The mass composition of cosmic rays from 3×10^{17} to 3×10^{18} eV

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Abstract

During the operation of the Haverah Park array data were collected on the risetime and lateral distribution of showers produced by primaries with energies above 3×10^{17} eV. These data clearly demonstrated the angular and energy dependence of two parameters which depend for their absolute magnitude on the position of the depth of shower maximum. Fluctuations in these parameters from shower to shower were also detected with very high significance. Shower models then available (ca 1980) were unable to account for even the average values of the risetimes and lateral distributions. However model-independent attempts to deduce the mass composition, based on Linsley's elongation rate theorem, were attempted (Walker and Watson 1981, Coy et al 1983). Now, 20 years later, shower models have advanced significantly, driven in part by the need for a full design study of the Auger Observatory. As a spin off, and also to guide future analysis of the Auger data, we are attempting to re-interpret the Haverah Park work using the most modern shower models. We present results from Monte Carlo calculations which predict the average risetime and lateral distribution of showers. New data on the elongation rate above 3×10^{17} are reported.

1 Introduction

At Haverah Park a number of measurements were made which are relevant to determination of the mass composition of cosmic rays above 3×10^{17} eV. In particular two parameters sensitive to the longitudinal development of showers were studied in some detail. These were the 10 - 50% risetime ($t_{1/2}$) of the signal from the 4×34 m^2 water-Čerenkov detectors (Watson and Wilson 1974, Walker and Watson 1981) and the steepness of the lateral distribution function (LDF). The LDF measured at Haverah Park is well described by the function: $\rho(r) = r^{-(\eta+r/4000\,\mathrm{m})}$. The steepness of the LDF is characterised by the parameter η which was measured with high precision using an infilled portion of the array (Coy et al. 1981). The risetime data were obtained from >7000 events and a total of 13000 pulses having densities above 1 m $^{-2}$ and lying more than 300 m from the shower axis. The risetime data contain events over the range of energies from 2×10^{17} to 10^{20} eV. The LDF parameter was measured in 1425 events which are dominantly in the range 3×10^{17} to 3×10^{18} eV. The much larger energy range of the risetime technique arises

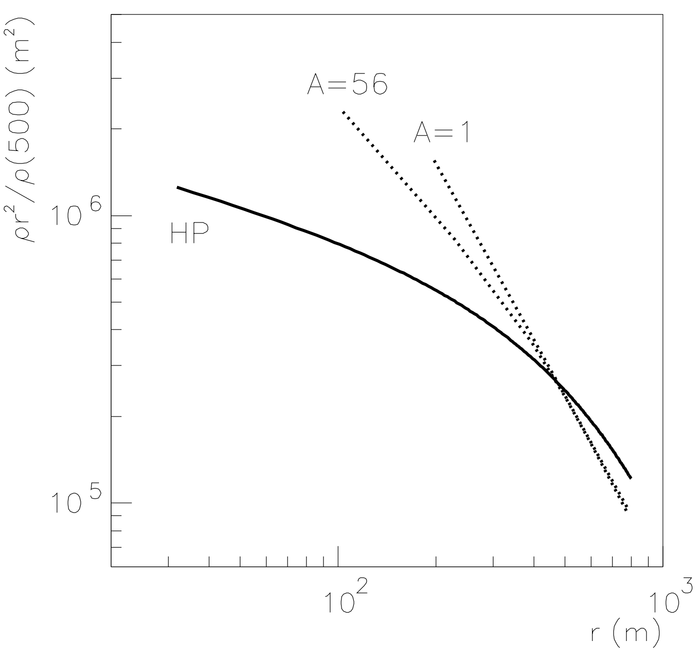

Figure 1: A comparison of Haverah Park data and the calculation of Gaisser et al. (1978). Reproduced from (Coy, 1984)

because it is impossible to cover a large area with the dense coverage of detectors required for an accurate measurement of η.
The risetime work established the first evidence of 'between shower' fluctuations to be obtained at high energies (Watson and Wilson 1974). This was supported by the demonstration of a physically reasonable correlation of $t_{1/2}$ with LDF steepness. It was not possible in the 1970s and 1980s to make accurate theoretical predictions for $t_{1/2}$ because of the computer intensive nature of the necessary 4-dimensional calculations. However the powerful elongation rate theorem of Linsley (1977) was used to measure the elongation rate over the energy range 0.2 to 100 EeV (Walker and Watson 1981). The value reported (70 ± 5 g cm^{-2} per decade) is in excellent agreement with the value subsequently measured much more directly by the Fly's Eye group (Bird et al. 1994).

The analysis of the η data also showed evidence of fluctuations very much larger than could be attributed to the experimental uncertainties. However the depth dependence of η could not be established directly from the data. Furthermore comparison of the measured average value of η with a highly regarded model calculation of the time (Gaisser et al. 1978) showed strikingly poor agreement: a mean cosmic ray mass very much heavier than iron was required to fit the data. However assuming that functional dependence of η on X_m is of the form $f(X/X_m)$ it was shown, following a suggestion of Cronin (1991), that the $t_{1/2}$ and η could be combined to give a model independent estimate of the depth of maximum at 5×10^{17} eV of 619 ± 99 g cm^{-2} to be compared with the Fly's Eye value at the same energy of $665 \pm 4 \pm 20$ g cm^{-2}.

In this report we describe a preliminary attempt to re-examine the available data using an air-shower Monte-Carlo (AIRES/SIBYLL) which has been developed as part of the Auger Observatory design study. We extract a new measurement of the depth of shower maximum above 3×10^{17} eV from the data on η and use the $t_{1/2}$ data to infer the depth of maximum to the highest energies. We plan to use the correlated data and the data on fluctuations in a later study.

2 New model calculations

Our new calculations use the AIRES air-shower simulation program (Sciutto 1998) incorporating the SIBYLL (Fletcher 1994) event generator. Calculations using the QGSJET (Ostapchenko 1997) event generator are in progress to assess the model dependence of η and $t_{1/2}$ calculations. The response of the water tanks has been simulated using WTANK(de Mello Neto 1998) and is being checked independently using the AGASim program (Pryke 1996).

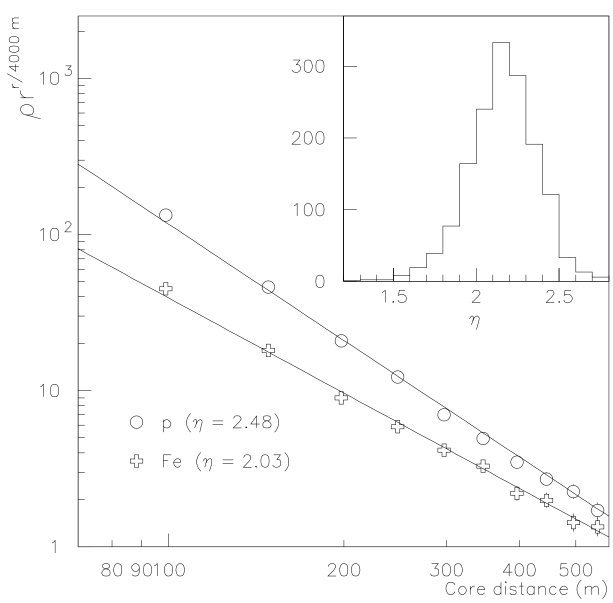

Figure 2: The lateral distribution of two simulated showers fitted with the Haverah Park ldf. The showers are of zenith angle 26° and energy 3×10^{17} eV, the approximate mean values for the data. The inset histogram shows the measured distribution of η.

Figure 2 shows the lateral distribution of two sample events of zenith angle 26° and energy 3×10^{17} eV. The Haverah Park parameterisation fits the simulated LDFs very well. The inset histogram shows the distribution of η in the data (the typical measurement error on η ~0.1). The range of η values observed is clearly consistent with the calculations.

In figure 3 we show the relationship between the parameters η and $t_{1/2}$ to the column density between the observer at the ground and shower maximum (Referred to as Y). Showers with zenith angles of 0-45° and energy from $3 \times 10^{17} < E < 3 \times 10^{18}$ are shown. There is a very strong correlation between the shower parameter Y and the two observables; $t_{1/2}$ provides a less mass dependent estimate of X_m. A greater mass dependence in the relationship of η to Y is apparent which introduces a systematic error of ~25 g cm^{-2} in estimates of Y (and hence X_m) from η. There is an additional uncertainty in X_m introduced by the choice of model. Work is underway to quantify this effect.

The computation of η is presently considered to be the more reliable as $t_{1/2}$ remains a computationally intensive parameter to calculate. Thus in what follows we have used the calculation of η to infer values of X_m.

3 Shower Maximum as a function of energy

In figure 4 we show five independent derivations of X_m obtained from the measurements of the average values of η as a function of energy. The SIBYLL model with a primary mass composition of 50% Fe and 50% protons is assumed in the calculation. The accord with the direct measurements of the Fly's Eye group is remarkable and suggests that the model used to compute the lateral distribution is a very reasonable one. The addition of risetime data at lower energies promises to provide a less mass dependent estimate of X_m. Care was taken to select the experimental data in a bias free way but this matter requires further study. The elongation rate from the five points is 85 ± 10 g cm^{-2} and from the last four points is 90 ± 12 g cm^{-2}. The box shows the elongation rate obtained from the risetime data in the range log E(eV) = 17.5 to 18.8 as reported in Walker and Watson (1981). The lower energy end of the box has been anchored at log E(eV) = 17.50 to a fit to the five risetime points as seems justified by the agreement between X_m measurements at this energy. The data are extended further in energy using 35 events above log E(eV) = 18.70 for which the elongation rate was measured to be 40 ± 20 g cm^{-2}.

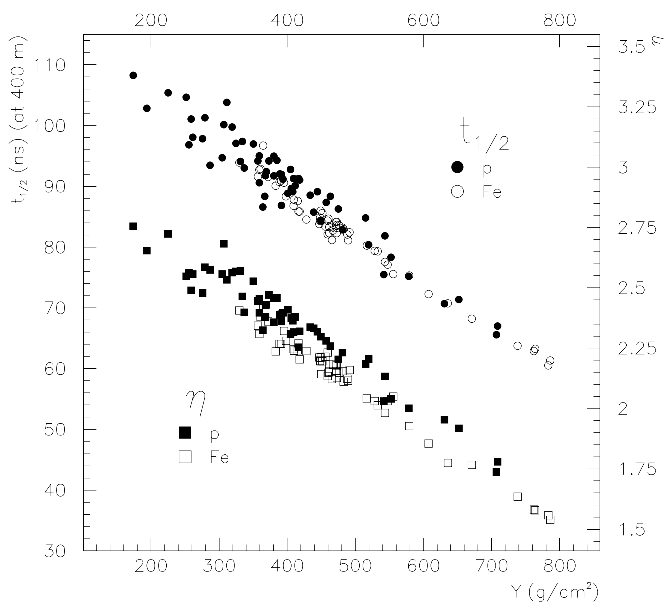

Figure 3: The relationship of $t_{1/2}$ and η to X_m using AIRES/SIBYLL. Showers of $0° < \theta < 45°$ and $3 \times 10^{17} < E < 3 \times 10^{18}$ are shown. Inclined showers are towards the right hand side of the diagram.

4 Conclusions

Our preliminary work suggests that further study should lead to valuable information on the mass composition in this important energy range.

5 Acknowledgements

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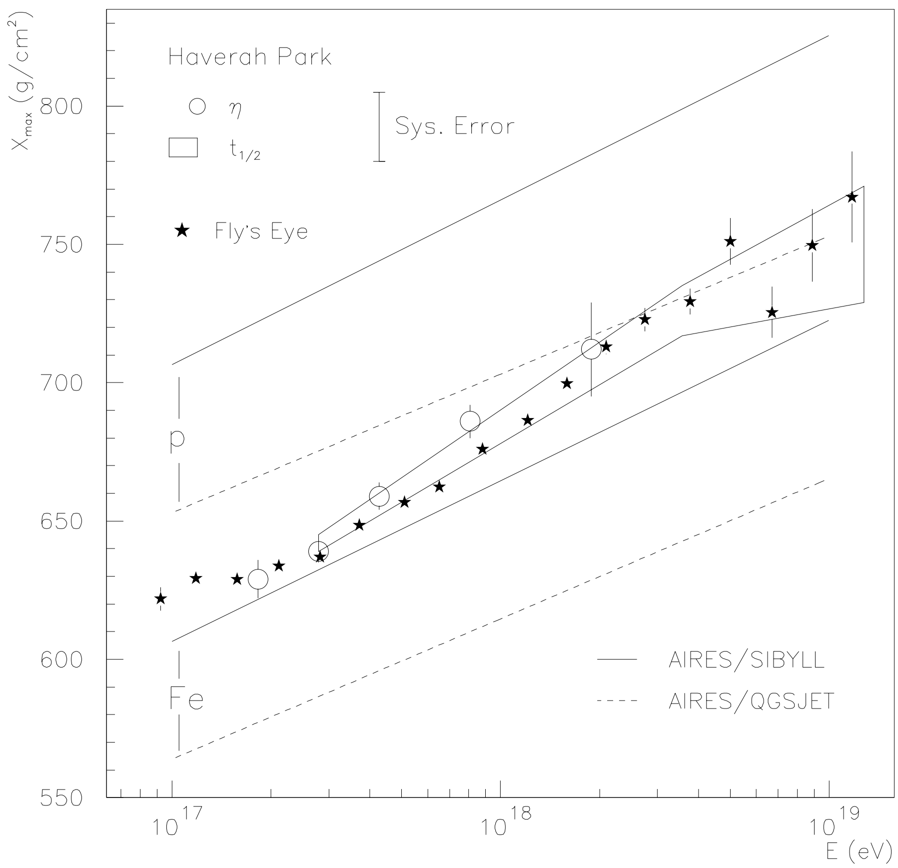

Figure 4: X_m versus energy from the Haverah Park η data. Data from Fly's Eye and calculations from AIRES are shown for comparison.

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