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Zenith Angle Dependence of Cosmic Ray Shower Development from Observations of the Time Structure of Atmospheric Cerenkov Pulses

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Abstract

The attenuation of extensive air showers has been studied using atmospheric Cerenkov techniques. Observations over a range of zenith angles are correlated and an attenuation length of 234 ± 38 g cm^{-2} obtained for showers with sea-level sizes of $\sim 10^6$.

The time structure of the pulse of atmospheric Cerenkov radiation produced by cosmic ray extensive air showers has been shown to be a sensitive measure of the distance from an observer to the maximum of shower development (Orford *et al.* 1975; Kalmykov *et al.* 1977; Thornton and Clay 1979). The time structure has normally been characterized by the full width at half maximum (FWHM) of the light pulse, and the dependence of this parameter on the shower development has been investigated theoretically by the groups in England and the USSR. We have shown (Thornton *et al.* 1979) that these theoretical dependences give rather similar results when applied in practice. An investigation of zenith angle effects in the observation of Cerenkov FWHM is of interest for a number of reasons. Provided that the zenith angle is not too great, one might hope to successfully apply theories developed for vertical showers and one can then investigate shower development by comparing similar showers observed in their passage through different atmospheric thicknesses. One can also check that the distribution of experimentally selected showers is largely unbiased and, by internal consistency, that the theory is working plausibly.

The data were recorded in 1978 and 1979 at the Buckland Park Field Station of the University of Adelaide using a Mullard XP 2040 photomultiplier viewing the sky with only slight mechanical collimation for reducing background light from large zenith angles. The output pulses were displayed on a Tektronix 7912 transient recorder in the non-store mode and retained photographically when an air shower triggered the particle array. The non-recorded pulse triggering rate was $\sim 10^{-1}$ Hz. The system FWHM was 5·3 ns and this was removed from measured pulse FWHM by assuming that they had added in quadrature. A total of 317 events were used with sea-level shower sizes (N_{eSL}) ranging from 10^5 to 10^7 and detector core distances selected to be between 150 and 350 m. We have determined the relationships between sea-level shower size and the depth of shower maximum (in g cm^{-2} from the top of the atmosphere) in three zenith angle (θ) intervals ($\theta < 15°$, $15° < \theta < 25°$, $\theta > 25°$). The height of shower maximum is determined for each shower using a relationship (given by Kalmykov *et al.* 1979) between Cerenkov FWHM and distance of shower maximum from the observer. This relationship relates the Cerenkov

FWHM at 300 m from the shower core to the distance of shower maximum from the observer. The relationship is unambiguous for showers at the appropriate core distance. For showers at other distances, it is only necessary to apply a lateral dependence of the FWHM to estimate the FWHM at 300 m before using the relationship. The exact form of this lateral dependence is not known but we have shown (Thornton *et al.* 1979) that similar results may be obtained using any of the more popular relationships. Having determined the distance to shower maximum, the shower zenith angle as determined by fast timing in the particle array may be employed in determining the depth of maximum in the atmosphere.

The relationships between depth of maximum and mean sea-level shower size (N_{eSL}) which we obtain from the three zenith angle intervals are displaced from one another since as larger zenith angles are observed, more shower size attenuation occurs in the atmosphere and showers with similar depths of maximum (and presumably mean shower maximum size) have sea-level sizes dependent on the thickness of absorber traversed. The displacement is thus a measure of shower attenuation in the atmosphere, and casual inspection of the data together with a knowledge of the mean zenith angle of each interval suggests an attenuation length of ~ 200 g cm^{-2} would superimpose the curves. Here we assume that shower attenuation in the atmosphere is of an exponential form (see e.g. Ashton *et al.* 1975). Ashton *et al.* (1975) have compiled measurements on the attenuation length over the sea-level shower size range from 10^3 to 10^9. The attenuation length does not appear to vary drastically over the whole of this range. If anything, it may change from ~ 160 g cm^{-2} at the smallest sizes to ~ 240 g cm^{-2} at the largest. There is a suggestion that much of this increase occurs in the size range $10^5 < N_{eSL} < 10^7$.

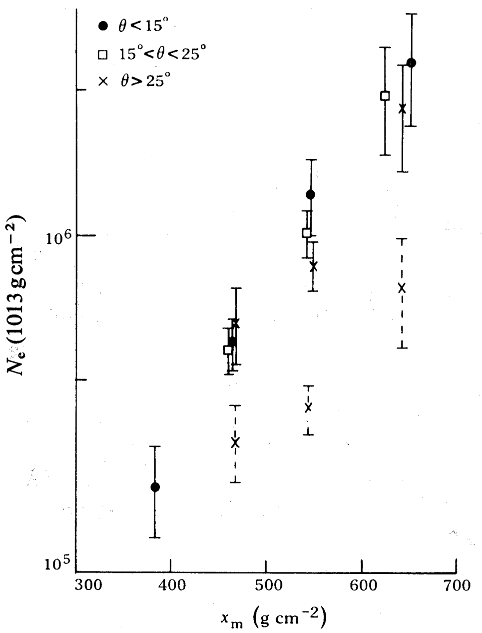

Fig. 1. Relationship between the depth x_m of shower maximum and the shower size N_e at a depth of 1013 g cm^{-2}, with an assumed attenuation length of 234 g cm^{-2}, for the three indicated zenith angle intervals:
$\theta < 15°$ (mean $\sec\theta = 1\cdot02$),
$15° < \theta < 25°$ (mean $\sec\theta = 1\cdot07$),
$\theta > 25°$.
Crosses with dashed error bars show the relationship between x_m and the sea-level shower size (N_{eSL}) for showers with $\theta > 25°$ (mean $\sec\theta = 1\cdot17$).

It is of interest to determine the best value of this attenuation length and we have studied this using a linear regression technique with all our data. If we assume a shower elongation rate of x_s g cm^{-2} per decade of primary energy, a total depth

x_T of atmospheric absorber traversed, a depth x_m of shower maximum for a shower size at maximum of, say, 10^4 being x_0, and a shower attenuation length of λ, we can then easily derive

$$\log N_{\mathrm{eSL}} = (C - x_0/x_s) - (x_T - x_m)/2\cdot 3\,\lambda + x_m/x_s\,.$$

A linear regression study of the relationship between $\log N_{\mathrm{eSL}}$ and $x_T - x_m$ results in a best fit value for the attenuation length of 234 ± 38 g cm^{-2}. The elongation rate (x_s) is poorly determined in this way (970 ± 300 g cm^{-2} per decade). We note that this technique requires a knowledge of the scale height of the atmosphere which we assume to be 8 km (we previously used 7·1 km) in accordance with local measurements (Young, personal communication). The scale height varies with time and ideally this should be taken into account.

Fig. 1 shows the relation between the shower size calculated for an atmospheric depth of 1013 g cm^{-2} and the depth of shower maximum in the three zenith angle intervals using the attenuation length derived above. It can be seen that good agreement can be achieved between showers which have travelled through substantially different atmospheric thicknesses. Results for the sea-level shower size against depth of maximum for showers with a mean value of $\sec\theta$ of 1·17 are also included in Fig. 1. These may be compared with the 'vertical' showers in the figure ($\theta < 15°$, mean $\sec\theta = 1\cdot 02$) to appreciate the magnitude of the correction. It is clear from Fig. 1 that the assumed attenuation length provides a reasonable fit over the full observed size range. This would not be expected if shower selection effects caused appreciable bias in the distribution of observed showers. For instance, one might expect fast Cerenkov detectors to preferentially select small sea-level showers which had an early development (large size at maximum and a narrow pulse). If the effect were large it would lead to an apparent experimental decrease in attenuation length with observed size.

In conclusion, observations of atmospheric Cerenkov pulse shape are sensitive to changes in the distance of shower maximum associated with changes of shower zenith angle. These changes are consistently compatible with an exponential shower attenuation with increasing atmospheric depth over the whole of the observed sea-level size range. The attenuation length of 234 ± 38 g cm^{-2} derived from our data is in reasonable agreement with results obtained in other ways and gives further confidence in the Cerenkov pulse shape technique as a method of studying air shower properties.

Acknowledgment

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