EAS Developement Curve at Energy of $10^{16} - 10^{18}$ eV Measured by Optical Cerenkov Light
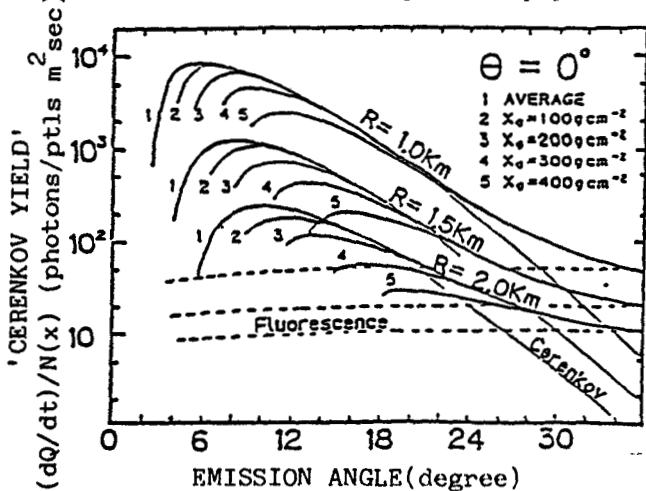
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The data of optical Cerenkov light from extensive air shower observed at the core distance more than 1 Km at Akeno are reexamined. Applying the new simulated results, we reconstruct the shower developement curves for the individual events. For the showers of 10^{17} eV the average depth at the shower maximum is determined to be 660 ± 40 gcm^{-2}. The shower curve of average development is found to be well described by a Gaisser-Hillas shower development function with above shower maximum depth.

1. Introduction.   The Cerenkov light from EAS is one of the most important observables to know the EAS developement. In order to know the shower maximum depth for EAS of $10^{16} - 10^{18}$ eV, the Cerenkov pulse shapes from EAS's at more than 1Km from the core are observed at Akeno air shower array by using 3 large telescopes(1). The data were analyzed by using the relation between the characteristics of Cerenkov pulse and the average development of showers in previous paper(2). In this paper we reanalyze the data for the construction of shower development curve by taking into account the first interaction depth, which is found to be important in interpretation of Cerenkov pulse shape.

2. Simulation results.   The calculation of pulse shape of Cerenkov light from EAS was carried out with the same assumptions and procedures for showers of average developement as in ref.3 except the model of atmospheric attenuation of Cerenkov light. The fraction of light reaching the observation level can be expressed by $\exp(-x/\Lambda)$, where x is the path length of Cerenkov light in the atmosphere. A constant value Λ (18Km) was assumed in the previos paper but here we use the same model as that of Hillas(4), which is a function of atmospheric depth. The effect of the first interaction depth of primary cosmic rays to Cerenkov pulse shape was calculated with various interaction models. In this calculation, observation level is taken to be 700m a.s.l., where the telescopes are set in Akeno air shower array.

2-1. Cerenkov yield per particle at the depth of photon source.

In fig.1 is shown 'Cerenkov yield',(dQ/dt)/N(x),observed number of Cerenkov photons

Fig.1 'Cerenkov yield' and photons from fluorescence.

divided by the electron size at the light source level in the atmosphere. As shown in the previous paper the 'Cerenkov yield' is independent of the interaction models at 1 - 2 Km from the core. This is also indicated by Ivanenko et al. up to less core distance(700m)(5). This value is a function of the height of photon emission in the atmosphere(x), zenith angle of the shower(θ), distance from the core(R) and also the first interaction depth of the primary cosmic ray(X_0). The abscissa of fig.1 is the emission angle of Cerenkov light to the shower axis. The fluorescent light from EAS is also shown in fig.1. If above parameters are experimentally determined we can construct the shower curve in the atmosphere from the Cerenkov pulse shape using the relation of fig.1.

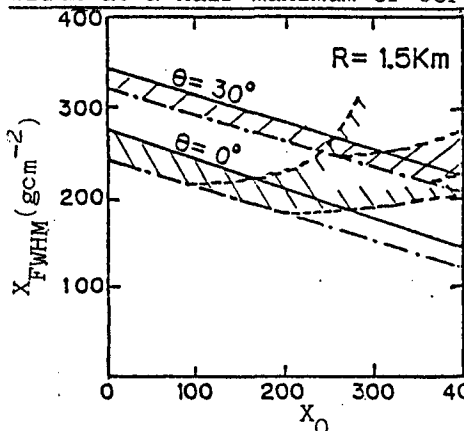2-2. The EAS path length in the atmosphere corresponding to the full width at a half maximum of Cerenkov pulse.   The full width at a half maximum(FWHM) of Cerenkov pulse is well known to have a good relation to the longitudinal development of EAS, especially to the shower maximum depth, but it has a poor relation to X_0. Here we find a parameter which has a good relation to X_0, that is , X_{FWHM}, the atmospheric depth which the EAS passes through during the time of FWHM of Cerenkov pulse. Fig.2 shows the relation between them. The parameter of X_{FWHM} is a function of θ, R, X_0 and the shower maximum depth(X_{max}). Our calculation is made in the range of X_{max} from 450gcm^{-2} to 800gcm^{-2} for showers of average development. In fig.2 solid and chain lines show the relation of X_{FWHM} - X_0 for showers of extremely fast

Fig.2 Relation between X_0 and X_{FWHM}.

and slow development respectively in our calculation. The contribution of fluorescent light from EAS is also shown by broken lines for two extremely developed showers. Consequently showers concerned in the present paper distribute in the hatched regions in fig.2. If we know the value of X_{FWHM} we can estimate X_0 with an error of about 100gcm^{-2} for such showers that Cerenkov light photons exceed the fluorescent light.
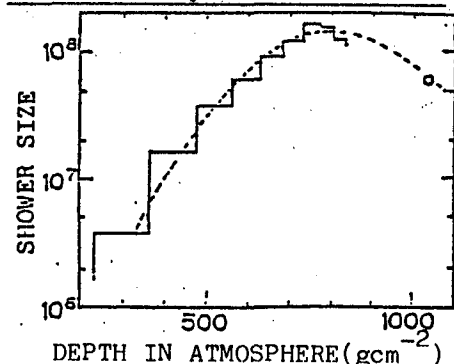
3. Data analysis and results.

Fig.3 An example of shower curve determined from Cerenkov pulse wave.

The data taken in 1981 and 1982 are reanalyzed. In the measurement of Cerenkov pulse, the time resolution is 100ns and the space resolution in the atmosphere is 4.5°x4.5°. Details of the experiment are described in ref.2. Finally 62 events were analyzed in order to determine X_{max} of EAS. Among them 38 events which have clear Cerenkov signals in more than 4 phototubes are selected.

First of all, for each event X_{FWHM} is determined from the Cerenkov pulse shape using shower parameters from the particle array and then X_0 is estimated in most case within the error of about 100gcm^{-2} by using the relation of fig.2. If we know X_0 we can construct the shower development

curve in the atmosphere from the Cerenkov pulse shape by using the relation of fig.1. Fig.3 shows an example of the shower development curve thus determined. In this experiment the space resolution in the
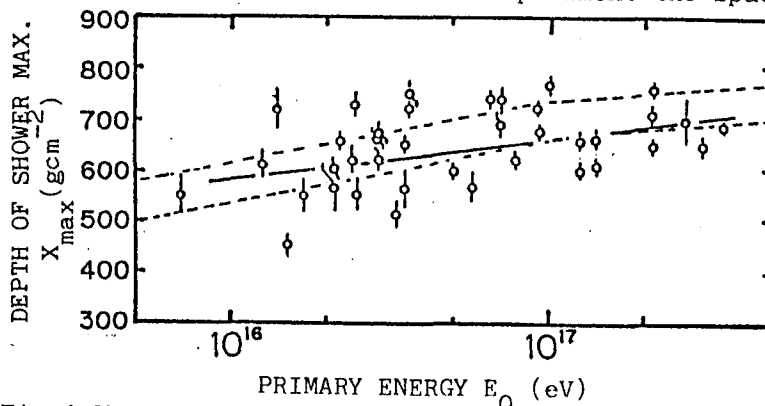

Fig.4 Shower Maximum depth determined by Cerenkov events.

atmosphere is limited by the time resolution of the registration system(100ns) for the Cerenkov pulse shape. In fig.3 open circle shows the shower size determined by the particle array for the event and broken line is a curve smoothly connected the data. From fig.3 we can determine both the depth of shower

maximum and the maximum shower size(N_{max}). The primary energy(E_0) is obtained by multiplying N_{max} by a constant value of 1.4GeV(5).

Fig.4 shows the relation between X_{max} and E_0 for all events determined by the same procedure. The values of X_{max} for events which apparently penetrate in the atmosphere($X_0 > 100 \text{gcm}^{-2}$) are corrected by subtracting of X_0. The determination error of E_0 is estimated to be about $\pm 20\%$ which is mainly due to the uncertainty of the background contribution to the data. In fig.4 solid line shows the least square fit for these data. Two broken lines show the region where almost all other experimental results are distributed(7). Our results seem to be consistent with other results. From fig.4 the average value of X_{max} at the primary energy of 10^{17} eV is $660 \pm 40 \text{gcm}^{-2}$.
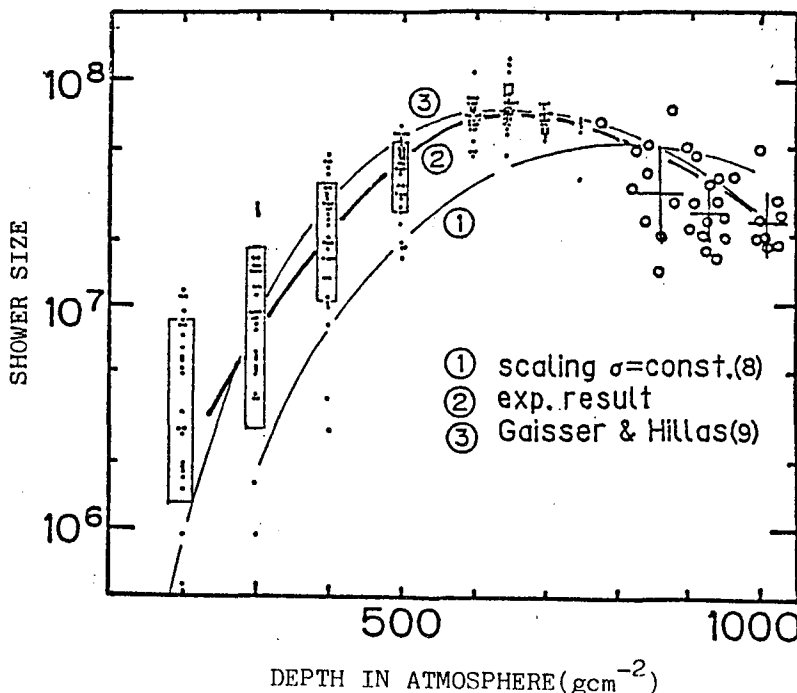

Fig.5 Shower development curve.

In order to know the average longitudinal development curve of showers, all data are normalized to the primary energy of 10^{17} eV(E_{17}) and to the maximum depth of 660gcm^{-2} using the average relation in fig.4 as follows.
(1) First the shower maximum depth of each event is moved to the average one of the same primary energy(E) in fig.4 and then the each atmospheric depth of the

shower curve is normalized to that of the primary energy of 10^{17} eV.

(2) Secondly each shower size(N) at each atmospheric depth determined from the Cerenkov pulse is normalized to that of the primary energy of 10^{17} eV by dividing a constant factor of (E/E_{17}).

Fig.5 shows normalized shower developments of 38 events(small points). In fig.5 squares show the one standard deviation of data distribution in shower size of log(N) and the ambiguity of the atmospheric depth determination. Open circles are shower sizes at Akeno level determined by the particle array. Crosses show the average and one standard deviations for the shower size determined by the particle array. Thick solid line is the curve smoothly connected to the average points of shower size distributions at each atmospheric depth except that of 200gcm^{-2} where the effect of backgrounds seems to be serious. Then, thick solid line(denoted by ②) is the average development curve of showers of 10^{17} eV normalized to the depth at the maximum development .

In comparison with data two curves are shown in fig.5. One is the simulation by Ivanenko et al. with the assumption of primary proton and constant cross section with scaling law(8) and the other is the shower development function by Gaisser and Hillas(9) with 660gcm^{-2} for X_{max}. In most case, theoretical average curves are averaged over different starting points, and so can not directly be compared with our experimental one which is normalized at the depth of shower maximum. But when the depth of shower maximum is moved to the same one, the shape of shower development curve can be compared with our result except that in deep atmosphere. From fig.5 the average development of showers of energy 10^{17} eV is well described by the Gaisser-Hillas development function.

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