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Examination of a Proposed Technique for the Economical Detection and Analysis of Ultra-high Energy Cosmic Ray Showers

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Abstract

A study has been made of a recently suggested scheme for the economical detection and analysis of ultra-high energy cosmic ray showers. It is demonstrated that the scheme should be feasible, particularly if detectors are used to sample the γ-ray component of the showers.

1. Introduction

There are several regions of the cosmic ray energy spectrum which have particular interest. The very highest energy region is especially interesting for here are found the most energetic particles known, the only ones with macroscopic energy, and the only ones which arguably should not be there at all. The difficulty in studying such particles is largely associated with their low flux, which can be measured in particles per square kilometre per century. It is clear that reliable detectors of large area are required. Several such detecting systems exist but, now that the University of Sydney SUGAR project (Horton *et al.* 1983*a*, *b*) has ceased operating, all of these are in the Northern Hemisphere. These systems are being actively developed. They will define a Northern Hemisphere cosmic ray energy spectrum at energies above 10^{19} eV and provide a measure of the directional distribution of the cosmic rays at the only energies at which one might expect astrophysical charged particle trajectories to approach straight lines (Efimov *et al.* 1983; Cunningham *et al.* 1983; Cady *et al.* 1983). It is not obvious that the energy spectrum should be the same in the Southern Hemisphere, since the particle sources may not be the same. Also, anisotropy measurements made only over one hemisphere will necessarily be incomplete. There are thus strong *a priori* arguments for Southern Hemisphere observations to follow on from the SUGAR project. What is required is a reliable cosmic ray detection system with a collecting area which approaches or exceeds 10^3 km^2 at a cost, to be affordable, not significantly exceeding \$1000 per square kilometre. Such a system should detect several 10^{20} eV events per year. It appears that a technique recently suggested by Linsley (1983) may represent a workable detection system which fulfils the criteria of economy and reliability. We have begun work to evaluate the suggestion.

We have made measurements with a single detector system in conjunction with the Buckland Park particle array to confirm the general feasibility of the technique

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and to examine some of its problems. The major limitation of the technique, poor particle statistics, is demonstrated to be avoidable if a detector specifically sensitive to low energy γ rays is employed. Such a system is critically examined.

2. The Linsley Array

Linsley (1983) has proposed a 'rooftop counter array' consisting of four scintillators each of area 1 m^2 placed at the corners of a 30 m square. This is a common air shower array arrangement. Linsley's innovative suggestion is that, by measuring the spread in arrival times of shower particles within each detector, one should be able to estimate the lateral distance to the core of the triggering shower. Other aspects of the system could be conventional.

It is well known that the width of the shower front increases progressively with core distance. If details of this increase (which will depend on the particle species detected) were known then, contrary to the current wisdom which usually requires analysable showers to fall within the array bounds, a small array could analyse any event triggering it. The inexpensive 900 m^2 enclosed array then becomes a system capable of detecting *and analysing* a 10^{20} eV shower up to distances approaching 2 km, a collecting area of more than 10 km^2. The system has clear attractions, but equally may have significant practical drawbacks. One would wish to know whether the particle pulse width was well defined for a given core distance, whether it could be defined at all in a practical way, whether it was a strong function of shower energy, and whether its fluctuations were large within a given shower.

3. Experimental Work at Buckland Park

The Buckland Park array normally detects cosmic ray showers in the size range 10^5–10^7 particles ($\sim 10^{15}$–10^{17} eV primary energy) within an enclosed area of $\sim 3 \times 10^4$ m^2. We placed a $2 \cdot 25$ m^2 plastic scintillator detector 200 m from the centre of the array and observed signal pulse shapes from that detector when operated in coincidence with the array.

The scintillator detector was constructed of 50 mm thick plastic scintillator and is sensitive mainly to the charged particle component of the shower. It was viewed by a Philips XP2040 fast photomultiplier. The signal was carried by 200 m of RG8A/U cable to a fast oscilloscope (Tektronix 7912) on which it was displayed and photographed when in coincidence ($\tau \sim 5$ μs) with a Buckland Park array event. The system response had a full-width-at-half-maximum (FWHM) of 36 ns, largely determined by the detector geometry (optimized for uniform light collection, not fast response). The mean oscilloscope triggering rate was ~ 2 Hz and the mean coincidence rate ~ 1 day^{-1}. The triggering threshold was nominally about 2 particles m^{-2}.

A total of 19 events was obtained, three could not be analysed by the main array, one had an off-screen pulse and did not allow a determination of the pulse width, and two events were suspect in that their predicted density at the test detector was not compatible with the observed density. This is an unusual proportion of rejected events, but is not surprising since the system effectively picked out the very largest detected showers which may not be well analysed due to detector saturation in some sites. Only two of the events used had sizes below 10^6 particles, normally regarded as a large size for the array.

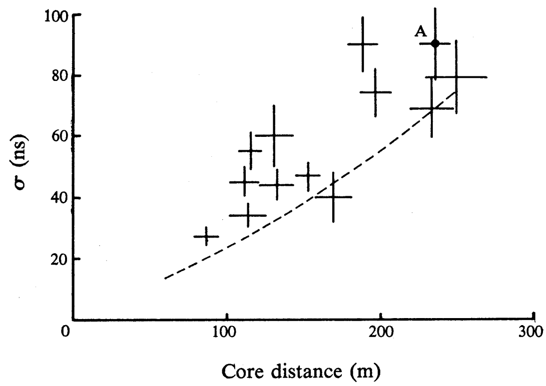

Fig. 1. Measured relationship between shower core distance and dispersion in arrival time of the air shower particles. The dashed curve is the function suggested by Linsley. The event marked A is discussed in the text.

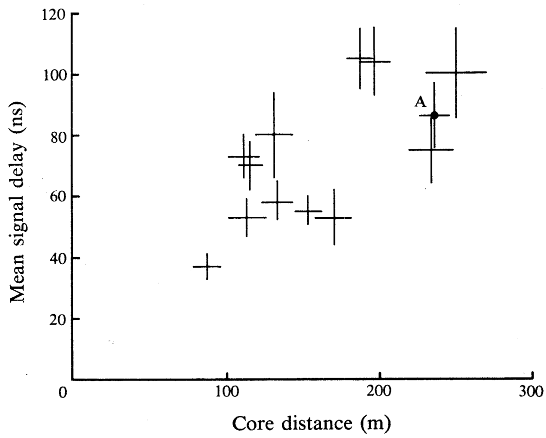

Fig. 2. Measured relationship between shower core distance and mean delay of particles behind the leading detected particle.

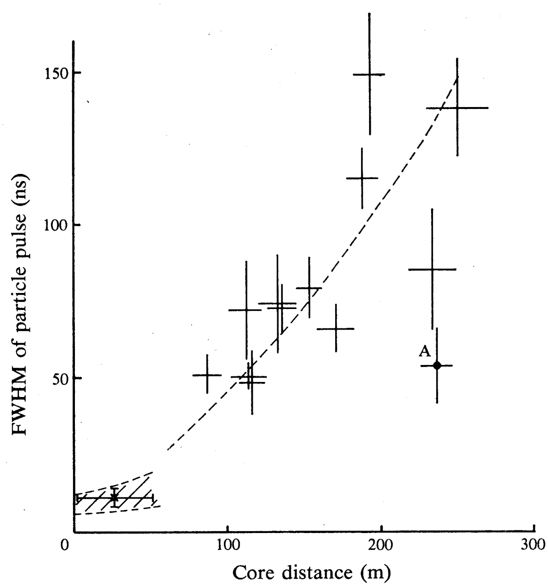

Fig. 3. Measured relationship between shower core distance and the FWHM of the particle pulse. The FWHM of the system was 36 ns. The dashed curve indicates the dispersion ($2\times$) given by Linsley as a rough approximation to the expected function. The data marked by a cross (at lower left) are undeconvolved results of McDonald *et al.* (1977). The hatched area is from Sakuyama and Suzuki (1981).

4. Experimental Results

The dispersion in arrival time of the air shower particles is given by

$$\sigma = \left(\int (t - \langle t \rangle)^2 p(t) \, dt \right)^{\frac{1}{2}},$$

where $p(t)$ is the probability of a particle arriving in time dt and $\langle t \rangle$ is the mean arrival time. Linsley (1983) has suggested that the dispersion, based on high energy events at large core distances ($r \geqslant 500$ m), can be written as

$$\sigma = 2 \cdot 6(1 + r/30)^{1 \cdot 5} \text{ ns}.$$

Fig. 1 shows the relationship found for the (non-deconvolved) pulses detected by our system. It is clear that the data follow the general trend of the Linsley fit (dashed curve, from a different core distance range) and also that they tend to have somewhat larger values of σ. These larger values will be due partly to the use of undeconvolved pulses. It is clear that a strong relationship exists in this previously unstudied core distance range.

Figs 2 and 3 show similar relationships for two other pulse shape parameters, the mean time of the pulse behind the pulse start and the FWHM of the pulse. Clearly these two parameters are also useful measures for our purposes. The event marked A is interesting. It fits badly in terms of the FWHM but fits well for σ and the mean signal delay. The reason for this is that the instrumental resolving time is appreciably less than the arrival spacing of the detected particles and it has become unrealistic to describe the scintillator signal as a pulse; rather, it is the succession of a number of partly superimposed pulses. This effect will become more important as the core distance increases and thus, for a practical system, one would, in general, be dealing with a signal consisting of a pulse train, not a single broadened pulse.

One may look at Fig. 1 and ask how well Linsley's technique would have analysed the observed showers, given a knowledge of the arrival directions. If one takes a straight line of best fit to Fig. 1 (not Linsley's line), a ratio of estimated shower size to the array shower size may be determined for each event. This ratio has a mean of $1 \cdot 1$ and a standard deviation of $0 \cdot 9$ in this case. The calculation used the measured detector densities from the film recording, not those predicted for the core distance in question. The factor of $1 \cdot 1$ is somewhat fortuitous, only four events being above this value and nine below (with a range $0 \cdot 3$–$3 \cdot 4$). It would appear that the system can provide a useful shower analysis since even a factor of three at 10^{19} eV would not be unacceptable and Linsley's arrangement could produce four individual measures and thus presumably be even better than this.

5. Discussion

One would like to know the practical limits to a scheme of this kind. The 30 m square can be used for fast timing to determine an arrival direction. One may, question how practical this is for events with only a few particles being detected, as the leading particle may be appreciably late and a lateness of only ~ 15 ns would give a directional error of 10°. Also, one can ask whether a realistic value of σ can be determined for such a small number of particles. We believe that Linsley's original estimates of particle numbers are pessimistic and that indeed, with appropriate design, the statistical problems need not be so great as they appear at first sight. Linsley has suggested that the particle density at $1 \cdot 8$ km from the core of a 10^{20} eV shower should be 6 m^{-2}. This value is in agreement with measured signals. However, these six vertical equivalent muons will not necessarily exist as real particles, but represent a ground parameter which measures the scintillator signal. The problem can be illustrated by using measurements of Blake *et al.* (1978) which follow from those of Kellerman and Towers (1970). At 500 m from the core of a shower with energy $\sim 10^{17}$ eV, the water Cerenkov detector signal is $\sim 0 \cdot 3$ vertical equivalent muons per square metre. The actual muon density is $\sim 0 \cdot 2$ m^{-2}, the electron density is ~ 1 m^{-2} and the photon density is ~ 10 m^{-2}. The ratio of photons to electrons increases rapidly with core distance and one can estimate that for a 10^{19} eV shower at 1000 m from the core, the muon and electron densities might be similar at ~ 3 m^{-2} but the photon density would be 200 m^{-2}. Clearly it would be advantageous to detect the photons efficiently. Typical photon energies at core distances of ~ 1 km are ~ 5 MeV and this value is not strongly distance dependent, varying roughly as $r^{-0 \cdot 7}$. These photons should be readily detectable in detectors of a suitable thickness; conventional scintillators would be too thin. It would appear that a water Cerenkov or liquid scintillator detector with a depth of ~ 500 mm is economical and suitable for the purpose. This should detect the Compton electrons but minimize the muon signal.

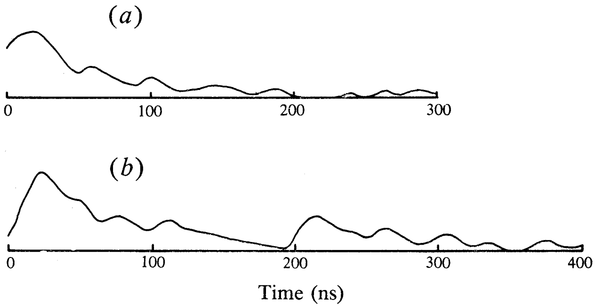

Fig. 4. Two observed pulses for (*a*) an analysed shower a little more than 200 m from the core (pulse area corresponds to $1 \cdot 1$ vertical equivalent muons); (*b*) a large shower at a large distance ($\geqslant 250$ m) from the core. No detailed array analysis is available for the second event which had a large zenith angle (46°) (pulse area corresponds to $1 \cdot 7$ vertical equivalent muons).

Fig. 4 illustrates the effect of multiple low energy particles by two traces from the experiment for events $\geqslant 200$ m from the shower core. The total number of vertical equivalent muons in the signal is appreciably less than the number of peaks in the signal. In view of the limited scintillator thickness, the signals are compatible with the estimate by Blake *et al.* of eight photons per electron at this distance.

It is illuminating to examine the likely response of a single 1 m^2 γ detector at large distances from large air showers. This involves extrapolation of the results of Blake *et al.* (1978) which extend to 500 m from the shower core. If one takes 10 detectable photons as an experimental minimum for defining a pulse width, one would detect 10^{18} eV showers typically at distances of ~ 1 km and with a rate of ~ 1 day^{-1}. The redundancy of a three or four detector system should make the measurements acceptably reliable. A similar detector limit for 10^{19} eV showers would result in a detection rate of ~ 1 $month^{-1}$ at a typical distance of $1 \cdot 8$ km.

Two points are worthy of note here. Firstly, the latter collecting area (with shower detection distances to ~ 3 km) is probably a useful upper limit for any higher energy, since, by now, the individual photon energies will be ~ 1 MeV and not resolvable as detector pulses unless elaborate expensive detectors are employed. Secondly, the dependence of photon density on core distance is so steep that little would be lost if a much larger number of photons were demanded before accepting an event. For instance, a threshold of 50 photons per square metre would only reduce the rate of detection of 10^{19} eV showers by a factor of two. This would make a highly attractive system.

Data presented by Hara *et al.* (1983) suggest that Linsley's concept may not provide a reliable measure of core distance. They measured the average delay time distribution of the fastest arrival particle. This is consistent with Linsley's average σ but the fluctuations of σ from event to event may be significant. It is worth commenting that these fluctuations will necessarily depend on the setting of the particle selection discriminator levels, and at Akeno these are unlikely to be optimized for the relatively abundant γ rays. The data of Hara *et al.* are useful in indicating that in the core distance range of interest here, and almost in the energy range also, the shower radius of curvature is $\sim$3000–6000 m suggesting that timing with a 30 m square may provide adequate, but not good, shower arrival directions.

An alternative technique for the determination of zenith angle would be a large version of that used by Mazets and Golenetskii (1981), where both vertical and horizontal thin scintillation detectors are employed. Similar total muon track lengths would be found for each detector since this is a volume effect, but the relative numbers of detected muons would measure the arrival angle.

6. System Costs

The type of system proposed by Linsley is apparently quite economical. Four water Cerenkov detectors, each of area 1 m^2, would be inexpensive in principle. The main technical problems to be overcome would be associated with system noise and stability. For instance, if one wished to detect γ rays, a wavelength shifter may be necessary to achieve reasonable signal-to-noise ratios with a uniform collecting area detector. The long-term stability of such an arrangement is unknown but is under investigation at Adelaide. If a stable system is achievable, significant savings in system cost or complexity may be achieved by counting photon (γ ray) signals for the determination of σ rather than deriving an analog sampled signal. This arrangement would discriminate in a worthwhile way against an excessive loading being given to the occasional large muon signal. We envisage a discriminator set at an energy deposition level of ~ 2 MeV which feeds a continuous shift register, as in a transient recorder, but merely recording the arrival (or not) of particles in a series of, say, 1024 intervals of 30 ns. An integrating amplifier and cheap sample-and-hold/ADC could measure the total signal. The latter system would be simple to analyse by using a microcomputer since the shift register would simply appear as 128 eight-bit words. Four detectors would give good statistics for this system which would be conceptually analogous to a Geiger array in its counting performance and give simple 30 ns (20°) fast timing directional resolution (about as good as one might hope with the expected shower radii of curvature).

A four detector site would cost $\sim$ \$5000 in hardware at present prices and could be used either as a stand-alone system with ~ 10 km^2 collecting area at 10^{20} eV or as part of a grid (~ 2 km spacing) with $\sim 4\ \mathrm{km}^2$ collecting area per site. Clearly further systems would be needed for an inner grid of smaller spacings to extend the spectrum downward and check the operation of the devices. However, for a total system cost between one and two million dollars a worthwhile count rate at 10^{20} eV should be achieved.

7. Conclusions

It would appear that a version of a new cosmic ray analysis technique suggested by Linsley is both feasible and economical. The technique makes a new very large collecting area system particularly attractive in the Southern Hemisphere.

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