

PARTICLE DISTRIBUTIONS IN $\sim 10^{13} - 10^{16}$ eV AIR SHOWER CORES AT MOUNTAIN ALTITUDE AND COMPARISONS WITH MONTE CARLO SIMULATIONS

A.G. Ash

Department of Physics, University of Leeds, Leeds LS2 9JT, U.K.

ABSTRACT

Photographs of 521 shower cores in an array of current-limited spark ('discharge') chambers at Sacramento Peak (2900m above sea level, 730 g cm⁻²), New Mexico, U.S.A., have been analysed and the results compared with similar data from Leeds (80m above sea level, 1020 g cm⁻²). It was found that the 'central' density differential spectrum is consistent with a power law index of -2 up to $\sim 1500\text{m}^{-2}$ where it steepens, and that shower cores become flatter on average with increasing size.

Scaling model predictions for proton primaries with a $\propto E^{-2.71}$ energy spectrum account well for the altitude dependence of the data at lower densities. However, deviations at higher densities indicate a change in hadron interaction characteristics between $\sim \text{few} \times 10^{14}$ and 10^{15} eV primary energy causing particles close to the shower axis to be spread further out.

1. Introduction. Experimental data on particle distributions within a few metres of the axes of air showers at Sacramento Peak (2900m above sea level, 730 g cm⁻²), New Mexico, U.S.A., are described. The data are the results of the author's analysis of photographs of showers in an array of current-limited spark chambers ('discharge' chambers) operated by Hazen et al. (1981). These photographs were originally obtained as part of a search for high- p_t subcores.

The results are compared with similar data from the 35m² discharge chamber array at Leeds (80m above sea level, 1020 g cm⁻²) (Hodson et al., 1985) and predictions from Monte Carlo simulations.

2. Experimental Details. The array was housed under a canvas tent and was photographed from above using a small camera. During the experimental runs used as the basis for the present work the array consisted of 20 lm² discharge chambers (nearly identical to those used at Leeds) arranged into 4 parallel rows each of 5 chambers, with $\sim 30\text{cm}$ gaps (walkways) between adjacent rows and the chambers in each row close-packed to give in most cases only $\sim 3\text{cm}$ width of dead space between them. The trigger condition was a particle density $\geq 50\text{m}^{-2}$ in a scintillator near the centre of the array in coincidence with at least one particle in a scintillator a few metres outside the array. The trigger rate was $\sim 10\text{hr}^{-1}$.

3. Analysis and Results. The methods of analysis of the shower photographs follow closely those of Hodson et al. (1983a,b) for the Leeds data. The photographs (negatives on 35mm film) were projected at a linear demagnification of 8 in array space and scanned by eye for cores. Core location and subsequent density measurements made use of an annular grid, superposed over the projected image, identical in pattern to that used for the Leeds photographs (see Hodson et al., 1983a) but with its dimensions (in array space) linearly scaled up by a factor $s=(1020/730)$. This was to take approximately into account the effect of the difference in air density on particle densities when comparing the data for Leeds and Sacramento Peak. As in Hodson et al. (1983a) the grid was used to determine a shower centre (centre of symmetry) for the particle distribution of each core located in the array area and, with the grid

centred on the shower centre, densities at various radial distances were determined. To reduce the effects of trigger bias and scanning bias the analysis excluded all showers with centres located in the walk-ways between the rows of chambers, those with centres falling in the 4 corner chambers and any in the remaining outer chambers with centres falling within 0.4m of the edge of the array. The total collecting area for shower cores was then equal to $\approx 12\text{m}^2$.

A count of discharges in the centre circle (radius 0.25sm) of the grid gave the 'central' density; when a walk-way overlapped part of the centre circle (maximum 50%) then symmetry was used to obtain the count for the whole of its area. Counts in the angular sections of the annuli at the scaled distances sm and 2.5sm gave densities at these distances. (In general, counts were made in only one randomly-selected section in each of these annuli.)

In the rest of this paper, observed particle densities per m^2 (i.e. count/actual bin area in array space) are given, rather than densities scaled up by a factor s^2 .

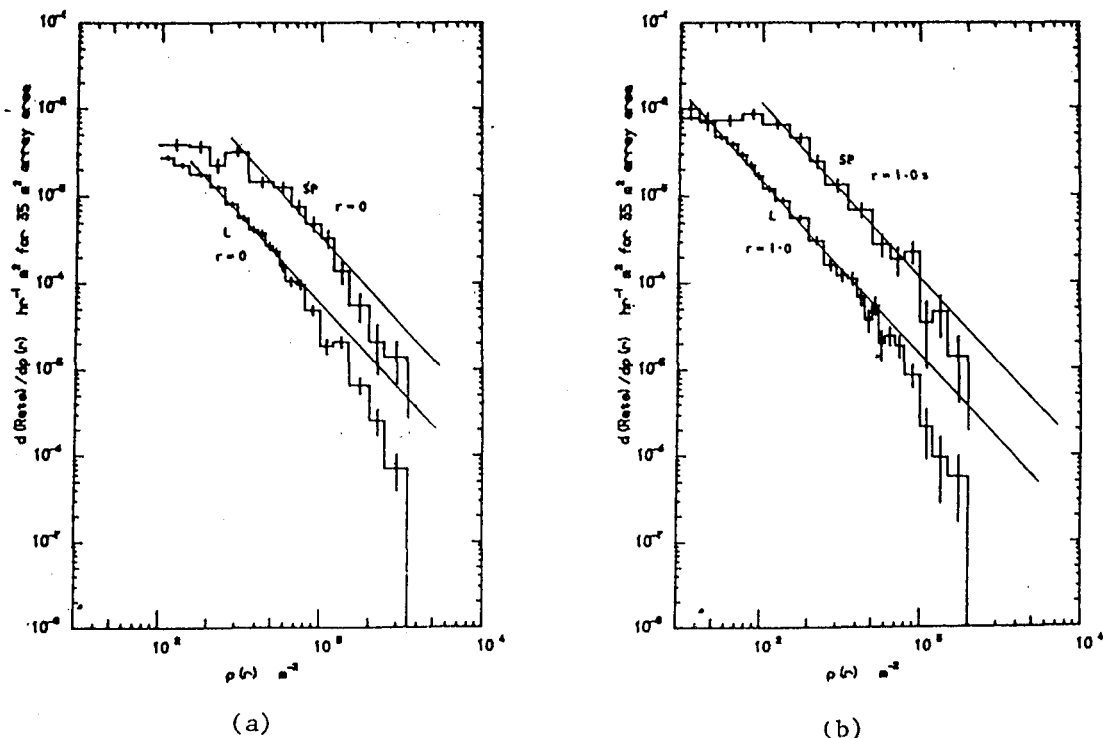


Figure 1 Differential density spectra $\rho(r)$ observed at Leeds (L) and Sacramento Peak (SP)

Figure 1 shows the differential density spectra for 521 cores at 0, 1.0s, and 2.5sm from the shower centre (normalised to a 35m^2 collecting area) as observed at Sacramento Peak, compared with the corresponding experimental data for Leeds. Power law lines of index -2 have been superposed on the spectra to show the steepening at high densities in the Leeds data (see Hodson et al., 1985) and for comparison with Sacramento Peak. (The deviations of the spectra from the -2 power law at low densities are due to trigger and scanning bias.) In Figure 1(a) there is evidence of a

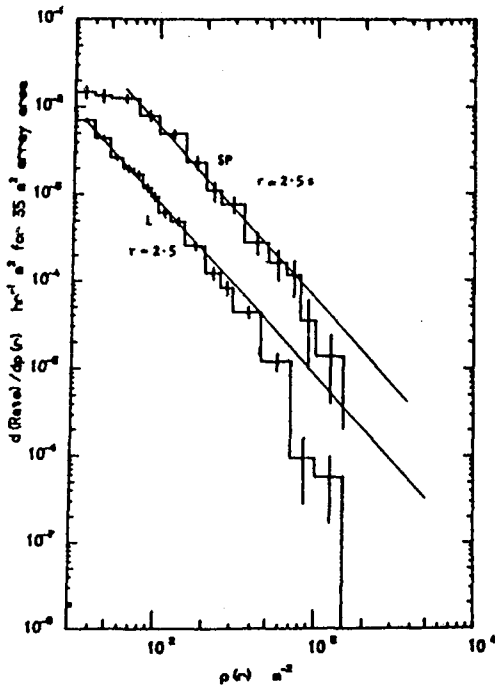
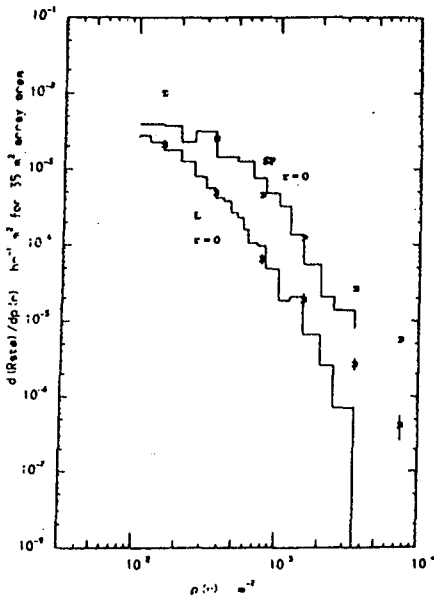


Figure 1(c)

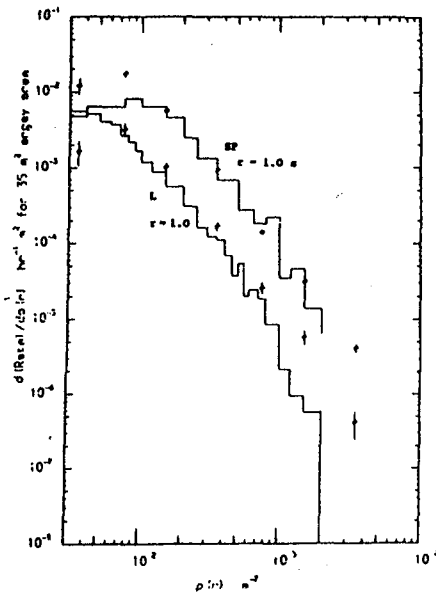
steepening from the -2 power law in the Sacramento Peak $\rho(0)$ spectrum at $\sim 1.5 \cdot 10^3 \text{ m}^{-2}$; the spectra further out (Figures 1(b) and 1(c)) may also steepen around 10^3 m^{-2} but this is less clear.

Figure 3 gives a plot of core 'flatness', $\langle \rho(1.0 \text{ s}) \rangle / \langle \rho(0) \rangle$, versus $\rho(2.5 \text{ s})$ (used as a measure of shower size, as $\rho(4.0)$ in Hodson et al., 1985); this shows a tendency for shower cores to become flatter within $s (= 1.4) \text{ m}$ as the showers become larger (as also reported for the Leeds data (Hodson et al., 1985)). Taking Figures 1 and 3 together, steep dense shower cores are observed at a lower rate than might be expected by extrapolation.

Figures 2 and 3 give comparisons with simulation predictions, after excluding all real and simulated showers with $\rho(0) < 100 \text{ m}^{-2}$, using scaling models (with EMC Model I) for proton



(a)



(b)

Figure 2 Comparison of observed differential density spectra (histograms) at Leeds (L) and Sacramento Peak (SP) with simulation predictions (points)

primaries, described by Ash (1985a). The full detailed core-mapping calculations were used for comparison with the Leeds data; for Sacramento Peak a simpler calculation was used, with the shower centre assumed to coincide with the shower axis. For the present purposes this

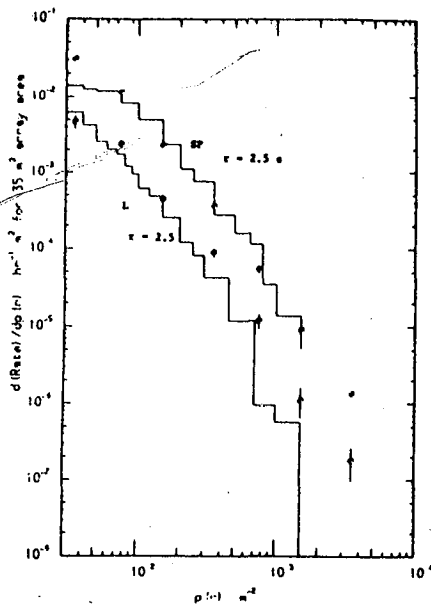


Figure 2(c)

The predictions agree well with the observed spectra both in slope and in absolute rates in the -2 power law region, where proton showers would be expected to dominate the spectra. At higher densities, all the Leeds spectra and the Sacramento Peak $\rho(0)$ spectrum are clearly steeper than those predicted.

Figure 3 shows that the predicted large proton showers have much steeper cores, on average, than those observed, as was also found for the Leeds data (Ash, 1985b).

4. Discussion. It is interesting to consider the mean primary energy $\langle E \rangle$ of showers with a given $\rho(r)$ at Sacramento Peak. At $\rho(0) \approx 1.5 \times 10^3 \text{ m}^{-2}$ the proton simulations predict $\langle E \rangle \approx 6 \times 10^{14} \text{ eV}$; if the steepening of the $\rho(0)$ spectrum is due to a rapid increase in the slope of the proton primary energy spectrum then a clear steepening should also occur for similar values of $\langle E \rangle$ in the density spectra further out. At 2.5 s and s m from the shower centre $\langle E \rangle = 6 \times 10^{14} \text{ eV}$ corresponds to densities of $\sim 200 \text{ m}^{-2}$ and 400 m^{-2} respectively; no steepening is evident at around these densities. This, together with the observed core flattening, lends support for a significant change in hadron interaction characteristics between primary energies of \sim a few $\times 10^{14}$ and 10^{15} eV . A natural explanation might be found in a mechanism which spreads particles out from within $\sim 1 \text{ m}$ of the shower centre. Complete understanding probably requires the combined effect of interaction changes plus some steepening in the proton energy spectrum.

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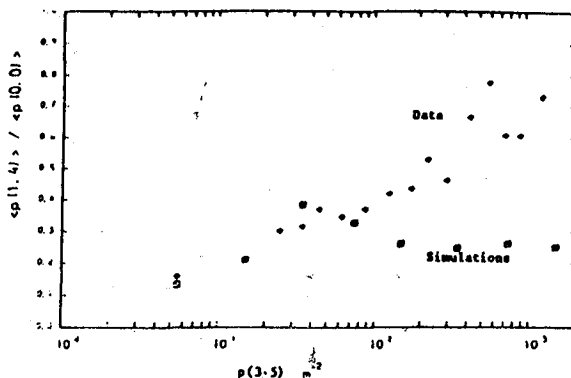


Figure 3 'Core flattening' at Sacramento Peak

difference is unimportant. The proton primary energy spectrum was $dn/dE = 1.36 \times 10^4 E^{-2.71} \text{ GeV}^{-1} \text{ m}^{-1} \text{ sr}^{-1} \text{ s}^{-1}$, consistent with balloon-based observations, here extrapolated to 10^{16} eV .