

THE STRUCTURE OF EAS AT  $E > 0.1$  EeV

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## ABSTRACT

We have obtained the ratio of EAS total shower energy in the electromagnetic channel ( $E_{em}$ ) to the size of the shower at maximum development ( $N_{max}$ ) from a direct measurement of shower longitudinal development using the air fluorescence technique(1). The values obtained agree closely with those estimated by Linsley(2). However, they are not inconsistent with values based upon track length integrals of the Gaisser-Hillas formula for shower development(3) or the known relation between shower energy and size at maximum for pure electromagnetic cascades. Using Linsley's estimates for undetected shower energy(2) based on an analysis of a wide variety of cosmic ray data we obtain the following relation for total shower energy  $E$  vs  $N_{max}$ :  $E = 1.31 \pm .14 (N_{max}/10^9)^{0.990 \pm .005} \text{ GeV}$ . Using the Gaisser-Hillas implied undetected shower energy fractions, we obtain  $E = 1.53 \pm .16 (N_{max}/10^9)^{0.99 \pm .005} \text{ GeV}$ .

1. Introduction. The estimation of total EAS energy from shower size measurements at ground level depends, among other things, upon a knowledge of the conversion factor  $E/N_{max}$ (2,4). This factor has been derived by Linsley indirectly from a large body of existing cosmic ray data(2). In addition, it has been calculated from models of shower development incorporating scaling(3) and radial scaling(5). Values quoted range typically between 1.3 and 1.7 GeV/particle for EAS energies in the range .01-100 EeV (1 EeV =  $10^{18}$  eV) the precise value being dependent primarily upon estimates of undetected shower energy in the non-electromagnetic channel. We present below the results of the  $E_{em}$  vs  $N_{max}$  relationship obtained from a direct integration of EAS longitudinal development profiles as measured by the Fly's Eye detector. We then infer values for the total shower energy relationship to  $N_{max}$  based upon Linsley's estimates of undetected shower energy from cosmic ray data(2) as well as estimates inferred from the Gaisser-Hillas parameterization of shower longitudinal development(3).

2. Measurement. The Fly's Eye detector has been described in detail elsewhere(1). Essentially, the detector observes the passage of EAS thru the atmosphere via nitrogen fluorescence. Shower sizes vs depth are calculated from measured light yields and experimentally determined shower trajectories(1). Electromagnetic shower energy,  $E_{em}$ , and shower size at maximum  $N_{max}$  is determined by fits made to resultant longitudinal development curves. Shower energy is given by:

$$E_{em} = \frac{\epsilon_0}{X_0} \int N_e(x) dx$$

where  $N_e(x)$  is the shower size vs depth and  $\epsilon_0/X_0$  is the ratio of the critical energy of an electron to its radiation length in air, taken to be 2.18 MeV/electron  $\text{g cm}^{-2}$  (6). We note that, if a shower development curve is represented by an equivalent Gaussian then

$$\frac{E_{em}}{N_{max}} = \sqrt{2\pi} \frac{\epsilon_0}{X_0} \sigma$$

where  $\sigma$  is the equivalent Gaussian width of the curve.

We have selected a sample of approximately 1150 showers observed during a 3 year interval whose equivalent Gaussian widths were measured to an accuracy of better than  $\pm 20\%$  and whose total observed track lengths subtended an angle in the sky of greater than  $60^\circ$ . This selection criterion ensured a sample of showers whose longitudinal profiles were well-known and whose subsequent ratios of  $E_{em}/N_{max}$  were determined to within  $\pm 20\%$ .

3. Results. Shown in Table 1 are the results of the measured  $E_{em}/N_{max}$  ratios as a function of total shower energy  $E_{tot}$ .

Table I.  $E/N_{max}$  vs  $E_{tot}$

Method	$E_{tot}(\text{EeV})$			
	.01	0.1	1.0	10.0
	$E_{em}/N_{max}$ (GeV/electron)			
E&M Cascade(8)	1.12	1.18	1.25	1.31
Gaisser-Hillas(3)	1.13	1.20	1.28	1.34
Linsley(2)	1.06	1.12	1.17	1.22
Measured	$1.11 \pm .09$	$1.17 \pm .10$	$1.19 \pm .10$	$1.20 \pm .10$
	Missing Energy (% of $E_{tot}$ )			
Linsley(2)	19	13	9	6
Gaisser-Hillas(3)	31	27	22	18
	$E_{tot}/N_{max}$ (GeV/electron)			
Measured(L)	1.37	1.34	1.31	1.28
Measured(GH)	1.16	1.60	1.53	1.46

In addition, we also show values of  $E_{em}/N_{max}$  derived in the following ways: (a) Pure electromagnetic cascades initiated by an electron (or photon) of energy  $E_{tot}$ , i.e.

$$N_{max} = \frac{0.31 E_{em}/\epsilon_0}{\sqrt{\ln(E_{em}/\epsilon_0) - 0.37}} \quad (7)$$

(b) By integrating the Gaisser-Hillas shower development curve(3) we obtain:

$$\frac{E_{em}}{N_{max}} = \frac{\epsilon_0}{X_0} \lambda \alpha^{-\alpha} \exp^{\alpha} \Gamma(\alpha+1)$$

where  $\lambda = 70 \text{ g cm}^{-2}$  and  $\alpha = 0.51 \ln(E/\epsilon_0) - 1$

(c) Linsley's estimated values quoted in ref.(2).

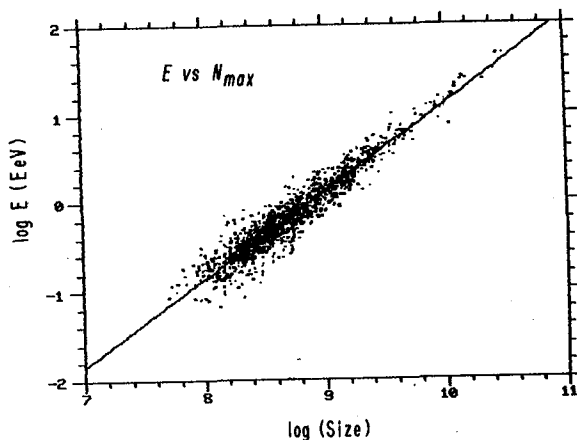
We note that the Gaisser-Hillas method yields  $E_{em}/N_{max}$  values remarkably close to those obtained from purely electromagnetic cascades. We also note that our measured values of  $E_{em}/N_{max}$  are in excellent agreement with the above estimates.

Finally, in order to convert  $E_{em}/N_{max}$  to  $E_{tot}/N_{max}$ , corrections for undetected shower energy (energy in the form of muons and neutrinos, undetected hadrons and nuclear excitation) must be applied. We have made such corrections in two ways primarily for the purposes of illustrating the uncertainties currently involved in accounting for total unobserved energy and thus obtaining the correct factors necessary to convert shower size measurements (or measurements of any other parameter basically dependent on the number of electrons in EAS) into total primary energy. The first estimate of missing energy is obtained directly from Linsley(2) who derives estimates of missing shower energy in a quite clever empirical fashion directly from measured electron and muon size spectra and the total assessed energy content of these respective components of the EAS. We have parameterized Linsley's estimates in the following way:

$$E_{em}/E_{tot} \cong 0.99 - .0782E_{tot}^{-0.175} \quad E_{tot} \text{ in EeV}$$

This parameterization is valid for  $1 \text{ PeV} < E < 100 \text{ EeV}$  and the resultant undetected energy percentages listed in Table 1.

Finally, we note that the amount of undetected energy based on the Gaisser-Hillas formula for shower development can be obtained directly from the values listed in Table 1 for  $E_{em}/N_{max}$  and noting that the Gaisser-Hillas formula is based on a constant value for  $E_{tot}/N_{max}$  of  $1.64 \text{ GeV/electron}$ . Thus the apparent undetected energy percentages inferred from the Gaisser-Hillas parameterization are as shown in Table 1. Finally, we also list in Table 1 the resultant  $E_{tot}/N_{max}$  ratios based on applying each of the above missing energy percentages corrections to the resultant measured values of  $E_{em}/N_{max}$  obtained directly from Fly's Eye data.



We note that the Gaisser-Hillas parameterization with its large amount of implied missing energy is based on fits to simulated showers which incorporate a simple scaling model with constant cross section for EAS development. Such models tend to generate penetrating showers in which the amount of undetected energy would be anticipated to be less than for those models

Figure 1. Scatter Plot of Total Shower Energy vs Shower Size at Maximum as Measured by the Fly's Eye Detector.

which led to more rapid shower development.

Finally, we show in Figure 1 a scatter plot of  $E_{\text{tot}}$ , assuming the Linsley estimates of missing shower energy, vs  $N_{\text{max}}$ . The best fit line is given by:

$$E_{\text{tot}} = 1.31 \pm .14 (N_{\text{max}}/10^9)^{0.990 \pm .005} \text{ GeV}$$

the scatter in the data points is due both to detector resolution as well as intrinsic fluctuations. Future work will concentrate upon an extraction of the detector resolution function in order to determine how much intrinsic scatter there is in  $N_{\text{max}}$  and thus its effect on total energy measurements which depend essentially on a measure of that parameter.

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