THE THICKNESS OF THE SHOWER DISC AS OBSERVED IN SHOWERS PRODUCED BY PRIMARIES ABOVE 10^{19} eV

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ABSTRACT

The thickness of the shower disc has been measured in showers initiated by primaries of energy $> 10^{19}$ eV using the large area water Cerenkov detectors of the Haverah Park array. Results are presented which (a) provide supporting evidence for the accuracy of our analysis procedures in giant showers, (b) offer an evaluation of Linsley's mini-array technique for the detection of giant showers and (c) extend earlier work on developmental fluctuations above 10^{19} eV.

1. Introduction. A unique feature of the Haverah Park shower array is the large area ($34\ m^2$) of the water-Cerenkov detectors of the 500 m array. These have been used in a succession of studies (Watson and Wilson 1974, Lapikens 1977, Walker and Watson 1981, 1982 and 1983) to provide measurements of the thickness of the shower disc as a function of core distance ($r > 250$ m), zenith angle ($\theta < 40^o$) and energy ($E > 2 \times 10^{17}$ eV). In particular these measurements were amongst the first to be used to demonstrate the reality of shower-to-shower fluctuations in large showers. Here we describe further results which have been deduced about giant showers produced by primaries with $E > 10^{19}$ eV.

2. Check on the accuracy of core location above 4×10^{19} eV. There is considerable contemporary interest in the shape of the cosmic ray energy spectrum above 10^{19} eV (e.g. Hill and Schramm 1985) and, despite considerable experimental effort world-wide, the shape of the spectrum remains in dispute (e.g. Bower et al 1983, Diminstein et al 1982, Horton et al 1983, Linsley 1983). In particular the Yakutsk group have reported no events of energy $> 10^{20}$ eV while the other three groups all claim events $> 10^{20}$ eV. The Yakutsk group have suggested that errors in core location and inadequate knowledge of the water-Cerenkov structure function have lead to gross over-estimates of the energy of some Haverah Park events (Vasilev et al 1983). We briefly describe a simple check, based on our detailed studies of shower disc thickness, which refute this hypothesis. This check has in fact been used in our work for many years and has been alluded to before (e.g. Lapikens 1977, Cunningham et al 1981).

It is found that the thickness of the shower disc increases with distance from the shower axis independent of detector type (Linsley and Scarsi 1962, Baxter, Watson and Wilson 1965). This arises because the source of particles at a large axial distance is essentially a line source. Furthermore as the shower energy increases the 'line-source' moves deeper in the atmosphere so that at a given distance the disc will become thicker.

These features, and others, have been quantified in the Haverah Park work through the measurement of $t_{\frac{1}{2}}$, the risetime of the signal in the water-Cerenkov detectors between 10 and 50% of full height. So far all of the work has been done with $34\ m^2$ detectors and the majority of data is derived from measurements on oscilloscope records.

The easiest and most common way to over-estimate the size of an air-shower is to misplace the core at greater than the correct distance from the centre of the array. The steepness of the lateral distribution, combined with the wide-spacing of detectors, make this an important and well-recognized problem. The shower disc thickness allows a check on the accuracy of the assigned core: if the core is placed too far from the array centre then the measured risetime will appear to be anomalously fast. The risetime of the pulse thus acts as an independent check on the core location analysis.

Figure 1: Plot of risetime against distance for events listed in Table 1.

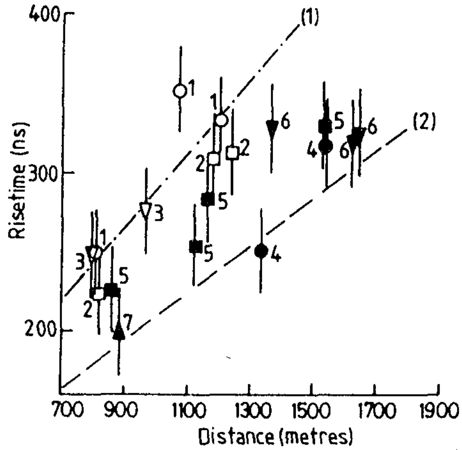


Table 1

	MR	θ	ID	Ep/eV
(1)	9597348	11°	1	6.7×10^{19}
	19384465	9°	2	5.1×10^{19}
	21220296	13°	3	4.2×10^{19}
(2)	9160073	30°	4	1.6×10^{20}
	12701723	29°	5	1.4×10^{20}
	16632298	34°	6	1.1×10^{20}
	17684312	35°	7	9.8×10^{19}

Events included in the Haverah Park energy spectrum (Brooke et al OG5.1-3) with $\theta < 40°$, $E > 4 \times 10^{19}$ eV and for which risetime measurements are avail-above are shown in Figure 1. The lines are for 11° and 32° but are appropriate to the 139 events with $5 \times 10^{18} < E < 4 \times 10^{19}$ eV ($\overline{\log E} = 19.0$) from which the regression relation

$$t_{\frac{1}{2}}\,(\text{ns}) = ((0.71 \pm .01) - (0.47 \pm .10)\sec\theta)\,r + (55 \pm 8)$$

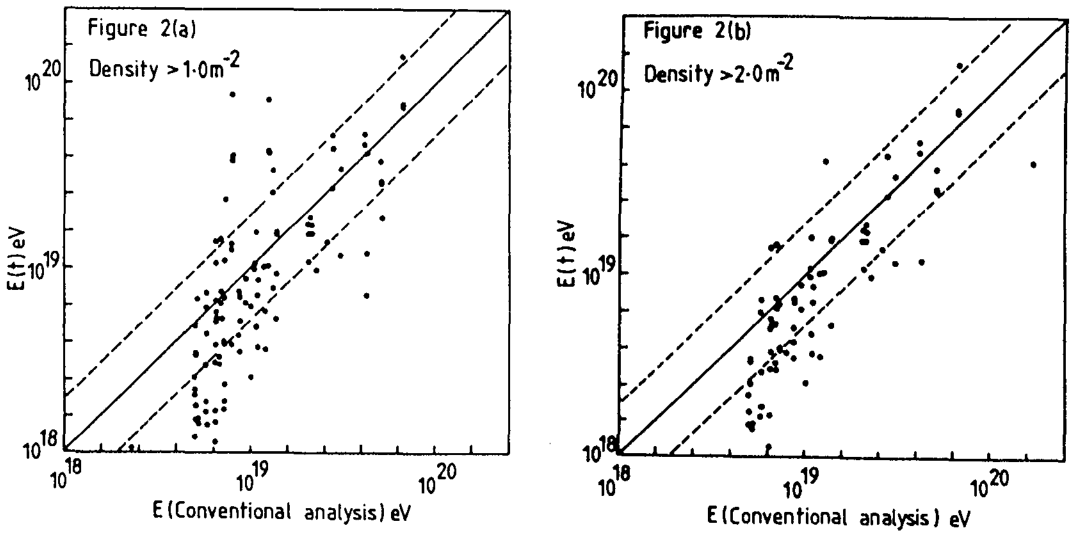
was derived. The points, on average, lie above this line as expected; specifically $\Sigma\sigma(\theta,r)/\sigma_m(t_{\frac{1}{2}})$ is +8.3 for the 18 risetimes measured in 7 events. Checks made in this way on the vast majority of showers with $E > 5 \times 10^{18}$ eV and $\theta < 40°$ underpin our confidence in the existence of primary cosmic rays above 5×10^{19} eV.

3. The mini-array method. Linsley (1983 and this conference OG-9) has proposed a cheap and novel method of detecting giant air-showers through the simultaneous measurement of shower disc thickness, density and direction at a small (∿50 m) shower array. His proposal was based on empirical data from the Volcano Ranch array obtained by averaging over many showers. We find this idea attractive and are presently instrumenting the peripheral arrays at Haverah Park for this purpose (Brooke et al 1983). As an interim step we have attempted to evaluate the potential of the method using existing data.

Events of known primary energy $> 5 \times 10^{18}$ eV and with at least one risetime measurement were selected. Using the zenith angle determined from the 500 m array detectors and the known regression line for giant showers (section 2 above) the distance of the core from each detector was estimated and hence, from the known density and assumed lateral distribution, the primary energy was derived. In Figure 2 the primary energy,

$E(t)$, derived from risetime measurement is compared with that from our normal analysis, the dashed lines indicating factors of two about the 1:1 line. Data for two threshold density cuts are shown.

Figure 2: Plots of energy derived from risetime against energy derived from conventional analysis.



An unweighted straight line fit to the points above 10^{19} eV yields gradients of 0.9 ± 0.2 and 1.2 ± 0.2 and the rms scatters about these lines are 100% and 75% for the two threshold density cuts respectively. A number of factors contribute to the spread in $E(t)$ and some of these will be discussed in the context of risetime measurement at 1 km in a 10^{19} eV shower at 30°.

(a) Zenith angle uncertainty. For the showers used above the typical zenith angle uncertainty is about 3°. However for realistic mini-arrays (such as those already set up at Haverah Park) $\Delta\theta \simeq 5^{\circ}$ (Brooke et al 1983). For a density recorded at 1 km this leads to an uncertainty in $E(t)$ of about 30%. It is possible that with suitable calibration improved zenith angle uncertainties might be achieved. Present work in optimizing angular resolution for UHE γ-ray astronomy might have spin-off here.

(b) Density threshold. The density threshold for the events in Figure 2(a) was set at $> 1\,m^{-2}$ (34 vertical equivalent muons). A detailed analysis of measurement errors shows that for the reference shower being discussed here $\sigma \simeq 20$ ns with the major contribution coming from the finite size of the density sample. This leads to an rms error in r of about 100 m and to an rms error in $E(t)$ of about 35%. The error in the risetime from this cause will vary as $1/\sqrt{\rho}$, where ρ is the density.

(c) Between shower variations. There are fluctuations in the longitudinal development of individual air-showers. These are unavoidable and cannot be overcome by new experimental techniques. For the reference shower $\sigma \simeq 20$ ns so that again the error in the deduced $E(t)$ is $\sim$ 35%.

These three factors when combined in quadrature predict an rms spread in $E(t)$ of $\sim$ 60% for a 10^{19} eV observed at 1 km and 30° with water-Cerenkov detectors of $34\,m^2$ area. With smaller area detectors the situation will be worse, but we propose to evaluate the problem using the sub-arrays at Haverah Park which are located 2 km from the centre of the array. Each, consisting of $4 \times 13.5\,m^2$ water-Cerenkov detectors, spaced at 50 or 150 m, is presently used to record small local showers ($> 10^{15}$ or 10^{16} eV) as well as being slaved by the giant array trigger. A single mini-array will have a collecting area of $\sim 6\,km^2$ at 10^{20} eV for a $1\,m^2$ threshold so that a x3 enhancement of our present system will be achieved at low cost. The uncertainties in energy measurement discussed above suggest that the mini-array technique will be more useful in the investigation of anisotropy at the highest energies than for the accurate determination of the cosmic ray spectrum.

The above evaluation refers to the use of $t_{\frac{1}{2}}$ to measure the disc thickness. In fact Linsley (1983) proposed the use of the dispersion and there will be differences of detail between an evaluation of that parameter and the present one.

4. Developmental Fluctuation. We have used our sample of 51 events above 10^{19} eV to estimate the fluctuation in the mean depth of maximum at 3×10^{19} eV. Details will be given elsewhere but the method is essentially that discussed in Walker and Watson (1983). The rms fluctuation in X_m, $\{X_m\}$, is found to be $33 \pm 8\,g\,cm^{-2}$, consistent with our previous work. The tendency for $\{X_m\}$ to decrease with energy and the conclusion that pure Fe can be excluded above 10^{19} eV are reinforced.

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