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Longitudinal Shower Development and its Signature at Observation Level

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Abstract. From a study of Čerenkov photon arrival times at various core distances at the observation level it has already been established that the photon front is well fitted with a spherical surface traveling at the speed of light and originating from a fixed point on the shower axis. The radius of curvature as measured at the observation level has been found to be roughly equal to the height of shower maximum from the observation level. In the present work we study the relationship between the radius of curvature of the shower front (R), the height of electron maximum (h_e), the Čerenkov photon maximum ($h_{\check{C}}$) and the average production height of Čerenkov photons ($\bar{h}$). Čerenkov pulse width (w) has always been used as a parameter to study cascade development especially at tens of PeV energies. We discuss the relation between the w and h_e at TeV energies for $\gamma-$ ray and proton primaries.

Key words: VHE $\gamma-$ray astronomy, Air shower simulations

1. Introduction

In atmospheric Čerenkov technique $\gamma-$rays from astronomical sources are detected indirectly by detecting Čerenkov light from extensive air showers generated by these $\gamma-$rays in terrestrial atmosphere. Cosmic rays also give rise to Čerenkov light and form an abundant background against which $\gamma-$rays are to be detected. It has been shown earlier that Čerenkov shower front produced by the air showers can be fitted with a spherical wavefront originating from a fixed point on shower axis (Chitnis and Bhat, 1999). Also the radius of curvature of the shower front (R) is found to be roughly equal to the height of shower maximum (h_e) from the observation level. This is expected since most of the Čerenkov emission comes from the vicinity of shower maximum, i.e. the place where the number of charged particles in the cascade reaches its maximum. Here we have a closer look at the relationship between R and various parameters describing the cascade development.

2. Parameters of longitudinal shower development

We have simulated a large number of showers initiated by $\gamma-$rays and protons of various energies incident vertically at the top of the atmosphere using a package known as CORSIKA (Heck et al. 1998). For $\gamma-$rays of energy 100 GeV and 500 GeV as well as for protons of energy 250 GeV and 1 TeV 200 showers were simulated, whereas for $\gamma-$rays of energy 1 TeV and protons of energy 2 TeV, 100 showers were simulated. For higher energies of primaries, i.e. 3.5 TeV $\gamma-$rays and 5 TeV protons, sample consists of 10 and 12 showers, respectively. Each shower was fitted with a spherical wavefront. Variation of fitted R as a function of h_e for $\gamma-$ray primaries, averaged over a sample of showers shows that R is consistently smaller than h_e by about a km.

Difference between these two quantities can be partially attributed to the shape of the electron growth curve. Electron growth curves are somewhat skewed resulting in average of the distribution occurring deeper in the atmosphere compared to peak or h_e (see Chitnis and Bhat, 1998). This is also reflected in the Čerenkov production height distributions. In addition, it is found that the Čerenkov maximum is above the electron maximum. This is perhaps due to the fact that the fraction of high energy electrons is larger above the electron maximum and these higher energy electrons are more efficient in emission of Čerenkov photons.

To further understand this difference we study the relationship between radius of curvature of the shower front (R) and three parameters describing the longitudinal development of shower, viz., height of electron maximum (h_e), height of Čerenkov maximum ($h_{\check{C}}$) and average production height of Čerenkov photons constituting the shower ($\bar{h}$). Distributions of all these parameters for a sample of 200 showers of 500 GeV $\gamma-$rays and 1 TeV protons are plotted in Figure 1. These distributions are broad, width of the distribution being about 5 km for $\gamma-$rays and about 10 km for protons. Also these distributions are overlapping.

We have also studied the energy dependence of these parameters. Figure 2 shows the variation of R, $h_{\check{C}}$, h_e and $\bar{h}$ averaged over a sample of showers with primary energy for $\gamma-$rays and protons. Relations between R and E, as given by best fit lines are,

$$R = (34.9 \pm 9.5) lnE + (144.3 \pm 62.7)$$

for $\gamma-$rays and

$$R = (19.4 \pm 14.5) lnE + (259.5 \pm 97.3)$$

for protons, where R is in $gm\ cm^{-2}$.

These relations as well as those between other parameters and primary energies are consistent with the empirical relations obtained by Rahman *et al.*, 2001.

3. Difference distributions for parameters of longitudinal development of showers

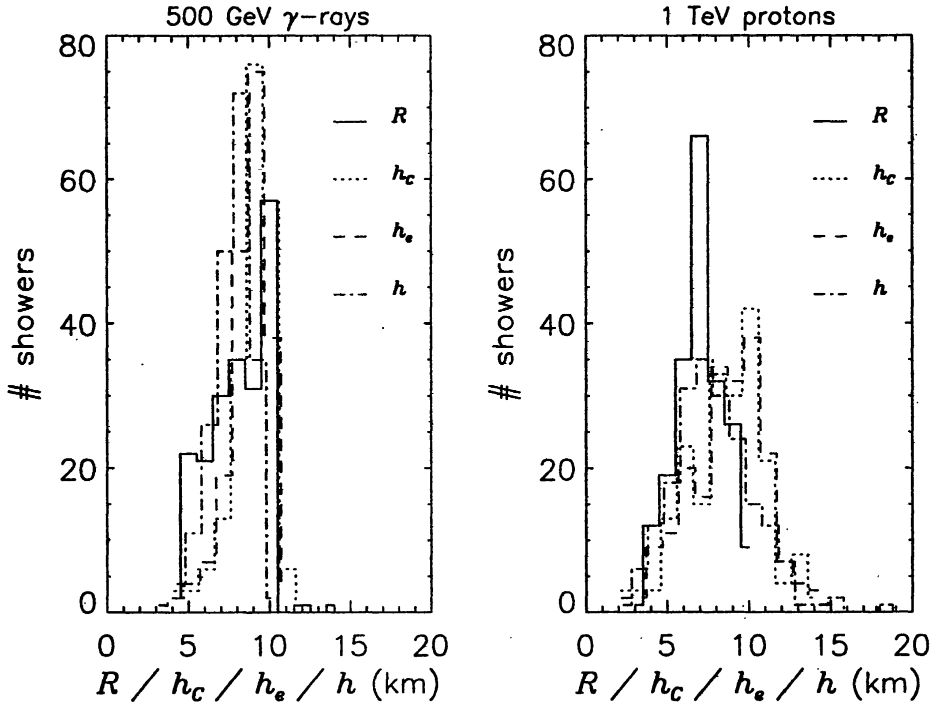

Figure 1. Distribution of R, h_e, h_C and h for a sample of 200 showers initiated by (a) γ–rays of energy 500 GeV and (b) 1 TeV protons, incident vertically at the top of the atmosphere. Values of all the parameters are measured with respect to the sea level.

In the previous section, we have studied the average behaviour of the parameters of longitudinal development of showers. Here we carry out shower-wise comparison of these parameters. Distributions of the difference between h_e and R for showers initiated by γ–ray and proton primaries of various energies have been generated. The above conclusions are borne out by these distributions as well as showing the energy independence of the above observations. Similar distributions have been generated for showers initiated by γ–rays and protons with primary energies following the power law distribution with index -2.65, over the energy range 500 GeV - 10 TeV for γ–rays and 1 TeV - 20 TeV for protons. It is found that the effective emission point or R is below the electron maximum h_e on the shower axis by about about 1-1.5 km for γ–rays and 0.8-1.0 km for protons.

4. Čerenkov pulse width as a measure of height of shower maximum

Strong correlation between the h_e and the FWHM of the Čerenkov light pulse at large core distances has been established at 10s of *PeV* energies. Measurements of FWHM has therefore been used to obtain an estimate of the fluctuations in the depth of cascade maximum which offers a strong constraint on nuclear mass composition of cosmic rays at these energies (see Hammond *et al.*, 1978 and Protheroe and Turver, 1979). However this

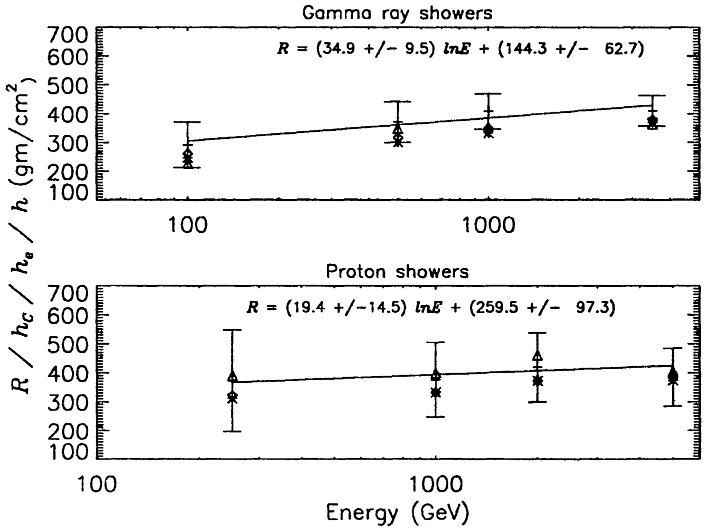

Figure 2. Variation of average R (indicated by $+$), h_e (diamond), h_C (asterisk) and h (triangle) as a function of primary energy for showers generated by γ−rays and protons. 1 σ error bars are indicated for R distribution. Best fit line for average R is shown.

property has not been established at TeV energies. From simulation studies of vertically incident γ−ray and proton primaries we investigate the relationship between the FWHM and the fitted radius of curvature of the Čerenkov front (R), which is approximately equal to the height of shower maximum (h_e) (see Figure 3 for proton primaries).

It is found that the relationship between FWHM and height of shower maximum is similar at TeV energies too. Also the FWHM is strongly correlated with R for both γ−ray and proton primaries at core distances beyond $\sim$ 75-100 m. The degree of correlation is relatively better for γ−ray primaries as compared to proton primaries. Further, at near core distances, $\leq$ 75-100 m, a strong anti-correlation is observed. This is primarily because of the fact that at near core distances photons produced lower down in the atmosphere reach the ground before those produced higher up. Finally, the slope is an increasing function of core distances for both γ−ray and proton primaries.

5. Conclusions

For both γ and proton primaries the fitted radius of curvature R is below the Čerenkov maximum $h_{\check{C}}$ by $\sim$ 10-15% for γ−rays and $\sim$ 10% for protons. Even though the emission takes place over a cylindrical region of diameter of $\sim$ 21 m and length of about 4 km for 1 TeV γ−rays and diameter of $\sim$ 70 m and length of about 4 km for 1 TeV protons (see, Fegan, 1997), the effective emission point seems to be below the Čerenkov maximum on the shower axis by about 0.8-1.0 km for protons and about 1-1.5 km for γ−rays. By comparing the electron growth curve and Čerenkov maximum it is found that the

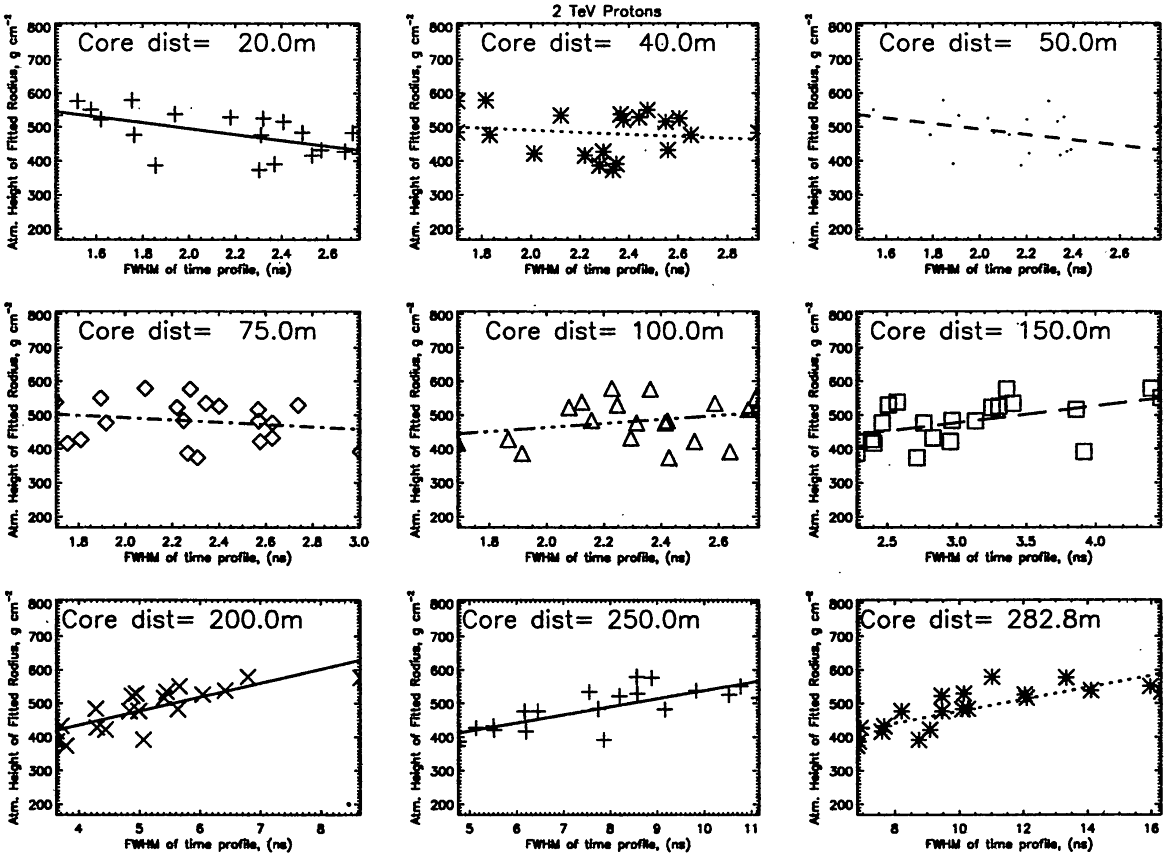

Figure 3. Variation of R with FWHM of Čerenkov pulse for proton primaries of energy 2 TeV incident vertically at the top of the atmosphere, at various distances from shower core.

Čerenkov maximum is above the electron maximum. This is due to the fact that the fraction of high energy electrons is larger above the electron maximum and hence more efficient in Čerenkov photon emission. At *TeV* energies, the FWHM of Čerenkov pulse is strongly correlated with R for both γ−ray and proton primaries at core distances beyond ~ 75-100 m. The degree of correlation is relatively better for γ−ray primaries as compared to proton primaries.

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