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Gamma ray and Hadron generated Čerenkov Photon Spectra at Various Observation Altitudes

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Abstract. We have studied the propagation of Čerenkov photons generated by Very High Energy $\gamma-$ rays and hadrons in the atmosphere. Photon production height distributions derived from semi-empirical methods agree with those obtained by Monte Carlo simulations. The Čerenkov photon spectra at various observation altitudes are obtained after applying wavelength dependent corrections for the attenuation of photons in the atmosphere. The calculations were done both for $\gamma-$ray and hadron primaries of various energies. The spectra are found to be dependent on altitude as well as primary energy. The peak of the photon spectrum seems to shift towards the shorter wavelength with increasing primary energy at a given altitude. The fraction of the UV component in the Čerenkov spectrum is also estimated. The hadron generated Čerenkov spectra are richer in UV light at higher altitudes.

Key words: Čerenkov spectrum, Atmospheric attenuation, Atmospheric Čerenkov technique, TeV $\gamma-$ ray astronomy

1. Introduction

Very High Energy (VHE) primary $\gamma-$rays and cosmic rays generate extensive air showers when they impinge on the atmosphere. The relativistic charged particles, like e^- and e^+ which constitues a bulk of the shower secondaries, emit Čerenkov radiation as they propagate down the atmosphere. To understand and optimize the response of atmospheric Čerenkov detectors to these radiations, we have carried out detailed calculations with VHE $\gamma-$rays and cosmic rays of various primary energies initiating extensive air showers in the atmosphere. The Čerenkov photon spectra as seen at the observation level are then derived after taking into account the wavelength dependent attenuation in the atmosphere. We have estimated the relative fraction of UV photons in these spectra as a function of primary energy as well as the radial distance from the shower core for both $\gamma-$ray and cosmic ray primaries. We have mainly used Pachmarhi (altitude: 1075 m) as the observer's location where an array of 25 Čerenkov detectors each of area 4.45 m^2 is deployed (Bhat, 2001; Gothe *et al.*, 2000). The calculations were also extended to other altitudes viz. 2 km and zero km above mean sea level.

2. Čerenkov Photon Growth Curve

For showers initiated by $\gamma-$ray primaries the longitudinal shower development is obtained using approximation A for cascade equations (Griesen, 1956). The atmosphere is divided into slabs of thickness 333 m (starting from the first interaction of primary) within which the density, refractive index of air are all assumed to be a constant. The number of electrons (and positrons) above the Čerenkov threshold is then computed for each slab using the relation given by Lythe (Lythe, 1990). Neglecting the lateral spread of the shower particles, the number of Čerenkov photons produced in each slab is arrived at. Thus the longitudinal Čerenkov photon profiles are calculated for $\gamma-$rays of various primary energies from 50 GeV to 1 TeV (see Rahman *et al.*, 2001 for details).

For hadron initiated showers the longitudinal Čerenkov photon profiles are calculated in a similar way. The empirical relations suggested by Gaisser and Hillas (Gaisser and Hillas 1977) for the average number of electrons at an atmospheric depth, and Zatsepin and Chudakov (Zatsepin and Chudakov 1962) regarding the energy spectrum of electrons which is independent of the stage of cascade development, are used (Rao and Sreekantan, 1998; Pyrke, 2000). The Čerenkov photon growth curves have been obtained for primary protons of energies 100, 200, 500, 1000 and 2000 GeV.

As a cross check, the longitudinal Čerenkov photon profiles were also obtained (Chitnis and Bhat, 1998) by Monte Carlo simulation technique using CORSIKA (Heck, *et al.*, 1998). The longitudinal profiles obtained by the two methods agree very well and are shown in Figure 1 for 500 & 1000 GeV $\gamma-$rays (a and b) and 1000 & 2000 GeV protons (c and d). The smooth curves in the figure shows the analytically calculated profiles while the histogram represents the simulated results which are averaged over 30 showers for $\gamma-$ rays and 50 showers for protons.

3. Photon attenuation in the Atmosphere

To study the atmospheric attenuation of Čerenkov photons the Elterman's atmospheric attenuation model (Eleterman, 1968) is used. The tabulation provides the attenuation coefficients for the Rayleigh and aerosol scattering as well as ozone absorption in an altitude dependent form for the wavelength range 270-1260 nm. It permits calculation for vertical path transmission at one kilometer intervals up to an altitude of 50 km, individually for each attenuating component. The atmosphere is divided into 1 km slabs and the number of photons of a given wavelength at the bottom of each slab is obtained as, $N(\lambda) = N_0(\lambda)\ e^{-B(\lambda,x)}$, where N_0 is the number of photons of wavelength λ entering the slab at an atmospheric depth of x $g\ cm^{-2}$ and $B(\lambda, x)$ is the corresponding

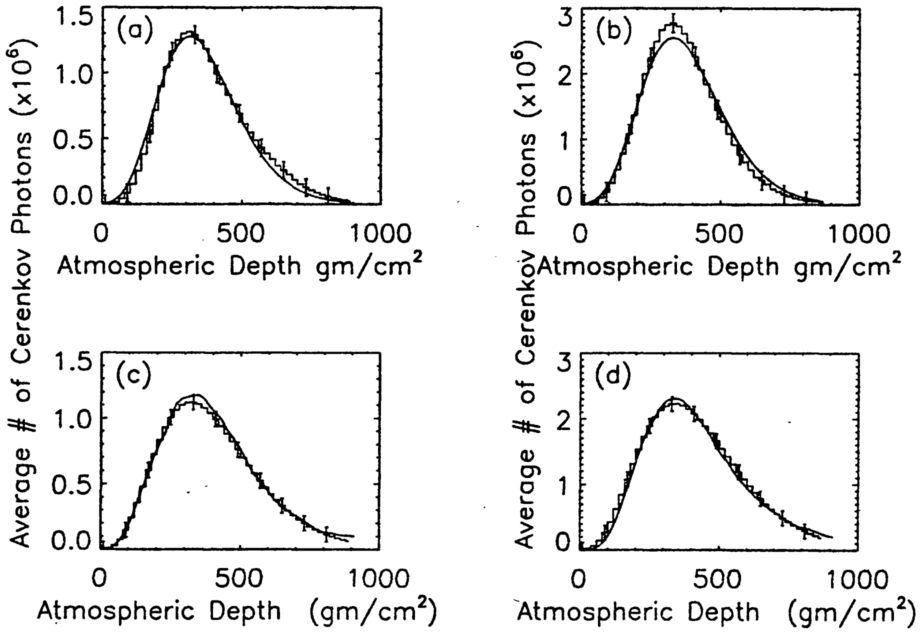

Figure 1. Average number of Čerenkov photons produced vs atmospheric depth ($g\ cm^{-2}$) for γ–rays of 500 GeV (a), 1 TeV (b) and protons of 1 TeV (c) and 2 TeV (d). Histograms are for simulation results and smooth curves for analytical calculations.

absorption coefficient. Photons pass through several such slabs with different attenuation coefficients, resulting in a modified longitudinal development profile for the Čerenkov photon that reach the observation altitude. We have confined the wavelength range to be 300-550 nm, dictated mainly by the band width of the photo-tube.

We define the transmission coefficient (T_c) as the ratio of the total number of photons received at an observation level to the corresponding number produced. It is found to vary as a power law with primary energy, both for γ–ray and proton primaries for the three altitudes considered. The increase in (T_c) with primary energy implies that high energy primaries penetrate deeper in the atmosphere and photons pass through lesser air mass. The shower maximum due to proton primaries occur lower down in the atmosphere compared to that due to γ–ray primaries of the same energy since the interaction mean free path in air for the former is nearly twice the radiation length. As a result, the Čerenkov photons in a proton shower have marginally higher average transmission coefficients ($\sim$ 1.2% at 100 GeV to 0.6% at 1 TeV). The attenuation of optical photons due to Rayleigh and aerosol scattering is more significant at lower altitudes.

The average path-length of Čerenkov photons reaching different core distances differ resulting in different attenuation. The variation in the average transmission coefficients for Čerenkov photons in the atmosphere with core distance and for different energies of γ–ray and proton primaries are shown in figure 2. Also shown are the radial variation in the mean production heights of photons. Simulation results are used to distribute the photons according to their lateral distribution.

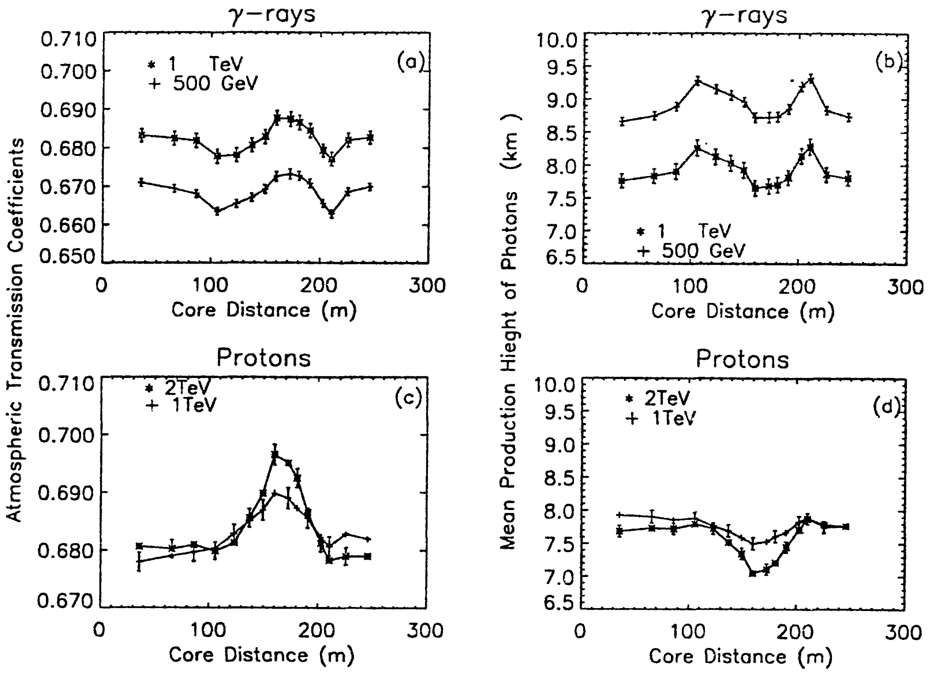

Figure 2. Core distance dependence of atmospheric transmission coefficients and production heights of Čerenkov photons

4. Čerenkov Photon Spectra

The spectrum of Čerenkov photons at an observation altitude is an important input for the design of an atmospheric Čerenkov experiment. We have computed the spectrum of Čerenkov photons at the three observation altitudes for γ−ray and proton primaries of various energy. The bandwidth considered for the calculation is 270 - 550 *nm*. Figure 3 shows the dependence of photon spectrum on (a) the primary energy, (b) primary species and (c) altitude of observation. The first two panels correspond to Pachmarhi altitude. As seen from the figure, the wavelength at peak intensity shifts to lower value with increasing primary energy as expected. It shifts from around 350 nm at 50 *GeV* to around 330 nm at 1 *TeV*.

5. The UV Component of the Čerenkov Spectrum

Since the Čerenkov light generated by cosmic ray primaries traverse lesser air mass compared to that due to γ− rays of the same energy, cosmic ray initiated showers are expected to have larger UV content. This property could be exploited to discriminate against hadronic showers (Zyskin *et al.*,1981) by the use of UV filters. Use of UV filters also helps to reduce the night-sky background. Therefore we have estimated the fraction of UV photons in the Čerenkov spectrum. We divided the spectrum as seen at the observation level into two groups *viz.*, the UV range comprising wavelengths 270-300 *nm* and the visible range comprising the wavelength band 300-550 *nm*. The ratio of number of

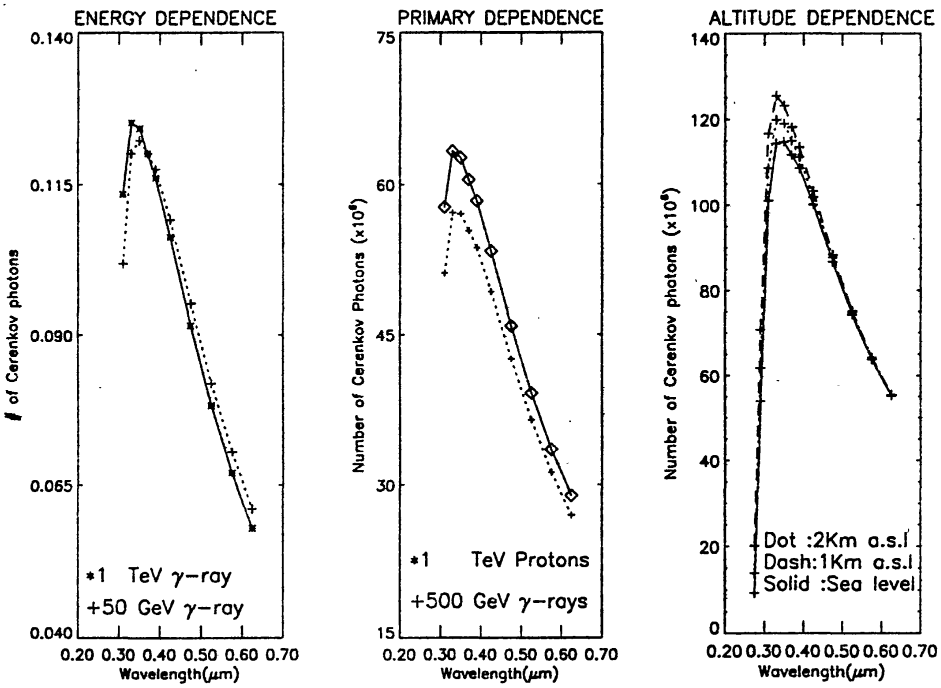

Figure 3. Dependence of Čerenkov photon spectrum on (a) primary energy, (b) primary species and (c) altitude of observation

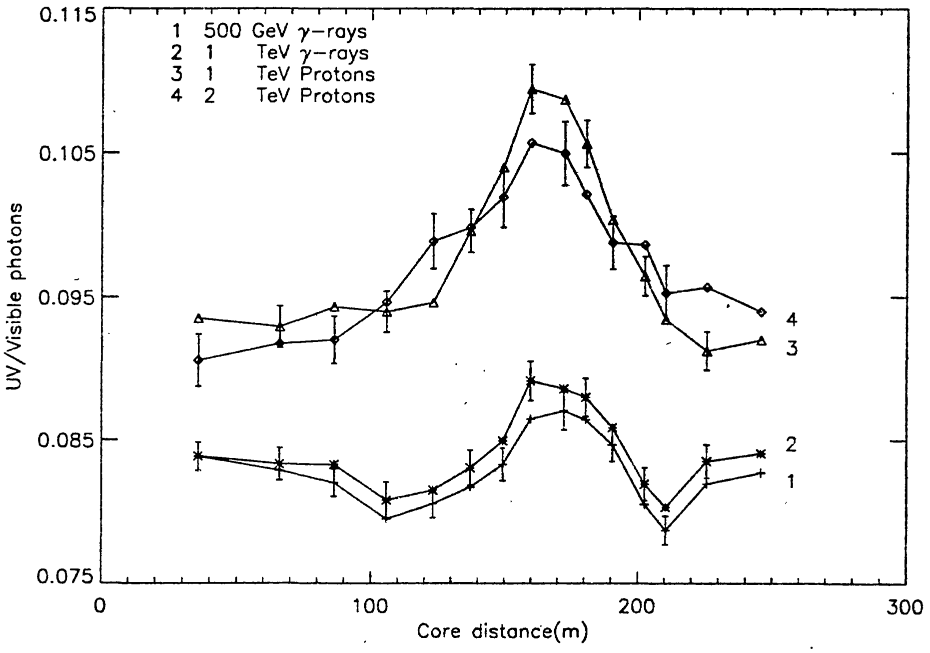

Figure 4. UV/Visible fraction of photons in the Čerenkov spectrum as a function of core distance

photons in UV range to that in the visible range is shown in Figure 4 for the observation altitude of Pachmarhi both for γ–ray and proton primary.

6. Conclusions

The average longitudinal profiles of Čerenkov photons as derived from the detailed simulation studies agree well with those derived by analytical calculations. This demonstrates that the simulation package does take into account almost all the interaction characteristics giving credence to conclusions drawn from the simulation studies. The position of the shower maximum obtained by us agrees with those of Miller & Westerhoff (Miller and Westerhoff, 1998). The analytical calculations that are carried out are useful to study the average shower properties, as this is much faster than the detailed simulations.

We have derived the Čerenkov photon spectra at three observation altitudes (0 - 2 *km* above m.s.l.) as a function of primary energy and species ($\gamma-$ray and proton). It is obtained by applying wavelength dependent corrections due to photon attenuation in the atmosphere. The spectrum is found to be both altitude and energy dependent and the peak shifts towards shorter wavelengths with increasing altitude or energy. Absorption of shorter wavelength photons, which is primarily due to atmospheric ozone, is comparatively larger for lower primary energy.

The fraction of UV content in the Čerenkov spectrum at the three observation altitudes is also estimated for $\gamma-$ray and Proton primaries. Hadron initiated showers are found to be richer in UV light especially at higher altitudes. Also, the relative strength of UV content increases at higher primary energy. However, the relative excess of UV photons in proton showers compared to $\gamma-$ray initiated showers decreases with primary energy. For example, the relative ratio of UV photons to the visible, in the case of proton primaries compared to $\gamma-$ray, is higher by about 16% at 50 GeV and decreases to 12% at 1 TeV. Hence, the hadron discrimination efficiency based on the UV content in Čerenkov light is relatively better at lower primary energies and. Thus, relative UV content of a shower could be a good parameter for rejecting cosmic ray background especially for large ground based arrays with low energy thresholds ($\sim$ 50 *GeV*). However, for this technique to be successful, It is necessary to measure UV and visible content of the Čerenkov spectrum in a shower accurately (better than $\sim$ 1%).

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