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Search for Coincidental Air Showers from the Direction of the Crab Nebula Using the Network Observation

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Abstract

We have searched for pairs of coincidental air showers, possibly induced by ultra-high-energy (E>50 TeV) gamma-rays from the Crab Nebula, using the data sets recorded at four stations of the LAAS group over the period from 1996 September to 1999 January. The motive for this analysis is the presence of a pair of air showers which has a mere arrival time difference of 195 μs and shower directions adjacent to the Crab. The significance of the excess from the direction of the Crab is 2.1 σ. We think that we need to accumulate more air shower data and improve analytical procedures.

1 Introduction:

The Crab Nebula is widely confirmed as a TeV gamma-ray source, as shown by several air Cherenkov telescopes. A recent report by the CANGAROO group (Tanimori et al., 1998) indicates that the spectrum extends to at least 50 TeV, beyond which standard air shower arrays become usable. In air shower experiments, however, isotropic cosmic-rays as backgrounds overwhelm small signals from the Crab. Therefore we need to enhance the signal to background ratio by eliminating cosmic-ray-induced showers selectively. A conventional method to do this is the muon method, in which muon-rich showers are rejected, assuming that gamma-ray-induced showers contain fewer muons. Unfortunately, because of a limited collection area of muon detectors this method is far from success. Several attempts by up-to-date sophisticated arrays failed to detect signals from the Crab (Borione et al., 1997; Alexandreas et al., 1993; Amenomori et al., 1997), except for the observation of a burst on 1989 February 23 (Alexeenko et al., 1992).

In this paper we take another approach to pick out signals from a sea of backgrounds. We direct our attention to pairs of coincidental air showers, even though to our knowledge no theoretical predictions for such events exist.

The models inside the Crab that can produce the hard gamma-ray spectrum observed by the CANGAROO group are still controversial. If our approach results in success, the feature of coincidental air showers places a strong constraint on them.

2 Experiment:

The Large Area Air Shower (LAAS) group consists of eleven air shower arrays (stations), and each of them has four to 22 scintillation counters. Each station is equipped with the Global Positioning System as a common clock, which can record arrival times of air showers with accuracy of a microsecond. The shower directions can be determined with resolution of typically five degrees. Energy thresholds are estimated to typically 100 TeV. A more detailed description of the experiment can be found elsewhere (Ochi et al., 1999).

This paper describes the analyses of data taken at four stations out of eleven. They are Okayama University (OU), Okayama University of Science (OUS), the No.31 building of Kinki University (KU1), and Nara University of Industry (NUI). Their locations are distant by 1 to 162 km, thus each data set can be treated as independent. The data sets span the period from 1996 September to 1999 January, and contain a total of about $1.45*10^6$ air showers.

3 Analysis: Coincidental Event of Time:

Before describing the analysis focused on the Crab, we will show the results from a preceding analysis. In this analysis, we searched for pairs of air showers of which arrival times are very close (time difference smaller than 300 μs). We call such a pair “TC event”. No directional restriction is imposed. If a bulk of primaries enters the atmosphere and induces a number of air showers simultaneously over very large area, they can be detected by this analysis. Historically, a network observation of air showers was made up in Switzerland, and a similar analysis was performed. However, their result was a negative one (Carrel, & Martin, 1994).

By comparing arrival times of air showers detected at different stations (typical trigger rate 0.3/min.), nine TC events with time difference smaller than 300 μs were extracted. Among them, the smallest time difference of 47 μs was seen between OU and NUI, which are 162 km apart. The chance probability of observing a time difference as small or smaller than 47 μs is 0.71, which is consistent with statistical fluctuations.

As a next step, we computed angular distances between the shower angles of each pair. Eight TC events, including the 47 μs event, had angular distances larger than 9.9 degrees; they are considered accidental coincidences and to have no physical implication. The remaining TC event of 195 μs, recorded between OUS and KU, which are 152 km apart, had the angular distance of 5.4 degrees; the only event within the angular resolutions.

Figure 1 shows the frequency of time difference of air shower pairs of which shower angles are very close (angular distance smaller than 6 degrees). As expected from statisticians, the number of chance pairs increases exponentially with time difference. By fitting a straight line to the background distribution, we got the chance probability of 0.09 for the 195 μs event mentioned above.

In Figure 2, the arrival directions of the nine TC events (eighteen air showers) are plotted in equatorial coordinates. Intriguingly, the 195 μs event is adjacent to the Crab Nebula (R.A.=5.58h, Dec.=20.0 degrees), which suggests that the event was induced by a bundle of ultra-high-energy gamma-rays from the object.

We assumed in the following analysis that a substantial part of ultra-high-energy gamma-rays from the Crab is in the form of bundles, thus signals will be enhanced by selecting pairs of air showers with small time differences and similar shower angles each other.

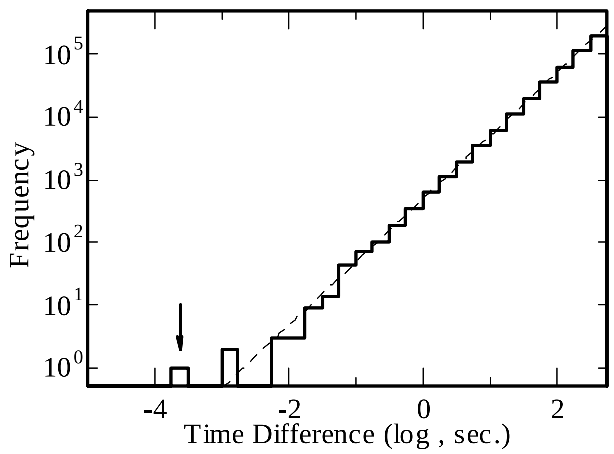

Figure 1: The frequency of time difference of air shower pairs that have angular distances smaller than 6 degrees.
Dashed line: a fit to the histogram except the 195 μs event (*arrow*).

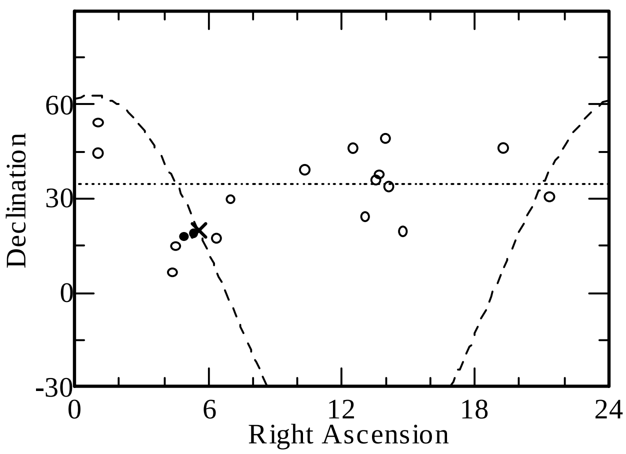

Figure 2: The arrival directions of the TC events (see text). *Solid Circles*: the 195 μs event. *Open Circles*: the eight other events. *Cross*: the Crab. *Dashed Curve*: the Galactic plane. Latitude of stations is +35°.

4 Analysis: Coincidental Event of Time and Direction:

This analysis is based on a pair of air showers which has a time difference smaller than a threshold value TD (TD varies from 0.125 to 64 seconds) and angular distances from the nominal source position (α_s) smaller than Ψ. We call such a pair "TDC event" assigned to α_s. In other words, longer TD than that of the preceding analysis is allowed by the restriction on shower angles. Ψ corresponds to a radius of a circular search bin and varies from 5 to 9 degrees dependent on the angular resolution of each station.

We have carried out a search for an excess of TDC events from the direction of the Crab by comparing the number of events in the source bin to the number of backgrounds estimated. Figure 3 shows a scan in right ascension for a band of declination centered on the Crab, for TD=16 sec. In the scanning, α_s was increased by a step of 0.10h, and the numbers of TDC events were accumulated in 24 bins of an hour each. A pair was not doubly counted. The number of events in any bin of Figure 3 is a total of the Ψ-weighted number of TDC events of all station-pair. The background estimation was performed as follows. For each α_s, the horizontal coordinates (θ,φ) of the source position is calculated and the corresponding frequency of air shower is extracted from the normalized real zenith angle distribution. The product (denoted by F) of this frequency, the trigger rate at that time, and the area of a search bin is proportional to the expected number of background showers for the α_s . Furthermore, the product $F_1 {*} F_2$ is proportional to the number of chance TDC events, here the subscripts represent different stations. Finally, this value is accumulated in 24 bins of R.A. every 12 minutes over the data period, and the total number is normalized to that of the real events.

In Figure 3, the bin containing the Crab (indicated by an arrow) has the maximum excess, though the significance is not so high. In this bin 50 excess events are observed above the estimated background of 569, corresponding to 2.1 σ. Figure 4 shows the distribution of significances derived from Figure 3. Here we define the significance as a ratio of the excess above background to its standard deviation. The distribution agrees well with a standard normal distribution, suggesting the correctness of background estimation.

The variation of significances for each bin is shown in Figure 5 as a function of TD. The number of chance TDC events is proportional to TD. In Figure 5, the number of TDC events is accumulative with TD, thus adjacent significances are not independent. The largest excess from any of bins is 3.2 σ, calculated for TD=32 sec. and R.A.=11–12h. However, the significances for the Crab bin are high all through the TD range; an average of significances for each bin over the TD range takes the highest value for the Crab bin.

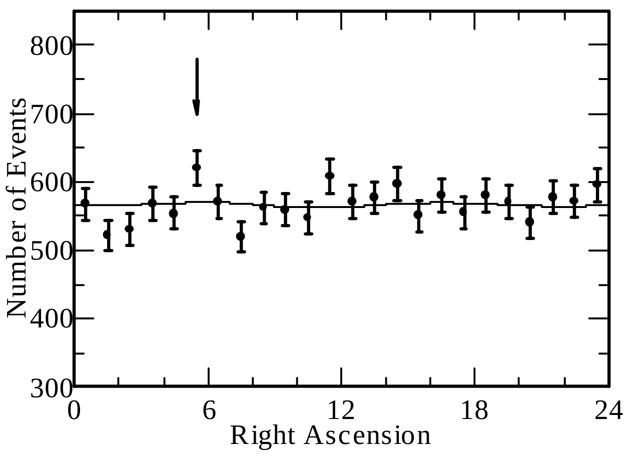

Figure 3: Scan in right ascension for a band of declination centered on the Crab, for TD=16sec. *Points*: data. *Histogram*: background. *Arrow*: the bin containing the Crab. The error bars show a 1σ fluctuation of the signal.

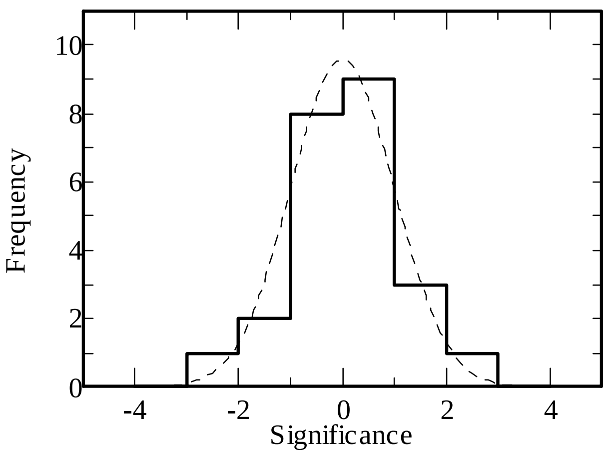

Figure 4: The distribution of significances derived from Figure 3. *Dashed Curve*: a standard normal distribution.

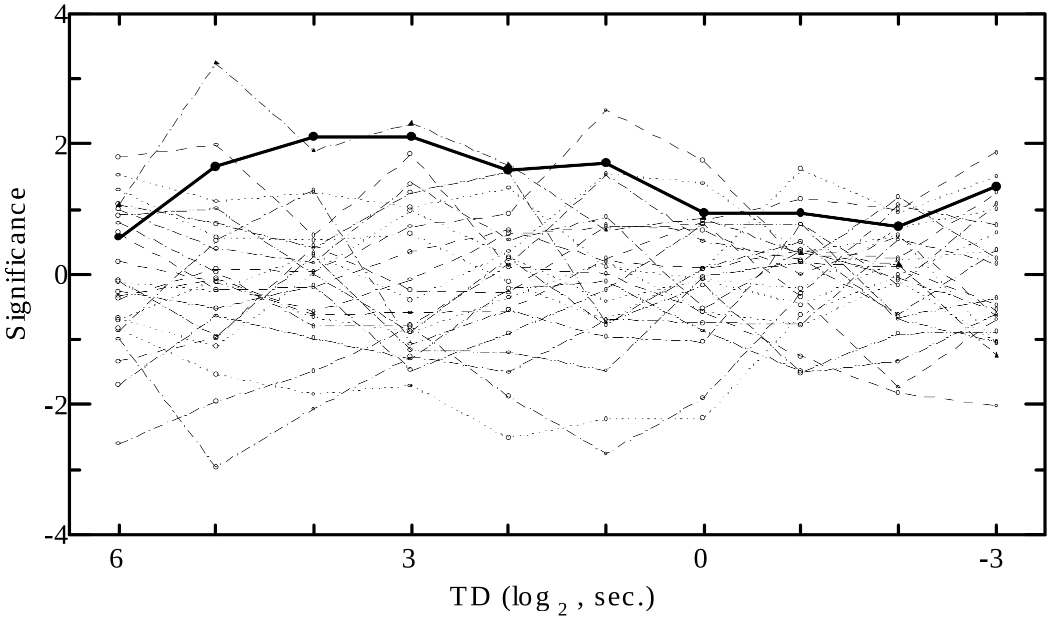

Figure 5: TD dependence of the significance of excess of TDC events for each bin. *Solid Curve*: for the Crab bin. *Other Curves*: for the 23 other bins.

5 Conclusion:

We have searched for pairs of coincidental air showers, possibly induced by ultra-high-energy gamma-rays from the Crab Nebula, using the data sets recorded at four stations of the LAAS group over about two years. The significance of the excess from the direction of the Crab is 2.1 σ for TD=16sec., which is too weak to claim the detection. However, the presence of the 195 μs event and the highest value of the average significance in Figure 5 could be taken as hopeful signs. We think that we need to accumulate more air shower data and improve analytical procedures and the background estimation algorithm.

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