Bull. Astr. Soc. India (2002) **30**, 135–145

Wavefront Sampling Technique: VHE γ–ray Experiments in India

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Abstract. Atmospheric Čerenkov technique is the only method which has been successfully used to probe the sky in the TeV energy band. However it has certain intrinsic drawbacks arising primarily out of the presence of cosmic rays which out-number γ–rays by around a factor of $\sim$ 1000. Second generation experiments in the field have developed some novel techniques by which a bulk of the cosmic rays could be rejected thus increasing the signal to noise ratio. Thus the field emerged from an era when the confidence level of positive results were rarely larger than a few standard deviations. The underlying technique responsible for this phenomenal success was the ability to identify the primary species from the Čerenkov images recorded at the observation level, first demonstrated by simulation studies. Subsequently, it was found again through simulation techniques, that the spatial sampling of Čerenkov photons too is potentially a viable as well as a powerful technique which is yet to be fully exploited. Several Čerenkov telescope arrays are now in advanced stages of operation which employ this technique in order to reduce the cosmic ray background. This technique, also called the wavefront sampling technique, is being employed for studying TeV γ–rays at the Pachmarhi Array of Čerenkov Telescopes (PACT). While comparing the two powerful techniques, we will also discuss the progress made by the PACT team in trying to achieve a significant signal to noise ratio by this method.
PACT has detected a steady flux of TeV γ-rays from the Crab Nebula at a significance level of 13.4σ. PACT also detected the TeV γ-ray flares from Mkn421 during two episodes, one in January 2000 and the other in January 2001. The variability of γ-ray count rate is consistent with other contemporaneous observations of the source.

Key words: Wavefront sampling technique, Atmospheric Čerenkov technique, VHE γ-ray astronomy, Extensive Air Showers, Čerenkov photon arrival time studies, gamma-hadron separation, Simulations, CORSIKA

1. Introduction

There are primarily two complementary ways to look at the atmospheric Čerenkov light resulting from extensive air showers generated by a primary incident at the top of the atmosphere, *viz.* (a) *Angular imaging* and (b) *Spatial sampling.* While the former method is, by now, a well established technique (Fegan, 1997; Ong, 1998; Hoffman, 1999), the latter technique needs to be proven. The spatial and temporal properties of the Čerenkov photons also contain valuable information on the development and propagation of the extensive air showers in the atmosphere. As a result, systematic studies of these photons as received at the observation level could lead to the development of techniques to distinguish between hadronic or photon primaries.

Based on extensive simulation studies as well as from preliminary experimental results we believe that the wavefront sampling technique is as powerful, if not better, than the imaging technique (Chitnis & Bhat, 98, 99, 01a;). Currently, there are six lateral sampling (also known as wavefront sampling) arrays around the world including the Pachmarhi array of Čerenkov telescopes (PACT).

2. Characteristics of wavefront sampling

In this technique one generally carries out the photometric as well as timing measurements of Čerenkov photons at various spatially separated points in the light pool at the observation level.

2.1 Čerenkov photon density measurements

Lateral distributions of Čerenkov photons (variation of Čerenkov photon density as a function of core distance) from showers initiated by $\gamma-$rays show a characteristic hump at the core distance of about 120-140 m, which decreases with increasing observation altitude. This is due to the effective focusing of Čerenkov photons from a large range of altitudes. Distributions are generally flatter within the hump region and the density falls rapidly beyond the hump. Lateral distributions from proton showers, on the other hand, show continuously falling density distribution as core distance increases (Rao & Sinha, 88; Chitnis & Bhat, 98). Also due to the kinematical differences, the lateral distributions from $\gamma-$ray showers are smooth compared to proton showers.

Measurement of Čerenkov photon densities at spatially separated points enable one to (a) measure the lateral distribution of Čerenkov photons, (b) estimate the energy of the primary as well as (c) relative spatial fluctuations (Chitnis & Bhat, 2001c).

2.2 Čerenkov photon arrival time measurements

Extensive studies are carried out on the temporal structure of Čerenkov photons arriving at the observation level. The potential of the temporal structure of the Čerenkov photons is that it gives an insight into the longitudinal cascade development. Photon arrival time measurements will lead to the estimation of the following parameters which relate to: (a) Timing jitter, (b) Pulse shape, (c) Wavefront curvature. While the first two parameters will enable us to reject hadronic background in the data (Chitnis & Bhat, 2001a), the third one allows us to estimate the vital shower parameters like the height of shower maximum, arrival direction and shower core (Chitnis & Bhat 2001b).

3. Gamma-hadron separation techniques

3.1 Rejection of off-axis events

Atmospheric Čerenkov telescopes generally have a limited field of view (w HWHM) in order to limit the signal dilution by the background light. γ-rays are directional whereas cosmic rays are isotropic. If one can estimate the arrival direction of each event to an accuracy of say, σ_θ, then one can reject events arriving at an angle larger than σ_θ from the direction of the source. The fraction of off-axis cosmic rays rejected will be $\left(1 - {\sigma_\theta}^2/w^2\right)$.

As one can see, the angular resolution plays significant role in rejecting off-axis background. For PACT σ_θ is estimated to be 0.1° (Majumdar *et al.*, 2001) while the telescope field of view is around 2° (HWHM) yielding an off-axis rejection factor of about 400. This is a very significant advantage of non-imaging arrays with good angular resolutions.

3.2 Rejection of on-axis events using Čerenkov photon density measurements

In order to study the sensitivity of Čerenkov photon density distributions on the ground to the primary species, we resort to simulation techniques. A large number of showers initiated by γ-rays of energy 500 GeV and protons of energy 1 TeV, incident vertically at the top of the atmosphere, have been simulated for this purpose using CORSIKA (Heck *et al.*, 1998).

We use quality factor as a figure of merit to distinguish between γ-ray and proton initiated showers. It is defined as:

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

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

3.2.1 Local density fluctuations

Local density fluctuation (LDF) is density jitter defined as the ratio of RMS to mean of photon densities from 7 mirrors of each telescope. The photon density jitter at the observational level is generally higher for proton primaries than that for γ-ray primaries. Hence LDF seems to be a useful parameter for cosmic ray background rejection. The optimum quality factor derived using LDF as a parameter is listed in table 1(row 1). It can be seen that it is possible to reject about 50% proton showers retaining about 85% of γ-ray showers, using LDF alone (Chitnis & Bhat, 2001c).

3.2.2 Medium range density fluctuations

PACT consists of four sectors of six telescopes each. We define medium range or sector-wise density fluctuation as the ratio of RMS to mean density, where RMS and mean are calculated using total photon densities at each of the six telescopes of a sector. Like LDF, MDF too is generally higher in magnitude for proton primaries than for γ ray primaries. Table 1(row 2) lists the quality factor based on this parameter. It can be seen that it is possible to reject nearly 60% of protons while retaining more than 80% of γ-rays by using MDF alone.

Table 1. Quality factors based on Čerenkov photon density fluctuation measurements. Three different parameters are tested.

Parameter used	Threshold value	Quality factor	Fraction of accepted $\gamma-$rays	Fraction of accepted protons
LDF	0.257	1.215 $\pm$ 0.011	0.888	0.534
MDF	0.245	1.332 $\pm$ 0.012	0.830	0.388
Flatness	0.52	1.55 $\pm$ 0.016	0.740	0.228

3.2.3 Medium range flatness parameter

The relative spatial fluctuations in lateral distributions can be parameterized using flatness parameter defined as :

$$\alpha = \frac{1}{N}\left[\sum_{i=1}^{N}\frac{(\rho_i - \rho_0)^2}{\rho_0}\right]$$

where N: no. of telescopes triggered, ρ_i: photon density measured by individual telescopes and ρ_0: average density. As mentioned before, the lateral distribution of Čerenkov photons at the observation level is generally smoother for γ-ray primaries and hence resulting in a lower value of α. Hence α is also a useful parameter to discriminate against proton primaries. The quality factor computed using α as a parameter is listed in table 1(row 3). Flatness parameter serves as a good discriminant for showers with smaller impact parameters. For telescopes within 100 m of shower axis it is possible to reject about 80% of the proton showers retaining about 70% of $\gamma-$ray showers based on flatness parameter.

3.3 Rejection of on-axis events using Čerenkov photon arrival time measurements

The γ/hadron separation techniques using Čerenkov photon arrival time information has been discussed in detail in Chitnis & Bhat (2001a). There are two classes of parameters based on Čerenkov photon arrival time measurements.

3.3.1 Čerenkov photon arrival time jitter

The relative timing jitter, defined as the ratio of the RMS to mean arrival at each telescope is found to be a species sensitive parameter. Chitnis & Bhat (2001a) have shown that one can improve the signal to noise ratio significantly using this as a parameter, especially against heavy primaries which can be rejected up to a level of 99%.

3.3.2 Čerenkov pulse shape parameters

Among the three pulse shape parameters *viz.* pulse rise time, decay time and pulse width (FWHM), pulse decay time exhibits better sensitivity to the primary species and hence is a useful discriminant against cosmic ray background (Chitnis & Bhat, 2001a). The quality factors are not very sensitive to the primary energy and enable one to reject nearly 98% of hadrons while retaining nearly 30% of γ-rays.

It has also been shown by Chitnis & Bhat, (2001a) that by using the aforesaid parameters in tandem one can achieve a quality factor of more than 12. In other words one can reject nearly 99.95% of the protons using these two parameters. In addition, radius of curvature of the shower front as well as the pulse width could be used as parameters with lesser efficiency.

Figure 1. Pachmarhi Array of Čerenkov Telescopes.

4. Pachmarhi Array of Čerenkov Telescopes

PACT, which adopts wavefront sampling technique is situated in the central Indian hill station Pachmarhi (longitude: 78° 26′ E, latitude: 22° 28′N and altitude: 1075 m). It consists of an array of 25 Čerenkov telescopes each of area 4.45 m^2 deployed in the form of a rectangular array spread over an area of 80 m × 100 m. The telescopes in the E-W direction have a separation of 25 m and in the N-S direction the separation is 20 m. Each telescope consists of 7 para-axially mounted parabolic reflectors of diameter 0.9 m at the focus of each of which is placed a fast photo-tube(Bhat, 1998). Complete PACT array has been in operation since December 2000. However half the array was being used for observations since November 1999.

4.1 Characteristics of PACT

There are several design features of PACT that offer special advantages in comparison to other non-imaging arrays currently in operation. Large field of view (4° FWHM) results in significantly larger collection area which in turn is responsible for the increased sensitivity. This feature also enables the measurement of the shower front curvature which in turn will enable us to estimate the vital shower parameters like the height of shower maximum, shower core and leads to a significant improvement in the primary energy resolution. Multiple sampling of the Čerenkov front at each telescope enable us to achieve very good angular resolution which happens to be the best in the world so far. The excellent angular resolution is the only parameter which will enable one to reject cosmic ray electron background. Electron background is a serious problem for the detection of low energy γ-rays (10's of GeV). Multiple sampling of the Čerenkov front also leads to the measurement of the photon arrival time jitter which is sensitive to the primary species, as mentioned above, thus enabling us to reject hadronic background very efficiently. The measurement of timing jitter leads to the estimate of the pulse shape parameters which otherwise is done by a far more expensive and difficult method (using flash ADC's). The pulse shape parameters too are species sensitive and hence are used for rejecting the hadronic background.

Multiple sampling of photon densities at each telescope, on the other hand, also lead to the measurement of the Čerenkov photon density fluctuations using which the hadronic showers could be further rejected. Present results show that in the VHE range an array of telescopes provide a better rejection of hadronic background as well as better energy and angular resolution compared to a single telescope of the same type. Multiple telescopes also provide opportunity to perform precision measurements of source signal.

4.2 Expected performance of PACT

Now that the 24 telescopes of PACT are ready and functioning we can evaluate its expected performance. The individual mirrors in each telescope are aligned to have their optic axes parallel to each other to an accuracy of $\sim 0.2°$. Since the timing information is available from each of the peripheral mirrors in each telescope, this improves the angular accuracy of the system considerably. The expected angular resolution of a sector is $\sim 0.3°$ while it is $\sim 0.1°$ for the entire array (Majumdar *et al.*, 2001). The night sky background at Pachmarhi has been measured to be 3.3×10^8 $ph/cm^2/s/sr$. From a preliminary simulation the energy threshold of the experiment is estimated to be $\sim$ 900 GeV for γ-rays. A preliminary estimate of the effective collection area for vertical showers is $\sim 10^5$ m^2 for a threshold energy of 1 TeV. The minimum detectable flux of γ-rays from a celestial point source is estimated to be 2.3×10^{-12} $ph/cm^2/s$ for a 5σ confidence level detection of γ-rays above 1 TeV and observation duration of 50 hours. It has been assumed that the off-axis events are rejected using an angular resolution mentioned above and 75% of the on axis events are rejected based on simulation cuts. In other words, minimum duration of observation to detect Crab nebula at a significance level of 10σ is 12 hours (6 hours ON-source and 6 hours OFF-source). Table 2 shows a comparative summary of capabilities of the currently active wavefront sampling arrays in the world.

Table 2. A comparative table showing the relative capabilities of different atmospheric Čerenkov telescope arrays operating around the world using wavefront sampling technique.

	PACT	SOLAR-2	STACEE	CELESTE	GRAAL
Location Latitude	22° 28′N		34° 58′N	42° 30′N	37° 5′N
Longitude	78° 26′ E		106° 36′ E	1° 58′ E	2° 21′ E
Altitude(m)	1075		1705	1605	
Energy Bandwidth (GeV)	≥ 50	20-300	50-250	50-250	≥ 100
Angular Resolution	0.3°	0.25°	0.25°	0.2	0.32°
# of collectors currently in use	25	64	32	40	27
Area / collector (m^2)	4.45($= 7 \times 0.64$) 26.7/sect.	40	37	54	40
FOV (FWHM)	3°		0.7°	0.57°	0.24°
γ/hadron separability	Very good	poor	poor	poor	poor
Expected Sensitivity @ $1TeV$ for 50 hrs; 5σ γ $cm^{-2}s^{-1}$	2.2×10^{-12}			3.3×10^{-11}	2.1×10^{-12}
Trigger Logic	4/6 Tel. Maj. logic & 2 sect.	5/8 Hel. & 3/4 sect.	5/8 Hel. & 3/4 sect.	8 Hel. summed & 3/5 sums	13 Hel. summed 2-sums coin
Current Energy Threshold (GeV)	900	190	190	50	190
GHS used	Off-axis cut # of tel.		χ^2 on Č front cut	Off-axis Flatness	Hadronicity cut
Results from Crab Nebula	13.3σ		6.8σ	5.7σ	4.5σ
Duration(h)	50.8		43.1	11.5	
γ-ray count rate from Crab (min^{-1})	4.4		1.57	3.5	1.7

5. Preliminary results & discussions

5.1 First Observations of Crab Nebula

The Crab Nebula was being observed since November, 1999 using only two sectors, *i.e.* 12 telescopes. Until January, 2001 we have logged a total of 83.3 hours of which 62.4 hrs was ON source while rest were OFF source observations. After rejecting runs taken during poor sky conditions, a total of 50.8 hrs of ON-source and 11.2 hrs of OFF-source data are used for further analysis. During our preliminary analysis we used only two types cuts on the data. The first cut was to ensure that the expected and observed arrival time of the Čerenkov front was $\leq 3\ ns$, while the second cut was to ensure that the signal events are within 1.2° from the source (or optic axis in the case of OFF-source data) direction. The following table summarizes the results.

Table 3. A table showing the summary of Crab results from PACT

	ON Source Events	OFF Source Events
Duration ($mins.$)	3743	1255
Raw	306783	125142
After rejecting bad runs	237824	67179
OFF-axis cut ($\leq 3.0\ ns$)	164504	47799
$\geq$ 10 telescopes	46582	15431
After Normalization ((using counts $\geq$ 1.2°)	45547	32188

The excess from the source direction is (13359 $\pm$ 1001) photons in 50.8 hrs, yielding a γ-ray count rate from Crab Nebula of (4.4 $\pm$ 0.5) min^{-1} . The confidence level of the signal is 13.4σ. The γ-ray flux from the Nebula above 900 GeV is estimated to be $(4.6 \pm 1.1) \times 10^{-11} photons\ cm^{-2}\ s^{-1}$. The error on the flux includes both statistical as well as systematic. Figure 2 shows the present results $vis-a-vis$ the other measurements from the source. Our data is consistent with the measurements made by the other groups.

There is also an evidence for a pulsed TeV γ-ray signal from Crab Pulsar at a modest significance of about 4σ. For more details see Vishwanath (2001).

5.2 First Detection of TeV γ-ray flares from Mkn 421

The nearest Blazar Mkn 421 has been observed by PACT (sectors 3 & 4 during January 2000 flare and all the 4 sectors during the January 2001 flare). We have a total of 73.3 hrs of ON-source data and 50.6 hrs of OFF-source data during the 2000 observing season while we have logged 45.6 hrs of ON-source data and 39.7 hrs of OFF-source data until the end of February 2001. From the vast amount of data, we have carried out only a preliminary analysis of the January 2000 and 2001 data because of the flaring activity

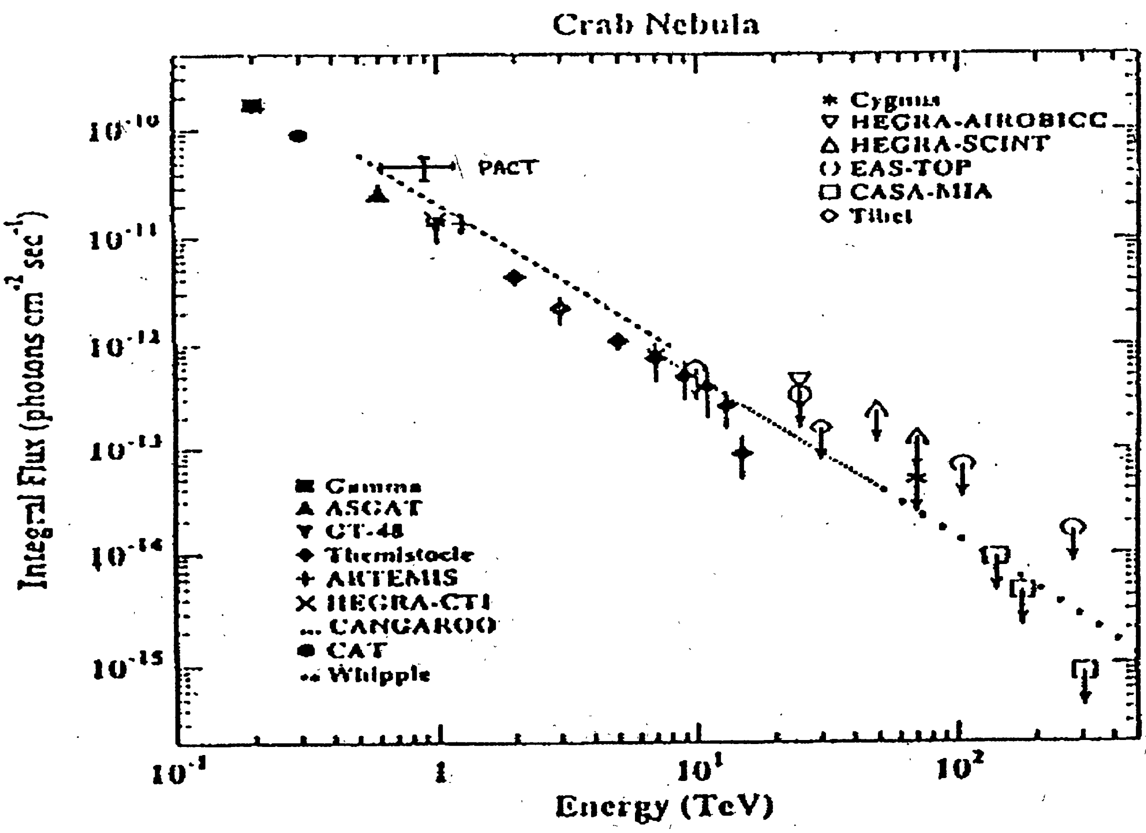

Figure 2. Integral spectrum of *TeV* γ-rays from the Crab Nebula.

reported by other groups (Gouiffes and Degrange, 2000, Boerst and Remillard, 2001). Figure 3 shows a plot of the γ-ray counting rate as a function of epoch during both the episodes. It can be seen that the γ-ray Blazar Mkn 421 has been detected by PACT during both January 2000 & 2001 periods. Evidence for nightly variability has been observed and the variability measurements by PACT are well correlated with those of CAT & CELESTE during Jan 2000 flare and with those of HEGRA CT1 during January 2001 flare. The increased count rate from PACT is a clear evidence of the significantly larger collection area of PACT. For more details regarding analysis procedures, systematics, cuts applied *etc.*, see Bhat *et al.* (2001).

6. Conclusions

Wavefront sampling technique offers some special advantages over imaging technique. Gamma/Hadron separation (GHS) parameters are energy independent unlike imaging parameters which become less efficient at higher primary energies. GHS parameters are effective at large incident angles while imaging parameters are less sensitive at > 30°. The

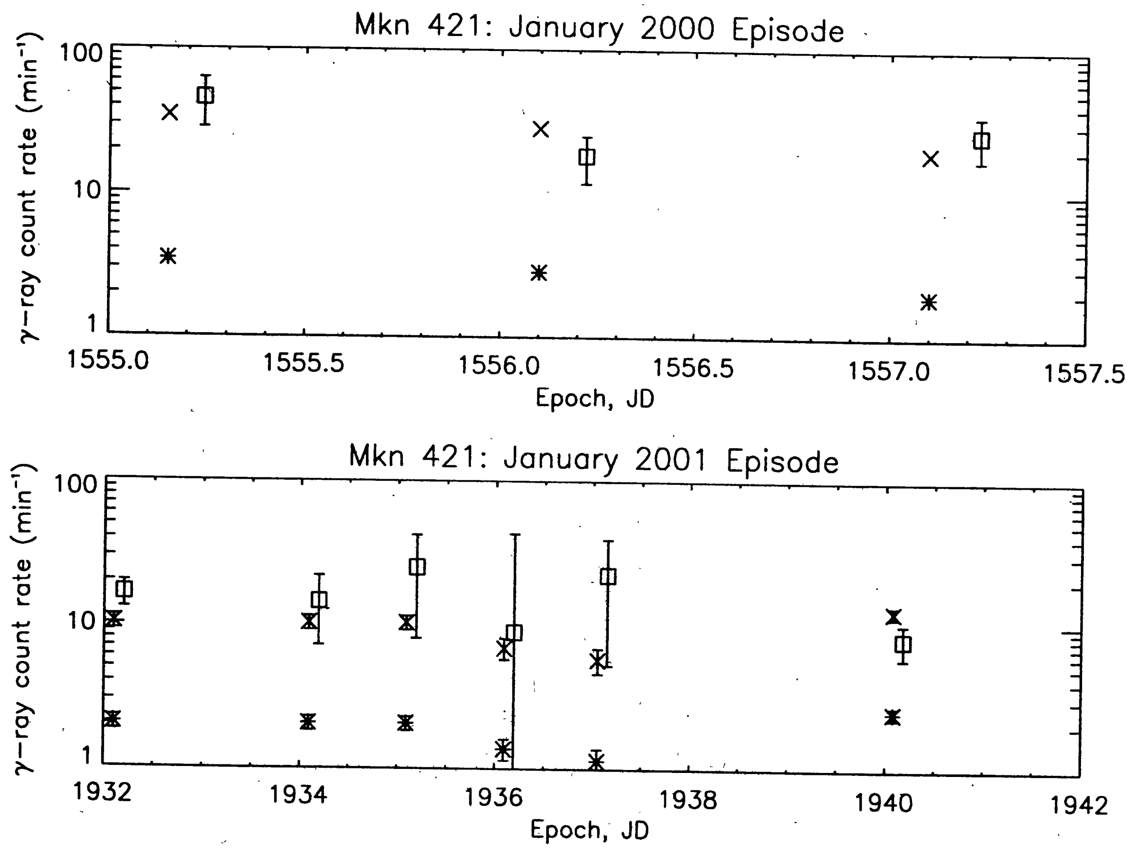

Figure 3. *TeV* γ-ray count rate from the Blazar Mkn 421 when it was the flaring state during (a) January, 2000 and (b) January 2001 as a function of epoch. The count rate observed by CAT and HEGRA-CT1 respectively are multiplied by factors of 10 & 5 respectively indicating the consistency of PACT observations with those of others.

effective collection area of telescope array is much more, $R \sim 250\,m$, whereas $R \sim 120\,m$ for imaging telescopes. Energy of the primary can be estimated rather easily by using the multiple samples of photon density at the observation level coupled with the estimate of the height of the shower maximum using the wavefront curvature. One can also estimate the core position and incident direction accurately using the wavefront curvature. At lower energies wavefront sampling can achieve good S/N compared to imaging *e.g.* e^- primaries by being able to reject cosmic ray electron background.

We have also shown that PACT has detected a significant signal from the Crab nebula and the estimated flux is consistent with the other positive detections. PACT has also detected a variable TeV γ-ray signal from Mkn 421 during two different flaring episodes. The variability is consistent with the contemporaneous observations of the source by other groups. In short, PACT has been shown to be a sensitive working telescope successfully adapting wavefront sampling technique.

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