Proceedings of ICRC 2001: 2914 © Copernicus Gesellschaft 2001

ICRC 2001

Gamma hadron separation using Čerenkov photon timing studies

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Abstract. Cosmic rays form the main source of background against which TeV $\gamma-$rays have to be detected using the atmospheric Čerenkov technique. Atmospheric Čerenkov arrays which adopt wavefront sampling technique need to develop suitable species sensitive parameters from the measurements at the observation level while the complementary imaging technique employs, by now, well established imaging parameters. We have derived several parameters based on Čerenkov photon arrival times which allow us to discriminate between $\gamma-$rays and cosmic rays. These are the wavefront curvature, pulse shape parameters and timing jitter. A systematic study of these parameters is carried out using detailed simulations and the resulting quality factors are computed for various primary energies and observation levels.

1 Introduction

Atmospheric Čerenkov Technique (ACT), is a well established and unique method for the astronomical investigation of Very High Energy (VHE, also referred to as TeV) $\gamma-$rays. It is based on the effective detection and study of the Čerenkov light emitted by the secondary particles produced in the extensive air showers initiated by the primary $\gamma-$rays. Present day experiments using this technique are based on either imaging technique (e.g. Whipple, CAT, CANGAROO, HEGRA, TACTIC etc) or wavefront sampling technique (e.g. CELESTE, STACEE, SOLAR-2, PACT etc) (Ong, 1998). All these experiments have to deal with a large background produced by Čerenkov emission from air showers initiated by cosmic rays. Hence it is necessary to devise methods using which one can suppress large fraction of cosmic ray background and thereby improve signal-to-noise ratio of the experiment. Lot of work has been carried out in this regard for experiments based on imaging technique. In these experiments background rejection is based on effective exploitation of differences in shapes and orientations of images generated by these two species. It is necessary to develop similar methods for effective background suppression for experiments based on wavefront sampling technique. Experiments using this technique record Čerenkov photon density and arrival time of Čerenkov shower front at various locations in Čerenkov pool. In the present work we study the efficacy of some parameters based on arrival time of Čerenkov photons.

2 Simulations

We have used CORSIKA package (version 5.604) (Heck *et al.*, 1998) to simulate Čerenkov light emission in the earth's atmosphere by the secondaries of the extensive air showers generated by cosmic ray primaries or $\gamma-$rays. We have considered Čerenkov radiation produced in the bandwidth of 300-650 nm by the charged secondaries in showers. This radiation is propagated to the observation level. In the present studies we have mainly used Pachmarhi (longitude: $78^\circ\ 26'$ E, latitude: $22^\circ\ 28' N$ and altitude: 1075 m) as the observation level where an array of Čerenkov telescopes called Pachmarhi Array of Čerenkov telescopes (PACT) is commissioned (Chitnis *et al.*, 2001). This array consists of 25 telescopes, each consisting 7 para-axially mounted parabolic mirrors. Total reflector area per telescope is 4.45 m^2. For simulations we have assumed an array of 17 detectors in the E-W direction and 21 detectors in the N-S direction with a separation of 25 m and 20 m respectively. This configuration, similar to PACT but much larger, is chosen so that one can study the core distance dependence of various observable parameters. Large number of showers initiated by $\gamma-$rays, protons and iron nuclei of various energies are simulated.

3 Shower front parameters

It has been shown long ago that the radius of curvature of the Čerenkov shower front is strongly correlated with the height of shower maximum from the observation level (Protheroe *et al.* 1975). This is expected since most of the Čerenkov

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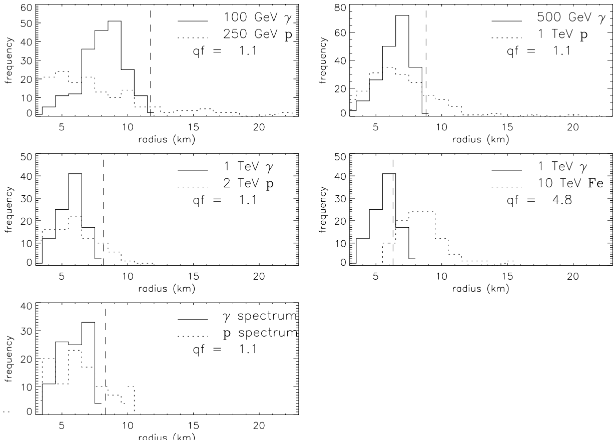

Fig. 1. Distribution of the shower front radii for $\gamma-$ rays (continuous line) and protons or Fe nuclei (dashed line) of respective energies as indicated in each panel. The vertical lines indicate the threshold values of parameters.

Table 1. Quality of radius of curvature of the spherical photon front as a discriminating parameter for vertical showers

Type of primary	Energy of primary (GeV)	Threshold radius of curvature (km)	Fraction of showers accepted (%)	Quality factor
$\gamma-$ rays	100	11.7	99	1.13±0.13
& protons	250		77.5	
$\gamma-$ rays	500	8.8	98	1.13±0.13
& protons	1000		75	
$\gamma-$ rays	1000	8.2	99	1.11±0.18
& protons	2000		80	
$\gamma-$ rays	1000	6.3	48	4.8±2.6
& Fe nuclei	10000		1	
$\gamma-$ rays	spectrum	8.3	100	1.13±0.18
& protons	spectrum		79	

emission originates in the vicinity of shower maximum. This has been found to be true for different species of cosmic rays (Chitnis and Bhat, 1999). For photonic primaries the height of shower maximum is decided by the radiation length in the atmosphere while that for hadronic primaries by the interaction length which in turn depends on the interaction cross-section in air. Hence the radius of curvature could be species specific. Therefore we have investigated the possibility of using the fitted radius of curvature of the shower front as a parameter to distinguish between $\gamma-$ray and hadron initiated showers. For this purpose, each of the simulated showers is fitted with a spherical wavefront. For vertically incident showers the relative arrival time delay [$t(r)$] of Čerenkov shower front at a core distance r can be 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 (Battistoni *et al.* (1998), Chitnis and Bhat (1999)). Figure 1 shows the distributions of the radii of shower fronts obtained by fitting the above equation, for different primary species of various energies. Sample consists of 200 showers initiated by $\gamma-$rays of energies 100 and 500 GeV and protons of energies 250 GeV and 1 TeV. For higher energy primaries, 100 showers were simulated. Last panel in the figure corresponds to the case where energies of $\gamma-$ray and protons are selected randomly from a power law distribution of a differential slope of -2.65. Energy bandwidths used for $\gamma-$ray and proton showers are 500 GeV - 10 TeV and 1 - 20 TeV respectively.

In order to study the quality of discrimination, quality factor is used as a figure of merit. It is defined as

$$Q_f = \frac{N_a^\gamma}{N_T^\gamma} \left(\frac{N_a^{pr}}{N_T^{pr}} \right)^{-\frac{1}{2}} \tag{2}$$

where N_a^γ (N_a^{pr}) is the number of $\gamma-$rays (protons) accepted (i.e. below threshold) and N_T^γ (N_T^{pr}) is the total number of $\gamma-$rays (protons). Larger the quality factor, better is the background rejection efficiency.

Optimum quality factors obtained using radius of shower front as a discriminating parameter are listed in Table 1. Corresponding threshold values of radii as well as fractions of accepted $\gamma-$rays and cosmic rays are also listed. It can be seen the radius of the shower front provides modest rejection of proton generated showers. Rejection is quite good against heavy primaries like iron nuclei.

4 Pulse shape parameters

Second type of parameters based on Čerenkov photon timing measurements is pulse shape parameters. Shape of the Čerenkov pulse at the telescope is related to the cascade development. Rise time of the pulse reflects the longitudinal growth of the cascade whereas decay time is related to the attenuation below the shower maximum. Width of the pulse, on the other hand, is a measure of Čerenkov photon production profile. Because of the kinematical differences in showers initiated by $\gamma-$rays and cosmic rays, pulse profiles are expected to be species specific. Hence we have investigated the possibility of using pulse shape parameters to discriminate between $\gamma-$ray and cosmic ray showers. Earlier we have fitted the Čerenkov pulses from individual telescopes using lognormal distribution (Chitnis and Bhat, 1999). Here we use pulse shape parameters from predicted lognormal distributions. Of the three pulse shape parameters, we find the decay time to be most sensitive to species at TeV energies. Figure 2 shows the distributions of decay times for monoenergetic $\gamma-$rays, protons and iron nuclei of various energies. Compared to the case of shower front radius, here $\gamma-$ray and hadron domains show better separation. This is reflected in larger values of quality factors listed in Table 2. Based on decay time it is possible to reject 96% of the cosmic ray showers retaining about one third of $\gamma-$ray showers.

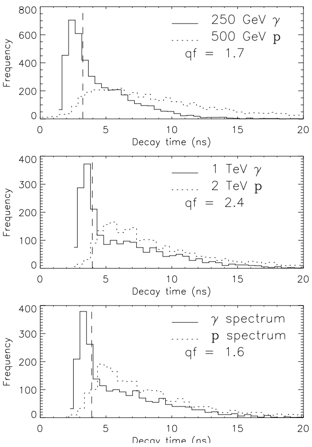

Fig. 2. Distribution of decay times for $\gamma-$ rays (solid line) and protons or iron nuclei (dotted line). The vertical lines indicate the threshold values.

5 Timing jitter

Finally we have studied timing jitter or spread in arrival time of Čerenkov photons. We have seen earlier that the bulk of Čerenkov emission comes from the vicinity of shower maximum. In addition to this there is Čerenkov emission originating from lower atmospheric heights, largely due to low energy electrons undergoing multiple Coulomb scattering. This emission decides arrival time jitter seen at various core distances. This jitter has a definite signature of the kinematics of the shower development. Cosmic ray showers are expected to show higher jitter than $\gamma-$ray showers. Hence timing jitter could be useful parameter for gamma-hadron separation. We have defined relative timing jitter as the ratio of RMS of average arrival times of Čerenkov photons at seven mirrors of the telescope to the mean of seven averages. This relative jitter is found to be roughly independent of core distance. Figure 3 shows the distributions of relative jitter for $\gamma-$ray and hadron showers. These two distributions are well separated.

Table 2. Quality of pulse decay time as a discriminating parameter for vertical showers

Type of primary	Energy of primary (GeV)	Threshold value (ns)	Fraction of showers accepted (%)	Quality factor
$\gamma-$ rays	250	3.2	37.7	1.67±0.02
& protons	500		5.1	
$\gamma-$ rays	500	3.7	35	2.22±0.03
& protons	1000		2.5	
$\gamma-$ rays	1000	3.9	30.4	2.41±0.06
& protons	2000		1.6	
$\gamma-$ rays	1000	4.0	32.1	2.48±0.06
& Fe nuclei	10000		1.7	
$\gamma-$ rays	spectrum	3.9	32.5	1.57±0.03
& protons	spectrum		4.3	

Table 3. Quality of jitter as a discriminating parameter

Type of primary	Energy of primary (GeV)	Threshold value	Fraction of showers accepted (%)	Quality factor
$\gamma-$ rays	100	0.23	49.8	2.83±0.05
& protons	250		3.1	
$\gamma-$ rays	1000	0.07	67.5	2.42±0.03
& protons	2000		7.8	
$\gamma-$ rays	1000	0.09	91.3	9.13± 0.25
& Fe nuclei	10000		1.0	
$\gamma-$ rays	spectrum	0.08	80.5	1.85± 0.02
& protons	spectrum		19	

Optimum quality factors are listed in Table 3. It is possible to reject more than 80% of the cosmic ray showers retaining about 80% of $\gamma-$ray showers based on timing jitter.

6 Altitude dependence of quality factors

So far we have studied efficacy of various parameters for Pachmarhi location which is at an altitude of 1 km. However the sensitivity of these parameters is expected to depend on observation altitude to some extent. This is because of the fact that as the altitude of observation increases, the shower maximum for a given primary energy comes closer to the observation level. As a result, the lateral distribution of Čerenkov photons changes with the altitude of the observation level. The core distance at which the hump appears as well as the prominence of the hump will be smaller with increasing altitude of observation (Rao and Sinha, 1988). Since the Čerenkov front is being intercepted at different observation levels during its propagation in the atmosphere, the shower parameters like the average arrival angle, time etc also will be different at different observation levels. Therefore we studied the role played by the observation altitude in using the various types of parameters studied here.

For this purpose, we have simulated a sample of 100 showers each for 500 GeV $\gamma-$rays and 1 TeV protons for sea level and altitude of 2.2 km above the sea level. Table 4 lists the quality factors for decay time and relative timing jitter for these two observation levels. Comparison with Tables 2 and 3 shows that the quality factors from decay time improve steadily with decreasing altitude while those from timing jitter are almost independent of altitude. To understand this we computed the quality factors, for telescopes only around the hump region after taking into account the varying hump distances from the core at three altitudes. These are found to be 8.1, 6.6, and 3.6 for sea level, 1 km and 2.2 km altitudes, respectively. Also we have computed quality factors exclusively for pre-hump, hump and post-hump regions (Table 5). Quality factors for pre-hump and post-hump regions are poorer than that for the hump region. Hence the improvement in quality factor at lower altitudes is mainly due to the increased prominence of hump at lower atmospheric depths.

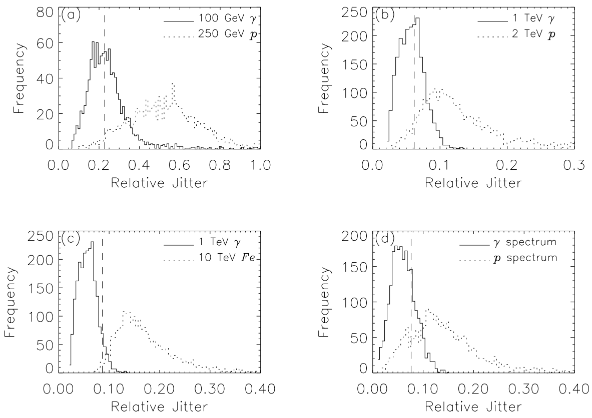

Fig. 3. Distributions of mean relative jitter for $\gamma-$rays (solid line) and protons or iron nuclei (dotted line) of different primary energies are shown. The vertical lines represent the threshold values.

The relative timing jitter, on the other hand seems to be much less sensitive to core distance and hence does not vary significantly with observation altitude.

7 Discussion and conclusions

We have studied the efficacy of three types of parameters based on Čerenkov photon timing measurements, viz., radius of shower front, decay time of the pulse and arrival time jitter, for various observation altitudes. We find decay time and timing jitter to be more sensitive to species compared to shower front radius. Using these parameters it is possible to reject large fraction of hadronic showers at various observation altitudes. Efficiency of discrimination using decay time improves at lower altitudes due to increase in prominence of the hump. Whereas timing jitter is insensitive to observation altitude.

So far we have considered the effect of these parameters applying them one at a time. It is possible to improve sensitivity of the experiment greatly by applying these parameters in tandem. Table 6 shows the results obtained by applying decay time and timing jitter cuts in succession to a sample of 100 showers each produced by 500 GeV $\gamma-$rays and 1 TeV protons at sea level. Quality factor improves dramatically by applying these parameters in tandem resulting in rejection of more than 99% of proton showers retaining about 27% of $\gamma-$ray showers. Quality of rejection can be further improved applying the parameters based on density measurements (Bhat and Chitnis, 2001). With proper use of various parameters, wavefront sampling experiments are expected to achieve background rejection comparable to imaging experiments.

Table 4. Quality of discrimination at various altitudes for showers initiated by 500 GeV $\gamma-$rays and 1 TeV protons

Parameter	Obs altitude (km)	Threshold value	Fraction of accepted $\gamma-$rays (%)	Fraction of accepted protons (%)	Quality factor
Decay time	0.0	3.2 ns	32.9	1.4	2.82±0.07
Decay time	2.2	4.2 ns	31.5	8.6	1.07±0.02
Timing jitter	0.0	0.08	52.5	2.7	3.18±0.06
Timing jitter	2.2	0.09	41.2	1.7	3.16±0.07

Table 5. Quality of decay time as a discriminating parameter for $\gamma-$ray (500 GeV) and proton (1 TeV) primaries at three different core distance ranges: pre-hump, hump & post hump

Core distance ranges	Threshold value (ns)	Fraction of accepted $\gamma-$rays (%)	Fraction of accepted protons (%)	Quality factor
Pre-hump	4.3	88.5	30.5	1.60±0.05
Hump	3.3	80.5	1.5	6.57±0.51
Post-hump	8.4	53.0	14.0	1.42±0.06

Acknowledgements. We would like to acknowledge the fruitful discussions with and helpful suggestions from Profs. K. Sivaprasad, B. S. Acharya and P. R. Vishwanath during the present work.

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Table 6. Application of pulse decay time and timing jitter in tandem

Parameter Type	Threshold value	Fraction of $\gamma-$rays accepted (%)	Fraction of protons accepted (%)	Quality factor
Decay Time	3.2 ns	32.9	1.4	2.82±0.07
Timing Jitter	0.08	52.5	2.7	3.18±0.06
Decay time & Timing jitter	3.2 ns 0.08	26.8	0.05	12.6±1.6