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Search for coincident air showers over a very large area

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Abstract. We are performing a network observation of air showers ($\overline{E}_0 \approx 10^{15}$ eV) since 1996 in Japan. Thirteen small-scale air shower arrays (stations) are scattered over a very large area of 130,000 km^2 in order to find out large-scale correlations in primary cosmic rays. Using air shower data from five stations of the network, we have searched for pairs of coincident air showers, hypothetically induced by ultra-high-energy γ-rays from point sources or by secondary particles from interactions of extremely-high-energy cosmic rays with interstellar matter. We find a coincident event with an extremely small time difference of 41 microseconds. Another intriguing event is observed in the direction of the Crab Nebula, a well-known ultra-high-energy γ-ray source. However, the significances of these events are not enough to claim the detection of large-scale correlation.

1 Introduction

The Large Area Air Shower (LAAS) group is performing a network observation of extensive air showers (EAS) since 1996 in Japan (Ochi et al., 2001a; Ochi et al., 1999). It has thirteen small-scale air shower arrays (stations) scattered over an enormous enclosing area of 130,000 km^2. The aim of the network observation is to find out large-scale correlations in primary cosmic rays.

In recent years, several groups reported their detection of large-scale correlation in arrival times of EAS. One of them is the University of Geneva group, who observed EAS by four stations separated by more than 50 km each other (an enclosing area of 5,000 km^2) (Carrel and Martin, 1994). The group found an unusual increase of coincident triggers among them with a typical time spread of 0.3 ms. In another report, the Kinki University group found the chaotic feature in arrival time intervals of serial EAS (Kitamura et al., 1997). The feature appeared simultaneously at three stations separated by more than 100 km. These large-scale correlations in EAS should be caused by large-scale correlations in primary cosmic rays. These new features of EAS can be important information for solving the mechanism of the formation and propagation of cosmic rays, if confirmed.

Here we take a simple approach to investigate large-scale correlation in EAS. We show results of the coincident event analysis using EAS data of the LAAS group. In this analysis we search for pairs of coincident EAS observed between stations separated by 1 – 900 km, as shown below. This paper describes an updated result from the previous one (Ochi et al., 2001b), with larger statistics.

A network observation of EAS which aims at the same goal as ours is in preparation now at CERN (Besier et al., 2000). They use the four detectors around the Large Electron-Positron Collider (LEP) to search for time-correlated EAS. The mutual distances between detectors are up to 8 km, and they cover an intermediate scale of about 60 km^2. It would be expected that their results and ours will be complementary to each other in the future.

The source of correlated cosmic rays is still an enigma. Among possible candidates are ultra-high-energy γ-rays from bursts of their sources and secondary particles from interactions of extremely-high-energy cosmic rays with interstellar matter. However, to date we have too little information about correlated cosmic rays to construct concrete models.

2 Network observation

In this paper we use EAS data collected at five stations of the LAAS group. They are Okayama University (OU), Okayama University of Science (OUS1), Kinki University (KU1), Nara University of Industry (NUI) and Hirosaki University (HU) (Ochi et al., 1999).

Each station has four to eight scintillation counters, as shown in table 1. The trigger conditions are different station-by-station: 3- to 8-fold coincidences, yielding the trigger rates of 309 to 1292 showers/day. The arrangement and trig-

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Table 1. The summary of station profiles

Station	HU	NUI	KU1	OU-a	OU-az	OU-b	OUS1-a	OUS1-b	OUS1-c
Latitude (N)	$40°35'$	$34°35'$	$34°39'$	$34°41'$	$34°41'$	$34°41'$	$34°42'$	$34°42'$	$34°42'$
Longitude (E)	$140°29'$	$135°41'$	$135°36'$	$133°55'$	$133°55'$	$133°55'$	$133°56'$	$133°56'$	$133°56'$
Distance from OU (km)	873	162	153	–	–	–	1	1	1
Distance from KU1 (km)	787	11	–	153	153	153	152	152	152
Number of Counters	5	7	5	8	8	8	4	8	8
Trigger Counters	5	7	5	5	3	3	4	8	4
Trigger Rate (/day)	566	367	446	566	1162	1292	725	309	724
Data Period	11/98 – 01/01	08/96 – 03/01	09/96 – 04/01	09/96 – 12/99	01/00 – 03/00	04/00 – 04/01	09/96 – 11/97	11/97 – 01/99	01/99 – 01/01
Number of Showers	413k	398k	652k	638k	99k	482k	270k	127k	478k

ger condition of OU array and OUS1 array were changed twice in the five years, so we treat the three periods independently as OU-a, OU-az, OU-b and OUS1-a, OUS1-b, OUS1-c. Mutual distances between stations are from 1.1 km to 873 km, so that plural stations can not be triggered by the same EAS. Most importantly for this analysis, each station has the Global Positioning System (GPS) as the common clock, so the arrival times of EAS can be recorded with an accuracy of 1 μs. Table 1 is the summary of the station profiles.

For OU array, the air shower simulation code CORSIKA (Ver.5.624 with EGS, QGSJET and VENUS options; Heck et al., 1998) is employed to evaluate the performance of the array. The primary energy range observed by the array is estimated to be from 50 TeV to 10 PeV with the mean energy at about 1 PeV. The angular accuracy is estimated to be 7.0 degrees (Ochi et al., 2001a). The primary energy range and angular accuracy of other stations are thought to be similar to these values.

This analysis is based on about 3.6×10^6 showers collected during the period from September 1996 to April 2001 with reconstructed zenith angles $\leq 45°$.

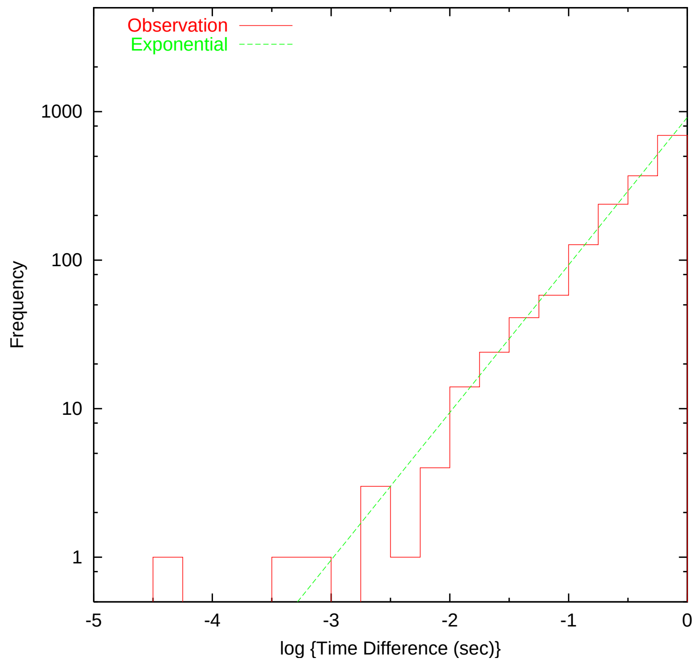

Fig. 1. The time difference distribution for OU-az and OUS-c.

3 Analysis and results

First we compare arrival times of EAS collected at two stations without directional restriction. Time differences between any EAS pairs in two stations' data are calculated and the distribution of them is drawn. This procedure is taken independently for any combination of two stations (31 station-pairs in total). As an example, figure 1 shows the time difference distribution for the combination of OU-az and OUS-c. As expected from chance coincidences, almost all events follow an exponential distribution (the broken line). In many cases, no feature but the bulk of chance coincidences can be seen in the distribution. However, as a rare case, there is an event of very small time difference, well separated from the exponential distribution, in figure 1. The time difference of this event is 41 μs and the chance probability of it is 0.040, which is calculated from the slope of the exponential distribution. Taking into account the number of station-pairs we search for, the chance probability rises to 0.71. Therefore, we can not claim that this event is due to correlation in primary cosmic rays. Table 2 shows events with very small time differences picked up by the procedure described above. No events in this table have significantly small time differences nor significantly small angular distances.

Next we search for EAS pairs with a small time difference and a small angular distance. The directional restriction of angular distance $\leq 10°$ is imposed to the EAS pairs. The resulting time difference distributions show almost identical feature with the previous ones. Again, there are several distributions which include very small time difference events. Figure 2 is an example of such distributions (OUS-b and KU1). Here the chance probability of the smallest time difference event (195 μs) is calculated as 0.010 from the slope of the exponential distribution and it becomes 0.28 when the number of station-pairs is taken into account. Table 3 shows events with very small time differences and angular distances $\leq 10°$. The 195 μs event has the very small angular distance of five degrees, which is within the angular accuracy of the arrays.

Table 2. The parameters of coincident event candidates (No directional restriction)

TD(μs)*	AD(deg)†	Stations	Date, Time‡	α (h)	δ (deg)	θ (deg)	ϕ (deg)
44	24.5	NUI→	09/26/99	6.7	11.9	24	157
		HU	79077	7.6	41.3	1	55
64	24.4	OU-az→	01/07/00	21.4	28.2	7	160
		HU	20057	22.8	13.5	29	204
41	20.8	OU-az→	02/07/00	22.5	20.9	29	112
		OUS-c	22729	23.4	5.2	32	153

* Time difference, †Angular distance, ‡Date (mm/dd/yy) and time (in seconds)

Table 3. The parameters of coincident event candidates (Angular distance $\leq 10°$)

TD(μs)*	AD(deg)†	Stations	Date, Time‡	α (h)	δ (deg)	θ (deg)	ϕ (deg)
256	10.0	OUS-a→	01/24/97	1.1	53.9	22	25
		NUI	32253	1.1	43.9	16	50
195	5.2	OUS-b→	09/24/98	4.9	18.0	19	151
		KU1	73332	5.4	18.6	16	167
212	9.1	OU-b→	07/04/00	3.6	22.5	17	227
		HU	82366	4.7	24.5	25	238
207	8.4	OU-b→	10/11/00	6.9	31.7	4	134
		OUS-c	74992	7.5	35.2	5	277

* Time difference, †Angular distance, ‡Date (mm/dd/yy) and time (in seconds)

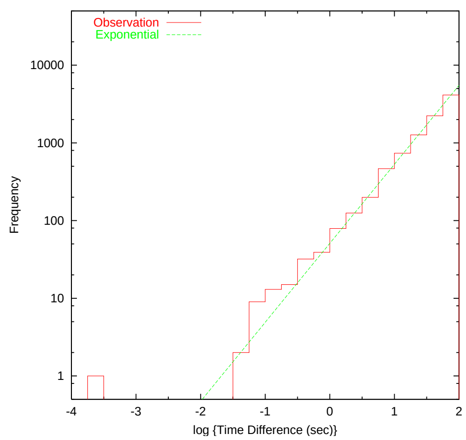

Fig. 2. The time difference distribution for OUS-b and KU1 (Angular distance $\leq 10°$).

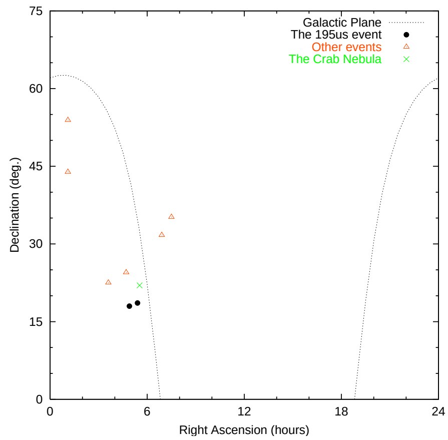

Fig. 3. The arrival directions of events shown in table 3.

Moreover, we inspect the arrival directions of these events. Figure 3 shows the arrival directions of events in table 3 in equatorial coordinates. The broken line shows the Galactic plane and the cross indicates the direction of the Crab Nebula. The 195 μs event is very close to the Crab Nebula. Though we can not claim that this event came from the direction of the Crab Nebula with the sufficient angular accuracy, one possible explanation for this event is that it was induced by the ultra-high-energy γ-rays from it.

4 Conclusion

We search for coincident air showers between stations separated by 1 – 900 km. The smallest time difference is 41 μs. An event with a very small time difference of 195 μs and the smallest angular distance of 5.2 degrees is found. The Crab Nebula, a well-known ultra-high-energy γ-ray source, is within the angular accuracy from the arrival direction of this event. However, the significance of these events are too low to claim the detection of large-scale correlation in cosmic rays. We need to accumulate more EAS data to confirm or disprove the existence of the correlation in cosmic rays.

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