Gamma-hadron Separation using Čerenkov Photon Timing Studies

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Abstract

Atmospheric Čerenkov technique largely depends on the ability of the experiment to detect the Čerenkov light produced by gamma rays from astronomical objects in the presence of an abundant background due to cosmic rays. We have carried out systematic monte carlo simulation studies of the timing information of Čerenkov photons produced by TeV energy gamma rays and hadronic primaries. The radii of curvature of the Čerenkov fronts have been found to be equal to the height of shower maximum irrespective of the species or the observation level. Possibility of deriving the pulse shape parameters like the rise time, decay time and full width at half maximum from the easily measurable quantities like the mean and RMS variation of photon arrival times has been demonstrated in an earlier paper. The efficiency of the pulse shape parameters as well as radii of shower fronts, to identify and reject the hadronic showers is demonstrated here in terms of 'quality factor'. In TeV energy range, we find that a reasonable rejection of hadronic showers can be achieved using relative arrival time jitter and decay time of the Čerenkov pulse.

1 Introduction:

The spatial and temporal properties of Čerenkov photons contain valuable information on the development and propagation of the extensive air showers in the atmosphere and hence can provide the information about primary species generating a shower. The possibility of applying pulse shape discrimination technique to improve the signal to noise ratio in the data from Crab nebula was first demonstrated by Tümer *et al.* (1990) based on the presence or absence of kinks and other anomalies like long trailing edges of the Čerenkov pulses indicating hadronic origin. Patterson and Hillas (1989) have checked the efficacy of this method for VHE $\gamma-$ ray astronomy. Using pulse shape parameters Roberts *et al.* (1998) have studied the possibility of discrimination between photonic and hadronic showers at large zenith angles ($\geq 35°$), for primary energies $\geq 40\ TeV$. In the present work, we have carried out systematic study of temporal profile of Čerenkov light from simulated $\gamma-$ ray and hadronic cascades with primary energy in the range 100 GeV - 2 TeV, incident vertically on the top of the atmosphere. We have tested the efficacy of the following parameters derived from temporal properties of Čerenkov photons, for discrimination of photonic and hadronic showers: 1. Radius of curvature of the Čerenkov front, 2. Rise time, decay time and FWHM of Čerenkov pulse, 3. Relative arrival time jitter of Čerenkov photons.

Efficiency of the parameter to distinguish between $\gamma-$ ray and hadron initiated showers is given in terms of quality factor defined as

$$QualityFactor, q = \frac{N_a^\gamma}{N_T^\gamma}\left(\frac{N_a^p}{N_T^p}\right)^{-\frac{1}{2}}$$

where N_a^γ is the number of $\gamma-$ray showers accepted, N_T^γ is the total number of $\gamma-$ray showers, N_a^p is the number of proton showers accepted, while N_T^p is the total number of proton showers.

2 Simulations:

CORSIKA package version 5.6 (Knapp and Heck, 1998) was used for simulation of air showers generated by $\gamma-$ rays and cosmic rays of various energies. The Čerenkov radiation produced by

Table 1: Quality of radius of spherical wavefront as a discriminating parameter

Type of primary	Energy of primary (GeV)	Threshold radius of curvature (m)	Fraction of $\gamma-$ rays accepted %	Fraction of protons accepted %	Quality Factor
$\gamma-$ rays and protons	100 250	6000	89	49	1.3
$\gamma-$ rays and protons	500 1000	5000	93	75	1.1
$\gamma-$ rays and protons	1000 2000	4000	96	74	1.1

relativistic charged particles in the shower, within bandwidth 300-650 nm is propagated to the ground level, which corresponds to Pachmarhi. We have considered an array of telescopes with area 2.11×2.11 m^2 each, consisting of 17 telescopes with spacing 25 m in E-W direction and 21 telescopes with spacing 20 m in N-S direction. This configuration is similar to the Pachmarhi Array of Čerenkov Telescopes (PACT, Bhat *et al.*, 1999), but array size taken here is much larger so that core distance dependence of various parameters can be studied. The position, angle, time and production height of each Čerenkov photon hitting the detector array was recorded. Wavelength dependent absorption of Čerenkov photons in the atmosphere is not taken into account.

3 Spherical shower front:

We have approximated the Čerenkov light from air showers generated by $\gamma-$ rays and cosmic rays as incident on the observation level with a spherical front moving with the speed of light c, originating from a fixed point on the shower axis. For vertical showers the relative time delay *t(r)* at a core distance r is approximated by :

$$t(r) = \frac{\sqrt{(R^2 + r^2)}}{c} - \frac{R}{c} \tag{1}$$

where R is the radius of curvature of the spherical front. Fit with spherical front is carried out to showers generated by $\gamma-$ rays and cosmic rays, and the radius of curvature of the shower front is found to correspond to the height of shower maximum from observation level. For details see Chitnis and Bhat (1999), (CB-I, hereafter).

Further, we have studied the usefulness of radius of curvature of the shower front as a discriminant between $\gamma-$ ray initiated and proton inititated showers in terms of quality factor defined above. Results are given in Table 1. Energies of primaries are chosen so that they have similar Čerenkov yields. From the table it can be seen that the radius of curvature is a better dicriminant at lower primary energies.

4 Pulse shape parameters:

For each telescope, for a given shower, there are a number of Čerenkov photons arriving at different times. We have fitted arrival time distribution of Čerenkov photons with two different pdf's *viz.* lognormal distribution function (LDF) and a Gamma function. It is found that LDF gives marginally better fit than Gamma function at all core distances (≤ 300 m). It is demonstrated by CB-I, that it is possible to derive these parameters from mean and RMS of arrival times of Čerenkov photons and there is a good agreement between derived and fitted parameters.

Table 2: Quality of pulse shape parameters as a discriminant

Pulse shape parameter	Type of primary	Energy of primary (GeV)	Threshold Value (ns)	Fraction of $\gamma-$ rays accepted %	Fraction of protons accepted %	Quality Factor
Rise time	$\gamma-$ rays and protons	250 500	1.2	92.1	76.3	1.1
	$\gamma-$ rays and protons	500 1000	2.5	99.2	95.1	1.0
	$\gamma-$ rays and protons	1000 2000	1.2	87.9	76.6	1.0
Deacy time	$\gamma-$ rays and protons	250 500	8.0	84.7	54.1	1.2
	$\gamma-$ rays and protons	500 1000	5.5	61.2	30.5	1.1
	$\gamma-$ rays and protons	1000 2000	6.0	58.6	25.1	1.2
FWHM	$\gamma-$ rays and protons	250 500	4.6	89.5	66.4	1.1
	$\gamma-$ rays and protons	500 1000	2.8	62.9	48.2	1.0
	$\gamma-$ rays and protons	1000 2000	3.6	71.1	48.5	1.0

Table 3: Quality of relative time jitter as a discrminating parameter.

Type of primary	Energy of primary (GeV)	Threshold Value	Fraction of $\gamma-$ rays accepted %	Fraction of protons accepted %	Quality Factor
$\gamma-$ rays and protons	100 250	0.26	70.6	28.8	1.3
$\gamma-$ rays and protons	1000 2000	0.14	74.5	46.0	1.1

Here we have investigated the possibility of using pulse shape parameters for discrimination between $\gamma-$ ray and proton generated showers. Quality factors are calculated using derived pulse shape parameters from all 357 telescopes, for a sample of 30 showers generated by $\gamma-$ rays and protons of each primary energy. All the Čerenkov photons incident at all angles on a given telescope are accepted during these fits. Results are summarized in Table 2 and in Fig. 1. From these tables it is obvious that rise time & full width are not very sensitive to the nature of the primary while the decay time could in principle be used to identify the primary species.

5 Relative time jitter:

Each telescope consists of 7 mirrors. Time jitter is the RMS of mean the arrival times of Čerenkov photons at 7 mirrors. Ratio of jitter to mean arrival time of Čerenkov photons is defined as the relative time jitter and is almost independent of core distance. We have checked for usefulness of this paramter for identifying primary species. Results are given in Table 3 and Fig. 1.

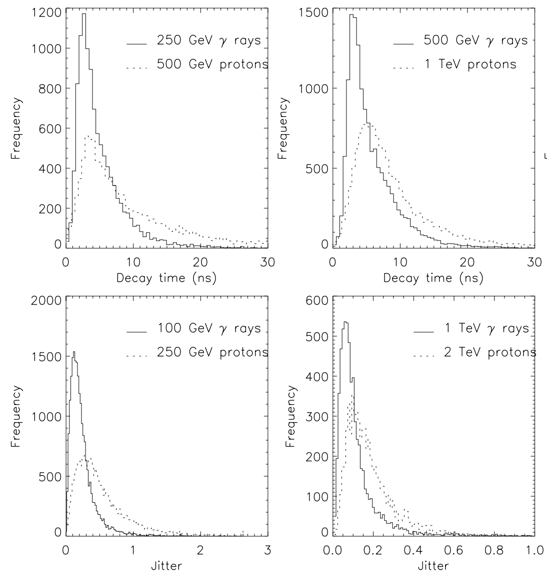

Figure 1: Distribution of decay times of pulse shapes and arrival time jitter for $\gamma-$ ray and proton primaries.

6 Conclusions:

The radius of curvature of the Čerenkov front could be an efficient parameter to isolate hadron initiated showers at lower primary energies ($\sim 250\ GeV$). The rise time and FWHM are not very sensitive to the primary species and hence not suitable parameters for rejecting hadronic showers. The decay time appears to be a good parameter for identifying hadronic showers especially at higher energies. The relative time jitter measured as a ratio of RMS to the mean arrival time is a good discriminating parameter preferably at lower primary energies. This parameter can be easily measured in a set-up like PACT.

Intutively one would think that a combination of these parameters applied in tandem might be more efficient discriminant againt hadrons. More work is in progress in this direction.

References

Bhat, P.N., *et al.*, 1999, Proc. 26th ICRC (Salt Lake City, 1999), OG 4.3.1

Chitnis, V.R., & Bhat, P.N. 1999, to appear in Astrop. Phys., astro-ph 9902253.

Knapp, J. and Heck, D. 1998, EAS Simulation with CORSIKA, V5.60: A user's Guide.

Patterson, J. R. and Hillas, A. M. 1989, Nucl. Instr. Meth., A 278, 553.

Roberts, M. D., *et al.* 1998, J. Phys. G: Nucl. Particle Phys., 24, 225.

Tümer, O. T., *et al.*, 1990, Proc. 21st ICRC (Adelaide, 1990), 2, 155.