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A search for bursts at 0.1 PeV with a small air shower array.

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The Cosmic Ray Extremely Distributed Observatory (CREDO) pursues a global research strategy dedicated to the search for correlated cosmic rays, so-called Cosmic Ray Ensembles (CRE). Its general approach to CRE detection does not involve any *a priori* considerations and the search strategy encompasses both spatial and temporal correlations, on different scales. Here we search for time clustering of the cosmic ray events collected with a small sea-level air shower array at the University of Adelaide. The array consists of seven one square metre scintillators enclosing an area of 10 m x 19 m. It has a threshold energy ~0.1 PeV, and records cosmic ray showers at a rate of ~6 mHz. We have examined event times over a period of almost two years (~294k events) to determine the event time spacing distributions between individual events and the distributions of time periods which contained specific numbers of multiple events. We find that the overall time distributions are as expected for random events. The distribution which was chosen *a priori* for particular study was for time periods covering five events (four spacings). Overall, this fits closely with expectation but has two outliers of short 'burst' periods. One of these outliers contains eight events within 48 seconds. The physical characteristics of the array will be discussed together with the analysis procedure, including a fit between the observed time distributions and expectation based on randomly arriving events.

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1. Introduction

It is usual to treat the arrivals of high energy cosmic rays as independent processes with their modulation in space and time determined only by the directions of their sources and the rotation of the Earth. However, this leaves a region of observational space which may not have been well investigated for observations of charged cosmic rays. That is, the possibility of short-term time correlations, bursts. The CREDO project [1] has a number of facets broadly related to searching for correlations within cosmic ray arrival time series and one thrust of that project is to investigate possible short-term time correlations. Clearly, the deflections of charged particles in interstellar and intergalactic magnetic fields preclude a useful memory of time correlations of events at the source, but more localised processes such as primary particle break-up in transit, or more nearby interactions of uncharged messengers, could result in spatial and temporal correlations.

Cosmic ray showers were discovered in the 1930s [2] and many searches for 'bursts' in the cosmic ray beam have been made over the past 50 years since gamma-ray bursts were discovered by the Vela satellites [3], and theories such as that of Hawking (1974) [4] have suggested numerous possible burst mechanisms. Early important reports were those of Fegan *et al.* (1983) [5] and Smith *et al.* (1983) [6]. There have now been many searches for non-random effects in cosmic ray arrival times but with diverse selection criteria and rarely with *a priori* selection criteria such that statistical significances could be confidently derived (e.g.[7,8,9]). Searches have covered periods as short as a few microseconds, and as long as days, since gamma-ray primary particles might be found in bursts which have times up to tens of seconds, or correlated times of charged cosmic rays could extend over very long periods depending on the distance from a possible original particle break-up.

Our aim here is to report a search for temporal correlations (bursts) with a small air shower array sensitive to cosmic particles with energies above ~0.1 PeV. The small dimensions of an array predominantly sensitive to the electromagnetic component of air showers preclude good individual event arrival direction determinations but merely the arrival time of a burst and the knowledge that this component is strongly attenuated at large zenith angles gives some directional limits. Our *a priori* choice of the selection of a burst was five events (four spacings) within 10 seconds. We will describe the observation of two such bursts, one of which probably has unacceptable properties, plus some related bursts with less stringent selection criteria.

This paper will describe our small array for the detection of cosmic ray air showers, describe our search for event time correlations over a recording period approaching two years, and discuss the interpretation of our data including the less stringently detected 'bursts'.

2.1 The Adelaide "Roof Array"

A small air shower array was built 20 years ago in the roof space of the Physics Department of the University of Adelaide (34.6^{o} S). Its basis is seven one square metre scintillators originally used in the Buckland Park air shower array. Those scintillators, housed in light-tight boxes, were each of thickness 50 mm and were each viewed by two photomultipliers, one for timing (2 ns risetime) and one for amplitude measurement. The purpose of the array was for use in advanced undergraduate teaching It is not temperature controlled, its directional precision is very limited, and event timing relevant to this paper is to one second accuracy using an internet synchronised computer clock.

The scintillator arrangement is with three scintillators in each of two rows of length 18.7 m separated by 9.7 m with a, roughly central, seventh scintillator. This arrangement was constrained to fit within the existing roof space. Event triggering employed fast discriminators (better than 1 ns timing) and required three triggered scintillators having detected particles (thresholds at ~1.5 particle level) including the central detector. This gave an overall event rate of about 6 mHz. The shower size threshold was about 10^4 particles, corresponding to ~ 0.1 PeV primary energy if the primary particles were protons. Relative detector trigger times were recorded to better than 1 ns. There was a dead time of ~0.5 s per event for CAMAC data transfer and other overheads. This means that the requirement for five events in 10 seconds was actually 5 events in a sensitive time of ~8 s.

For this work, the array was maintained in a stable manner (with occasional down time for maintenance or power interruptions) from 2019 May 21 21:55 UTC to 2021 Feb. 12 17:31 UTC. In that time ~294k events were recorded.

2.2 Event Spacing Distributions

We have examined our ~294k event dataset to study the distributions of time intervals between groups of events. The intervals between individual events should have an exponential distribution with the exponent being related to the mean event time spacing. This exponential is shown in red in figures 1 and 2.

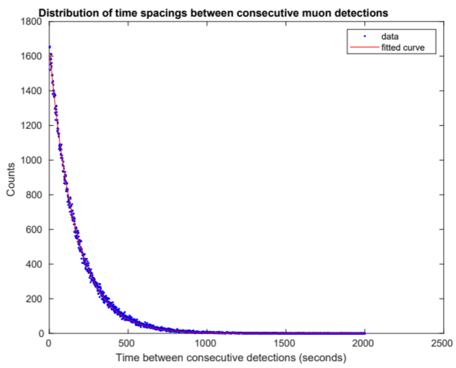

Figure 1. The distribution of times between successive events. The solid red line is the fitted exponential distribution.

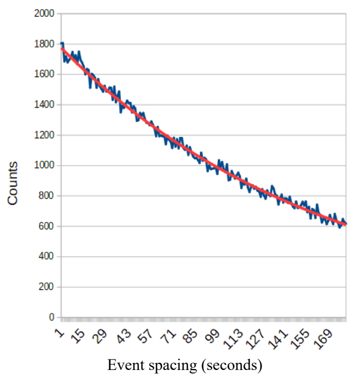

Figure 2. Expansion of figure 1 (excluding the first channel which is reduced due to dead time effects). The distribution of times between successive events is shown. The solid red line is the fitted exponential distribution.

The distributions for times covering multiple events can be derived and curves fitted to times covering three events and five events are shown in figures 3 and 4.

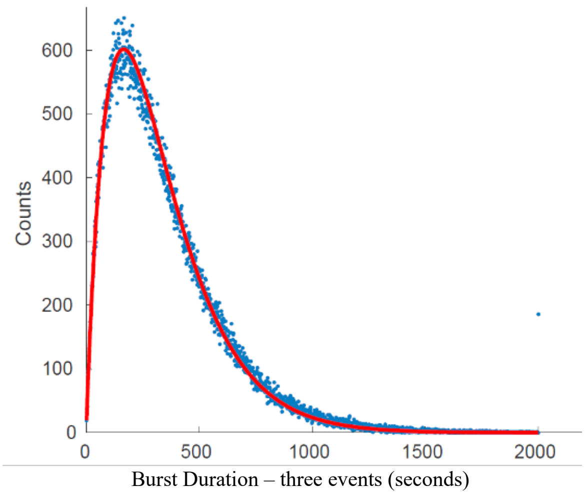

Figure 3. The distribution of times (seconds) covering three events. The solid red line is the expected curve based on the event rate for the data fitted in figure 1.

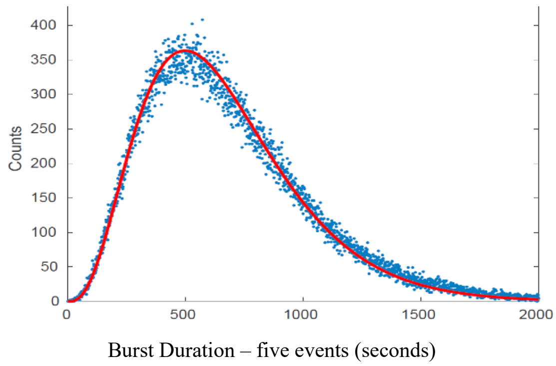

Figure 4. The distribution of times (seconds) covering five events. The solid red line is the expected curve based on the event rate for the data fitted in figure 1.

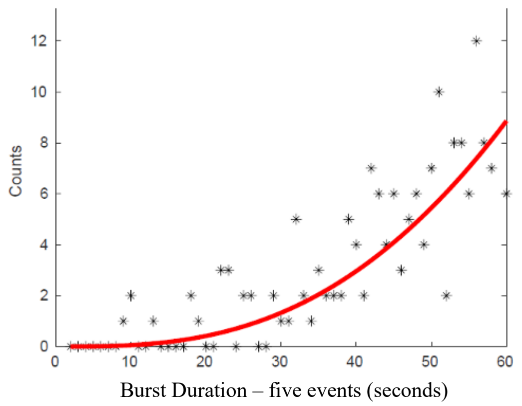

Figure 5. The distribution of times (seconds) covering five events (expansion of figure 4). The solid red line is the expected curve based on the event rate for the data fitted in figure 1.

The fit for five events (four spacings) is shown as an expansion in figure 5. There are two ‘bursts’ when the times covering the bursts are below 10 s (one long burst appears as two counts in the figure).

2.2 Interpreting the two bursts

The two 'bursts' fitting the *a priori* criterion occurred at 2019 June 18 05:15 UTC (six events in total from 05:15:53 to 05:16:03) and 2019 July 19 18:47 UTC (8 events in total from 18:47:42 to 18:48:30). The corresponding array local sidereal times were 9.36 h and 0.97 h, being the right ascensions of the array zenith at those times. The events in the 19 July burst seem to be broadly as expected. All have good timing data, all have some signal in a nearby small particle calorimeter, and most have signals in a 1 m^2 detector below the array. The June 18 events have good particle density signals, including the detector below, but there is no consistency within the timing triggers and no signals were recorded in the small calorimeter. These are highly unusual characteristics.

We are confident that one (19 July) of these 'bursts' is 'real' and, from the expected distribution, we can examine the probability of finding 'bursts' covering four spacings (five events) within 10 s in a dataset of 294k events. The probability of one such burst occurring (allowing for 0.5 s dead time per event) is $2x10^{-7}$ and, with 294k events, the likelihood of our observing such an event by chance is then ~6%, not significantly unlikely. If both burst candidates could confidently be interpreted as astrophysical, their combined significance would be outside 5σ limits. We note that the 19 July burst could be regarded as having significantly exceeded the *a priori* criterion since it probably contained more than five events in total, with spacings (s): 6, 18, 14, 3, 0 ,6, 1. That is 8 events in a period of 48 s within a dataset having a mean single event time spacing of ~160 s.

2.3. Additional Data

The data period discussed above was specifically determined for astrophysics using the *a priori* criterion and attempts were made in that period to ensure the stability of the systems. However, before this period, the array was collecting data, but with less quality control. Incorporating those additional data gives a full dataset of 466727 events from 2017 October 03 and the previous analysis was performed on the additional dataset. Three more 'burst' events were found. All three were in the earliest period in which the event rate was higher (0.01 Hz) due to a requirement of only two triggering timing detectors (three for the data discussed previously). The events had mean shower sizes/primary energies of about one half of the previously discussed events. However, we note that it happens that all events in these bursts would have satisfied the previous more stringent triggering criteria and, unlike the June 18 events, show no unusual characteristics. Those bursts occurred at 2017 October 08 10:35 UTC, 2017 October 10 23:00 UTC, and 2017 October 29 11:39 UTC.

3.1 'Burst' Directions

In total, five possible bursts have been found. Many of the events within them had arrival directions which the array could determine. However, the array has a characteristic angular uncertainty which is large (~20° but not uniform in azimuth) due to the small size of the array and the timing thickness of the shower front. Figure 6 shows a sky map of those directions which could be determined. They are not obviously randomly distributed but this is not necessarily surprising as only five 'bursts' were found.

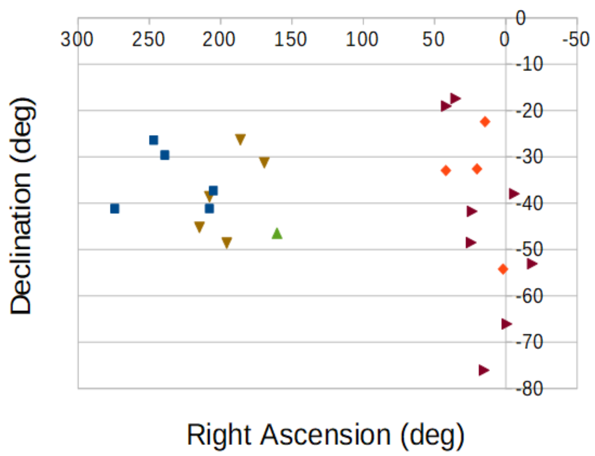

Figure 6. Scatter diagram of burst event arrival directions from five bursts. Purple: 2019/07/19 Green: 2019/06/18 Blue: 2017/10/29 Red: 2017/10/10 Brown: 2017/10/08

4. Conclusions

A search has been made for bursts in the time series of southern hemisphere cosmic ray events with an energy threshold of about 0.1 PeV. The criterion for a burst was that there should be five events (four spacings) within a period of 10 s from a time series with a rate ~6 mHz and an event dead time ~0.5 s. Two bursts were recorded in 294k events. One burst did not fit with normal operational data and was not considered in probability calculations The probability of the remaining burst occurring by chance is ~$2\times10^{-7} \times 2.94\times10^{5}$ or about 6%.

In an earlier period, whilst the array was not so well controlled, a further three possible bursts were recorded.

5. Future Work

Our current burst procedure has been to look for multiple events within a short time interval. An alternative procedure, consistent with the philosophy of the CREDO program is to search for coincident events which are spatially separate. We have improved our roof array event timing to millisecond uncertainty and we are about to instrument a second system at a distance of 45 km in order to search for coincident, but spatially separated, events.

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