MUON FLUCTUATION STUDIES OF EAS > 10^{17} eV

P. R. BLAKE, M. LUKSYS, W. F. NASH and A. J. SEPHTON
University of Nottingham, England.

1. Introduction Fluctuation studies need to compare a parameter which is sensitive to longitudinal fluctuations against a parameter which is insensitive. Cascade calculations indicate that the shower size parameter at Haverah Park, $\rho(500)$, and the muon density are insensitive while parameters that significantly reflect the longitudinal development of a particular EAS include the muon/water Cerenkov response ratio and the muon arrival time dispersion. This paper presents conclusions based on muon fluctuation studies of EAS measured between 1976 and 1981 at Haverah Park.

2. Description of Muon Detectors Three 10 m^2 shielded scintillators situated at 0, 150 m and 250 m from the centre of the Haverah Park array. Due to practical considerations the detectors had slightly different absorber thicknesses leading to calculated vertical muon thresholds of 317, 431 and 488 MeV respectively. Two of the muon detectors (those at 0 m and 150 m) had immediately neighbouring large area water Cerenkov detectors so that a local response ratio between the two detectors could be directly measured. The recording of the three detectors was triggered from the water Cerenkov 500 m array by the arrival of EAS with primary energies $\gtrsim 10^{17}$ eV.

3. Fluctuations in μ/c Ratio The ratio of the density response of the muon detectors to the density of the water Cerenkov detectors (symbolised by μ/c) was used to study fluctuations between EAS. For a data set consisting of those EAS with two direct measurements of μ/c an analysis of variance (AOV) was carried out in order to extract the between-EAS variance (σ_B^2) from the total measured variance (σ^2).

R(m)	secθ	Number of EAS	$\sigma_B/(\mu/c)$	F	P
120	1.0-1.1	61	22.4% (±10)	2.44	<0.01
→220	1.1-1.2	36	19.7% (±12)	2.57	<0.01
	1.2-1.3	28	24.7% (±20)	2.23	0.01<p<0.025
220	1.0-1.1	83	0.0% (-0 +15)	0.74	>0.1
→320	1.1-1.2	52	19.9% (±19)	1.46	0.05<p<0.1
	1.2-1.3	37	23.4% (±12)	3.15	<0.01
320	1.0-1.1	54	0.0% (-0 +27)	0.94	>0.1
→420	1.1-1.2	36	1.1% (-1 +40)	1.00	>0.1
	1.2-1.3	23	4.4% (-4 +35)	1.02	>0.1

Table 1 Between-EAS fluctuations in μ/c.

Because the different energy thresholds lead to different μ/c ratios the AOV was carried out using standard residuals defined by S.R. = $[(\mu/c) - \overline{(\mu/c)}]/\sigma$, where μ/c is the normalised measured ratio, $\overline{(\mu/c)}$ is the average value and σ the standard deviation for the interval under consideration. The results of the AOV are presented in Table 1.

Also included in the table are the F ratio (mean square deviation between EAS to mean square deviation within EAS) and p, the probability that random variations in the data could account for the quoted between-EAS fluctuations. The results indicate that at core distances ~200 m the magnitude of the between-EAS fluctuations is ~20%. Such a result would be consistent with at least a 50% proton primary flux at ~10^{17} eV [eg. Marden et al, 1971].

4. Fluctuations in Muon Risetime The muon arrival timespread at each of the 10 m^2 muon detectors is characterised by the time interval between 10% and 70% of the full pulse amplitude (T_{70}). The instrumental response was found to be T_{70} = 32 ns. For a specific R and θ, fluctuations in T_{70} occur arising from fluctuations in the longitudinal development. AOV techniques allow between-shower fluctuations in T_{70} to be separated from within EAS fluctuations. Such analysis leads to a value of σ_B/T_{70} = 10.7(±2) ns/63 ns = 17% at 325 m, for secθ = 1.1.

Detailed cascade model calculations relating to T_{70} fluctuations remain to be carried out. As a consequence the significance of the T_{70} fluctuations is treated in Section 7 in terms of fluctuations in the height of electromagnetic maximum

5. Correlations of μ/c and η_C The water Cerenkov response lateral distribution function used by the University of Leeds group to analyse the EAS is of the form:

$$\rho_C = k R^{-(\eta_C + R/4000)}$$

It has been found that η_C is sensitive to EAS longitudinal development. Thus a strong correlation is expected between fluctuations in μ/c and η_C. Table 2 gives the derived correlation coefficients for the data sets from two muon detectors and also the significance of the correlation.

Detector	secθ	N	r	P
A	1.0-1.1	190	0.449	<0.001
	1.1-1.2	81	0.342	<0.01
	1.2-1.3	40	0.420	<0.01
	1.3-1.4	20	0.598	<0.001
C	1.0-1.1	117	0.398	<0.001
	1.1-1.2	52	0.595	<0.001
	1.2-1.3	34	0.515	<0.01
	1.3-1.4	10	0.618	<0.1

Table 2 Correlation between fluctuation in μ/c and fluctuation in η_C. r = correlation coefficient.

The strong correlation confirms that μ/c and n_c are sensitive parameters to EAS development.

6. Correlation of μ/c and T_{70} A small positive correlation is found between the values of SR(μ/c) and SR(T_{70}) at all zenith angles (see Table 3).

Detector	secθ	No of EAS	r	P
A - μ/c	1.0-1.1	20	0.032	>0.1
B - T_{70}	1.1-1.2	15	-0.306	>0.1
	1.2-1.3	4	0.541	>0.1
	1.3-1.4	7	-0.405	>0.1
A - μ/c	1.0-1.1	32	0.016	>0.1
C - T_{70}	1.1-1.2	19	0.278	>0.1
	1.2-1.3	25	0.172	>0.1
	1.3-1.4	10	0.438	>0.1
C - μ/c	1.0-1.1	44	0.203	>0.1
A - T_{70}	1.1-1.2	31	0.006	>0.1
	1.2-1.3	25	0.245	>0.1
	1.3-1.4	12	0.323	>0.1
C - μ/c	1.0-1.1	15	0.122	>0.1
B - T_{70}	1.1-1.2	16	0.013	>0.1
	1.2-1.3	12	-0.197	>0.1
	1.3-1.4	9	0.382	>0.1

Table 3 Correlation between μ/c and T_{70} fluctuations

Because of the different core distance dependences the two correlating parameters were measured simultaneously from two different muon detectors. The significance of the correlation coefficients in Table 3 is statistically limited due to the small amount of data available for the analysis.

7. Fluctuations in Depth of Electromagnetic Maximum Fluctuations in the depth of maximum (X_{max}) are closely related to the mass spectrum of the primary particles. It is not possible to measure X_{max} directly at Haverah Park. However the fluctuation in X_{max} can be determined indirectly from the measurement of some shower parameters, eg. μ/c which is sensitive to X_{max}. Assuming

$$\Delta X_{max} = \frac{X_{max}}{X} \frac{(\mu/c) - (\overline{\mu/c})}{\partial(\mu/c)/\partial X}$$

and using the AOV carried out on the μ/c fluctuations observed at two detectors (for core distances 120 m < R < 220 m and secθ < 1.3) yields:-

N	σ_B(g cm^{-2})	F	p
125	73.2	2.39	<0.01

The value of σ_B is the between-shower fluctuation (in g cm^{-2}) obtained from the AOV and gives an initial estimate of the fluctuation in X_{max}. The values of F and p show that highly significant between-EAS fluctuations are present in the data. Removing the spurious contribution to σ_B from the pressure correction, the corrected fluctuations in depth of maximum, $\sigma(X_{max})$ for EAS in the energy range $10^{17} - 10^{18}$ eV is given by $\sigma(X_{max}) = (71 \pm 12)$ g cm^{-2}). Using a similar technique the fluctuations in T_{70} yield $\sigma(X_{max}) = (69 \pm 28)$ g cm^{-2}.

Measurement of $\sigma(X_{max})$ at energies above 10^{17} eV have been reported by other groups from a variety of studies. The values obtained above are in good agreement with these other measurements.

8. Conclusions It was stated in section 3 that the μ/c fluctuations are consistent with at least a 50% proton primary flux at $\sim 10^{17}$ eV. This conclusion is supported by the $\sigma(X_{max})$ results. None of the different model predictions available give such a large $\sigma(X_{max})$ value based on a pure iron primary beam [eg. Gaisser et al (1982), Chantler et al (1983)]. Since the value of $\sigma(X_{max})$ measured in the present work, 71 ($\pm$ 12) g cm^{-2}, is $\sim 3.5\ \sigma$ above even the largest calculated estimate for iron nuclei it is extremely unlikely that cosmic rays in the energy range $10^{17} - 10^{18}$ eV are dominantly iron nuclei. This measurement of $\sigma(X_{max})$ is however consistent with a pure proton mass composition on the basis of the calculations of Chantler et al (1983) [$\sigma(X_{max}) = 60$ g cm^{-2}].

Large fluctuations in X_{max} can arise if several masses are present in the primary beam. For a mixed composition in which P:He:(Mg:CNO):Fe is 50:19:19:12, it is found that $\sigma(X_{max}) = 57$ gcm^{-2} based on Gaisser et al (1982).

In conclusion the fluctuation in X_{max} seen at energies in the range $10^{17} - 10^{18}$ eV can be accounted for by a mass composition in which > 50% of the primaries are protons. Primaries at these energies cannot be dominantly iron.

REFERENCES

Chantler, M. P., Craig, M. A. B., McComb, T. J. L., Orford, K. J., Turver, K. E. and Walley, G. M. J. Phys. G 9 L27 (1983).

Gaisser, T. K., Stanev, T., Freier, P. and Waddington, C. J. Phys. Rev. D, 25, 2341 (1982).

Marsden, D. J., Hillas, A. M., Hollows, J. D. and Hunter, H. W. 12th Int. Cos. Ray Conf., Hobart p.1013 (1971).