THE MUON CONTENT OF EAS AS A FUNCTION OF PRIMARY ENERGY

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1. Introduction At Haverah Park the muon content of EAS has been measured over the wide primary energy range 10^{16} to 10^{20} eV. At the Bangalore Conference it was reported (Blake et al, 1983) that the relative muon content of EAS decreases smoothly [$\sim \rho(600\ m)^{0.94}$) over the energy range 10^{17} - 10^{19} eV and therefore concluded that the primary cosmic ray flux has a constant mass composition over this range. In the same paper (on the basis of a preliminary analysis) it was also reported that an apparent significant change in the power index occurs below 10^{17} eV [$\rho_c(250\ m)^{0.78}$]. Such a change would indicate a significant change in primary mass composition in this range.

Further analysis confirms the earlier conclusions concerning EAS of energy $\geq 10^{17}$ eV. However post-Bangalore analysis of data in the 10^{16} - 10^{17} eV range revealed a previously overlooked selection bias in the Bangalore data set. This paper presents the full analysis of the complete data set in the energy range 10^{16} - 10^{17} eV with the selection bias eliminated.

2. Methods Three 10 m² muon detectors ($\sim$ 400 MeV threshold) were operated in conjunction with the deep water Cerenkov tank array (operated by the University of Leeds EAS group) at the Haverah Park site. Two of these muon detectors were immediately adjacent to large area water Cerenkov detectors, enabling a direct measurement of the ratio of the muon response to the water Cerenkov response (ρ_μ/ρ_c) to be made. The water Cerenkov response (ρ_c) is dominated at low core distances by the electromagnetic response. The directly measured ratio (ρ_μ/ρ_c) has the advantage of not being very sensitive to EAS parameters and therefore not sensitive to any inaccuracies in determining these parameters.

3. Results (10^{16} - 10^{17} eV) The basic problem in establishing an accurate determination of the muon content over a large primary energy range arises from the measurement technique. Inevitably in most arrays (including the Haverah Park array) the core distance range covered is a strong function of primary energy (or shower size). The ratio (ρ_μ/ρ_c) itself will be a function of core distance and thus direct determination of ρ_μ/ρ_c at a specific core distance is limited to a small range of primary energies. If a relationship of the form $\rho_\mu = k\ \rho_c^{\alpha}$ is adopted, k can normally be regarded as constant at a particular core distance (R); the power index (normally 0.94) may be a function of core distance and shower size. A core distance dependence would arise if the lateral density distributions of ρ_μ or ρ_c significantly change with shower size. Measurements indicate that the lateral distribution of ρ_μ is unchanging at energies > 10^{16} eV. However the lateral distribution function of the electromagnetic component (and therefore ρ_c) does

show some change as the electromagnetic cascade maximum penetrates more deeply into the atmosphere as E_p increases. Thus in determining the exponent 'α' it is sensible to limit the core distance range to as small a core distance interval as is statistically feasible.

The available experimental data were divided into three overlapping intervals of core distance:- 50 m $\leq$ R $\leq$ 150 m; 100 m $\leq$ R $\leq$ 200 m; and 150 m $\leq$ R $\leq$ 250 m. The data were further subdivided into four $\sec\Theta$ intervals 1 $\rightarrow$ 1.1 $\rightarrow$ 1.2 $\rightarrow$ 1.3 $\rightarrow$ 1.4 and six shower 'log' size intervals. The data were then used to calculate the mean measured muon and water Cerenkov responses at R = 100 m, 150 m and 200 m. The results for 1.0 < $\sec\Theta$ < 1.1 are displayed in Table 1 & Figure 1. Clearly the ρ_μ/ρ_c ratios change smoothly over this decade of primary energy.

Table 2 shows the best fit values of α obtained from linear regression fits on the relationship $\rho_\mu = k\rho_c^{\alpha}$ for all the R and $\sec\Theta$ intervals.

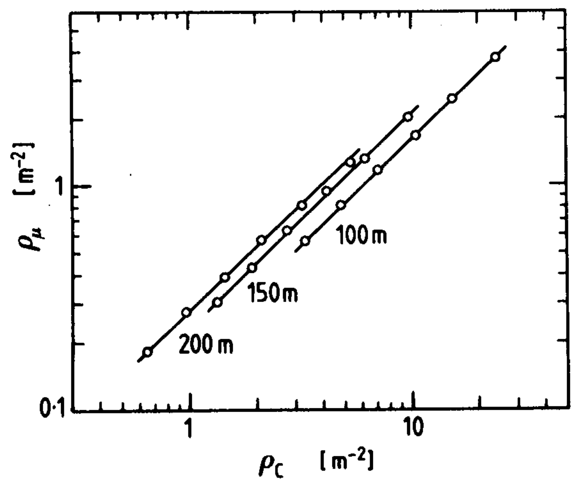

FIGURE 1 Measured ρ_μ versus measured ρ_c at three specific core distances.

R	/m² ρ_{150}	N	/m² $\bar{\rho}_\mu$	$\pm\Delta\rho_\mu$	/m² $\bar{\rho}_c$	$(\bar{\rho}_\mu/\bar{\rho}_c)$	$\pm\Delta\rho_\mu/\rho_c$
100 m	1.23	2466	0.560	0.011	3.306	0.169	0.003
	1.81	2362	0.805	0.017	4.833	0.167	0.004
	2.66	1793	1.188	0.028	7.091	0.168	0.004
	3.90	1106	1.664	0.030	10.586	0.157	0.003
	5.73	529	2.430	0.11	15.841	0.154	0.007
	8.41	234	3.764	0.25	24.209	0.155	0.010
150 m	1.23	2040	0.306	0.007	1.333	0.230	0.005
	1.81	2303	0.432	0.009	1.915	0.226	0.005
	2.66	2065	0.634	0.014	2.773	0.229	0.005
	3.90	1397	0.930	0.025	4.119	0.226	0.006
	5.73	820	1.301	0.045	6.239	0.209	0.007
	8.41	378	2.025	0.104	9.907	0.205	0.010
200 m	1.23	904	0.179	0.006	0.648	0.276	0.009
	1.81	1335	0.272	0.007	0.979	0.278	0.007
	2.66	1540	0.368	0.010	1.438	0.268	0.007
	3.90	1287	0.584	0.016	2.098	0.278	0.008
	5.73	886	0.809	0.027	3.255	0.249	0.008
	8.41	470	1.255	0.058	5.141	0.244	0.011

Table 1 (previous page) Mean muon ($\overline{\rho_\mu}$) and water Cerenkov $\overline{\rho_c}$ densities as a function of core distance (R) and shower size (ρ_{150}) - $1.0 \leq \sec\theta \leq 1.1$.
[ρ_{150} is the water Cerenkov response in vertical equivalent muons at 150 m from the EAS axis. N = no. of EAS used in the analysis]

R	Secθ 1.0 - 1.1	Secθ 1.1 - 1.2	Secθ 1.2 - 1.3	Secθ 1.3 - 1.4
100 m	0.95(0.01)	0.92(0.02)	0.90(0.02)	1.01(0.04)
150 m	0.94(0.02)	0.95(0.02)	0.99(0.02)	0.99(0.06)
200 m	0.94(0.02)	0.94(0.03)	0.93(0.08)	0.90(0.05)

Table 2 Values of α in the relationship $\rho_\mu = k\rho_c^{\alpha}$ as a function of R and θ.

Clearly, at least for low zenith angles, an average value of α = 0.94 fits the data well in the core distance range 50 m → 250 m and over the primary energy range 1.6×10^{16} eV < E_p < 1.6×10^{17} eV.

4. Muon Content $10^{16} - 10^{19}$ eV Data acquired in the primary energy range $10^{17} - 10^{18}$ eV from the infilled 500 m detector array at Haverah Park enables ρ_μ (200 m) and ρ_c (200 m) to be determined for the decade of energy above 10^{17} eV. The results are plotted in Figure 2 which shows the complete data from $10^{16} - 10^{18}$ eV.

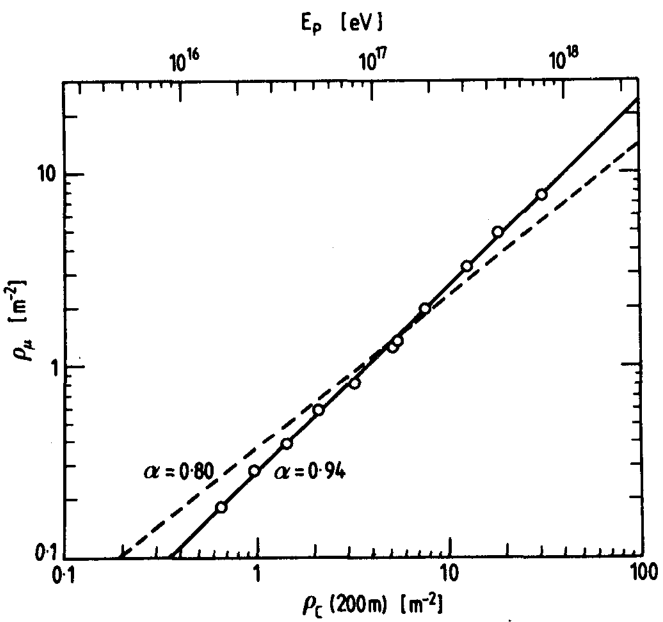

FIGURE 2 Measured ρ_μ versus ρ_c at 200 m over energy range approximately $10^{16} - 10^{18}$ eV.

It is clear that a relationship of the form $\rho_\mu(200\ \mathrm{m}) \propto \rho_c(200\ \mathrm{m})^{0.94}$ fits smoothly and well over these two decades of energy. This implies a smooth gradual change in the height of the electromagnetic cascade maximum throughout these two decades.

Thus the muon data yields strong evidence that there is no marked primary mass change occurring in the 10^{16} to 10^{17} eV region as has been suggested. If there is a significant change in primary mass, as suggested by Chantler et al (1983), then the muon density would be approximately 50% higher at 10^{16} eV than is measured leading to a value of $\alpha \sim 0.8$ [Blake et al, 1983]. Such a low value of α is clearly incompatible with the measured data (see Figure 2).

Comparison of the 10^{17} to 10^{18} eV decade with energies above 10^{18} eV has been carried out at a core distance of R = 600 m. In this region the data and conclusions remain unchanged since Blake et al (1983). Again the observations yield a smooth and normal change in muon content in the range 10^{17} eV to 10^{18} eV, implying no significant primary mass change over the energy range.

5. <u>Discussion and Conclusions</u> The results presented above lead to the conclusion that the muon content of EAS (relative to the water Cerenkov response) decreases smoothly in a constant manner at primary energies above 10^{16} eV and therefore suggest a constant primary mass composition in this energy region. A direct and constant relationship between the primary mass energy (E_p) and the water Cerenkov response $\rho_c(R)$ is assumed. The water Cerenkov response at 500 m core distance, $\rho(500)$, [or at 600 m, $\rho(600)$] is used as the shower size parameter at Haverah Park for energies > 10^{17} eV and the relationship between $\rho(500)$ and E_p is of the form $E_p = 3.87 \times 10^{17} [\rho(500)]^{1.018}$ [HILLAS, Model A]. Thus $\rho_\mu \propto \rho_c^{0.94}$ implies $\rho_\mu \propto E_p^{0.92}$ at 500 m from the EAS axis.

Assuming therefore that this result does indicate a constant primary mass composition at energies greater than 10^{16} eV it does give strong support to the results from other studies of muons in EAS at these energies. The Akeno group (Nagano et al, 1984) find that the size spectra for both electrons and muons are unchanging above 10^{16} eV. Thus any change from heavy primary nuclei to a light mass composition flux must occur at energies below 10^{16} eV.

<u>References</u>

Blake, P. R., et al.; 18th Int. Cos. Ray. Conf., Bangalore, <u>11</u>, 289 (1983).

Chantler, M. P., et al.; J. Phys. G <u>9</u>, L27 (1983).

Nagano, M., et al.; J. Phys. G. <u>10</u>, 1295 (1984).