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Clusters of cosmic rays above 10^{19}eV observed with AGASA

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Abstract. Arrival direction distribution of extremely high energy cosmic rays observed with the Akeno Giant Air Shower Array (AGASA) is studied. Some small-scale anisotropy – clustering of cosmic rays – is observed, while no statistically significant large-scale anisotropy is found on the celestial sphere. Above 4×10^{19}eV, there are one triplet and five doublets within a separation angle of 2.5° and these form a sharp peak at small separation angles in a self-correlation separation angle distribution. The separation angle scale is consistent with the angular resolution of the AGASA experiment. The clusters of AGASA events, therefore, favor point-sources of EHECRs. The observed energy spectrum of cosmic rays contributing to clusters is harder than that of those arriving from general directions.

1 Introduction

Since our recent publication (Takeda et al. , 1999), Tinyakov and Tkachev (2001) have introduced a good method of studying clusters of extremely high energy cosmic rays (EHECRs) using the AGASA and Yakutsk data sets, and have suggested that EHECRs favor compact sources. Almost events above 4×10^{19}eV come from the AGASA data set. Using the updated AGASA data, we have examined clusters of EHECRs and investigated their features.

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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 an AGASA detector system, operated as a prototype from 1984 to 1990 (Teshima et al. , 1986), and as an integral part of AGASA since then. The details of the AGASA instrumentation has been described in the above references (Teshima et al. , 1986; Chiba et al. , 1992; Ohoka et al. , 1997). In this analysis, we have selected events with zenith angles smaller than 45° and with core locations inside the array area. We observed 775, 59, and 8 events with energies above 10^{19}eV, 4×10^{19}eV, and 10^{20}eV, respectively. Above 4×10^{19}eV, two more doublets were detected in the updated data set. The number of clusters appears to increase steadily with AGASA exposure.

The accuracy of determination of shower parameters was evaluated through the analysis of a large number of artificial events. These artificial events were generated taking into account experimentally determined air shower features and fluctuations. The accuracy of arrival direction determination The results appeared in our recent publications (Takeda et al. , 1998, 1999). The accuracy of energy determination is estimated to be ± 30 % above 10^{19}eV. Of artificial events above 10^{19}eV (4×10^{19}eV), 68 % have better accuracy in arrival directions determination than 2.8° (1.8°).

3 Results

Figure 1 shows arrival directions of cosmic rays with energies above 4×10^{19}eV in Equatorial coordinates. Circles and 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. Area in this figure corresponds to the AGASA exposure. The central region with a heavy shade and the outside region correspond to the celestial regions excluded in this paper due to the zenith angle cutoff of $\leq 45°$. Details of the cosmic rays above 4×10^{19}eV are available on our web page [1].

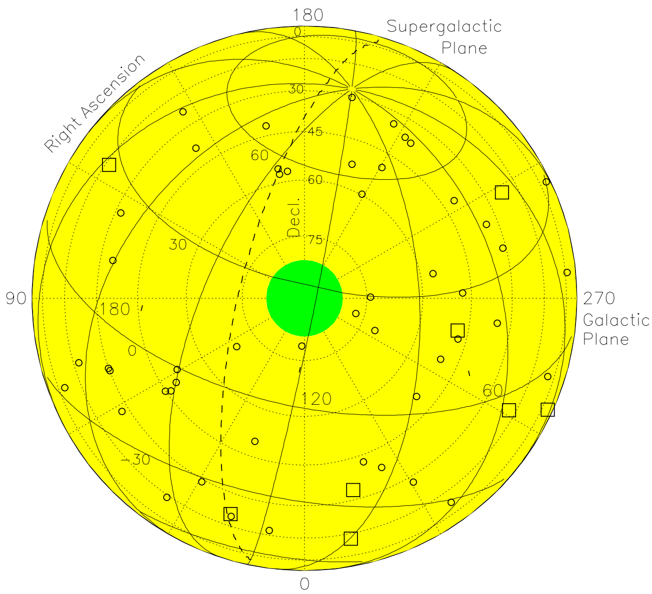

Fig. 1. Arrival directions of cosmic rays with energies above 4×10^{19}eV. Circles and squares represent cosmic rays with energies of (4–10) $\times 10^{19}$eV and $\geq 10^{20}$eV, respectively. Area in this figure corresponds to the AGASA exposure. The central region with a heavy shade and the outside region correspond to the celestial regions excluded in this paper due to the zenith angle cutoff of $\leq 45°$. Solid curves show Galactic coordinates, and dotted curves indicate equatorial coordinates.

First of all, we follow the same cluster analysis procedure described in §3.4 of Takeda et al. (1999). A cluster of cosmic rays is defined as follows: (i) Define the *i*-th event; (ii) Count the number of events within a circle of radius 2.5° centered on the arrival direction of the *i*-th event; (iii) If this number of events exceeds a certain threshold value N_{th}, the *i*-th event is counted as a cluster. This sequence was repeated for all 59 events above 4×10^{19}eV, and the total number of clusters for N_{th} was determined. The chance probability P_{ch} of observing this number of clusters under an isotropic distribution was 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 sequence described above. Out of 10,000 simulations, 5 trials had the same amount or

[1] `http://www-akeno.icrr.u-tokyo.ac.jp/AGASA/pub/`

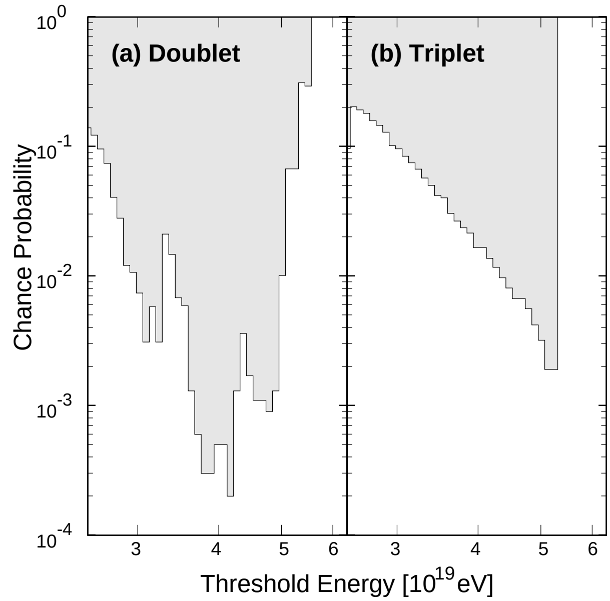

Fig. 2. Energy dependence of the chance probability of observing (a) doublets and (b) triplets.

more doublets ($N_{th} = 2$) than the observed data set, giving $P_{ch} = 0.05\%$; $P_{ch} = 1.66\%$ for triplets ($N_{th} = 3$).

Here, the simulated data sets have a uniform distribution in right ascension and declination and energy distributions which follow experimental observations. The uniformity of the observation time in right ascension results from the uniform observation in solar time over more than ten years. This is expected for a surface array detection system such as AGASA operating in stable conditions. The fluctuation of the observation time in local sidereal time is only (0.2 ± 0.1) %, which is small enough compared with the anisotropy in the energy range of interest, such that the exposure in right ascension is quite uniform. The declination distribution reflects the zenith angle dependence of the AGASA exposure and is consistent with the distribution expected if cosmic rays come isotropically from the celestial sphere. Since the trigger efficiency is independent of energy above 10^{19}eV at a zenith angle less than 45°, this distribution is applicable to higher energies.

Next, the threshold energy dependence for observing doublets and triplets are estimated, and the results are shown in Figure 2. When a new cluster is added above a threshold energy, the histogram changes discontinuously. At the maximum threshold energy where the triplet is detected, we find $P_{ch} = 0.19\%$ in Figure 2(b). The narrow peaks above 4×10^{19}eV in Figure 2(a) result from five doublets and one triplet, and another doublet is found just below 4×10^{19}eV. The chance probabilities are smaller than 0.1 % for doublets and 1 % for triplets in this range. The smallest chance probabilities are obtained around 4×10^{19}eV, and this energy may indicate some critical energy for clusters. The chance probabilities in this figure are estimated without taking account of

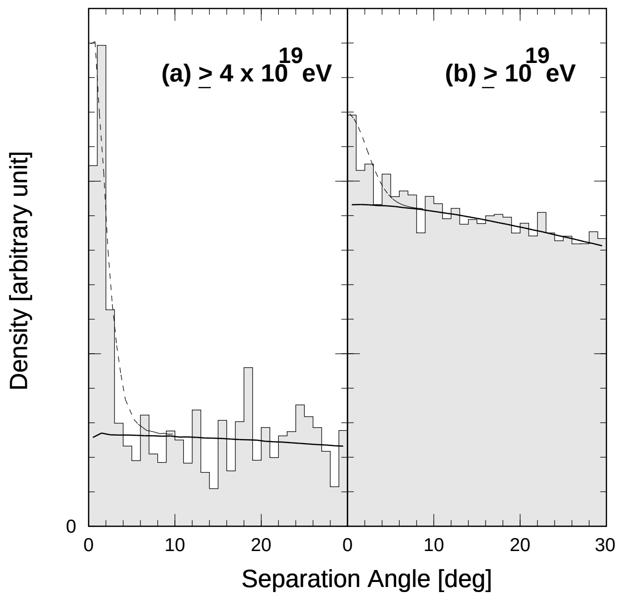

Fig. 3. Self-Correlation analysis above (a) 4×10^{19}eV and (b) 10^{19}eV. Histogram: observed data set; Curve: average of 10,000 simulated data sets; Dashed curve: the AGASA point spread function.

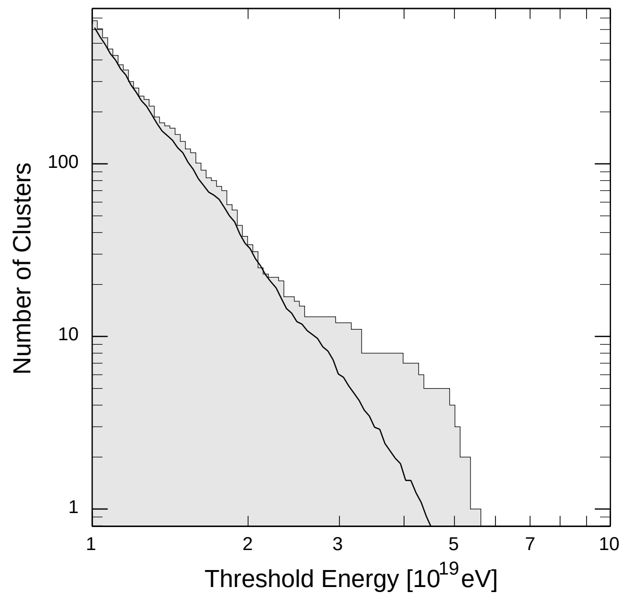

Fig. 4. Number of clusters in the self-correlation analysis. The energy dependence on the separation angle is taken into account.

the degree of freedom on the threshold energy. The chance probabilities may not be increased by a factor of 4 even if we take the degree of freedom into account, because the number of independent data sets in this energy range is less than 4 with considering the energy resolution of the AGASA experiment.

The above cluster analysis was a certain condition (θ, N_{th}) = (2.5°, 2). All possible conditions were also examined with a step of 0.5° for θ and 1 for N_{th}, and the original condition was found to be most significant. To show clear dependence on the separation angle θ, self-correlation analysis is introduced and shown in Figure 3(a). The vertical axis indicates an event-pair density:

$$N(\theta) = \sum_i \sum_{j \neq i} R_{ij}(\theta)/(2\,S(\theta)), \tag{1}$$

where

$$R_{ij}(\theta) = \begin{cases} 1 & \text{if } \theta_{ij} \text{ in } d\theta \\ 0 & \text{otherwise} \end{cases} ,$$

and θ_{ij} is the separation angle of two events on the celestial sphere and $S(\theta)$ is the area of a concentric ring at $\theta d\theta$. This density increases as the multiplicity of clusters increases. The histogram is the observed distribution and the solid curve is expected from an isotropic distribution, obtained from the same 10,000 simulated data sets as that used in the cluster analysis. There is a clear sharp peak in the small separation angles within 2.5°, and no statistically significant deviation from the expected curve is observed. This peak results from the six clusters and the maximum separation angle is determined to be 2.5°. Since the dashed curve indicates the point spread function of the AGASA experiment and is well fitted to the observed distribution, the clusters are regarded as point-like sources against the AGASA angular resolution. For another threshold energy of 10^{19}eV, the same plot is shown in Figure 3(b), and a small but significant peak is again observed within 4.0°. The separation angles of 2.5° (4.0°) at 4×10^{19}eV (10^{19}eV) are equivalent to the AGASA angular resolution multiplied by a factor of $\sqrt{2}$. Within such energy-dependent separation angles, Figure 4 shows the number of clusters both for the observed (histogram: N_{obs}) and simulated (curve: N_{exp}) data sets. The simulated data sets were obtained using 10,000 trials under an isotropic distribution. Some excesses are found around 1.0, 1.7, 4.5 $\times$ 10^{19}eV. The significance of $(N_{obs} - N_{exp})/\Delta N_{exp}$ is shown in Figure 5, where ΔN_{exp} is the deviation of N_{exp} obtained from the above simulated data sets. The clusters around 4 $\times$ 10^{19}eV have 5 σ or more significance, while two of them at lower energies have only about 2 σ.

Next, we derived the integral energy spectrum of events contributing to clusters. Figure 6 shows this spectrum with the AGASA integral energy spectrum. From this figure, the integral spectral index is $-0.8 \pm$ 0.5(stat) $\pm$ 0.5(sys).

Finally, we estimate the number of sources if we assume that all observed events above 4×10^{19}eV came from a particular type of source. Sources have the following conditions: (i) The number of sources is N_S; (ii) The frequency of observation of cosmic rays from each of sources follows the Poisson distribution $P(x, \mu)$ with an average μ: $x = 3$ (2) corresponding to sources of a triplet (doublet) and $x = 0$ is a non-observed source. From multiplicity distribution of N_x = 46, 5, 1, 0, 0 at $x = 1, 2, \cdots, 5$, we found $N_S \simeq 220^{+207}_{-100}$ for

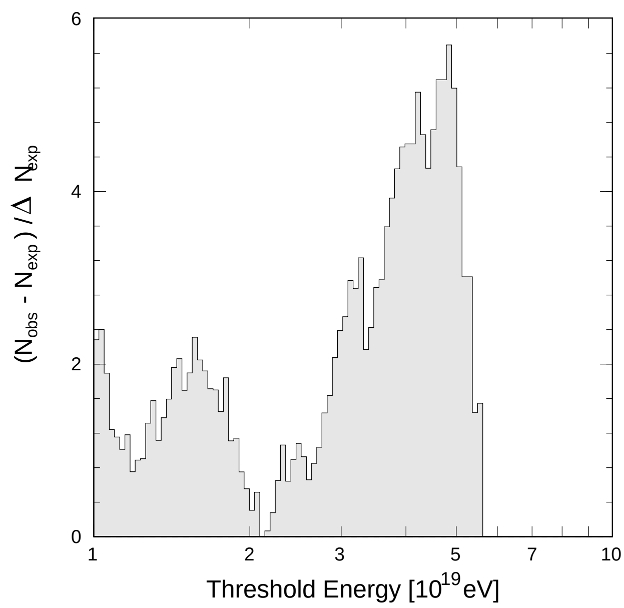

Fig. 5. $(N_{obs} - N_{exp})/\Delta N_{exp}$ in the self-correlation analysis. The values N_{obs}, N_{exp} are obtained from Figure 4.

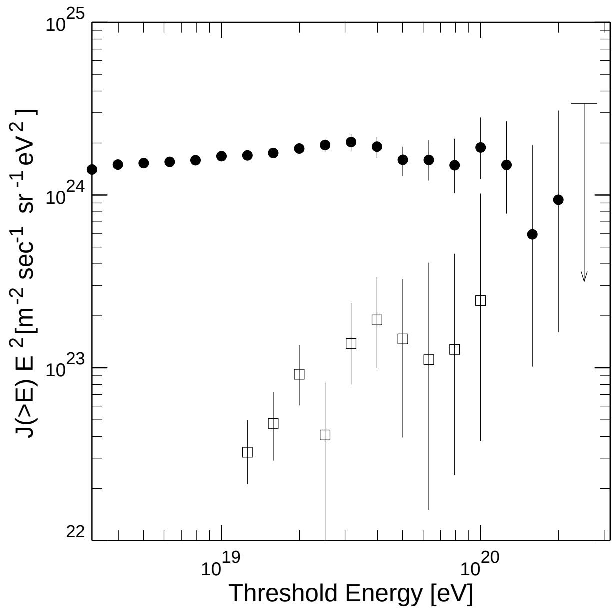

Fig. 6. Integral energy spectrum of cosmic rays contributing to clusters (open squares) with the AGASA integral energy spectrum (closed circles).

$\mu = 0.27^{-0.14}_{+0.30}$ with 68 % C.L. This N_S is about four times as large as the number of events observed with AGASA while we neglected characteristics and distances of sources. However, we don't know how many fraction of $N_{x=1}$ results from the assumed type of source. If we consider two (or more) types of source, one of which corresponds to a "cluster" component with a hard spectrum, $N_S \simeq 427$ is the upper limit for the number of sources in the observed celestial region.

4 Summary

Our previous result that a fraction of extremely high energy cosmic rays above 4×10^{19}eV were clustered was confirmed using the updated data set. One triplet and five doublet were observed in this energy range. Above 10^{19}eV, the weak correlation was also found within the angular separation of experimental accuracy 4.0°. The peaks, above 4×10^{19}eV and 10^{19}eV, in the self-correlation analysis have 4.6 σ and 2.3 σ deviation from the distribution expected for an isotropic distribution. The separation angle distribution in the self-correlation analysis follows the point spread function of the AGASA experiment taking into account the angular resolution. The cosmic rays contributing to clusters are expected to have a hard energy spectrum with the integral spectral index of -0.8 ± 0.5(stat) $\pm$ 0.5(sys) corresponding to a differential spectral index of -1.8. The multiplicity of clusters above 4 $\times$ 10^{19}eV tells that the upper limit for the number of their sources is expected to be $\simeq 427$ in the observed celestial region. However, it is still open as to whether or not source density varies over various celestial regions. To reveal this, much better statistics, expected from the next generation experiments, is required.

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