EAS CERENKOV MEASUREMENTS OF THE COMPOSITION OF THE COSMIC RAY FLUX AROUND 10^{16}eV

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1. Introduction Information can be obtained about the nature of a primary cosmic ray by looking at the way in which an EAS develops in the atmosphere. Thus, heavy nuclei will give rise to showers that develop high in the atmosphere and the depth of maximum development will be subject to much smaller fluctuations than will be the case, say, for showers originating from protons. This development can be followed directly by optical methods based on the observations of Cerenkov light or fluorescence light. In the case of Cerenkov observations, there are two complementary techniques: measurement of the time profile of the Cerenkov pulse with resolution of a few nanoseconds and measurement of the lateral distribution of the Cerenkov light. In each case the measured quantities must be related to some characteristic development parameter, such as the depth of maximum, by means of theoretical. Both techniques are complementary and ideally, simultaneous measurements on both would be desirable but, so far little has been done along these lines.

At the time of the Bangalore Conference it seemed clear that for energies above about 10^{17}eV the depth of maximum changes slowly with energy at an elongation rate of about 50 gcm^{-2} per decade but that in the energy interval 10^{16}eV to 10^{17}eV the elongation rate becomes much larger and, in the decade below 10^{16}eV, the depth of maximum is much deeper in the atmosphere than would have been expected on the basis of the shower behaviour at higher energies. Comparisons with calculations based on a scaling model with rising cross sections suggest that this behaviour can be accounted for if the primaries are of a mixed composition but that in the energy region 10^{15} to 10^{16}eV the primaries are predominently iron, although the data from Samarkand (Alimov et al 1983) would be compatible with a mixed composition. The situation at somewhat lower energies, 10^{13}-10^{15}eV, is less clear, largely because of the difficulty in observing in this energy region, but there is a suggestion that the composition may be approaching the mixed composition that is well-known from direct measurements in the energy region accessible to balloons and satellites.

2. The experiment The present paper describes measurements on the lateral distribution of Cerenkov light from EAS in the energy region 10^{15} to 5×10^{16}eV which were carried out at the Buckland Park field station of the University of Adelaide in association with the particle array. There were nine Cerenkov light detectors consisting of open-faced EMI 9623B photomultipliers with broad collimation. Their location is shown in figure 1. The overall arrangements for the experiment were therefore similar to those described by Kuhlmann and Clay (1981) but differed in having a better signal-to-noise ratio, better stability and calibration and in being more automatic in operation.

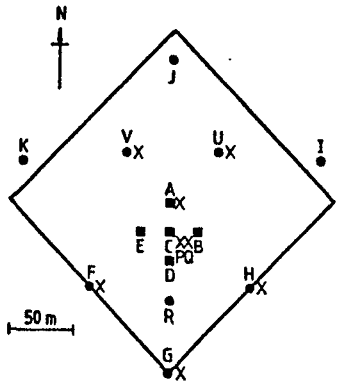

Figure 1: The Cerenkov lateral distribution array with the elements of the Buckland Park particle array used in the experiment.

The data were collected on clear moonless nights from October 1983 to March 1984. The Cerenkov recording system was triggered by the particle array which was also used to assign shower size, core location and arrival direction to each event. The triggering requirements were coincident signals corresponding to >2 particles m^{-2} in three of the central five (ABCDE) detectors. During 103 hr recording time, 9575 of these particle events were recorded. A total of 1279 of these events was selected for the purpose of measuring the Cerenkov lateral distribution. These showers arrived within 35 degrees of the zenith, were well-analysed in terms of the particle data and possessed at least 5 Cerenkov densities. This selection put a lower limit on the acceptable shower size at about 10^5 particles.

3. Analysis The use of the particle array for triggering is not ideal because there is necessarily an a priori selection bias towards late-developing showers. However, in the present case the selection biases associated with the particle array and its analysis procedures have been investigated by an extensive series of simulations. The data below are compared with model calculations in which the actual selection properties of the array and the analysis procedures are included.

In our interpretation of the measured lateral distributions we have used the calculations of Patterson and Hillas (1983b) which show that the shape of the lateral distribution within 150m of the shower axis is sensitive to shower development. Outside this radius the shape is not so sensitive, and the flux at a large radius is a measure of the energy of the primary particle. Ideally, this radius should be $\gtrsim$200m, although for small showers it is often only possible to measure the lateral distribution out to ~150m. The flux at 150m is still expected to be a measure of the primary energy, but it will be subject to larger fluctuations than the flux at a larger radius. Patterson and Hillas suggest that the flux ratio Q(50m)/Q(150m) (as suggested by Andam et al 1982) is the best measure of the shape of the lateral distribution inside 150m. They have related this parameter to H_m, the distance along the shower axis to shower maximum. We have fitted exponentials of the form $Q(r) = A \exp(-br/10^4)$ to our data for 25m<r<150m and have found them to be good fits. Indeed, in the majority of cases the exponential is also a good fit at larger radii. Using these fits, the ratio Q(50)/Q(150) was found for each event and hence H_m. Knowing the zenith angles of the shower axes, depths of maximum were derived assuming an exponential atmosphere with a scale height of 8.0km.

The 1279 showers analysed in this manner have been binned in a variety of ways. Figure 2 shows the data plotted as depth of maximum (DOM) vs the equivalent shower size at a depth of 1000 gcm^{-2} , $N_e(1000)$, the latter being calculated from the observed size and a shower attenuation length of 185 gcm^{-2} (Clay and Gerhardy 1982). Alternatively, the data may be binned in terms of a primary energy estimator. Here we use the Cerenkov flux at a distance of 150m from the shower axis, Q(150), as shown in figure 3. In both cases, the error bars represent standard deviations within the bins. Figure 3 shows that in terms of energy there is a bias towards the selection of late developing (large DOM) showers. This bias is not so obvious in figure 2 which is based on shower size. In this case there appears to be sufficient mixing of low energy showers to mask this effect.

The experimental distributions were interpreted using Monte Carlo simulations of proton and iron-produced showers in which the selection effects of the particle array were taken explicitly into account. (We believe that there is no significant bias specifically associated with the Cerenkov array). In these simulations, shower energies were selected from a broken-power-law energy spectrum between 10^{13} and 10^{18}eV. A depth of maximum for each shower was selected using the distributions given by Protheroe and Patterson (1984). Given a DOM, the sea level size of the shower was calculated by assuming the E_p - $N_e(max)$ conversion given by Hillas (1983) and by using a shower development profile given by Patterson and Hillas (1983a). The simulated showers were then allowed to fall on the particle array using appropriate zenith and azimuth angle distributions and those showers which triggered the array were reanalysed for core position and shower size using the same shower analysis program as was used for the experimental data. Thus, provided that selection biases exist only for the particle array, the simulated data are now directly comparable with the experimental distributions. Figures 4 and 5 show selected simulation results. Here again the error bars represent standard deviations, which reflect the fluctuations in the DOM. The bias imposed by the array is especially evident in figure 5. The only showers observed below 10^{15}eV are late developing proton events.

In our attempts to match the experimental DOM vs $N_e(1000)$ distribution, a number of mixtures of proton and iron-produced showers was tried. It was found that a mixture of 95% Fe and 5% P produced a distribution consistent with the data (fig.2).This mixture also produced an agreement in the energy representation when a particular Q(150) - E_p assignment was made (fig. 3). It is noted that it is not necessary to invoke a changing composition across the energy range in question in order to match the data. Unfortunately there are not sufficient data in the high energy region to see the expected effect of a change in composition back to predominantly light nuclei above about $3x10^{16}$eV. (e.g. Nagano 1983).

Thus we conclude that, having used simulations which include a realistic model of longitudinal development and the effects of particle array selection bias, we find that our data are consistent with a cosmic ray primary composition rich in iron over the energy range $3x10^{15}$ to $5x10^{16}$eV.

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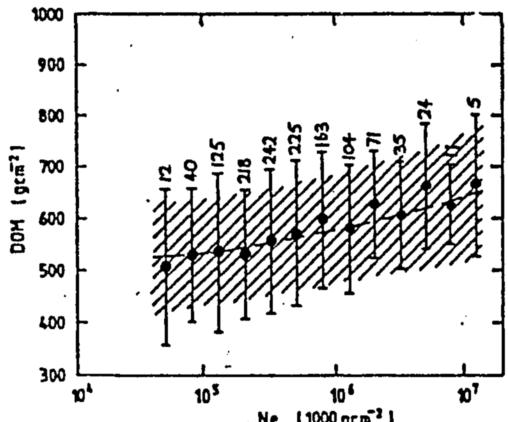


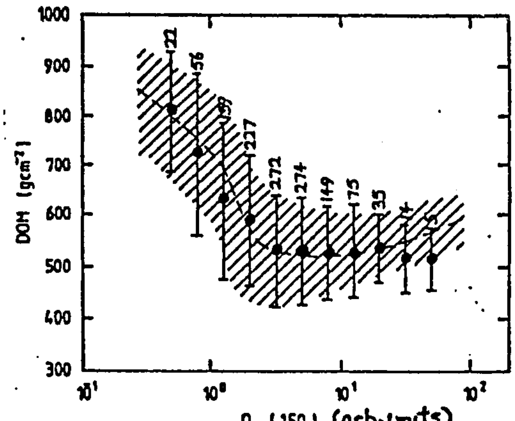
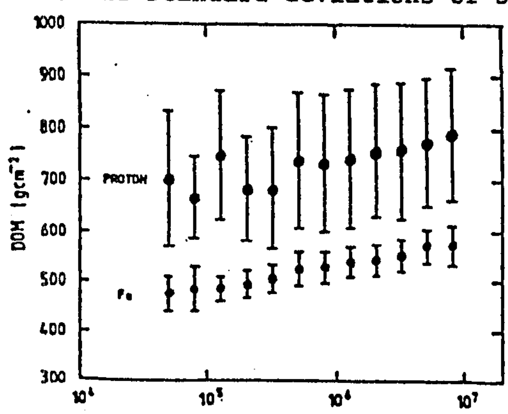


Figure 2 and Figure 3: Experimental distributions of DOM vs. N_e (1000) and primary energy estimator Q(150). Error bars in each figure represent standard deviations and the numbers indicate the number of events in each bin. The dashed lines and hatched regions represent the means and standard deviations of simulated data (95%Fe,5%P)(see text).



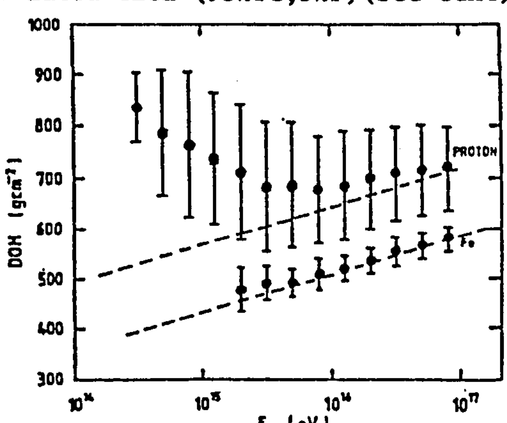


Figure 4 and Figure 5: Simulated distributions of DOM vs. N_e(1000) and primary energy E_p which take into account array selection biases. Error bars indicate standard deviations. The dashed lines in figure 5 represent the input distributions of mean DOM from Protheroe and Patterson (1984).