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Arrival direction of successive air showers(*)

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Summary. — We have studied the features of series of air shower events (AS cluster) concentrated within short intervals of time of arrival. When the number of events in the cluster reaches the maximum values in the considered data set, the arrival directions of the AS are prevailingly observed around values of right ascension $\alpha \simeq 5$ h and $\alpha \simeq 20$ h. These values indicate parallellism of directions between the shower directions and the galactic plane. This can be explained by the presence of Ultra-High Energy (UHE) gamma-ray sources, generating showers from their specific direction. The analysis uses three data set of 253k, 664k and 231k events. The results are similar in the three data set.

PACS 96.40.Pq – Extensive air showers.
PACS 98.70.Sa – Cosmic rays (including sources, origin, acceleration, and interactions).

1. – Introduction

In 1983, Smith *et al.* [1] observed 32 successive air shower events in 5 minutes. They found them from the 150k events recorded during about 1.5 years of observation. The mean energy of the air shower by their detectors was 3×10^{15} eV and the mean event number of air shower was 1 event per 5 minutes. It was estimated that the probability of 32 air shower events being accidentally detected within 5 minutes was 10^{-35} at this mean frequency. On account of the generation mechanism of the shower, this cannot be a normal phenomenon. Fegan *et al.* [2] reported the experimental fact that air shower events ($\sim 10^{14}$ eV) which lasted for 20 seconds simultaneously were observed at two

(*) The authors of this paper have agreed to not receive the proofs for correction.

observation stations 250 km apart, using air shower data during 3 years. However, they have not yet established their relation with cosmic ray sources.

These phenomena have the common peculiarity of being concentrated in short time intervals and the collected events themselves could provide us with the clue to their origin. In 1980, Bhat *et al.* [3] reported that events observed within time interval $\Delta T <$ 40 s showed an excess in their distribution at (5 ± 3) hours of right ascension. One experiment [4] confirmed this result, while other groups [5, 6] reported negative results. Recently, Katayose *et al.* [7] observed that the arrival direction of clusters of events with very low "random probability" points to the vicinity of the galactic plane with significance level < 0.05. They found five clustered events which ranged from small 41(19.2 min) to large 2591(40.0 hour) ones, using 3651k air shower events. However, no sign that the clustered events are initiated by UHE gamma-rays or neutral particles was found, in spite of appearing as if they were coming from near the galactic plane. In explaining the tendency to collect the arrival direction without contradicting the existence of the galactic magnetic field, it must be considered that an unknown phenomenon might be involved. This is mysterious, if all clustered events actually came from the direction of appearance.

We have also noticed that the AS cluster selected by a simple method [8, 9] shows anisotropy. In this paper, we will show that the arrival directions of AS clusters, selected by a simple method from 1148k air shower events, are parallel to the galactic plane and present a possible explanation with an assumption on why the arrival direction of such AS cluster indicates the galactic plane. This assumption does not require any change with respect to other experimental observations and features of the air shower phenomenon.

2. – Air shower detectors and data

The data used in this analysis was obtained from the air shower arrays of the Large Area Air Shower (LAAS) group consisting of nine air shower stations [10]. The air shower array in each station consists of similar detectors with NIM/CAMAC modules except for the number of plastic scintillation counters ($50 \times 50 \times 5$ cm^3) and their configuration. The mean energy of the air shower observed by the LAAS group is estimated to be $(3–5) \times 10^{14}$ eV. We use the data collected by three arrays (Kinki, Okayama and Hirosaki) in which the trigger condition is not changed during the observation period, because the fluctuation of the event rate due to an unstable operation becomes an important problem in this analysis. Table I indicates the profiles of these arrays.

TABLE I. – *Profiles of Kinki, Okayama and Hirosaki arrays.*

	Kinki array	Okayama array	Hirosaki array
Location	34°38′56″N	34°41′10″N	40°34′57″N
	135°35′30″E	133°55′28″E	140°28′35″E
Number of detectors	5	8	5
Trigger condition	5-fold coinc	5-fold coinc	5-fold coinc
Event rate (events/min)	0.269 ± 0.020	0.408 ± 0.030	0.412 ± 0.028
Observation period	14May1993–10Apr1995	12Sept1996–22Dec1999	13Nov1998–10Dec1999

Kinki array (data set A):
The air shower detection system has five scintillation counters placed at the center and on each corner of a 19 m × 19 m square. The event, which has all hits in the five counters within 60 ns, is collected. This condition allows us to record the air shower events which have an energy of 2×10^{14} eV or more. This array system indicates that the mean frequency of the air shower events is 0.269 ± 0.020 events/min, where the error term indicates a standard deviation. Data of 253k events were obtained during 2 years, since May 1993.

Okayama array (data set B):
Okayama array is located about 150 km west of Kinki array. Five scintillation counters for triggering are arranged on the corners and in the center of a 10 m × 10 m square. Three non-trigger counters are situated at 10–20 m from the center. The time window for triggering with a 5-fold coincidence is 45 ns. The event rate is 0.408 ± 0.030 events/min. The total number of events obtained during 3 years since July 1996 is 664k.

Hirosaki array (data set C):
Hirosaki array is located about 790 km north-east of Kinki array. The Hirosaki array consists of five scintillation counters which are located on each corner and in the center of a 15 m × 16 m rectangle. A 5-fold coincidence within 150 ns is used on the trigger condition for air shower events. The event rate is 0.412 ± 0.028 events/min. The number of events obtained in the observation of about a year period, since November 1998, is 231k.

For signal processing, we customized the circuit configuration for the detection of random phenomena such as cosmic rays. In the Kinki apparatus, the arrival time of the air shower, formerly measured with a time resolution of 10 μs, is now measured with GPS techniques with an accuracy of 1 μs; in Okayama and Hirosaki apparatuses, the measurement has been performed with GPS since the beginning.

The air shower size is calculated using the data of the 144k events in the Kinki array to check our air shower observation system using the ADC data. We can determine the air shower size of approximately 98% of the events. The remaining 2% is for cases in which one ADC value is much bigger than the mean value, and it does not seem to be possible to determine the air shower size because of the processing software. We examine the integral size distribution of air shower events. Since an air shower with low energy rarely reaches the ground (nearly the sea level), there are few samples of less than $10^5 (\sim 10^{14}$ eV). The slope γ of the corrected distribution can be evaluated to ∼1.6 by fitting to the function $N_e^{-\gamma}$, where N_e indicates the air shower size. The mean air shower energy is estimated to be 3×10^{14} eV.

We also examine the distribution of arrival time differences among the air shower events. The result of fitting to the exponential function is obtained in either data set. There is also no defect in the time difference data in the range from 10 ms to 1 s, when the events within 1 second time difference are examined.

We calculate the arrival direction of the air shower using the TDC data so that an arrival time difference is recorded in each counter, assuming that the front of the air shower is a plane because the scale of our shower array is small. It is evaluated with $n = 9.7 \pm 0.1$ when the distribution of the zenith angle θ is fitted to a function $\cos^n \theta$. The difference between the data sets is not found within 50 degrees. The azimuthal angle ϕ data shows a uniform distribution in either data set. These results agree with the features of the air shower at the sea level expected from the uniformity of the arrival

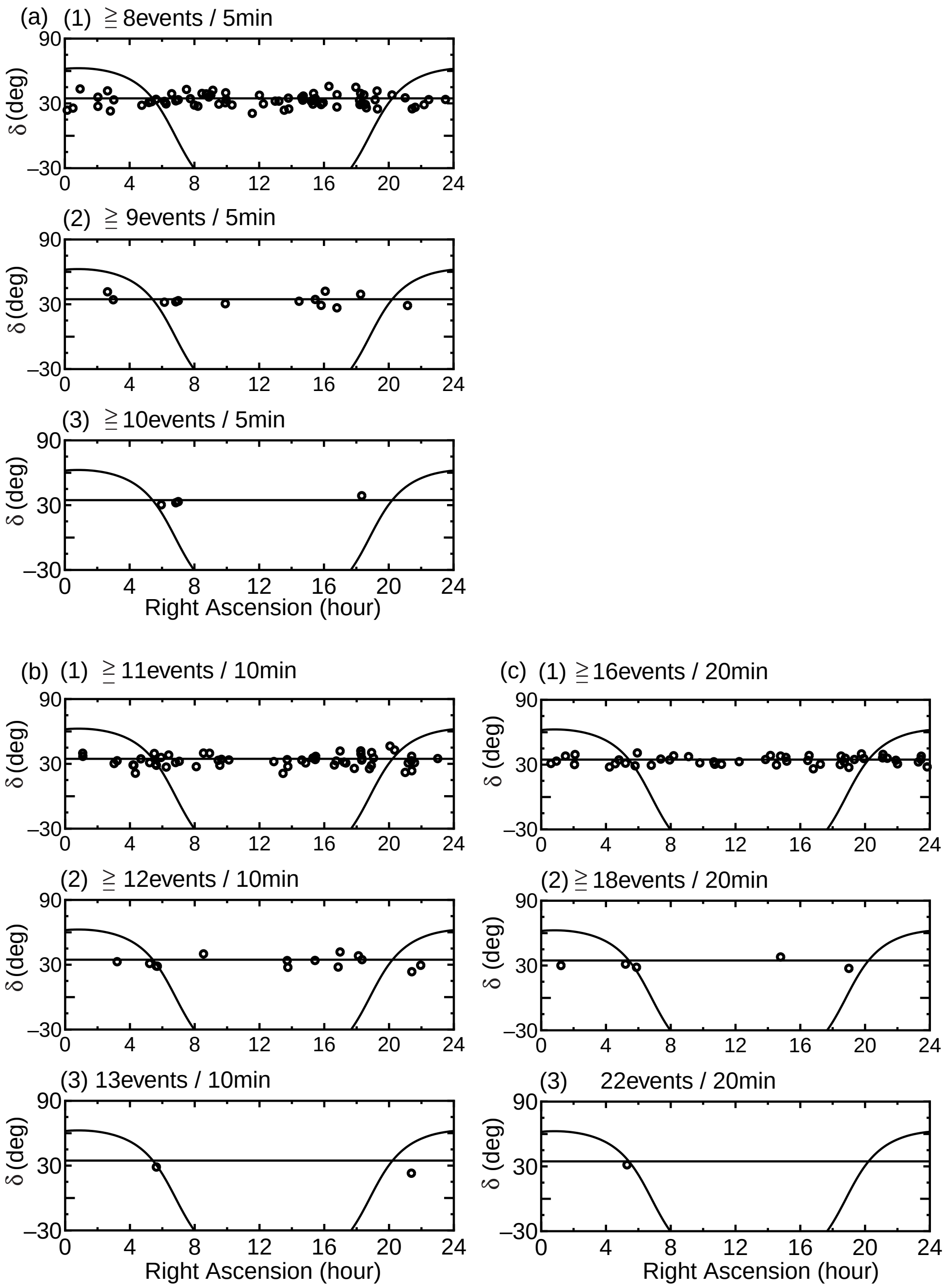

Fig. 1. – The distribution of AS clusters plotted in the right ascension *vs.* declination coordinates for ΔT: 5 minutes (a), 10 minutes (b) and 20 minutes (c) in data set A. Open circles correspond to AS clusters. The curve indicates the galactic plane.

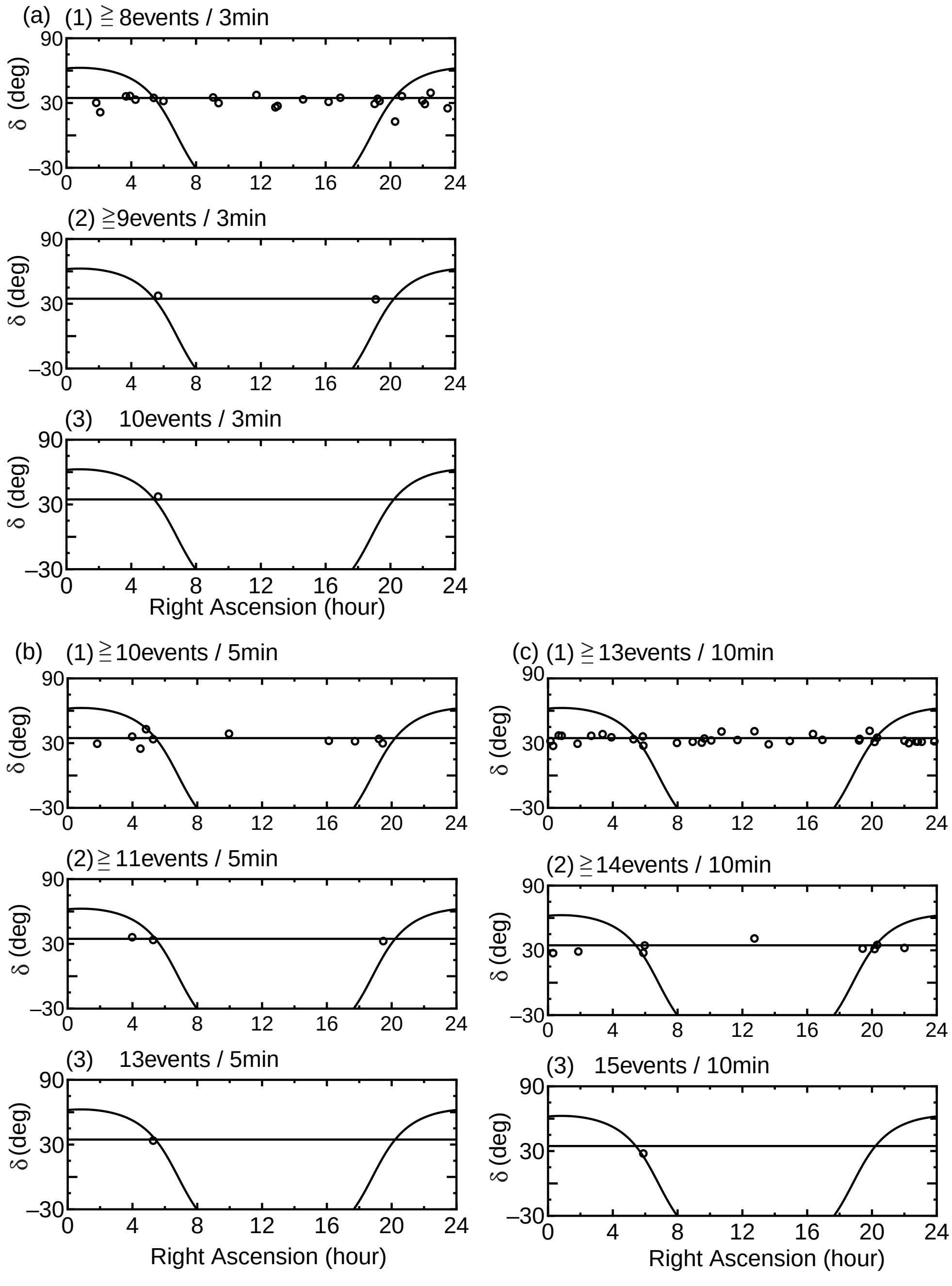

Fig. 2. – The distribution of AS clusters plotted in the right ascension *vs.* declination coordinates for ΔT: 3 minutes (a), 5 minutes (b) and 10 minutes (c) in data set B.

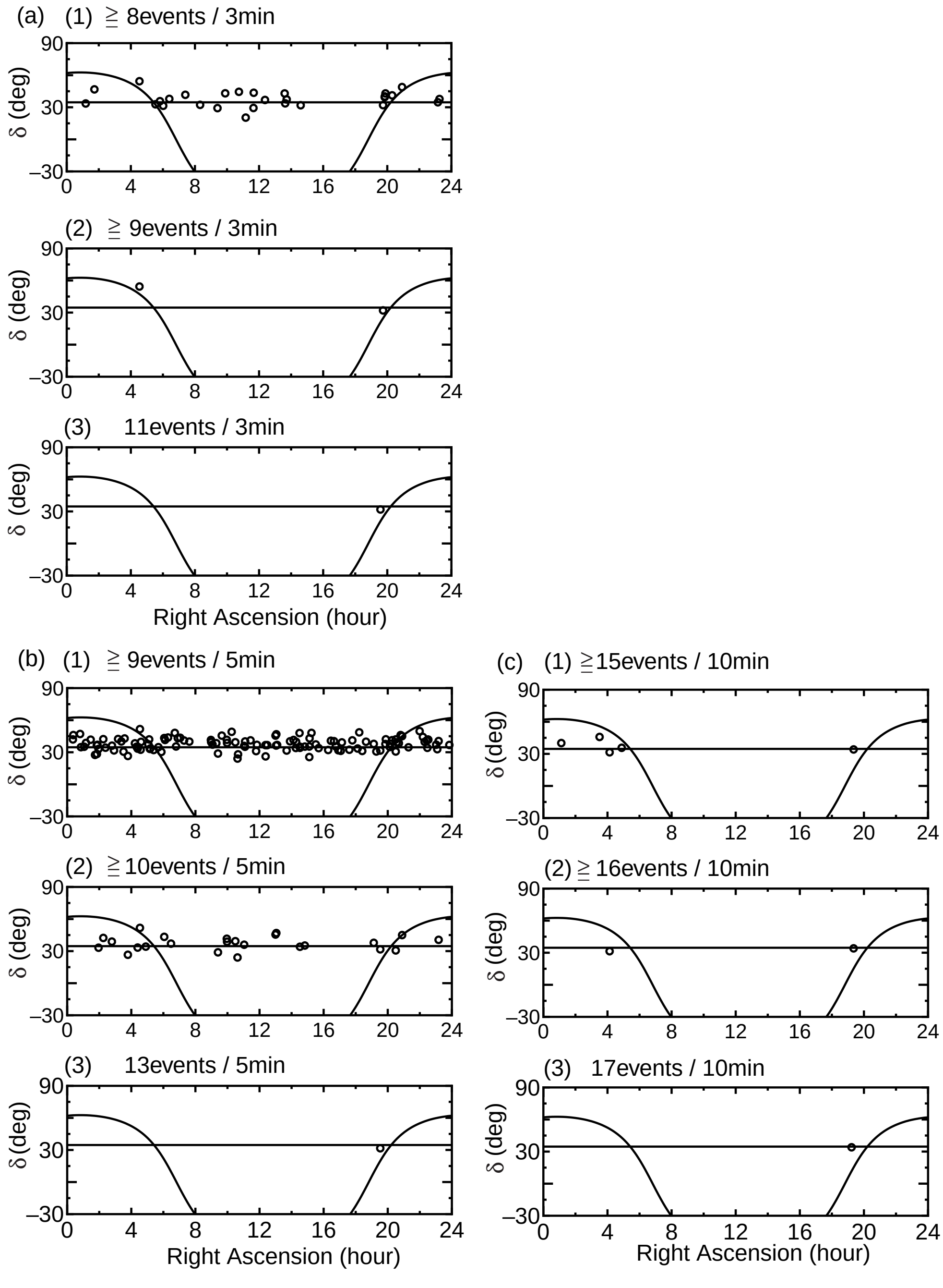

Fig. 3. – The distribution of AS clusters plotted in the right ascension *vs.* declination coordinates for ΔT: 3 minutes (a), 5 minutes (b) and 10 minutes (c) in data set C.

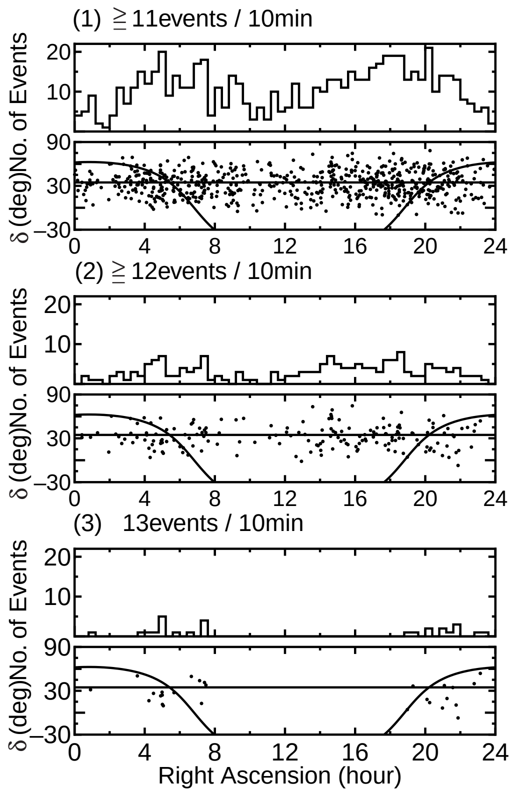

Fig. 4. – The distribution corresponding to fig. 1(b) for all the events which constitute the AS cluster. In the lower side, the AS clusters plotted on α-δ coordinates are shown, and the right ascension distribution integrating over the declination is shown in the upper side.

direction of the cosmic ray, the energy spectrum and the effects of oblique incidence with respect to the atmosphere. The error of arrival angle measurement performed by our AS apparatus is evaluated to be $\pm(5\text{–}7)^\circ$.

3. – Searching AS clusters

We define a series of air shower events that satisfied the below requirements for the AS cluster. The following restrictions are imposed: zenith angle for arrival direction $< 50^\circ$, deviation length for the fitting plane to the air shower front < 2 m. About 85% of events passed with this selection criteria in the original data. The number of arrival events N, observed in the time interval ΔT, is much more than an average of arrival events.

The data set A, B and C indicate the data from Kinki, Okayama and Hirosaki arrays, respectively. We investigate how the AS clusters distribute in the right ascension (α) *vs.* declination (δ) coordinates for various values of N and ΔT. Figure 1 shows the distribution of AS clusters plotted on α-δ coordinates for ΔT of 5 minutes (a), 10 minutes (b) and 20 minutes (c) in data set A. Figures 2 and 3 show the same distributions as in fig. 1 for ΔT of 3 minutes (a), 5 minutes (b) and 10 minutes (c) in data set B and C,

TABLE II. – *The samples of AS clusters with maximum $N/\Delta T$ obtained from the data set A.*

No.	date (UT)	time (UT)	$\langle\alpha\rangle$ (hour)	$\langle\delta\rangle$ (deg)
(a) 10 events/5 min				
1	28 Jun. 1993	4: 5:15.89	6.9 ± 0.6	32 ± 6
2	6 Oct. 1993	19:10:55.45	6.0 ± 0.5	30 ± 5
3	24 Oct. 1993	7: 1:27.57	18.3 ± 0.6	39 ± 5
4	14 Jan. 1994	14:13:51.04	7.0 ± 0.5	33 ± 6
(b) 13 events/10 min				
1	2 Jun. 1993	19:46:46.62	21.4 ± 0.5	23 ± 6
2	6 Oct. 1993	19: 5:20.69	5.6 ± 0.4	29 ± 4
(c) 22 events/20 min				
1	6 Oct. 1993	18:55:19.70	5.3 ± 0.3	31 ± 4

respectively. The curve in the figures shows the galactic plane. Open circle correspond to AS clusters. We use the mean value of the right ascension and declination for the events which constitute an AS cluster. The error estimate for the mean value is rather complicate. Figure 4 shows the distribution corresponding to fig. 1(b) for all events which constitute the AS cluster, not for the AS cluster itself. As shown in fig. 4, the events in the AS cluster are widely distributed within 50 degrees of the arrival angle and spread according to the period of ΔT. The errors of the mean values $\langle\alpha\rangle$ and $\langle\delta\rangle$ of the AS cluster are evaluated to be ± 0.7 hours and $\pm 8°$, respectively. The title "(1) ≥ 8 events/5min" in fig. 1(a) denotes that the AS cluster consists of 8 or more air shower events which arrive successively in 5 minutes. The value of N in title (3) of each part of the figure indicates the maximum value of N for that ΔT in the possible limits. When the value of N is smaller than the value shown in the figure, the excess in the distribution of AS clusters at the specific direction disappears. For example, the distribution becomes flat when the value of N is smaller than 9 in the case $\Delta T = 10$ min in data set A.

As N increases, AS clusters concentrate in the vicinity of values of right ascension of 5 and 20 hour. The AS clusters selected by the title (2) in the figure are contained in AS clusters selected by the title (1), and the AS clusters selected by the title (3) are contained in AS clusters selected by the title (2). In practice, we investigate the feature of

TABLE III. – *The samples of AS clusters with maximum $N/\Delta T$ obtained from the data set B.*

No.	date (UT)	time (UT)	$\langle\alpha\rangle$ (hour)	$\langle\delta\rangle$ (deg)
(a) 10 events/3 min				
1	27 Jan. 1998	12: 0: 2.18	5.7 ± 0.7	37 ± 8
(b) 13 events/5 min				
1	27 Jan. 1998	11:58: 0.64	5.3 ± 0.6	34 ± 7
(c) 15 events/10 min				
1	6 Jan. 1998	13:24:53.08	5.9 ± 0.4	28 ± 5

TABLE IV. – *The samples of AS clusters with maximum $N/\Delta T$ obtained from the data set C.*

No.	date (UT)	time (UT)	$\langle\alpha\rangle$ (hour)	$\langle\delta\rangle$ (deg)
(a) 10 events/3 min				
1	9 Apr. 1999	20:20:13.24	19.6 ± 0.5	32 ± 5
(b) 13 events/5 min				
1	9 Apr. 1999	20:19:15.36	19.5 ± 0.5	32 ± 4
(c) 15 events/10 min				
1	9 Apr. 1999	20:20:13.24	19.2 ± 0.5	34 ± 4

AS clusters for ΔT in the range of 1 to 40 minutes. When the size of ΔT is much smaller, the mentioned feature does not appear clearly because maybe the random fluctuation of the event rate becomes dominant. When the size of ΔT is much bigger, the feature is not clear since the visual field of view from the space gets too large. Here, the result is shown for the three cases in these ΔT.

When the event rate increases, the number of showers arriving in a fixed time interval increases. The appropriate value of ΔT depends on the average event rate. In our experiment, the above feature is shown most clearly when ΔT is 1–3 times the average arrival time difference. The tendency to remain near the specific directions on the right ascension axis is observed both at the highest event rate and at a little lower event rate. Especially, as shown in figs. 1(b), 2(b) and 3(c), the aspect that AS clusters distribute in the vicinity of two directions is clearly observed, even if N in the time interval ΔT does not yet reach the obsevation upper limit of arrival event number. This indicates that AS clusters do not collect by chance near the specific direction.

Tables II, III and IV show the date and time (UT) of the first event in constituent events in AS cluster, the mean value of the right ascension $\langle\alpha\rangle$ and declination $\langle\delta\rangle$ of AS cluster with the highest event rate or maximum $N/\Delta T$ for data set A, B and C, respectively.

However, an abnormal operation of apparatus can also contribute to anisotropy. This may have influenced the detection efficiency of air shower or event rate. The daily variation of event rate during the observation period for data set A, B and C is shown in fig. 5(a), (b) and (c), respectively. The horizontal straight line in the figure shows the average event rate. The short vertical bars in fig. 5(a) indicate the arrival time of the AS clusters shown in fig. 1(b) (1). It is not observed from the figure that the AS cluster is concentrated in the time in which event rate systematically rises.

4. – Circular statistical tests

The probability for AS clusters to be casually inclined, so as to remain near two specific directions, is calculated by using the technique of circular statistics [11, 12] as described below.

i) The procedure is, first, to sample θ_i uniformly on $(0,\ 2\pi)$ and perform a change of variables

$$\alpha^{(1)} = \theta_i - \beta_1, \qquad \alpha^{(2)} = \theta_i - \beta_2, \tag{1}$$

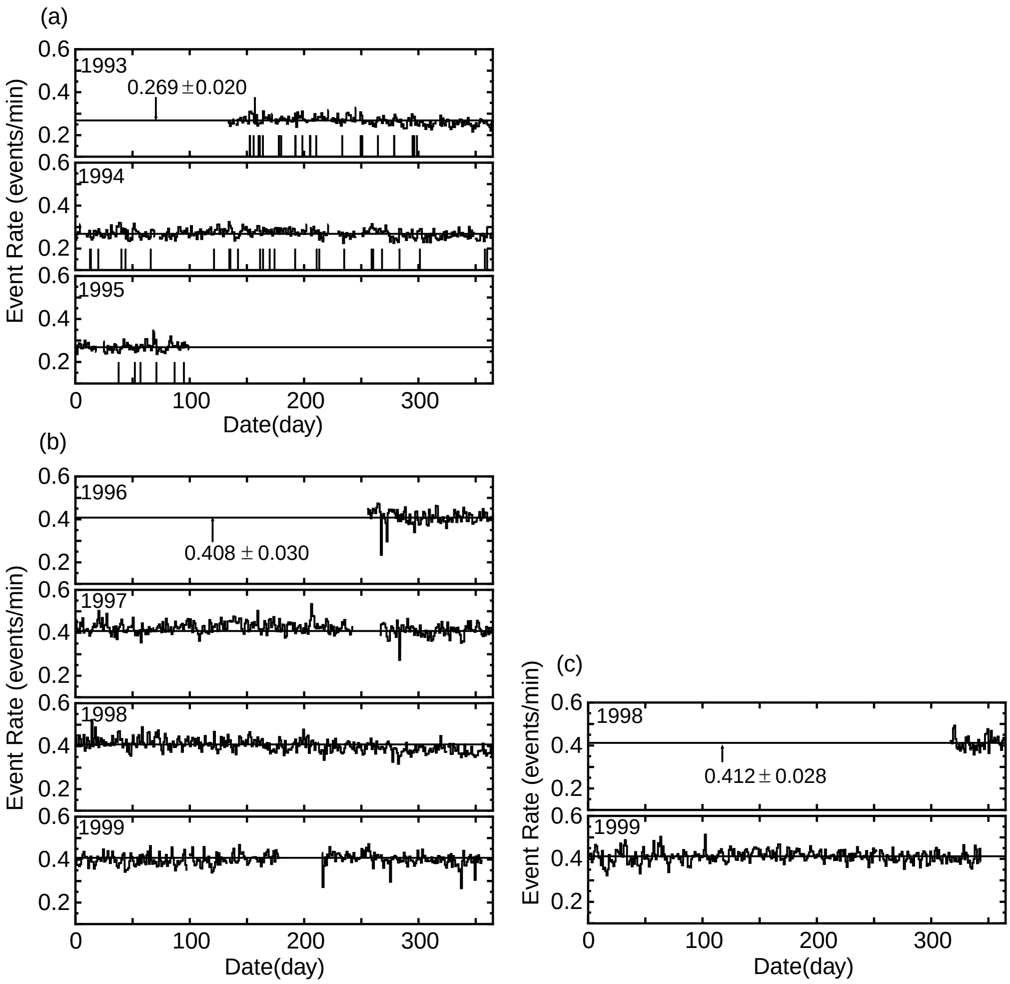

Fig. 5. – The daily variation of event rate during the observation period. The straight line shows the average event rate. (a) The event rate in Kinki array (data set A) is shown on the data of about 2 years since May 1993. The short vertical bars show the arrival time of AS clusters in fig. 1(b) (1). (b) The event rate in Okayama array (data set B) is shown on the data of about 3 years since July 1996. (c) The event rate in Hirosaki array (data set C) is shown on the data of about a year since November 1998.

where θ_i is the arrival angle of the air shower on the right ascension axis, and β_1 and β_2 represent the right ascension 5 and 20 hour in unit radian, respectively.
ii) Second, to replace $\alpha^{(j)}$ with a new value according to the value of $\alpha^{(j)}$ for $j = 1$ and 2 as follows:

$$\alpha^{(j)} = \alpha^{(j)} - 2\pi \quad \text{if} \quad \alpha^{(j)} > \pi, \tag{2a}$$

$$\alpha^{(j)} = \alpha^{(j)} + 2\pi \quad \text{if} \quad \alpha^{(j)} < -\pi. \tag{2b}$$

TABLE V. – *The probability of casual occurrence of AS cluster for the data set A.*

	(a) /5 min	(b) /10 min	(c) /20 min
(1)	≥ 8 events ($n = 71$) 0.530	$\geq 11(56)$ 0.010	$\geq 16(49)$ 0.229
(2)	$\geq 9(13)$ 0.246	$\geq 12(14)$ 0.168	$\geq 18(5)$ 0.208
(3)	10(4) 0.030	13(2) 0.050	22(1) ——

iii) Comparing the absolute values of $\alpha^{(1)}$ with $\alpha^{(2)}$, we adopt the smaller one and set to

$$\alpha_i = \alpha^{(1)} \quad \text{if} \quad |\alpha^{(1)}| < |\alpha^{(2)}|, \tag{3a}$$

$$\alpha_i = \alpha^{(2)} \quad \text{if} \quad |\alpha^{(1)}| \geq |\alpha^{(2)}|. \tag{3b}$$

By repeating the above procedure, we can obtain α_i ($i = 1, 2, ..., N$). The statistic r is defined using α_i as follows:

$$r = \frac{1}{N} \sum_{i=1}^{N} \cos \alpha_i. \tag{4}$$

In order to evaluate the randomness, when θ_i's originally are uniformly distributed on the right ascension axis, we first make a distribution $u(r)$ of r on the simulated AS clusters, each consisting of N events. We use r_0 obtained from experimental values of θ_i ($i = 1, 2, ..., N$) as a test statistic. The probability is given by

$$P(r > r_0) = \int_{r_0}^{1} u(r)\mathrm{d}r \Big/ \int_{-1}^{1} u(r)\mathrm{d}r. \tag{5}$$

Tables V, VI and VII show the probability of a casual occurrence of AS cluster for data set A, B and C, respectively. n or the number in parentheses in the tables indicates the number of AS clusters. The result in case of $n = 1$ is removed because it has no meaning. It is found from column (b) in table V that randomness is excluded at 1%

TABLE VI. – *The probability of casual occurrence of AS cluster for the data set B.*

	(a) /3 min	(b) /5 min	(c) /10 min
(1)	≥ 8 events ($n = 24$) 0.189	$\geq 10(10)$ 0.019	$\geq 13(34)$ 0.402
(2)	$\geq 9(2)$ 0.027	$\geq 11(3)$ 0.004	$\geq 14(9)$ 0.137
(3)	10(1) ——	13(1) ——	15(1) ——

TABLE VII. – *The probability of casual occurrence of AS cluster for the data set C.*

	(a) /3 min	(b) /5 min	(c) /10 min
(1)	$\geq$ 8 events ($n = 28$) 0.803	$\geq$ 9(123) 0.427	$\geq$ 15(5) 0.028
(2)	$\geq$ 9(2) 0.006	$\geq$ 10(24) 0.593	$\geq$ 16(2) 0.024
(3)	11(1) —	13(1) —	17(1) —

significance level (number of samples $n = 56$) in case of fig. 1(b) (1). As a whole, the randomness can be excluded by this test at $(0.4 \sim 5)\%$ significance level for the AS cluster whose $N/\Delta T$ has a maximum or is close to a maximum, though it is hard to exclude randomness in case (c) in data set A and B, and also in case (b) in data set C, while in any case the AS cluster remains near 5 or 20 hour on the right ascension axis at maximum $N/\Delta T$. Though the condition for extracting the AS cluster at maximum $N/\Delta T$ is slightly different between the three data sets, eight AS clusters near the galactic plane are obtained by collecting the cluster which can be distinguished from not identical one according to the date shown in tables II, III and IV.

5. – Conclusions and discussions

Now, we consider the following discussion, in the awareness that the frequency of occurrence of AS cluster with maximum $N/\Delta T$ is usually very low, in terms of probability, because it belongs to the terminal tail of the Poisson distribution. The feature of the AS clusters around the specific direction on α-δ coordinates is observed in three data sets. It should be noticed that this feature appears not only at maximum $N/\Delta T$ condition but also near the maximum. This supports that the feature is statistically right. This feature cannot be explained with a fluctuation, considered the result of the probability calculation and that a similar feature is obtained from three data sets.

Right ascensions of 5 and 20 hour indicate specific directions when the vertical line to our air shower array location on the earth is parallel to the galactic plane, as shown in fig. 6. The region within 35 degrees of zenith angle has about 90% of air showers in our observed events. We survey the universe towards the vertical direction to our array on the ground rotating with turning earth, that is, along a line on the right ascension with a constant value of the declination, for instance, $(34.6 \sim 40.6)$ degrees in our arrays.

Though there is partially a lack of events during the observation period due to maintenance, this does not affect our result. Because the lack of events contributes to eliminate the AS clusters to be plotted on α-δ coordinates. The distribution of the right ascension using all data shows no serious influence by this lack. Then, the AS clusters remaining near the right ascension 5 and 20 hour seem to come from the galactic plane direction.

However, all air shower events which constitute AS cluster cannot be UHE gamma-rays or neutral particles in view of many experimental facts by the present. Even if it is partially so, the remainder, *i.e.* the charged particles, do not seem to come from the direction of the appearance, considering the existence of interstellar magnetic field. The number of AS clusters with maximum $N/\Delta T$ is consistent with the frequency expected

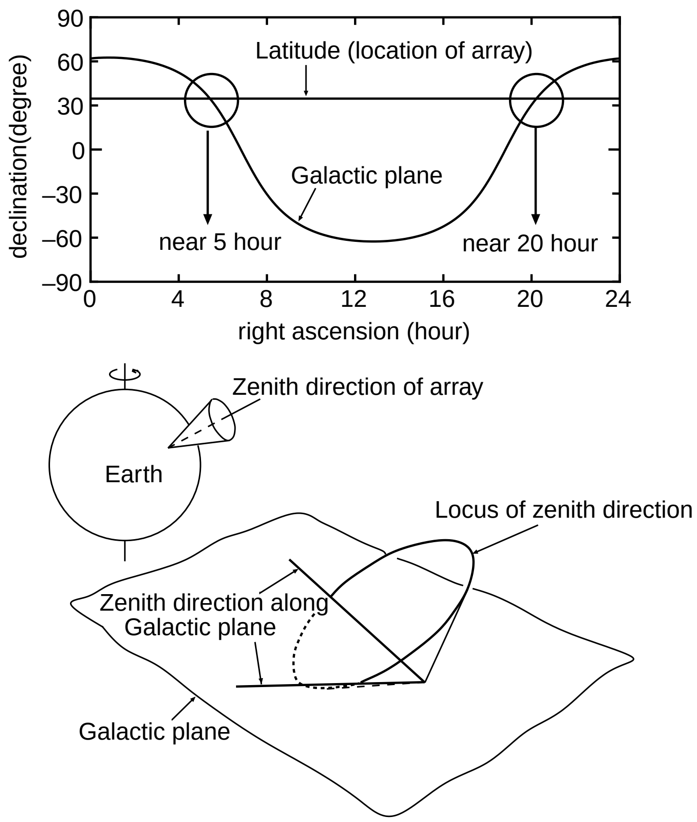

Fig. 6. – Schematic drawings which show the relation between our air shower array and the galactic plane.

by the Poisson distribution of air shower events per ΔT. Therefore, it is reasonable that the cosmic ray, by which the air shower constituting AS cluster is initiated, is a conventional cosmic ray component, though some AS clusters may contain a few UHE gamma-ray events. Why does the arrival direction of AS cluster with maximum or near maximum $N/\Delta T$ indicate nearness to the values of right ascension 5 and 20 hour?

The fact that the number of air shower events per fixed time interval follows the Poisson distribution does not depend on the right ascension or declination because the cosmic ray comes to the earth isotropically and randomly. The occurrence probability of a series of successive air showers which consist of N events in ΔT, also, does not depend on the right ascension or declination.

Now, we assume that UHE gamma-ray sources which cause the air shower exist in the specific direction in the space, such as the galactic plane. As we described above, the successive air showers arriving in ΔT are observed on the ground rotating with turning earth. When the vertical direction to our array turns around the specific direction, a few air showers initiated by UHE gamma-rays are accidentally caught by our array and may be added to the conventional cosmic ray air showers observed during the period ΔT. It is impossible to distinguish which is the UHE gamma-ray air shower in these. A large portion of air showers is initiated by the conventional cosmic ray component. The shape

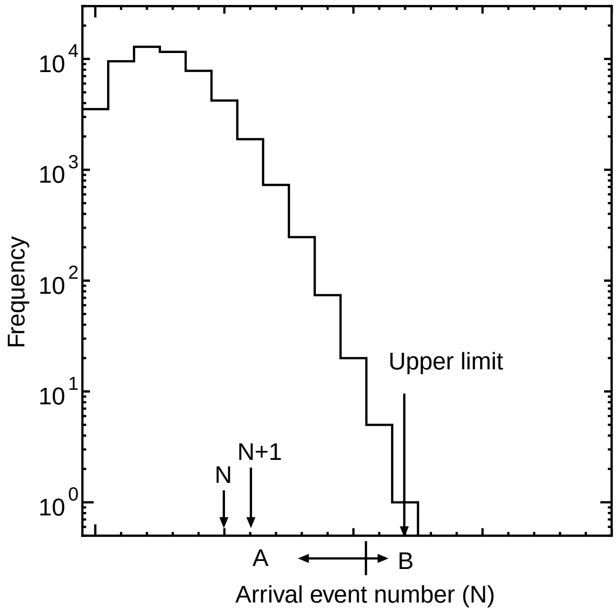

Fig. 7. – An example of the distribution of the number of showers per fixed time interval to explain the role of air showers induced by UHE gamma-rays. The horizontal axis indicates the arrival event numbers (N) and the vertical axis the frequency of arrival events in a fixed time interval.

of the Poisson distribution function of arrival event number N is not reduced, whether it includes UHE gamma-ray or not. We assume that, when there is a N successive air showers in ΔT, a cosmic ray from UHE gamma-ray source is arrived at the same time. An arrival event number is shifted to a large region on the event number axis by the UHE gamma-ray. This sample contributes to the frequency of "$(N + 1)$ events" in the Poisson distribution. When the value of N is smaller as compared with an observation upper limit of arrival event number, as shown by the region A in fig. 7, the frequency of "$(N + 1)$ events" of the air shower initiated by a conventional cosmic ray component is much greater than the frequency of "$(N + 1)$ events" together with an air shower initiated by UHE gamma-ray. The excess in the frequency is not observed in the specific direction. However, when the value of N equals a upper limit of arrival event number of conventional cosmic ray air showers, the arrival event number becomes possible to have $(N+1)$ which exceeds the upper limit, by adding UHE gamma-ray air shower. The occurrence probability of "$(N+1)$ events" is very small so that it is impossible to observe a sample of such events consisting of the conventional cosmic ray air showers. Now, we can observe "$(N+1)$ events" with an air shower initiated by UHE gamma-ray. A similar discussion is also established for a few UHE gamma-rays considered and for the value of N nearly equal to the upper limit, as shown by the region B in fig. 7. In this case, one would be able to observe excess in the frequency in the specific direction.

This method seems to enable the detection of UHE gamma-ray by tagging an AS cluster consisting of a series of events arriving successively in a short time interval. Simultaneously, it is shown that UHE gamma-ray sources do not exit uniformly in the whole space as long as the search is done through the air shower observations, if it is understood that UHE gamma-ray is found by this method. Because, if the UHE gamma-ray sources uniformly exist, it could not be observed the difference between the frequency in the specific direction and that in the other direction. Finally, the UHE gamma-ray sources should exist in the galactic plane.

In our observation location, the increase in the frequency at maximum event rate was found near the values of right ascension 5 and 20 hour. The right ascension value in which this feature is observed varies according to the latitude of the observation location. For example, it is anticipated that the frequency will increase around the right ascension 8 and 18 hour in Australia.

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