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Search for non-random features in arrival times of air showers(*)

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Summary. — We have searched for non-random components in arrival times of air showers of mean energy of 1 PeV. By counting the number of air showers observed within time windows of 20-60 minutes, we find small deviation of air shower data from the conventional view of uniformly random cosmic ray injection. The arrival directions of the non-random events concentrate at the direction of the Galactic plane. Though the significance of these events is not so high because of the lack of statistics, they may be induced by sporadic non-random injection of ultra-high energy γ-rays from the Galactic plane.

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1. – Introduction

Usually extensive air showers (EAS) are observed randomly both in time and in direction. This is because ultra-high-energy (UHE) cosmic rays, which induce EAS in the atmosphere, come to the Earth uniformly randomly after traveling through the galactic magnetic field for a long time. However, sporadic non-random components in arrival times of EAS were found by several observation groups. Smith *et al.* reported the detection of an "EAS burst" by their small EAS array [1]. They observed 32 EAS of estimated mean energy of 3 PeV within five minutes. The trigger rate of background cosmic rays was 1.1 per five minutes, so the chance probability of the burst event was calculated as 10^{-35}. In other reports, Fegan *et al.* and Bhat *et al.* also observed

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TABLE I. – *The profiles of stations and data.*

Station Name	HU	NUI	KU1	KU2	OUS1	OU
Latitude (N)	40°35′	34°35′	34°39′	34°39′	34°42′	34°41′
Longitude (E)	140°29′	135°41′	135°36′	135°36′	133°56′	133°55′
# of Counters	5	7	5	7	8	8
Trig. Counters	5	7	5	7	4	5
Trig. Rate (/day)[a]	567	306	451	317	704	566
Data Period	11/98 – 12/99	08/96 – 06/98	09/96 – 12/99	07/98 – 04/99	09/96 – 12/99	09/96 – 12/99
# of Showers[a]	221k	168k	447k	62k	651k	638k

([a]) Showers with zenith angle $\leq 45°$.

unusual increases of EAS rates [2,3]. In a more recent paper, Katayose *et al.* applied a sophisticated "cluster analysis" algorithm to the arrival times of EAS in order to extract "clustered events" from them [4]. They picked up five clustered events with moderate significances and plotted their arrival directions in equatorial coordinates. The clustered events concentrated at the direction of the Galactic plane, giving a chance probability of 0.016.

These reports were the motivation for our "successive air shower analysis" described here. We search for non-random components in arrival times of EAS using a large amount of data collected by our network observation [5]. Though the origin of the non-random cosmic rays is still an open question, it should have interesting and significant astrophysical implication. The aim of this work is the same as that reported in ref. [6], but another analytical procedure is taken here.

2. – Air shower observation and data

EAS data used here has been collected at six stations of the Large Area Air Shower (LAAS) group in Japan. The group, described in ref. [7], was originally established in 1996 in order to study correlations in primary cosmic rays. Each station has five-to-eight 0.25 m^2 scintillation counters arranged over a few hundreds of square meters. The trigger conditions are different among stations; 4- to 8-fold coincidences are applied yielding trigger rates of 300 to 700 showers/day. The primary energy range observed by our arrays, estimated by CORSIKA (Ver.5.624 with EGS, QGSJET and VENUS options), is from 50 TeV to 10 PeV with mean energy of 1 PeV. The estimated angular accuracy is about 7.0 degrees. Each station has the Global Positioning System (GPS) as common clock, so the arrival times of EAS can be recorded with an accuracy of 1 μs. The data period used here is from August 1996 to December 1999. Under the shower restriction of the reconstructed zenith angle $\leq 45°$, about 2.2×10^6 showers are employed in this analysis. The profiles of stations and data are summarized in table I. It has been confirmed for all stations data that the arrival directions of all showers are distributed uniformly over the entire sky with fluctuation expected from statistics.

3. – Analysis and results

In order to investigate whether our EAS data contains non-random components, we count the number of detected EAS (N) within a time window (20–60 min.). After

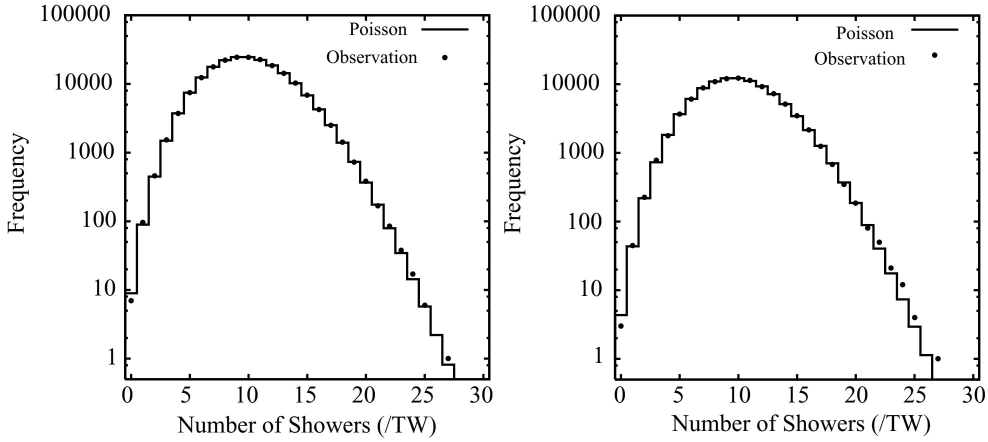

Fig. 1. – The N distribution for all data (left) and for data with higher N_{72} (right).

that, we compare the N distribution with the Poisson distribution. The N distribution will agree with the Poisson distribution if EAS data does not contain any non-random components, while some deviation is expected if it does.

In this analytical procedure, the width of a time window should be decided with great care. Since years-long EAS data involves the long-term fluctuation of the trigger rate, a constant value of widths of time windows does not work. Instead, we take variable widths of time windows. That is, first we fix the start time of a time window and count the number of EAS within 72 hours centered at this time (N_{72}). Next, we calculate the width of the time window so that the average of the N distribution is 10. The end time will be the start time of the next time window (that is, adjacent time windows are not overlapped). For example, the width of time windows for EAS data from OU-station varies between 25 min. and 35 min. in this procedure. Another merit of the use of variable time windows is that we can get N distributions with constant average of 10 from data sets that have different trigger rates.

This procedure is applied to each station's data set independently. The resulting N distributions are almost identical among all stations; very good agreement between observation and the Poisson distribution is obtained. Figure 1 (left) shows the N distribution of all stations'N distributions summed up. The observation is shown by circles, while the Poisson distribution is the histogram. No sign of non-random components is gained from this figure.

Here we will make an assumption. As well known, the long-term fluctuation of the EAS trigger rate is mainly due to fluctuations of the atmospheric condition and the detector condition. When the atmospheric pressure is low, the trigger rate is high. We assume that, when the trigger rate is high, the detector is more sensitive to lower energy cosmic rays, so that EAS data contains more non-random components. Thus we divide the total N distribution into two distributions; one for time windows with the higher half of N_{72} and the other for time windows with the lower half of N_{72}. As a result, the upward deviation of the observation from the Poisson distribution is found only for higher N_{72} and in the largest-N bins (fig. 1 (right)). In other words, the deviation from the Poisson distribution is observed when the EAS trigger rate is very high; this result is comparable with previous reports described earlier. We call events in these bins

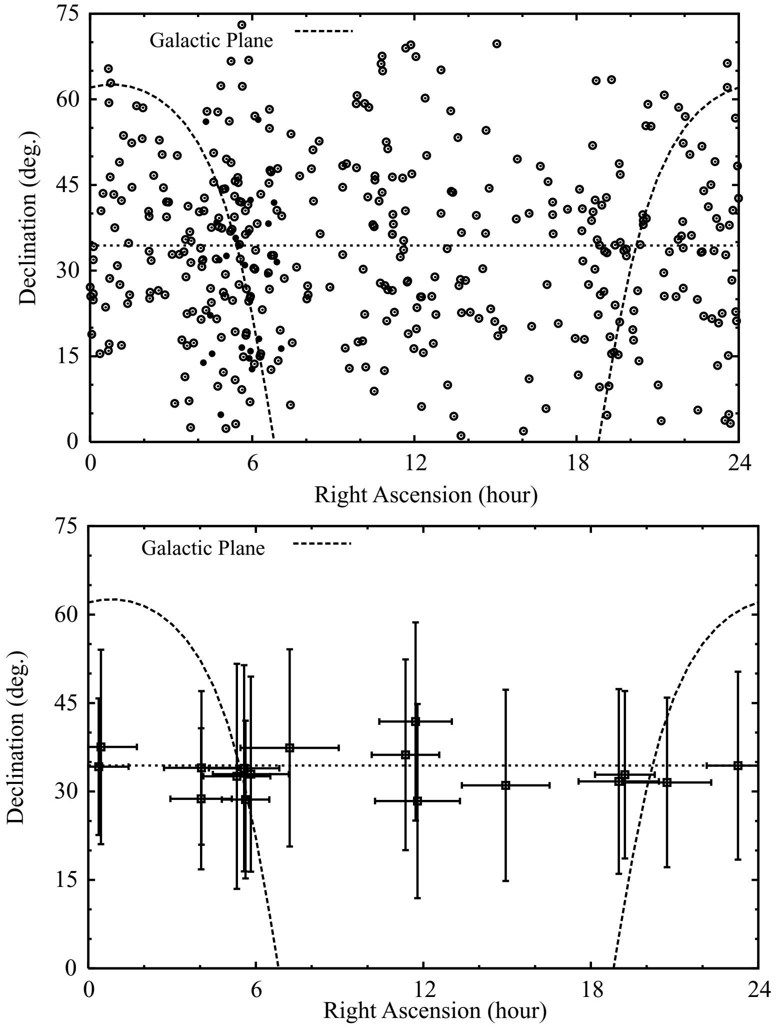

Fig. 2. – The arrival directions of SAS events of $N \geq 24$; every EAS (top) and averaged direction (bottom). Solid circles in the top panel show the typical dispersion of EAS in a SAS event.

"successive air shower" (SAS) events. Though the deviation is not so significant, we expect that this is due to sporadic non-random components in cosmic rays and proceed to the next step.

To investigate whether the SAS events have a connection with the Galactic plane as the "clustered events" by Katayose *et al.* do, we inspect their arrival directions. First, we plot the arrival direction of every EAS in the SAS events of $N \geq 24$ (17 events) in equatorial coordinates, as fig. 2 (top). It seems that the EAS density around the Galactic plane at right ascension (RA) of 5 hours is higher than that of other RA ranges. However, plotting every EAS in SAS events is problematic, because the arrival directions of EAS in a SAS event inevitably form a cluster around the sidereal time of the observation. Thus the fluctuation of EAS density will be exaggerated unless a large number of SAS events is used. At the same time, we cannot expect that signals from the Galactic plane will be plotted exactly on the broken line in this figure. For explanation of this, we show the typical dispersion of EAS in a SAS event by solid circles in the figure. Considering the angular accuracy of our arrays and the thickness of the Galactic plane, almost all EAS in this SAS event can be candidates for the signals from the plane. Moreover, we cannot distinguish γ-induced EAS from hadron-induced EAS. Therefore, the arrival direction of each EAS is not informative and treating all EAS as a cluster seems more reasonable.

In fig. 2 (bottom), we plot the arrival directions of the SAS events of $N \geq 24$ using the average and the standard deviation of RA and declinations of all EAS in each event. Now the concentration at the direction of the Galactic plane, especially at RA $= 5$ hours, can be seen more clearly. The chance probability of the concentration at the Galactic plane is calculated as 0.18 from this figure.

4. – Discussion

The deviation in fig. 1 (right) is small and is not so significant. We need more EAS data to judge whether it is due to real non-random components in cosmic rays or due to fluctuation.

Assuming that the deviation is due to real non-random components, fig. 2 suggests that the SAS events are attributed to some kind of emission from the Galactic plane, presumably UHE γ-rays. However, it is not necessary that all EAS constituting the SAS events are induced by γ-rays from the Galactic plane. The superposition of only a few γ-rays on conventional cosmic rays is enough to make up the SAS events, because the difference of the number of EAS belonging to the SAS events and the Poisson-distributed ones is small. Unfortunately the stations used here do not have muon detectors, so it is experimentally unknown whether the observed SAS events contain γ-ray–induced EAS.

5. – Conclusion

We perform a successive air shower analysis using six stations data of the LAAS group in Japan. When the trigger rate is very high, the upward deviation of the N (number of EAS in a time window) distribution from the Poisson distribution can be seen. The arrival directions of the SAS events concentrate at the direction of the Galactic plane, giving a chance probability of 0.18. These results are consistent with the recent report by Katayose *et al.* One possible interpretation is that we observed UHE γ-rays from the Galactic plane superimposed on conventional cosmic rays. However, the significance of the SAS events is not enough and we need more EAS data.

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