times 1°$ in the equatorial coordinates. At each cell, we sum up densities within 2.5° radius for Figure 3. These radii are obtained from $\sqrt{2} \times \Delta\theta$, and they would make excess regions clearer. The reference distribution is obtained from an isotropic distribution.

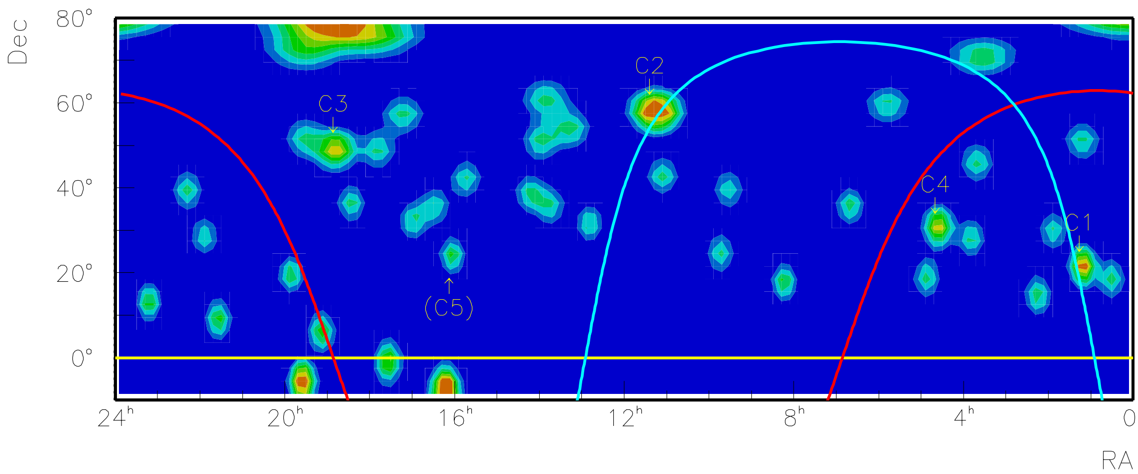

Figure 3: Significance map of cosmic-ray excess/deficit above 4×10^{19}eV. The red and blue curves indicate the galactic and supergalactic plane, respectively.

For small statistics of observed events, Figure 3 reflects the arrival directions of individual events (open squares and open circles in Figure 2). Four brighter regions (C1 – C4) in the middle declination are found in

Figure 3. The brightest peak is at the C2 cluster where three cosmic rays are observed against expected 0.05 events. The arrival directions (left) and arrival time – energy relation (right) for the C2 clusters are shown in Figure 4. A radius of each circle in the left panels corresponds to the logarithm of its energy, and open circles in the right panels denote members of the C2 clusters. Several lower energy cosmic rays are observed very close to the C2 cluster. 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 in our previous analysis (Hayashida et al., 1996). With the data sets of Haverah Park, Yakutsk, and Valcano Ranch (Uchihori et al., 1996) and AGASA, another triplet is found at the position of the C1 cluster within experimental error box on 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.

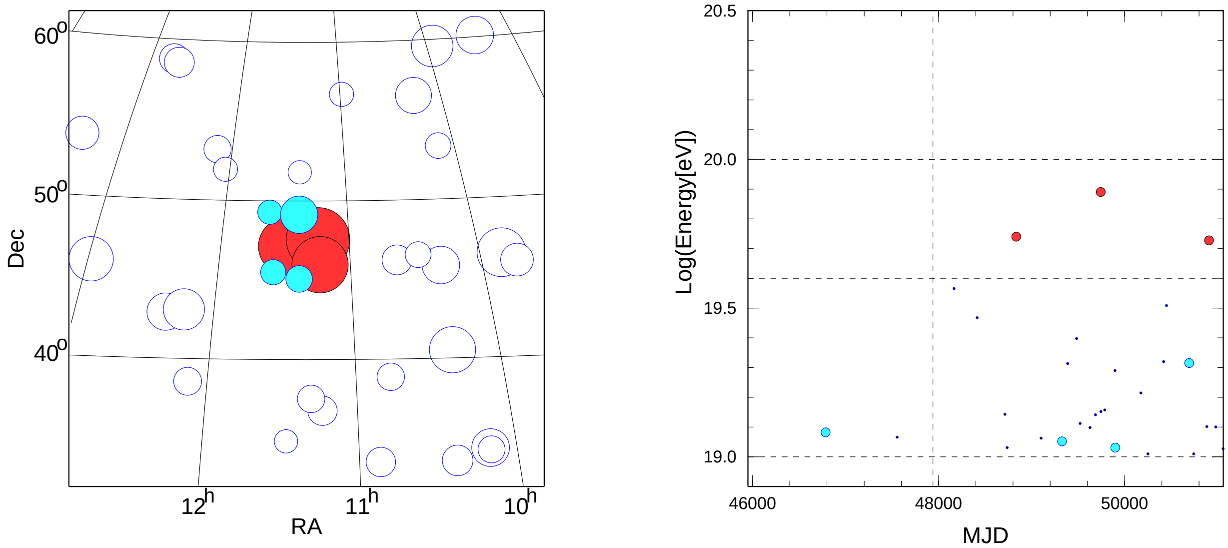

Figure 4: C2 cluster. (Left: Arrival directions of cosmic rays around the C2 cluster. Radius of each circle corresponds to $\log$(E[eV]). Right: Arrival time – energy relation. Open circles denote members of the C2 cluster and dots are cosmic rays near the C2 cluster. After the vertical dotted line, A20 is combined with AGASA.

Next, we estimate the chance probability of observing one triplet and three doublets from 50 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 total 50 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, 43 trials had equal or more doublets ($N_{th} = 2$) than the observed data set, so that $P_{ch} = 0.43\%$. And $P_{ch} = 0.95\%$ for triplets ($N_{th} = 3$). These chance probabilities are not sensitive to the threshold energy (now 4×10^{19}eV).

Table 1: Kolmogorov-Smirnov test for the celestial coordinates.

	KS-Probability		KS-Probability
Azimuth Angle (ϕ)	0.270	Zenith Angle (θ)	0.892
Right Ascension (α)	0.194	Declination (δ)	0.028
Ecliptic Longitude	0.082	Ecliptic Latitude	0.476
Galactic Longitude (l^G)	0.171	Galactic Latitute (b^G)	0.570
Supergalactic Longitude (l^{SG})	0.660	Supergalactic Latitude (b^{SG})	0.169
Opening Angle form GC (θ_{GC})	0.252		

In Figure 2, the declination of seven 10^{20}eV cosmic rays seem to concentrate around $\delta \simeq 20°$. To check whether these seven events distribute isotropically or not, we compare celestial distribution of seven 10^{20}eV events with that for events between 10^{19}eV and 10^{20}eV in ten different coordinates. The Kolmogorov-Smirnov (KS) test was used for avoiding any binning effect. The results are summarized in Table 1. The smallest KS probability in Table 1 is 2.5 % for the declination distribution; but this probability becomes larger using data set above 6.3×10^{19}eV. One interesting feature is that five 10^{20}eV cosmic rays come from south-west of the AGASA array, where the strength of the geomagnetic field component which is perpendicular to an air shower axis is larger than the other directions (Stanev and Vankov, 1997).

4 Summary

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 %. Especially the triplet is 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 most interesting; they are triplets found in the world data sets and are located near the supergalactic plane. One should wait for the further high-rate observation to distinguish whether the members of clusters come from a single source or different sources. 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 detailed study on arrival direction distribution using the data set until August 1998 will be printed in ApJ (Takeda et al., 1999).

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