Observation of Time Correlations in Cosmic Rays

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Abstract

A set of four detectors enclosing an area of 5000 square kilometres has been used to search for cosmic rays travelling in a wave front as if originating in a shower or in a single short burst. No such events were found; however time correlations between cosmic rays were observed with a typical spread estimated to about 0.3 ms.

Introduction

Time correlations between secondary cosmic rays as they occur when a primary particle enters the atmosphere and produces an Extensive Air Shower (EAS) have been studied since the sixties. But the time correlations between primary cosmic rays are less well known; in fact if we exclude the observation of the X-ray bursts[1], we are not aware of the observation of such correlations.

Correlations we want to measure are those arising from hypothetical single events far outside of the earth's atmosphere which produce bursts or showers of particles travelling on a plane or front (Fig 1). These enter the atmosphere and produce EAS, the secondaries of which are detected. Three detectors are needed to measure the direction of the particle front, and at least one other in order to impose a constraint.

Figure 1: the expected event.

In order to measure time correlations of primary cosmic rays, detectors at ground level must be placed at distances larger than the size of EAS typically of 1 km; therefore locations distant by more than 50 km were chosen. At these locations, each detector must measure and record the arrival time of a substantial sample of particles. The accuracy needed for this time measurement is limited by the time spread within an EAS relatively to a flat front, typically 100 ns; therefore available clocks with an accuracy of a hundred nanoseconds were estimated to be suitable. Finally, for an expected data rate of about 100 Hz per square meter of detector a data storage capacity of about 50 Mbytes per day is needed.

A few years ago this type of measurement became feasible at low cost: clocks with the desired accuracy became available commercially as well as data storage systems in the range of gigabytes. This fact has been our main motivation for starting this measurement[2]: having the possibility to do it relatively easily and with a moderate budget was hard to resist, even though to our knowledge no predictions for such short time correlations exist.

The detectors

Four detectors have been built and placed in Switzerland, at Geneva, Le Locle, Basel and Bern (Fig 2). Each detector is made of three identical units $70 \times 40 \text{ cm}^2$ placed side by side, each unit consisting of three scintillator planes 6 mm thick on top of each other, with a 10 cm lead layer between the lower and the middle planes. The whole detector is enclosed under a small roof and heated to reduce moisture problems. The photomultiplier gains were adjusted to be well on the efficiency plateau, at a value of about 95 %.

Figure 2: a) the locations of the four detectors b) the basic unit of the EAS detector.

The electronics consists of coincidences between each scintillator in the upper plane and its corresponding member in the middle plane, and of an input register to record the status in the nine scintillators. A trigger was generated for each single or multiple coincidence, the arrival time was read from the clock and recorded, as was the register for the scintillator hits.

The clock is a 5 MHz oscillator controlled by signals from the navigation system LORAN-C[3]. This system consists of groups of three or four transmitters, the transmitters of one group being distant by several hundreds of kilometres from each other. They emit short signals (tops) at intervals of typically 80 ms, with carefully controlled phases. The time delays between the reception of pulses from several transmitters is used to calculate the position of the receiver. We have used the transmitter located at L'Estartit in Spain, which gives signals with a period of 79.9 ms, and whose tops were counted in a 24 bits scaler. Pulses from the 5 MHz oscillator were counted in a second 24 bit scaler, which was reset by each LORAN-C top. The content of the LORAN-C scaler and of the 5 MHz scaler were recorded for each trigger, thus providing a relative time measurement of the desired accuracy. The correspondence between the four LORAN-C counters was obtained about 15 times per day by synchronization triggers, for which encoded time signals generated by a transmitter called DCF at 77.5 kHz (transmitter at Mainflingen, Germany) were registered, together with the clock and LORAN-C counters. These signals are accurate to about 10 ms, well sufficient to identify LORAN-C tops.

The error on the time measurement has two contributions: one purely due to electronics, including the LORAN-C receptor, clock drift and roundoff, and another due to fluctuations in wave propagation from L'Estartit to the different detector sites. The first one has been measured by placing detectors at the same position and measuring time differences for a common trigger: a value of 92 ns (rms) has been obtained. The second one can be estimated from the fluctuations of the geographical position obtained by the system which are typically 200 m. The resulting time accuracy was therefore estimated to be about 400 ns.

At each site, the data acquisition is controlled by a PC interfaced to the CAMAC crate containing the hits register, the counters and the synchronization clock interface. The full information is contained in 8 bytes per event. At typical rates of 100 to 150 Hz, files of about 30 Mbytes were written on the PC hard disk every 8 hours. These files were then saved on exabyte tapes (2 min writing time). With a capacity of 5 Gbytes, the exabyte tapes provide in principle an autonomy of about 40 days.

Data collection

An initial data collection was done from Nov. 1988 to May 1989 with a preliminary version of the detectors. These were modified to the version just described, and a second run was done from Dec. 11th 1991 to July 27th 1992 or 234 days. The four detectors were simultaneously in operation for 149 days or about 60 % of the time, and a total of about $7.5 \cdot 10^9$ events were recorded.

The rates measured at the four locations are in the range of 135 per second (Basel) to 155 per second (Le Locle). The proportion of tracks signed by a signal in the two upper counters and no signal in the lower one (called 'electrons') is 0.42 to 0.48 for the four detectors.

Data analysis

After correcting for the different transit times from L'Estartit to the receivers, coincidence candidates have been selected by requiring that the four time measurements, one from each detector, fall within a given window. Two values for this window have been tried: 0.62 ms for the whole sample and 1.5 ms for part of the data. The small value corresponds to the transit time for horizontal photons between Basel and Geneva: the rate of events thus selected is 0.39 s^{-1} or a reduction by a factor of about 300 compared to the rates of singles.

Most of the selected quadruplets are random coincidences. In order to extract a signal, a background sample of quadruplets was constructed, where short time correlations are known to be absent. It was obtained from the data themselves by shifting the times of all detectors relatively to each other by amounts larger than the measurable correlation time, but small enough to conserve the same counting rates at each detector. Specifically, these time shifts were chosen as multiples of the LORAN-C steps which are 79.9 ms. A sample with statistics ten times larger than the data was built in this way. After normalization, this sample of accidental coincidences (A) is compared to the quadruplets selected from the data (D).

The analysis described below has been done in three steps. First, a coincidence search (groups of four signals in the four detectors close in time) was done, and an excess of such events has been found. Then a search for a possible direction of origin of these events was attempted, without success. Finally, an estimate of the time dispersion of the signals has been obtained.

1. Coincidence search

The comparison of data and accidentals was first done for the whole sample and for electrons only, but no significant difference was found:

	TOTAL	ELECTRONS
D:	5 071 247	259 834
A:	5 069 957	258 837

Figure 3: difference between observed number of quadruplets and accidentals in units of standard deviations versus operating time.

This comparison was then repeated for shorter time intervals, which were chosen as 180 hour slices. The difference between the data and the accidentals versus time, measured in units of standard deviations, is shown in Fig 3. An excess of 4.8σ is seen at around 1000 hours, corresponding to a period from Dec. 15th 1991 to Dec. 22nd 1991. During this time, the number of electron quadruplets in the data and in the background are:

D	11 776
A	11 228

The excess of 548 events has a statistical significance of 4.8 standard deviations. This would correspond to a probability of about 10^{-6} for being a statistical fluctuation if the selection had been unbiased. Taking into account the choice and the number of bins in the histogram, the resulting probability for the signal to be statistical is still lower than 10^{-4} .

2. Search for a wave front

After this first step, an attempt was made to estimate the direction from which these particles came from. The wave front of Fig 1 is completely specified by three parameters, which we chose as its arrival time and two components of the unit vector along its direction of propagation. For each time quadruplet, a least squares minimization procedure with one constraint provides the best estimates of the values of these parameters. This fit is not a true chisquare minimization, because the time dispersion is unknown. As mentioned above, this dispersion contains both the measurement error, which is known, and the true dispersion of the times relative to that of the supposed wave front, which is unknown. The minimized quantity Q^2 is defined as

$$Q^2 = \sum_i \frac{(t_i - t_0 - \vec{x}_i \cdot \vec{n})^2}{\sigma^2} \quad \text{with } i=1,4$$

where the t_i are the measured times, the $\vec{x}_i$ the position vectors of the four detectors, t_0 the mean arrival time and $\vec{n}$ the unit vector in the direction of propagation. The quantity σ has been chosen arbitrarily as 400 ns, twice the step of the 5 MHz clock, and is our unit of time. The minimized value of Q^2 is zero for vanishing time dispersion.

The resulting Q^2 distribution is shown in Fig 4. The peak at $Q^2 = 0$, which has the shape of a usual 1_c chisquare fit, is due to events where all time differences between detectors are compatible with a physical solution to the problem: they are shorter than the travel times at the speed of light between these detectors. The bump is $Q^2 = 500 \cdot 10^3$ due to events where one or more of these time differences are longer. The detailed shape however need not be discussed in more detail as the search for a signal is done in the same way as described above for the quadruplets: by comparing the Q^2 distributions of the data to that of the accidentals. The ratio R of the data Q^2 distribution (D) to that of the normalized de-correlated events (A) should display the presence of time correlations if they exist, by an increase of R close to zero. This ratio is shown in figure 5 for values of Q^2 up to 10^5 , corresponding to values of times of 126 μ s. Its first bin corresponds to a time interval of 12.6 μ s or about twenty times the measurement resolution. No signal is visible, ruling out the presence of a well defined wave front within our statistics.

Figure 4: Q^2 distribution for quadruplets in the 0.62 ms time window; a value of $Q^2 = 1000 \cdot 10^3$ corresponds to time $t = 400 \mu$ s (data are with errors bars, accidentals are in full line).

Figure 5: ratio R of the Q^2 distribution of the data to the Q^2 distribution of the accidentals; the range of Q^2 shown corresponds to times up to 126 μ s.

Despite this negative result, a further search was made: the obtained directions have been transformed to an inertial system to produce a map of possible origins for these events. Should a point source exist somewhere, a two-dimensional plot is more sensitive statistically than a one-dimensional Q^2 plot. No localized source has however been observed.

3. Time dispersion

In order to search for correlation times in the millisecond region, the time window was enlarged from .62 ms to 1.5 ms. The Q^2 distributions of the data and of the de-correlated events have been compared and give a probability lower than $2.5 \cdot 10^{-3}$ for being compatible. The resulting value of R is shown for values of Q^2 up to $5 \cdot 10^6$ (Fig 6). A slight excess for values of Q^2 in the range $0 < Q^2 < 5 \cdot 10^5$ is visible, this range corresponding to times up to 0.3 ms; the integrated signal in this range has a significance of 4.2σ . A similar analysis for periods outside of Dec. 15th to Dec. 22nd shows no such excess.

With correlation times in the millisecond range, a directional search is obviously not feasible with the present spacing of the detectors. However another crude directional information can be obtained from the time of the day when the signal is visible, as it should not be present when the source is below the horizon. The difference between the data and the de-correlated sample is shown in Fig 7 in units of standard deviations as a function of the local time. The signal seems to come at two definite periods 12 hours apart: at 5 am and at 5 pm with a significance of 3.5 and 4.5 standard deviations. By comparison, data outside the period from Dec. 15th to Dec. 22nd show no such structure. Although the presence of two times in the day at which the signal appears is puzzling, the implied periodicity of one day seems to indicate a fixed source location in an inertial system.

Summary and conclusion

Four cosmic ray detectors have been built and installed at locations distant by more than 50 km to search for time correlations between extensive air showers. At each detector site the cosmic ray arrival time was measured with a clock accurate to about 400 ns. Three signatures were observed:

i) an excess of quadruple hits, one hit in each detector within a time window of 0.62 ms has been observed with a significance of 4.8σ . This excess appeared during a period between Dec. 15th and Dec. 22nd 1991.

Figure 6: ratio R of Q^2 distributions for events in the 1.5 ms time window (full line represents data in the period from Dec. 15th to Dec. 22nd 1991, dashed line represents data outside of this period); the excess of events, in the first bin, has a significance of 4.2 standard déviations

Figure 7: difference between observed number of quadruplets and accidentals in unit standard deviations versus time of the day (full line is for data in the period from Dec. 15th to Dec. 22nd 1991, dashed line is data outside of this period).

ii) a least-squares minimization of time differences assuming a particle front showed that the arrival times at the four detectors are contained within about 0.3 ms relatively to the times implied by the front. This second signature (4.2σ) is seen for the same period as the first one, and is not observed outside of this period. No correlation was found in the microsecond range, and the presence of 'cosmic showers' arriving as a sharp wave front has therefore not been detected.

iii) the arrival times as a function of the time in the day show an excess of events twice a day at 12 hour intervals (3.5 and 4.5σ). This signal is also seen only during the same active period as the two previous signatures.

Each of the observed three signatures has a probability lower than 10^{-4} for being statistical in nature. The fact that they are observed during the same period of about 7 days and not at other times makes it likely that they belong to the same events. In this case, their combined significance is still higher, but no estimate of this global significance will be attempted.

The nature of these events is difficult to analyze in the absence of other information such as the directions of the detected cosmic rays. One possibility among others is that the secondaries of very large EAS propagating horizontally have been detected. A source of very high energy cosmic rays would then be observed when it is at the horizon, twice a day; however the horizontal disposition of the detectors does not favour this explanation, unless off-axis secondaries are detected. Another possible reason for these effects could be linked to solar activities.

Despite this lack of definite conclusions and the remaining (small) probability that the observed effects are statistical fluctuations, these observations make it desirable to continue this search with increased means and a substantial increase in the number of new detectors.

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References

- [1] V.S. Berezinski, S.V. Bulanov, V.A. Diogel, V.L. Ginzburg et V.S. Ptuskin, *"Astrophysics of cosmic rays"*, North-Holland, 1990, 240
- [2] O. Carrel, *"Recherche de gerbes cosmiques extraterrestres"*, Ph. D. Thesis, University of Geneva, 1994
- [3] B.E. Blair, *"Time and frequency: theory and fundamentals"*, US department of commerce, 1974, 253