SEARCH FOR COSMIC RAY BURSTS AT PEV ENERGIES*

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Over the past forty years, there have been occasional reports of the observations of 'bursts' by small air-shower arrays operating at energies of about 1 PeV. These would seem to be of astrophysical origin and related to the thrust of studies pursued by the CREDO program. The bursts are rare and few burst searches have extended past a time required to record more than a handful of potential events. There have also been discussions of the burst data which offer alternative non-astrophysical explanations. This paper will critically review some burst results, which may suggest that interesting burst events have been detected at a rate of ~ 1 per year. If these exist, the astrophysical processes of their origin need to be examined and some possibilities will be briefly discussed in the paper.

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1. Introduction

Cosmic rays are predominantly highly energetic charged nuclei and are not usually considered to have significant time or geographic correlations since their sources are expected to be at great distances and the primary particles reach us after passing through turbulent galactic magnetic fields. There is a component of gamma-rays and neutrinos which do not suffer such scattering but these only represent a small (but important) component of the total flux. Bursts of gamma-rays have been studied for many decades. These have total durations from seconds to minutes but bursts of charged cosmic rays have not been expected and have rarely been the subject of searches.

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The study of cosmic ray showers continues to be a core component of the field of high-energy astrophysics. There have been occasional reports of unexpected time and spatial correlations in the arrivals of cosmic ray showers above energies of a fraction of one PeV, and early important reports of bursts found in the records of cosmic ray showers were those of Fegan *et al.* [1] and Smith *et al.* [2]. Those early reports described transient increases in the rate of recorded showers (at spaced recording stations [1] and at a single station [2]), which were found in multi-year datasets. A number of further searches have been made 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.* [3–6]). Such searches have covered potential burst periods as short as a few microseconds and as long as days. Correlated arrival times of charged cosmic rays could extend over very long periods depending on the distance from a possible initiating particle break-up.

The CREDO project [7] 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. It has been suggested that relatively local processes such as primary particle break-up in transit, or nearby interactions of uncharged messengers, could result in spatial and temporal correlations.

This paper discusses one particular burst recorded with a small air-shower array at the University of Adelaide, together with an analysis of arrival data for events recorded over several years by the University of Adelaide Buckland Park array.

2. Burst data

2.1. Adelaide Roof Array

The Adelaide Roof Array is a small air-shower aray consisting of seven one square metre scintillators with arrival directions determined by shower front fast timing and shower sizes estimated from particle densities. The array has been discussed in some detail in Refs. [8] and [9]. The events have a mean long-term rate of $\sim$ 6 mHz (mean time spacing $\sim$ 166 s) and a total of about 450 k events (in two periods with 300 k and 150 k events, respectively) have been recorded over almost three years. With *a priori* selection criteria (five events in specified time periods), three bursts were found and were described in the previous papers [8, 9]. One 'burst' was found to substantially exceed the *a priori* time criterion (arrival time: 2019 July 19 18:48:06; mean R.A. 1 h 43 m, mean dec -37 deg).

The eight events in this burst arrived with between-event spacings of 6, 18, 14. 3, 0, 6, 1 s with spacings immediately prior being 190, 98, 267 s and spacings following being 99, 119, 134 s. The mean underlying spacing for that time with pressure and temperature correction would have been 137 s (showers have an attenuation length of $\sim$ 0.2 atmosphere and variations of atmospheric pressure at the millibar level can appreciably change the underlying rate). Figure 1 shows the expected (based on a toy Monte Carlo calculation for 3 million events) and the observed number of events as a function of the time taken to record 8 events. The figure shows a differential distribution with an excess at very short time intervals, the shortest being this burst with eight events covering only 49 s. In the figure, there are results from Monte Carlo calculations based on the average spacing in the dataset (166 s), the expected spacing for the day of the burst based on local temperature and atmospheric pressure (138 s), and the shortest average spacing found in a day within the dataset (120 s). The extreme calculation (120 s) has its lowest time for eight events (in 3 million trials) as 54 s, still longer than the observed burst.

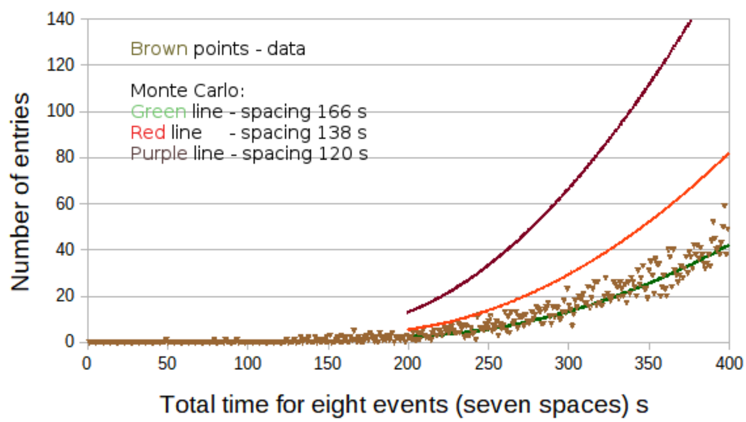

Fig. 1. Plot of eight-event burst durations for 300 k roof array events. The lines are Monte Carlo calculations based on a number of relevant mean event spacings as discussed in the text (each calculated from 3 million events).

The eight events in this unusual burst appeared to be 'normal' events. The trigger requirement for each event was three detectors, including the central detector in the array. In the burst of eight events, only seven out of 56 possible individual detectors did not trigger and there was internal consistency between trigger times within events (timing uncertainty $\sim$ 2 ns). Despite this, with an array of small dimensions, the angular uncertainty for individual events was probably $\sim$ 10–20 degrees. At the time of examining those events, even with a poor angular resolution, it was concerning that the burst event arrival directions were not closely spaced on the sky.

2.2. Buckland Park array

The Buckland Park air-shower array [10] began operating in 1972 and was progressively developed and extended until the mid-1980s (Fig. 2). It was originally used for studies of radio emission from air showers and anisotropy studies close to the knee of the cosmic ray energy spectrum. With an improved angular resolution, it was operated in the 1980s, additionally, for source direction searches. It ran stably in its final form from 1984 to 1989. It was a sea-level scintillator array with a collecting area $\sim 40,000$ square metres, a threshold energy of a few hundred TeV, and an angular resolution of ~ 1 degree. The array field of view was strongly collimated vertically with a median zenith angle of ~ 19 degrees.

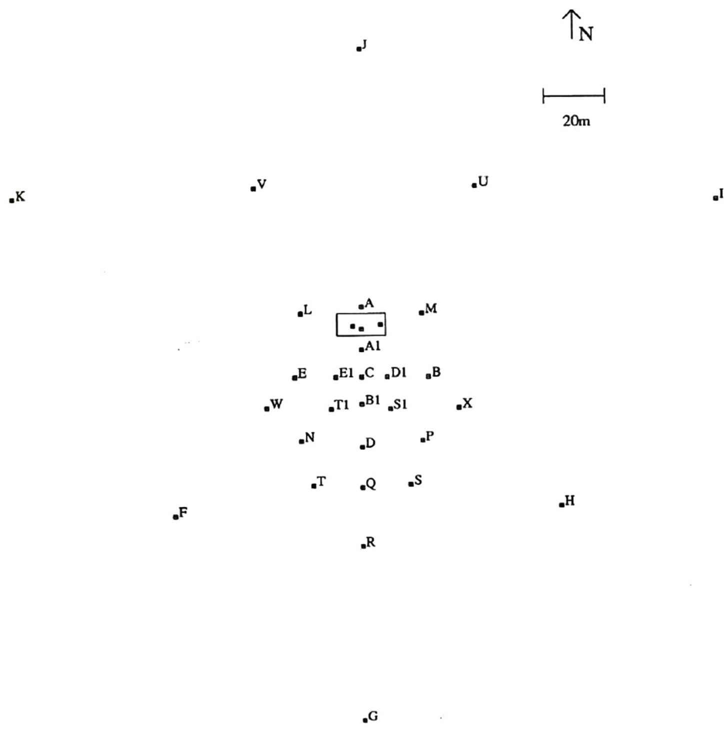

Fig. 2. Plan of the Buckland Park air-shower array as it operated in 1984–1989. Most of the detector sites housed one square metre scintillators. The inner detectors were capable of fast timing. All detectors were used for measuring particle densities.

2.2.1. Searching for bursts with Buckland Park

From 1984 to 1989, the array recorded ~ 7 million events whilst in a stable configuration. The mean event time spacing was 12.7 s which can be found from exponential fits to event spacing distributions such as in Fig. 3.

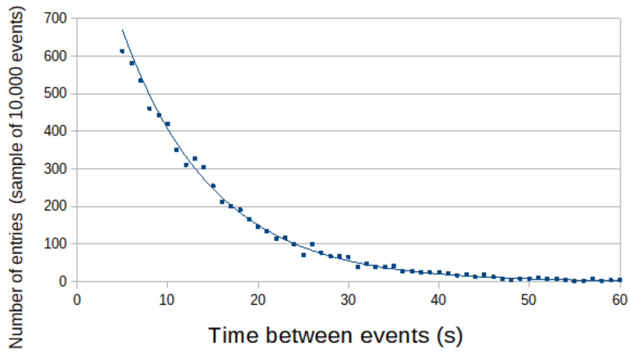

Fig. 3. Plot of the distribution of times (s) between Buckland Park events. An exponential fit to the distribution can provide a long-term mean event spacing (12.7 s).

This array had an event rate over ten times greater than the Adelaide Roof Array and a different *a priori* burst selection criterion was necessary. Monte Carlo studies suggested that a suitable criterion for accepting bursts would be to demand ten events within a time of 15 seconds or less. A burst duration of 16 s was also unlikely by chance and any bursts with this duration may also warrant future study. The studies described here initially assumed an event recording deadtime of 750 ms and a mean event spacing of 12.7 s. Two bursts were found with a time duration of 14 s in the 7 million events (Julian Times: 2446046.244005 and 2446634.633275) and six bursts had a duration of 15 s. The event arrival time resolution was 1 s. The events in these bursts were generally fitted well in shower analyses but a conservative event selection removed event lateral distribution fits with values of reduced chi-squared greater than 2.5 (Fig. 4). These were then well-fitted real events. Figures 5 and 6 show skymaps of the remaining events in these 'bursts'.

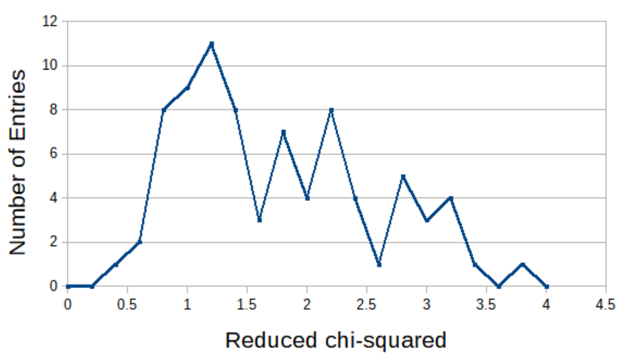

Fig. 4. Plot of the chi-squared distribution for burst events with times 15 s or less. A value of 2.5 was selected as a conservative cut.

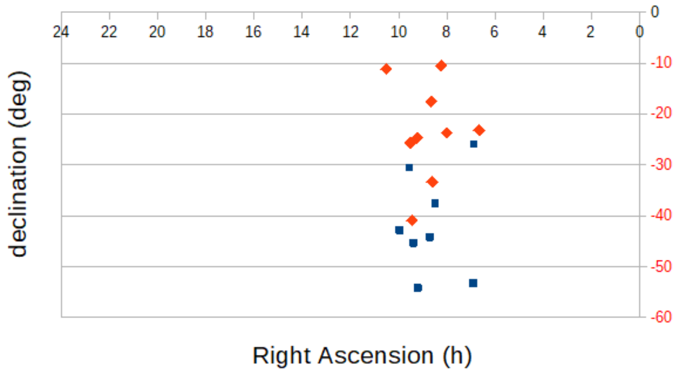

Fig. 5. (Colour on-line) Skymap of the Buckland Park events which were in bursts fitting the criterion of (at least) 10 events within 14 s ONLY. The bursts are identified by different colours (1984 event — blue squares, 1986 — red diamonds). Two events were removed due to poor fits.

Monte Carlo modelling of 7 million events with the event spacing expected for the local atmospheric pressure of 1008 mb (the same for both 14 s bursts and lower than the average of 1013 mb) gave no 14 s bursts and only two 15 s bursts.

Whilst the skymap in Fig. 5 contains only two bursts (14 s burst duration), it is notable that the local sidereal times of the array for the events (separated by two years) were very close (8.24 h and 8.76 h). The Fig. 6 skymap is for the events within the six '10 event' bursts which were contained in 15 s. Those directions are much more spread but, notably, still have many events at about 10 h Right Ascension.

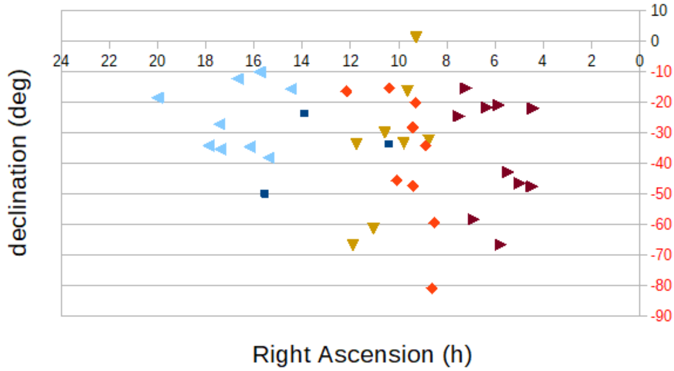

Fig. 6. (Colour on-line) Skymap of the Buckland Park events which were in bursts fitting the criterion of 10 events within 15 s ONLY. The bursts are identified by different colours. 14 events were removed due to poor fits.

3. Discussion

A previous paper described three bursts of cosmic ray showers recorded by the Adelaide University Roof Array (including the one described here). This paper describes a number of additional bursts which were found in the archive of the Buckland Park air-shower array. All the bursts which have been found were consistent with *a priori* determined selection criteria. For the Roof Array, the selection criteria suggested that the bursts would have occurred by chance with a probability below 1/10,000. The Buckland Park toy Monte Carlo calculations, using the rate corrected for local atmospheric pressure, did not yield any bursts as short as the observed 14 s.

The arrays were very different in size and event spacing but had similar cosmic ray energy thresholds of a fraction of one PeV. The events themselves, within the bursts, did not show exceptional properties which might have suggested that they were affected by local electrical (or other) disturbances. There was no exceptional meteorological condition at the time of any burst.

The two events with durations of 14 s from the Buckland Park dataset occurred at close-by sidereal times which could be of astrophysical interest. However, those times and their corresponding Right Ascensions were quite different from that of the Roof Array event (~ 2 h sidereal).

Whilst the bursts appear statistically unlikely in themselves, it is very difficult to understand the astrophysics which would result in a burst of cosmic ray events being localized in time to seconds but spread in arrival directions. This could result from relatively local interactions of some sort [11] but time spreads of a few seconds are incompatible with a local interaction resulting in directions which cover a very large range [7].

4. Conclusions

Datasets from two cosmic ray air-shower arrays have been examined and a number of burst events have been identified. This paper discussed one event recorded by the Adelaide Roof Array and events recorded by the Buckland Park air-shower array selected using *a priori* criteria out of seven million recorded events in five years. None of these bursts were to be expected on the basis of toy Monte Carlo calculations for the circumstances of the arrays at the time (atmospheric pressure determining the particular event rate). It remains that bursts such as these do exist in cosmic ray datasets and their physical origins remain unclear.

Neville Wild was responsible for much of the hardware discussed in this paper. Bruce Dawson, Philip Edwards, and Andrew Smith particularly contributed to the successful operation of the Buckland Park array.

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