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Observation of a Burst of Cosmic Rays at Energies above 7×10^{13} eV

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The authors report on an unusual simultaneous increase in the cosmic-ray shower rate at two recording stations separated by 250 km. The event lasted for 20 s. This event was the only one of its kind detected in three years of observation. The duration and structure of this event is different from a recently reported single-station cosmic-ray burst. The simultaneity of the coincident event suggests that it was caused by a burst of cosmic gamma rays. There is a possibility that this event may be related to the largest observed glitch of the pulsar in the Crab Nebula.

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The possibility of extending the spectrum of astrophysical observations to photon energies $> 10^{12}$ eV has received considerable stimulus as a result of recent observations which have been made with use of extensive-air-shower arrays. At a threshold energy of 2×10^{15} eV, Samorski and Stamm¹ have detected an excess of showers from the direction of the binary x-ray source Cygnus X-3, which shows the characteristic 4.8-hr source modulation. Morello, Navarra, and Vernetto² have also observed a similar effect from the same source in a sample of small air showers ($E_0 > 3 \times 10^{13}$ eV) observed at mountain altitude. Both results have recently been verified by Lloyd-Evans *et al.*,³ using shower data taken with the Havarah Park array. A 4.1σ excess of muon-poor showers from the direction of the Crab Nebula has been observed by Dzikowski *et al.*⁴ at a threshold energy above 10^{16} eV. Using the "flys-eye" detector, Boone *et al.*⁵ observed a 3.1σ excess of Čerenkov-light flashes from the Crab, for observations made in December 1980 at a threshold energy in the range 10^{15} to 10^{16} eV. The existence of at least two point sources of high-energy gamma rays in the energy range 10^{12} to 10^{16} eV would seem to be reasonably established by these positive observations, despite the upper limits reported by Hayashida *et al.*⁶

Independent of all of these observations, a number of groups have attempted over the past decade to search for bursts of high-energy gamma rays in the 10^{12} to 10^{16} eV energy range. By operating small groups of scintillation counters in flexible trigger mode and by exploiting relative time resolution of at least a microsecond, it has been possible to look for astrophysical bursts over time scales ranging from microseconds to

seconds.^{7,8} Such bursts might possibly arise from supernova explosions^{9,10} (SN) or the evaporation of primordial black holes^{11,12} (PBH), or might be associated with cosmic gamma-ray bursts (GRB) observed at low energies by various satellites.^{13,14} Despite extensive search programs, which in some cases lasted a number of years, no positive effects have been reported of bursts of high-energy gamma rays lasting over the time scales of $1 \mu\text{s}$ to 1 s. However, several useful null results have set upper limits on the detectable burst rates from both PBH evaporation and SN explosions.¹⁵⁻²⁰

In contrast with these null observations, the time-structured cosmic-ray-burst event reported by Smith *et al.*²¹ is a singularly intriguing event. Here a random temporal sequence of 32 extensive air showers, of mean energy 3×10^{15} eV, was observed at one station at Winnipeg, Canada on 20 January 1981. The burst lasted 5 min, the event being one of a kind in an experiment which sampled 150 000 shower triggers over an 18 month period. If verified, the astrophysical consequences of such structured bursts would be profound both from the point of view of the long duration of the event as well as from the questions of energetics and source generation mechanism. The time scale of the event reported is such that it is almost certainly not a prompt SN burst where 10^{44} ergs is expected to be emitted in high-energy gamma rays on a time scale of 10^{-7} to 10^{-9} s. Similarly the emission time scales for PBH evaporation are also short. The elementary-particle model predicts the liberation of 10^{30} photons of energy 5×10^{12} eV during the final 0.1 s of the evaporation process. Neither a PBH evaporation nor a SN explosion would

satisfy the temporal or photon energy requirements of the event in question.

A burst of the nature of that reported by Smith *et al.*²¹ almost certainly would have very appreciable lateral structure if its origin were astrophysical and therefore the detection credibility for such possible events would be enormously enhanced by operating a number of small cosmic-ray stations in time coincidence. We wish to report here an unusual event which was observed with use of such a long-baseline coincidence system.

The experiment consists of two cosmic-ray detection stations located marginally above sea level, one at University College Dublin, and the other at University College Cork. The interstation separation is 250 km. If a burst of gamma rays, of sufficient intensity and time scale, strikes the local atmosphere, it should be detectable in coincidence at the two stations, by virtue of the blanket of showers produced in the atmosphere. It is required, therefore, to monitor the local cosmic-ray counting rates at each station over as wide a dynamic range of time scales as possible, and if sudden excesses or bursts occur, to code the time scale involved and to record the absolute time of the event as accurately as possible.

Each station consisted of four scintillation counters (each of area 1 m²) with associated electronics, details of which have been described elsewhere.²² The following combinations of detected events were formed at each station by the coincidence logic: (a) coincidence between all four scintillators; (b) all combinations of three out of four; (c) all combinations of two out of four; and (d) summed counting rate of the four

individual counters. Event types (a), (b), and (c) taken together are defined as being class *B* while type (d) is defined as class *A*. The class-*B* rate is typically 3.0 s⁻¹ while the class-*A* rate is typically 780–820 s⁻¹. The simultaneous occurrence of (a), (b), and (c) would yield one class-*B* event.

Presettable counters monitored the event rates of each class over a range of time scales. If the preset count was exceeded during any sampling interval, the absolute time of occurrence was recorded to an accuracy of 1 ms. Details of the preset levels and associated sampling intervals are shown in Table I. It should be noted that the number of showers detected in any sampling interval is not recorded. The presence of a coded trigger pulse simply indicates that the preset threshold has been exceeded by virtue of an upward fluctuation in the quiescent counting rate. As such the excess showers in an interval represent minimum values. The code-9 events represent an option which was automatically servoed to remove long-term (> 15 min) fluctuations in the singles rate arising from slow barometric effects.

The detection system operated almost continuously for the 3 yr from January 1975 to December 1977 giving 807 d of overlap between both stations. The analysis procedure adopted involved dividing the data into subgroups of different characteristic time scales which were suggested by possible transient astrophysical phenomena. For each coded subgroup, the individual event times at each station were compared by computer to search for prompt twofold coincidences within a given resolving time. Upper limits on the rate of detection of coincident transient events over various time scales from 1 μ s to 1 s have been

TABLE I. Preset levels and associated sampling intervals.

Sampling time interval	Preset count level	Event class	Code type	Poisson predicted rate (d ⁻¹)	Typical observed rate (d ⁻¹)
100 μ s	5	Class A	0	21.7	18.2
1 ms	9	Class A	1	14.3	15.7
10 ms	26	Class A	2	2.2	3.0
100 ms	122	Class A	3	7.7	8.7
10 s	3 σ > mean	Class A	9
100 μ s	2	Class B	7	38.7	38.3
10 ms	4	Class B	4	0.3	0.2
1 s	12	Class B	5	4.8	4.3
10 s	50	Class B	6	1.9	1.7

reported elsewhere.^{17,18}

The only prompt coincidence event recorded by the experiment is considerably longer in duration than what was considered at the time to be astrophysically probable at the photon energies in question. The event occurred on 25 February 1975 (day 56). At that time the lower-energy threshold mode for class A was not operational. The event consists of two code-6 events in adjacent time bins at station 1, coincident with a single code-6 event at the other station. This latter code-6 event also has an inclusive code-7 event. The 20-s burst began at 21.56.50 GMT. No Vela-type gamma-ray burst was recorded on that day although one of the Vela satellites indicated a 3σ rate increase over a period of 16 s at this time.²³ The Vela satellites require a 5σ rate enhancement before a trigger is generated. This event was unique in that it was the only coincident event observed in 807 d of operational overlap for both stations. The random probability of observing a code-6 event with a coincident code-7 event at station 1 which is in coincidence with a pair of back to back code-6 events at station 2 is 2.7×10^{-5} over the 807 d of observation.

The code-6 option operated at a preset count level of 50 in any 10-s interval in order to produce a trigger. The mean expectation value for any 10-s interval, based on a class-B rate of 3 s^{-1} , is 30 events. Hence two successive code-6 events at one station requires an energy input of 40 excess showers of energy $> 10^{14} \text{ eV}$. The collection area of the array for class-B events is 10^3 m^2 which corresponds to a burst flux of $6.4 \times 10^{-4} \text{ erg cm}^{-2}$ at the top of the atmosphere, similar to that observed from the strongest GRB events.

It is, however, highly unlikely that the coincident event reported here was a GRB of the type observed with photon energies less than a few megaelectronvolts. Analysis of our 3 yr of data has indicated that despite being live for more than twenty reported GRB events we have never observed any coincident or correlated rate enhancements at the reported times of the bursts. Similar conclusions have also been reached by Bhat *et al.*,²⁴ based on the Ootacamund experiment.

The nature of the event reported by Smith *et al.* is quite different from our event in that its duration was a factor of 15 greater. Looking at the structure of the Winnipeg event in detail, we see that the first four showers of the burst occur in 3 s, the first nine showers occur in 31 s, and

there is another grouping of nine showers in 4.5 s towards the end of the burst. Any astrophysical source capable of producing such an event sequence at $3 \times 10^{15} \text{ eV}$, and with an E^{-1} spectrum such as Cygnus X-3, might be expected to produce at least 90 events in less than 5 s in an experiment like ours which operates at $> 10^{14} \text{ eV}$. Yet no such burst was ever observed. Also we might have expected some of our short-interval codes (0 through 5) to undergo successive rapid activation at both stations, but no such triggering was ever observed. When the hypothetical 90 events in 5 s is compared with the rate increase actually observed in our event, an excess of 10 events per 5-s interval over a duration of 20 s, then the two events are seen to be quite dissimilar. We would conclude that the Winnipeg event must be either (a) an event with exceedingly low probability of occurrence, (b) one event from a class of bursts with an exceedingly flat spectrum, or (c) an event of terrestrial rather than astrophysical origin.

Finally, we wish to point out that at the time of observation of our coincident event the Crab Nebula would have been in the fields of view of both stations. It is interesting to note that on 4 February 1975, just 21 d before our observation, the pulsar in the Crab Nebula underwent a speed-up glitch of magnitude $\delta\nu = 0.097 \text{ period d}^{-1}$.²⁵ This glitch is the largest ever observed from the Crab pulsar and had long-term effects qualitatively different from previous glitches.²⁶ It had previously been pointed out by Fazio *et al.*²⁷ that the high-energy gamma-ray emission ($> 2.5 \times 10^{11} \text{ eV}$) from the Crab Nebula was observed to show a substantial increase in the interval 60 to 120 d after three major spin ups of the pulsar observed on 29 September 1969, 2 August 1971, and 25 October 1971. The delays either may be due to some time delay in the particle acceleration process at the source or may be due to some geometrical light travel-time delay from the region of the Nebula where the gamma rays are produced. It is intriguing to suggest that our event might be a delayed burst causally linked to the 4 February 1975 spin up of the Crab pulsar. It is also interesting to note that the time-integrated flux of $6.4 \times 10^{-4} \text{ erg cm}^{-2}$ over the 20-s interval of the reported event corresponds to a total energy of $2 \times 10^{41} \text{ ergs}$ from the Crab, under the assumption of isotropic emission and a distance of 1700 parsecs. The wisps in the Nebula near the pulsar have also been observed to brighten up 60 to 120 d after a major pulsar spin up^{28,29}

and the energy associated with such brightening of the wisps might well be as high as 6×10^{45} ergs.

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