# MINI AND SUPER MINI ARRAYS FOR THE STUDY OF HIGHEST ENERGY COSMIC RAYS

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## ABSTRACT

The chief difficulty in studying the highest energy cosmic rays is the extremely low intensity, only ∿ 5 particles per $km^2$ sr century above $10^{20}$ eV. Instead of attacking the problem by assembling all of the available resources in one place, as has been done in the past, I suggest a way that the task can be performed at much less cost per unit sensitive area, by using numerous inexpensive mini arrays operating independently of each other. In addition to the quantities usually observed, each mini array will record shower particle arrival time distributions. At $10^{20}$ eV the saving in cost per primary particle is estimated to be a factor of 10 or better, compared to methods now in use, even for mini arrays newly built from scratch for just this purpose.

Clearly, however, all of the existing air shower arrays can be made to serve as mini arrays, without interfering with their other functions, by simply adding transient recorders to the existing instrumentation. Giant arrays such as the one at Haverah Park can be made to function as clusters of mini arrays. The new array-telescopes being planned and built for UHE $\gamma$-ray astronomy will add further to the number of these installations.

The main difficulty which can be forseen is in determining shower directions accurately. Ideally one would like to be able to identify nearly horizontal but upward moving showers produced by $> 10^{19}$ eV neutrinos, and one would like to obtain information on shower profiles for measuring the interaction mean free path of the primary particles. Compact installations with which it may be possible eventually to carry out these difficult tasks, called 'super-mini arrays', will also be described.

<u>1. Introduction.</u> In the 1950's the empirical upper limit of the cosmic ray energy spectrum was quickly raised from $10^{17}$ to $10^{19}$ eV (more than one joule) by using arrays of simple counters to detect extensive air showers. In the 1960's these arrays attained giant size (tens of $km^2$) and the limit was pushed to $10^{20}$ eV. Since then detailed studies have shown that the primaries are nuclei mostly as light as hydrogen or helium. Above $10^{19}$ eV the arrival directions are markedly anisotropic and the energy spectrum has an interesting flattening or bump. But returns are diminishing; in order to make further progress one needs a 100-fold increase in collecting area without a proportionate increase in cost. Methods relying on radio and acoustic signals have their advocates, but they have not yet produced worthwhile results. The Fly's Eye atmospheric fluorescence detector has proven to be useful for studying the structure of very large showers, but it is not cost-competitive for areas as

large as are needed. Mini arrays are low cost counter systems designed to make fuller use of the information carried by air shower secondary particles, especially those with large impact parameters (1-2 km). They can operate practically anywhere--in cities, for example. Super-mini's are an advanced form capable of determining the profile of a shower as well as its energy and direction.

2. Using arrival time spread to measure core distance. My suggestion depends on a well known property of air showers, whose utility has been somehow overlooked, the fact that the longitudinal thickness of the particle swarm increases rapidly with increasing distance from the shower axis, from 1 or 2 m at $r < 10$ m to hundreds of m beyond 1 km.[1,2] This is shown by data on arrival time distributions using as a measure of width the dispersion defined by $\sigma_t = [\int(t-\langle t\rangle)^2 p(t)dt]^{\frac{1}{2}}$, where $p(t)$ is the probability of a particle arriving in dt, and $\langle t\rangle$ is the mean arrival time. In Fig. 1 the points are for single particle distributions built up from observations of individual particles belonging to showers of energies $\sim 10^{17}$ eV and various zenith angles < 45°.[2] The curve represents an empirical formula,

$$\sigma_t = 2.6(1 + r/30)^b \qquad (1)$$

with $b = 1.5$, where $\sigma_t$ is in ns and r is in m, which fits these results and those for smaller r.[3-6] Can this be used *in individual events*, to determine r from measurements of $\sigma_t$? It can, within accuracy limits that depend on 1) the sensitivity of the parameters to primary energy and zenith angle, and 2) the effect on the parameters of hidden variables such as starting depth, primary mass and so forth.

To investigate these limits, and at the same time simulate use of the proposed method, I made use of the original records (oscilloscope photographs) of the Volcano Ranch experiment. Only those for the final year of operation (1962-63) still exist, but in that year 16 showers were recorded which satisfied the condition ($E > 10^{19}$ eV) for inclusion in the *Catalogue of Highest Energy Cosmic Rays*.[7] These are enough for the present purpose. The *Catalogue* lists the observed values of r and particle density S for each detector of the array as well as the size, energy, zenith angle and so forth of the event as a whole. For events such as these most of the 19 detectors were struck by one or more particles. The first step was to select in an unbiased manner one pulse per event. It should not be too small because of statistical errors nor too large because of a technical problem (particle densities > 10 $m^{-2}$ were encoded in such a manner that pulse duration information was lost). The one chosen in each case is the one with greatest S such that $S < 7\ m^{-2}$. Tracings of the selected pulses are shown in Fig. 2, together with tracings of a bandwidth limited (BWL) test pulse and a typical train of 1 MHz timing pulses. The number of particles contributing to the various pulses ($n = AS\cos\theta$

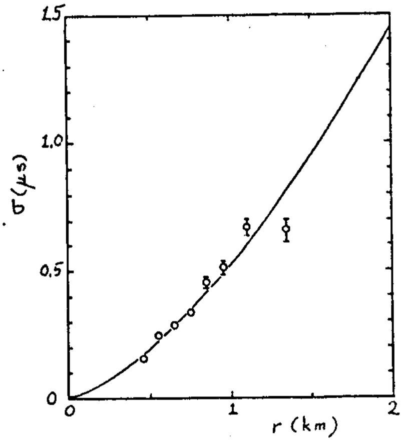

*Fig. 1. Dispersion vs distance from AS core. Points from single particle delay distributions (Linsley and Scarsi 1962), curve from (1).*

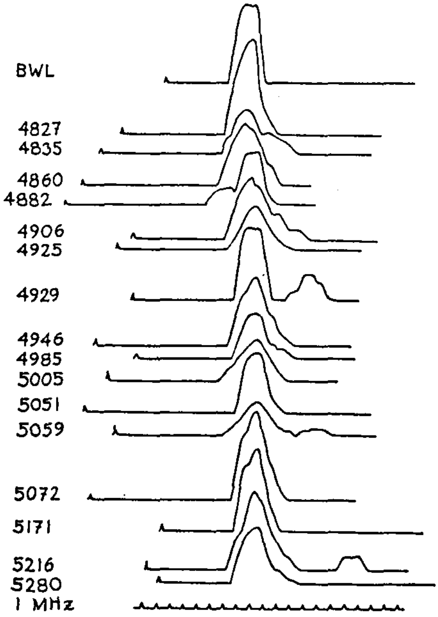

*Fig. 2. Selected pulses for 16 AS with E > $10^{19}$ eV, identified by event No., with a typical bandwidth limited test pulse (BWL) and typical train of 1 MHz timing pulses.*

where A is the detector area, 3.26 $m^2$) ranges from 6 to 22, averaging 12, and the values of r range from 0.9 to 2.0 km, averaging 1.4 km. The average energy of the showers is $3 \cdot 10^{19}$ eV; the zenith angles range from 7° to 55°.

The scintillator pulses and a number of test pulses were digitized and the dispersions were calculated. The dispersion of the input signal was estimated using the relation $\sigma_{in}^2 \sim \sigma_{obs}^2 - \sigma_{BWL}^2$. In earlier work with scintillators it had been found that arrival time distributions are θ dependent, but no energy dependence had been found.[2] In this case, setting the exponent in (1) equal to $b_1 + b_2 \sec\theta + b_3 \log(E/10^{17}\mathrm{eV})$, it was found from the high energy sample that $b_1 = 1.94 \pm .08$, $b_2 = -0.39 \pm .06$. By comparison with the lower energy data of Fig. 1 it was found that $b_3 = 0 \pm .06$. This is consistent with the amount of energy dependence found by Barrett *et al.* using water Cerenkov detectors.[8] Fig. 3 shows the agreement between results of Ref. 2, results for the 16 events from the *Catalogue* (normalized to b = 1.5), and results for another previously published large event (normalized the same way).[1] Core distances denoted by r' were then calculated for the *Catalogue* events, using (1) with θ-dependent b, and compared to the values of r found previously in the usual way.[7] The dispersion of r'/r was found to be 30%.

3. Determining the energy. The final step in this simulation was to find new energy estimates. I used the Volcano Ranch method, but the Yakutsk method could just as well have been used.[9] Either relies on empirical studies of the way particle density varies with core distance and zenith angle. Letting E' be the energy required to procuce the observed density at r', and E the energy found previously, I found that as expected the systematic difference was negligible (10%). Because the structure function is very steep at large distances it was expected that the random errors would be quite large. The

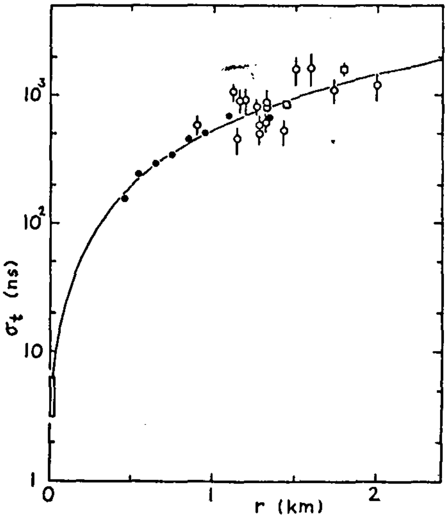

*Fig. 3. Dispersion vs core distance. Filled circles and curve as in Fig. 1, open circles for individual events of Fig. 2, squares for event No. 2533 (Linsley Scarsi and Rossi 1961).*

rms deviation from the mean of log(E'/E) was, indeed, 0.3, corresponding to a factor of 2 in the ratio. The largest deviations were a factor of 5 over and a factor of 4 under.

This is not far from being acceptable. In order to provide a sensitive area of 10 km$^2$ per mini array at $10^{20}$ eV one must measure r out to 1.8 km. At that range S = 6 m$^{-2}$, so with 4 m$^2$ of scintillator, n = 20 particles as compared to 12, the average for these 16 events. Thus the simple statistical errors in $\sigma_t$ and S would be less even in the extreme case. For a *median* $10^{20}$ eV event (r $\sim 1.8/\sqrt{2}$ km) I find n = 70, so the improvement would be substantial. One should begin, of course, with mini arrays located at the existing giant arrays (Haverah Park, Yakutsk) so as to calibrate the new method.[10] Work of this kind will lead to refinements in (1) so that more accurate corrections can be made for systematic variations with E and θ. With such improvements and modern instrumentation I am confident that the random error in r can be reduced to 10%, leading to a random error in E of a factor 1.5. This would be entirely adequate for studies of the primary cosmic ray spectrum and anisotropy above $10^{19}$ eV, which now are limited by inadequate sensitive area, especially in locations where the southern sky is visible.[6]

4. Super mini arrays. The successful operation of the Utah Fly's Eye proves that with the information carried by air shower *photons* one can find shower energies, trajectories and profiles, out to distances of order 10 km. However such an instrument is expensive to build and operate, it must be located in a remote area with a favorable climate, and it can be turned on only 5-10% of the time. The underlying idea of a mini array is making more efficient use of the information carried by shower *particles* at large core distances. Why not go further? The number of particles is adequate even at 1.8 km, about 50 in 10 m$^2$, half of them muons. Suppose one could record both the direction (within 1 or 2 degrees) and the arrival time (within 10 ns) of each particle. The muons will arrive first; suppose they are separated from the electrons by shielding. Neglecting scattering and geomagnetic deflection, *the muon directions will all lie in the shower-detector plane. Within this plane the muon directions will be distributed in a manner that corresponds exactly to the longitudinal profile of the muon sources.* In the same approximation, assuming v = c as well, the arrival times will be perfectly correlated with the directions. It can be shown, still in this approximation, that *data giving the arrival direction and relative arrival time of just 3 particles are sufficient to determine the shower trajectory: the impact parameter and the direction in space*, albeit the data must be rather precise. Will the advantage of having 25 or more particles rather than 3 be enough to compensate for imperfections of the model and the measurements?[11]

References. [1]LINSLEY *et al.* 1961, Phys. Rev. Lett. 6, 485; [2]LINSLEY and SCARSI 1962, Phys. Rev. 128, 2384; [3]BASSI *et al.* 1953, Phys. Rev. 92, 441; [4]WOIDNECK and BÖHM 1975, J. Phys. A 8, 997; [5]McDONALD *et al.* 1977, Proc. 15th ICRC 8, 228; [6] CLAY and DAWSON 1984, Aust. J. Phys. 37, 309; [7]LINSLEY 1980, in *Catalogue of Highest Energy Cosmic Rays*, ed. M. Wada (Inst. Phys. and Chem. Res.: Tokyo) 1, 3; [8]BARRETT *et al.* 1977, Proc. 15th ICRC 8, 172; [9]BOWER *et al.* 1983, J. Phys. G 9, L53 and Proc. 18th ICRC 9, 207; [10]BROOKE *et al.* 1983, Proc. 18th ICRC 9, 420; [11]LINSLEY 1983, Univ. New Mexico Res. Report UNML-9/26/83.