2.1. Introduction:

When a fast charged particle passes through a dielectric medium with a constant velocity but greater than the phase velocity of light in the medium, visible light having a continuous spectrum is emitted in a cone about the direction of the particle. The phenomenon was first discovered by Cerenkov in 1934 who, while studying luminescence of Uranyl salts by gamma rays observed that a very weak radiation was visible even from pure solutions having no fluorescing properties. Accordingly, the radiation was named Cerenkov radiation after the name of the inventor. It may be mentioned here that it was Mallet (1926, 1928, 1929) who first really studied the phenomenon but made no attempt to explain it. The observation of Cerenkov radiation was first interpreted by Frank and Tamm (1937) with the help of classical electromagnetic theory.

Blackett (1948) first suggested that when cosmic ray particles passed through the atmosphere, Cerenkov radiation might be emitted. The expected contribution as calculated by
him amounts to about $10^{-4}$ of the total intensity due to starlight and other sources and as such was not detectable by normal photometric methods. However in case of an extensive air shower (EAS), the total contribution from the large number of electrons which would arrive simultaneously with velocities close to that of light, might be quite appreciable.

Jelley and Galbraith (1953) first detected such pulses of Cerenkov light from EAS at ground level. Later on (1955), the experiment was carried out at mountain altitudes by them as well as by Nesterova and Chudakov (1955) which confirmed the phenomenon. In what follows a theoretical discussion on Cerenkov radiation in general and its applications to EAS in particular will be given. A brief discussion on related experiments such as those of Galbraith and Jelley (1953, 1955) and other workers will also be given.

2.2. Physical Nature of Cerenkov Radiation:

A fast charged particle while passing through a dielectric medium produces a polarising effect in the atoms of the medium. As the particle passes on, electromagnetic waves are emitted in the process of deexcitation of the polarised atoms. The resulting electromagnetic wave, in general, is cancelled by destructive interference in all directions if $\beta n < 1$ (where $\beta$ is the velocity of the charged particle in units of velocity of light in vacuum and 'n' is the refractive
Fig. 2.1: HUYGENS' CONSTRUCTION TO ILLUSTRATE COHERENCE

Fig. 2.2: THE FORMATION OF CARMEN'S CONE AND THE POLARISATION VECTORS.
index of the dielectric medium). However, if $\beta n > 1$, i.e., if the velocity of the particle is greater than the phase velocity of light in the medium, there will be one direction in which phase coherence takes place.

The situation may be depicted by the Huygen's construction shown in fig. 2.1. If the particle moves in one second from A to B during which the light wave moves from A to C or A to E, the wavelets originating from the different points in the track will be coherent and they will reinforce one another to form a plane wavefront BC or BE. From the condition of coherence, one gets,

$$\sin \phi = \cos \theta = \frac{C}{\beta n} \times \frac{1}{\beta c} = \frac{1}{\beta n}$$

(2.1)

The radiation thus emitted is confined to a conical surface of semivertical angle $\theta$ with the direction of motion of the particle as its axis. The distribution in $\theta$ of the light intensity approximates a $\delta$-function and the polarisation is such that the electric vector $E$ is everywhere perpendicular to the surface of the cone and the magnetic vector $H$ is tangential to the surface as shown in fig. 2.2.

There are two other conditions that are to be fulfilled for the emission of Cerenkov radiation.

Firstly, the path length $'l'$ of the particle in the medium should be large compared to the emitted wavelength of the radiation in question. Otherwise diffraction effects will
become dominant. As a result, light will be distributed over an angle $d\theta \sim \frac{dl}{l \sin \theta}$ instead of appearing at an angle $\theta$ as given by equation (2.1) (Jelley, 1953).

Secondly, the velocity of the particle must be constant during its passage through the medium, or to be more specific, the difference in the times for the particle to traverse successive distances $\lambda$ shall be small compared to the period $\lambda/c$ of the emitted wave.

There is a threshold energy limit (corresponding to a minimum value of $\beta$) as determined by the condition $\beta n > 1$ which varies with mass of the particle and the medium concerned. The following table shows the threshold energies of electrons, muons and protons in air and in water.

Table 2.1

<table>
<thead>
<tr>
<th>Particle</th>
<th>Threshold energy</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>In air</td>
<td>In water</td>
</tr>
<tr>
<td></td>
<td>$n = 1.00029$</td>
<td>$n = 1.33$</td>
</tr>
<tr>
<td>Electrons</td>
<td>21 MeV</td>
<td>260 KeV</td>
</tr>
<tr>
<td>Muons</td>
<td>4.4 GeV</td>
<td>54 MeV</td>
</tr>
<tr>
<td>Protons</td>
<td>39 GeV</td>
<td>475 MeV</td>
</tr>
</tbody>
</table>
At the threshold energy, $\theta = 0$ and the radiation is parallel to the direction of motion of the particle. In case of air showers, the main contribution to the Cerenkov light comes from the electrons in the showers. The contributions of muons and nucleons are negligibly small. This is also apparent from the table 2.1 where the threshold energies of different particles in different media are given.

2.2. a. Maximum Value of Cerenkov Angle ($\theta_{\text{max}}$) in Air:

In case of ultra relativistic particles, for which $\beta \approx 1$, there is a maximum angle of radiation $\theta_{\text{max}}$ given by

$$\theta_{\text{max}} = \cos^{-1} \left( \frac{1}{n} \right) \approx \sqrt{2} \eta$$

(n = 1 + $\eta$)

which at sea level comes out to be 1.3°.

2.3. Theories of Cerenkov Radiation Loss:

Several workers studied the problem of emission of Cerenkov radiation on the basis of both classical electromagnetic theory and quantum mechanics. The theory due to Frank and Tamm (1937) is one of them. This theory, based on classical electromagnetic theory, explained the phenomenon rather satisfactorily as has been shown by later more refined calculations. An excellent account of the various theories has been given by Jelley (1958). The theory of Frank and Tamm will be discussed now.
2.3.a. Classical Theory of Frank and Tamm:

It was shown by Frank and Tamm (1937) that an electron moving in a dielectric medium radiates light, even if its velocity is constant, provided that the velocity is greater than the phase velocity of light in that medium.

A number of basic assumptions were made while developing the theory. Only the macroscopic structure of the medium was considered by treating the latter as a continuum. Dispersion effects and radiation reaction were neglected. They also assumed the dielectric medium to be perfectly isotropic so that the conductivity was zero, the magnetic permeability \( \mu = 1 \) and there was no absorption of radiation.

Using Maxwell's equations, they showed that the energy radiated per unit length of path by an electron of charge \( 'e' \) moving through a medium with a constant velocity \( 'v' \), to be equal to

\[
\frac{dW}{dl} = \frac{e^2}{c^2} \left[ \frac{1}{\beta^2 n^2} \right] \omega \, d\omega 
\]

\[\text{energy per unit length} \quad \ldots \quad 2.2\]

where \( 'n' \) is the refractive index of the medium and \( '\omega' \) is the frequency of the molecular oscillators of the medium.

In case of particle of charge \( 'Ze' \), the energy loss per unit path as obtained from above equation is
Equation (2.3) shows that Cerenkov radiation loss, like ionisation loss, varies as the square of the charge $Z e$ of the particle. Since no frequency cut off has been applied in the above deduction, the radiation output given by equation (2.3) is infinite. Actually this is not the case, as there are two factors which set an upper limit to the frequency spectrum and cause the radiation yield to be finite.

Firstly, in case of real medium, dispersion effects must be considered, so that the radiation is confined to those frequencies for which $n(\omega) > 1/\beta$. The absorption bands in the medium which are transparent at visible wavelengths are such as to limit the radiation to the near ultraviolet and longer wavelengths excluding infrared region where again there may be absorption. In the X-ray region, $n(\omega)$ is always less than 1 and radiation is therefore forbidden, while at radio frequencies $n(\omega) = \epsilon$ ($\epsilon$ is the dielectric constant of the medium) and there is again a pass-band as in the visible region. The general form of the dispersion curve for a typical transparent medium over the entire electromagnetic spectrum is shown in fig. 2.3.

The second factor relates to the finite size of the electrons. This restricts the radiation yield to wavelengths
Fig. 2.3: THE DISPERSION CURVE OF A TYPICAL TRANSPARENT MEDIUM OVER THE WHOLE ELECTROMAGNETIC SPECTRUM. (After Jenkins and White, 1937).
which are greater than the classical diameter 'd' of the electron in order to satisfy coherence condition. So, integrating equation (2.2) from \( \omega = 0 \) to \( \omega = \frac{c}{nd} \) (i.e., from \( \lambda = \infty \) to \( \frac{\lambda}{2\pi} = d \)) one would obtain,

\[
\frac{dW}{d\ell} = \frac{e^2}{2n^2d^2} \left( 1 - \frac{1}{\beta^2 n^2} \right) \quad \ldots \ldots \quad (2.4)
\]

since \( d = 5.6 \times 10^{-13} \text{ cm}, \ \lambda_{\text{min}} = 3.5 \times 10^{-4} \text{ A} \).

This limitation to the radiation yield is, however, very artificial since such wavelengths occur in the gamma ray region of the spectrum.

2.3.a(i). Radiation Yield of Cerenkov Effect

In order to make an estimate of radiation yield from energy loss by Cerenkov effect, the equation 2.2 can be utilised. For that purpose, the approximate value of \( n \) is written as (Sommerfeld, 1954),

\[
n^2(\omega) = 1 + \left( \frac{A}{\omega_0^2 - \omega^2} \right) \quad \eta^2(0) = \varepsilon = 1 + \frac{A}{\omega_0^2} \quad (2.5)
\]

where '\( \varepsilon \)' is the dielectric constant of the medium, 'A' is another constant, and '\( \omega_0 \)' is the frequency of the first resonance in the medium. Substituting equation (2.5) in equation (2.2) one obtains the following expression for
Cerenkov radiation loss per unit path for a fast electron \((\beta \sim 1)\)

\[
\frac{dW}{dl} = \frac{e^2 \omega^2}{2c^2} (\xi - 1) \ln \left(\frac{\xi}{\xi - 1}\right) \quad \cdots \cdots \cdots (2.6)
\]

In a typical medium, \(\omega_0 = 6 \times 10^8/\text{sec} \) so that \(\frac{dW}{dl}\) is of the order of several KeV per cm., or \(\sim 0.1\%\) of the energy loss by ionisation for a relativistic particle.

2.3.a(ii). Spectral Distribution of Cerenkov Radiation:

Equation (2.3) may be used to calculate the spectral distribution of Cerenkov radiation as follows:

The total energy of \(N\) number of photons, each of frequency \(\xi\) will be \(W = Nh\xi\) \(\cdots \cdots \cdots (2.7)\)

and \(\omega = 2\pi\xi\)

Assuming the refractive index 'n' to be constant over the visible region of the spectrum, equation 2.3 can be written as

\[
\frac{dW}{dl} = \frac{4\pi^2 \xi^2 e^2}{c^2} \int \left(1 - \frac{1}{\beta^2 n^2}\right) d\xi \quad (2.8)
\]

\[
= \frac{4\pi^2 \xi^2 e^2}{c^2} \int \left(1 - \frac{1}{\beta^2 n^2}\right) \frac{d\lambda}{\lambda^3} \quad (2.9)
\]
2.3. a(iii). Maximum Radius of Light Pool due to a Single Particle at Ground Level

The distance \( r \) from the particle's axis where the light cone strikes the ground increases from zero according to the relation \( r = h \theta \) where \( h \) is the height above ground and \( \theta \) the Cerenkov angle, which is 1.3° at ground level. However, at the top of the atmosphere, \( \theta \) is zero and as such \( r \) is also zero. Hence at some height \( r \) must have a maximum value, \( r_{\text{max}} \).

To calculate \( r_{\text{max}} \) let us consider an element \( dh \) of the track of the particle at height \( h \). Let \( \beta = 1 \) and \( n = 1 + \eta \) where \( \eta \) is very small compared to 1. Let us recall that \( \cos \theta = 1/\beta n \) and hence for small values of \( \theta \), we have

\[
\theta = (2\eta)^{1/2} \quad \ldots \quad (2.10)
\]

\( \eta \) varies with height approximately as

\[
\eta = 2.9 \times 10^{-10} e^{-h/\lambda} \quad \ldots \quad (2.11)
\]

where \( \lambda \) is about 7.1 km when \( h \) is measured in kilometres.

The radius of the cone of light at sea level comes out to be (Galbraith, 1958)

\[
r = h \theta
= (5.8 \times 10^{-4})^{1/2} he^{-h/2\lambda} \quad \ldots \quad (2.12)
\]
which has a maximum value when $h_{\text{max}} = 2\lambda \simeq 14 \text{ km}$.

At this height, the atmospheric pressure is $140 \text{ g cm}^{-2}$ and $\eta$ is only $4 \times 10^{-5}$ which gives the value of $\theta \sim 9 \times 10^{-3}$ radians. Thus, the maximum radius of light pool at ground level,

$$r_{\text{max}} = 126 \text{ metres}.$$

2.3. a(iv). Light Intensity at Ground Level from a Single Particle:

The light intensity due to a relativistic particle travelling vertically downwards can be calculated from eqn. (2.9) by neglecting dispersion and writing $n = 1 + \eta$. The eqn. (2.9) becomes

$$\frac{dW}{dt} = 8 \pi^2 z^2 e^2 \eta \left( \int \frac{d\lambda}{\lambda^3} \right) \text{ erg/cm} \ldots (2.13)$$

For a singly charged particle, the amount of radiation in the region $\lambda = 4000\AA - 7000\AA$ is

$$\frac{dW}{dt} = 3.8 \times 10^{-9} \eta \text{ erg/cm} \ldots (2.14)$$

$$\simeq 0.7 \text{ eV/cm}$$

Since the energy of a photon of wavelength $4000\AA$ is approximately $2 \text{ eV}$, the Cerenkov radiation amounts to $0.3$ photons per cm. path.
The energy loss due to ionisation by fast particles in air is about $1.6 \times 10^{-3}$ eV cm$^{-1}$. Thus the energy emitted as Cerenkov radiation is less than 0.05% of the total energy loss by ionisation.

The emission falls off with height in the atmosphere because of variation of $\eta$ with height (eqn. 2.11) as (Dalbraith, 1958)

$$\frac{dW}{dt} = 1.1 \times 10^{-12} e^{-h/7.1} \text{ erg/cm}$$

$$= 0.7 e^{-h/7.1} \text{ eV/cm} \quad \ldots \quad (2.15)$$

The intensity ($I$) of light at ground level can be written as a function of $r'$, the distance from the path of the particle since,

$$I = \frac{dW}{2\pi kd^2} \text{ eV/cm}^2 \quad \ldots \quad (2.16)$$

or,

$$I = 4.7 r^{-1} e^{-h/14.2} \text{ eV/cm}^2 \quad \ldots$$

per cm. of track where $r$ is measured in cm.

Thus, the intensity falls off with distance from the axis more rapidly than $r^{-1}$. For a cm. of track at 7 km , the intensity as given by equation (2.16) falling at the ground at $r$ ($\sim 100$ m) is $2.85 \times 10^{-4}$ eV/cm$^2$ or about $10^{-4}$ photons/cm$^2$ per particle.
Experiments carried out to detect the Cerenkov pulses (e.g., in the experiment by Galbraith and Jelley, 1955), showed on estimation the flux of photons produced in EAS as detected by the Cerenkov detector to be approximately 3 photons/cm². Thus the number of particles in such showers must be greater than $3 \times 10^4$, since to record such pulses, one requires this number of particles travelling vertically downward.

2.3.a(v). Further Extension to the basic Theory:

Tamm alone in 1939 made a more rigorous, and general treatment of the problem. He considered the effects of slowing down of the particle by ionisation and other processes. Nevertheless, the final expression obtained for Cerenkov radiation loss was identical with eqn. (2.2).

The problem of emission of Cerenkov radiation was also studied theoretically by Fermi (1940), Schiff (1955) and others. In Fermi's calculation on polarisation effect, the Cerenkov radiation appears as a contribution to the total energy loss of a particle traversing a condensed material and forms part of the energy loss calculated by the Bohr's theory of ionisation.

The various theoretical aspects of emission of Cerenkov radiation by relativistic particles passing through a dielectric medium are pointed out above. These aspects will now be extended to the actual case of extensive air showers.
2.3.a(vi). Intensity of Cerenkov Radiation from Extensive Air Showers

There are certain difficulties in making an accurate estimate of the Cerenkov radiation due to EAS. Because, in order to extend the calculation on light intensity at ground level for a single particle to include all the particles in EAS, the angular distribution of the electrons in the showers and their energy distribution must be accurately known. But there are still uncertainties in our knowledge about the angular distribution and energies of electrons as function of distance from the core and as function of altitude.

Jelley and Galbraith (1955) calculated the shower energy that might be detected by a light receiver with the help of a few simplifying assumptions. They assumed that all shower axes, detected by a light receiver pointing to the Zenith were vertical and that the main contribution to the Cerenkov light came from particles near the axis.

Calculations based upon a nucleon cascade model for the air shower were made to find the number of electrons having energies greater than $10^8$ eV at different altitudes for primary particle of various energies. The intensity of Cerenkov light produced by those particles at ground level was then found by multiplying the intensity calculated for a single particle (eqn. 2.16).
Fig. 2.4: Relative intensity of Cerenkov light from showers of different sizes, as a function of distance from the shower axis. (After Galbraith and Jelley, 1955).

Fig. 2.5: Relative probability that light pulses greater than a certain threshold value will be produced by showers whose axes fall at various distances from the light receiver. (Goldanski & Antonev, 1954).
The lateral distribution functions for Cerenkov light obtained from these calculations are shown in fig. 2.4. Here, the relative intensity of Cerenkov light from showers of different sizes at two different altitudes are plotted against distance of the light receiver from the shower axis. The graphs reveal that at least at sea level and to a lesser extent at mountain altitudes, the light intensity is fairly uniform up to quite large distances from the shower axis. This means that a single light receiver will be able to detect showers whose axes fall within a large area around it.

A more accurate attempt to calculate the light intensity due to air showers was made by Goldanskii and Zhadinov (1954). They first found out the number of light photons as a function of distance from the shower axis, incident on a light receiver and produced by electrons of given energy at a given height above ground. They then integrated over all energies and all heights. The result of their calculations is shown in fig. 2.5. In the figure, the relative probability that light pulses greater than a threshold value will be produced by showers whose axes fall at various distances from a light receiver is shown. They also considered the cases in which the mean angle of Coulomb scattering was greater than the angle of emission of Cerenkov radiation and also when it was smaller. The probability curve
had a distribution tail towards larger distances which was due to the diffused radiation produced by Coulomb scattering of electrons in the core, the scattering angle of which is greater than the angle of emission of Cerenkov radiation.

2.4. Shape of Cerenkov Pulses from EAS:

Fomin and Khristiansen (1972) made some calculations to study the shape and duration of Cerenkov pulses at different distances from the shower axis and their possible relation with the cascade curve. They obtained the results for showers generated by primary particle of energy $10^{17}$ eV.

Although their method of calculation was same as that of Zatsepin and Chudakov (1962), they introduced certain simplifications which were permissible at large distances ($r > 500$ m) from the shower axis. The following expression for the waveform of Cerenkov pulse due to primary particle of energy $E_0$ GeV was obtained

$$\phi(r,t) = 1.14 \times 10^{14} N(\lambda) \frac{\sin \Theta_{Ceren}}{-\lambda^2 + r^2} \left( -\frac{1}{1 - \sqrt{1 - \frac{r^2}{E_0}}} \right)$$

$$\times \exp \left\{ -\left( \arctan \frac{r}{\lambda} \right)^2 \left( \frac{1 + 32E}{0.245} \right) \right\}$$

$$\int dE \left[ 1 - \exp \left( -10 \frac{1}{(1 + 32E)^2} \right) \right]$$

\(\ldots \ldots (2.17)\)
Fig. 2.6(a): Waveforms of Cherenkov pulse in a shower from a primary proton with energy $E = 10^{17}$ eV at different distances from the axis. I: $r = 0.5$ km, II: $r = 1.0$ km, and III: $r = 2$ km. The intensity values on the ordinate axis are multiplied by $10^{13}$, $10^{12}$, and $10^{11}$ photons/m$^2$ sec for curves I, II, and III respectively.

Fig. 2.6(b): Different shapes of the Cherenkov pulse at a distance $r = 2$ km from the shower axis; (c): Corresponding cascade curves.
where 'E' is the energy in GeV, 'N' is the number of electrons at a height 'h', 'n' is the refractive index of air, and 'θ_сер' is the angle of the cone on the surface of which the radiation is concentrated. Contribution of all the electrons whose energy exceeded the threshold energy \( E_0 \), for emission of Cerenkov radiation were taken into consideration.

Using equation (2.17) Fomin and Khristiansen obtained for shower of primary energy \( E_0 \) \( \approx 10^{17} \text{ eV} \), the dependence of Cerenkov light flux density on time for three different distances from the shower axis, namely, at 500, 1000 and 2000 m. These waveforms are shown in fig. 2.6. Another interesting finding was the effect of fluctuation of the cascade curve on the waveform of the Cerenkov pulse. It was shown that the shape of the Cerenkov pulse depended on the shape of the cascade curve.

The result of their analysis was that if the shape of the Cerenkov pulse could be experimentally determined, this could lead to the determination of shape of the cascade curve and hence the energy of the primary particle initiating the shower. However in their opinion, primary particle identification was difficult because of large fluctuations in the shapes of the photon cascade curves.

Bohm et al. (1975) studied the time structure of the Cerenkov light pulses from EAS and found that the arrival
Fig. 2.7: Lateral distribution as obtained from Cerenkov pulse shape (continuous lines) and electron density measurements (○) and also the 'N-K' distribution function obtained from the fit (thick line) (After Bosia et al., 1975).
time distribution of light depended on the lateral distribution of the shower particles rather than their longitudinal development. The method was further extended to study the 'substructures' (G. Bosia et al., 1975) associated to secondary peaks in the shower. The lateral distributions for two showers obtained by them are shown in fig. 2.7, which show good agreement between study of pulse shape and particle density measurements. More recent works carried out both theoretically and experimentally have shown that the intensity and waveform of pulses of Cerenkov light have a strong correlation to the longitudinal shower development (Protheroe et al., 1975, Orford et al., 1975, Kalmykov et al., 1975).

Hammond et al. (1977) reported results from both simulation and actual measurements which show that analysis of Cerenkov light pulses from EAS could directly interpret the arrival direction, core location and primary energy. The optical flux at a core distance of about 200 m has been shown to be a good measure of the primary energy, being largely independent of cascade development fluctuations. Further, in 1978, they developed an alternative method for analysing and interpreting the measurements of Cerenkov light in large cosmic ray shower. Their method provides directly an image of the shower in Cerenkov radiation developing through the atmosphere. The depth of initiation of the cascade and rate of growth and decay provide, according to them information
directly relevant to the studies of the energetic interactions, especially to the determination of the mass of the primary particle. Their direct analysis provides an accurate arrival direction of the shower as well.

Very recently, Thornton et al., (1979) showed that the shape of the Cerenkov pulse is sensitive to shower development. Further, they have shown experimentally that the pulse F.W.H.M. (full width at half maximum) is a sensitive measure of the distance of the shower maximum from the detector. Their detailed study on time structure in Cerenkov pulses confirm the utility of the Cerenkov pulse technique as a tool for shower structure studies.

2.5. Experimental Works of Galbraith and Jelley:

The first experiment to detect optical Cerenkov radiation from EAS, as has been mentioned earlier, was attempted by Galbraith and Jelley in 1952. The light receiver used in this experiment was a parabolic mirror of 10" diameter, with a photomultiplier tube (type EMI 6260) at its focus. The light receiver was placed at the centre of an array of sixteen G.M. counters. The crucial experiment was in which the light pulses were used to trigger the oscilloscope beam which displayed the G.M. pulses. Correlation was immediately obtained between the light pulses and particle pulses but as was
Fig. 2.8: PULSE HEIGHT DISTRIBUTION OF OPTICAL CHerenkov PULSES FROM SAS (Galbraith and Jelley, 1953).
expected not all pulses had associated G.M. pulses. A histogram showing the pulse height distribution as obtained in those experiments are shown in fig. 2.8.

After this preliminary work, further experiments were done by the group under ideal observing conditions at Pic du Midi observatory in France (altitude 2860 m) during the summer months of 1953.

It was found that the rate of light pulses of height greater than $H$ was a power law of the form:

$$N(H) = AH^{-\delta}$$ ...

(2.18)

where 'A' is a constant, and $\delta = 1.6 \pm 0.1$.

One of the main aims of these experiments was to show that the light pulses were consistent with Cerenkov radiation and not due, for example, to light emitted in ionisation processes or in recombination processes. Accordingly, experiments were done to study the different properties of the light emitted by air showers and these showed that the light was similar to Cerenkov radiation in having similar polarisation, directional emission and spectral distribution. Galbraith and Jelley also studied the effect of zenith angle on the frequency of the optical Cerenkov pulses and found that the frequency of light pulses $R(\theta)$ as a function of Zenith angle $\theta$ over the range $0 < \theta < 70^\circ$ is given by

$$R(\theta) \propto \cos^n \theta$$
where $2 < \nu < 3$.

Additional evidence of Cerenkov radiation from EAS was obtained from a crude analysis of the colour of the light using gelatine colour filters.

Further experiments of Nesterova and Chudakov (1955) also proved beyond doubt that Cerenkov radiation was emitted by EAS and this was experimentally detectable. Studies are extended to utilise its potentialities as a means of revealing the lateral and longitudinal development of EAS, locating point sources of cosmic radiation etc. by many workers in the latter years (Kreiger and Bradt, 1969, Smith and Turver, 1973, etc.).

Another very important prediction as pointed out by Jelley (1955) was that the low frequency end of the Cerenkov radiation might give rise to emission of radio waves of detectable strength in case of high energy showers. This was subsequently proved to be right and radio pulses were detected by several workers at frequencies 100 kHz to about $530 \, \text{kHz}$. This has ushered a new field in the study of EAS.

In the next chapter a brief study on the mechanism of production of radio pulses will be given. This will be necessary to understand the proposed study of their correlation or otherwise with optical Cerenkov radiation.