Preliminary Results from the Crab Nebula with the PACT Array

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Abstract

We have observed the Crab nebula using Pachmarhi Array of Čerenkov Telescopes (PACT) during November 1999 to January 2002. PACT is an array of 25 distributed telescopes and we use the wavefront sampling technique for the reconstruction of showers. Preliminary results show steady emission of TeV $\gamma-$ rays from the Crab nebula.

1. Introduction

The Crab nebula is one of the most comprehensively studied galactic objects at TeV energies. The inverse Compton scattering of relativistic electrons on the ambient radiation fields results in the $\gamma-$ ray production at energies above 100 GeV (de Jager and Harding, 1992). Even though the first evidence for a VHE signal from the Crab nebula was reported more than 25 years ago (Fazio, 1972), only recently TeV $\gamma-$ rays were detected at a high confidence level, after the Whipple collaboration's successful exploitation of the so-called imaging atmospheric Čerenkov technique (Weekes, *et. al.* 1989). It is used as a standard VHE $\gamma-$ ray candle. The differential energy spectrum of TeV $\gamma-$ rays from the Crab nebula is given by the Whipple group as J = $(3.2 \pm 0.17 \pm 0.6) \times 10^{-7} \times$ (E/1 TeV)$^{-2.49\pm0.06\pm0.04}$ m^{-2} s^{-1} TeV^{-1} and the integral flux at $>$ 1 TeV as $\sim (2.1 \pm 0.2 \pm 0.3) \times 10^{-7}$ m^{-2} s^{-1} (Hillas *et. al*, (1998)). Since then, many groups have successfully detected VHE $\gamma-$ ray signal from this object (Ong, 1998).

We have observed the Crab nebula using the newly built Pachmarhi Array of Čerenkov Telescopes. In this paper we present the observational details, data analysis and the preliminary results.

2. Pachmarhi Array of Čerenkov Telescopes

The experiment at Pachmarhi (longitude: 78° $26'$ E, latitude: 22° $28'N$ and altitude: 1075 m), is based on the wavefront sampling technique and em-

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ploys an array of Čerenkov telescopes, called the Pachmarhi Array of Čerenkov Telescopes(PACT), to sample the Čerenkov pool. PACT is now fully functional.

The experimental set-up has been explained in detail elsewhere (Bhat, *et. al.*, 2000, Majumdar, *et. al.*, in these proceedings). Briefly, it consists of an array of 25 atmospheric Čerenkov telescopes deployed in the form of a lattice with a spacing of about 20-25 *m*. All the telescopes can point to the putative source with a mean error of $0^{\circ}.003 \pm 0^{\circ}.1$ (Gothe, *et. al*, 2000). The alignment accuracy of the mirrors is checked periodically by drift star scan method and it is ensured that all the mirrors are parallel to each other within an error of about 0.2°. The array has been divided into 4 sectors with six telescopes in each. The analog pulses from 7 PMTs in a telescope are added linearly to form a telescope sum pulse called *royal sum*. Each *royal sum* from the 6 telescopes in a sector are suitably discriminated (typical *royal sum* rates $\sim$ 30-50 kHz.) and a trigger is generated by a coincidence of any 4 of these 6 *royal sums*. The typical event rate is $\sim$ 2-5 Hz per sector. For every event, information on the relative arrival times (TDC) and density (ADC) of Čerenkov photons are recorded for the 6 peripheral mirrors/PMT in each telescope in each sector. The relative arrival times of *royal sum* pulses are recorded both in the respective sector and in the central data processing station.

The arrival direction of a shower is determined by measuring the relative arrival time of Čerenkov photon front at each telescopes accurately and reconstructing the shower front. The accuracy of timing measurement is $\sim$ 1 ns. The angular resolution of PACT using the plane front approximation has been estimated to be $0^{\circ}.24$ using *Royal Sum* pulses and $\sim 2.4'$ using *individual mirror* information (Majumdar, *et. al.*,2003).

3. Observations on Crab Nebula

The Crab nebula has been observed for a total 95 hrs (52 runs) and corresponding background regions for about 50 hrs spanning over a long duration from November 1999 to January 2002. The data acquired on the Crab nebula has been divided into 4 different sets, namely Data Set I (November 1999 to February 2000), Data Set II (October 2000 to December 2000), Data Set III (November 2001 to January 2002) and Data Set IV (January 2001). 12 telescopes were operative during first three data-sets while 18 telescopes were used during the observations of Data Set IV. Only those runs taken under good weather conditions are accepted. We are then left with 70 hrs of ON source data and 41 hrs of OFF source data which were subjected to further analysis.

4. Analysis Procedure

In the present analysis, reconstruction of the shower front and estimation of the direction of the shower has been made based upon timing information of the *royal sum* pulses and/or the individual PMT pulses. The space angle distributions from source and background were then compared over the same zenith angle range. After imposing zenith angle cuts, we are left with 30 hrs of data which have been used for the present analysis. Two types of cuts were put during the analysis, *viz.* (a) a cut on the number of degrees of freedom (*ndf*) to ensure that both source and background have similar *ndf* distributions and (b) rejection of events with $\chi^2 > 5\%$ CL for mean *ndf* for royal sum pulses and $\chi^2 > 1\%$ CL for the cases in which individual PMTs were used in analysis. The above mentioned data sets are further classified into various groups depending upon various trigger conditions applied during analysis. Table 1 shows the preliminary reduction of data based on these groups and cuts applied. Data Set A refers to royal sum information using single sector events where a majority logic of any 4 out of 6 telescopes is used for the trigger(Data Sets I and II), Data Set B refers to a trigger in which at least 8 telescopes out of 12 from two stations should be present in an event(Data Sets I, II and III), Data Set C refers to the case in which 18 telescopes were used for the run in January 2001 (Data Set IV) and Data Set D refers to the case in which individual PMT TDC data were used for analysis with the condition that at least 1 PMT should have valid TDC data in a telescope (Data Set I, II and III). The space angle distributions of source and background are normalised in the space angle region $> 3°$ for royal sum pulses (Data Sets A, B and C) and $> 2°$ for individual PMT pulses (Data Set D). This normalisation is carried out in the region which is beyond 5σ of the angular resolution for the particular Data Set used. The background distribution is then subtracted from the source distribution to get the amount of signal events; to be referred to as excess events or $\gamma-$ rays. The excess events are calculated within the angle which is $\sim 3\sigma$ of the angular resolution obtained for various Data Sets (Majumdar, *et. al*, 2003). Table 2 lists the results from the various data sets.

The left panels of Figures 1 and 2 show the space angle distributions of events arriving from the direction of the Crab nebula and the normalised distributions for the background regions over the same zenith angles as of source for the Data Sets B and D respectively. The right panels show the excess events as a function of space angle. It is seen that the excess events peak at $\sim 1.5°$ for Data Set A, 1.25° for Data Set B, 0.85° for Data Sets C and D. The improvement in the space angle distributions for higher degrees of freedom is clearly seen. The corresponding thresholds(E_{th}), effective colection area(A_γ) and fluxes are shown

Table 1. Data Set of Crab

Data Period	Region	Total Number of Events		
		Raw	ndf cut	χ^2 cut
Nov 99-Dec 2000	ON	147816	134189	126390
Data Set A	OFF	150838	135131	128349
Nov 99-Jan 2002	ON	169236	156918	150620
Data Set B	OFF	188709	168067	161205
January 2001	ON	2441	2414	2230
Data Set C	OFF	3638	3630	3335
Nov 99 - Jan 2002	ON	76668	72072	71255
Data Set D	OFF	88273	83716	81955

Table 2. Preliminary Results on Crab Nebula for Various Data

Data	Duration (mins)	γ ray rate/min	E_{th} (GeV)	A_γ (m^2)	Flux $\times 10^{-11}$ ph $cm^{-2}s^{-1}$
Data Set A	1092.1	3.23±0.39	800±50	61575.2	8.74±1.06
Data Set B	1715.7	3.45±0.24	1100±100	77437.1	7.43±0.52
Data Set C	80.2	2.03±0.75	1300±100	63347.1	5.34±1.97
Data Set D	1817.0	1.44±0.14	1700±150	70685.8	3.39±0.33

in columns 4, 5 and 6 of Table 2 respectively. Figure 3 shows the excess event rate from the direction of Crab as a function of Julian Day (JD) for Data Set B. The signal event rate is more or less constant.

5. Conclusions

The Crab nebula has been observed with the Pachmarhi Array of Čerenkov Telescopes. The observations were carried out over a span of more than two years. Statistically significant steady signal was detected from the Crab nebula during each observation. The fluxes are higher than the Whipple fluxes by a factor of about 3. The systematic errors are not included at present in the analysis. Further analysis to refine the signal using on-source cosmic ray rejection parameters are in progress. In addition we have shown that the angular resolution can be further improved significantly by using the TDC information from individual mirrors. We would improve the sensitivity to search for possible temporal variations in TeV flux from the source. Efforts are also on to derive the energy spectrum of the $\gamma-$ ray signal using ADC information.

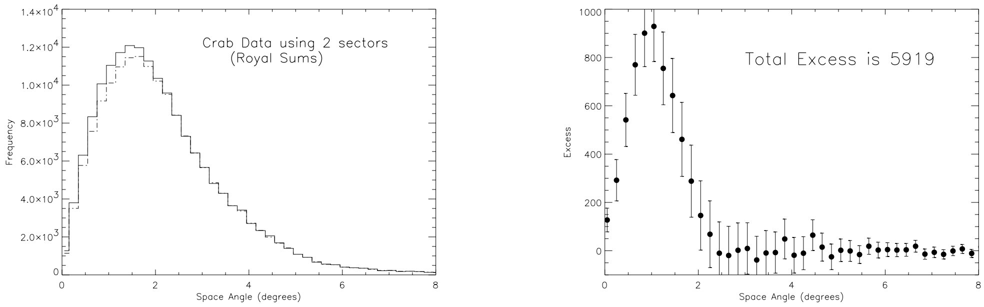

Fig. 1. *Left panel*: Space angle distributions of events from Crab for Data Set B. The solid line refers to source and dotted broken line refers to the background *Right panel*: Excess Events from Crab (Data Set B) as a function of space angle.

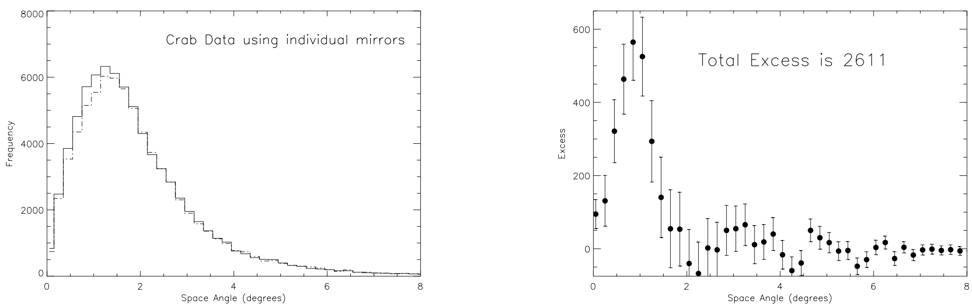

Fig. 2. *Left panel*: Space Angle distributions of events from Crab for Data Set D. The solid line refers to source and dotted broken line refers to the background *Right panel*: Excess Events from Crab (Data Set D) as a function of space angle.

6. References

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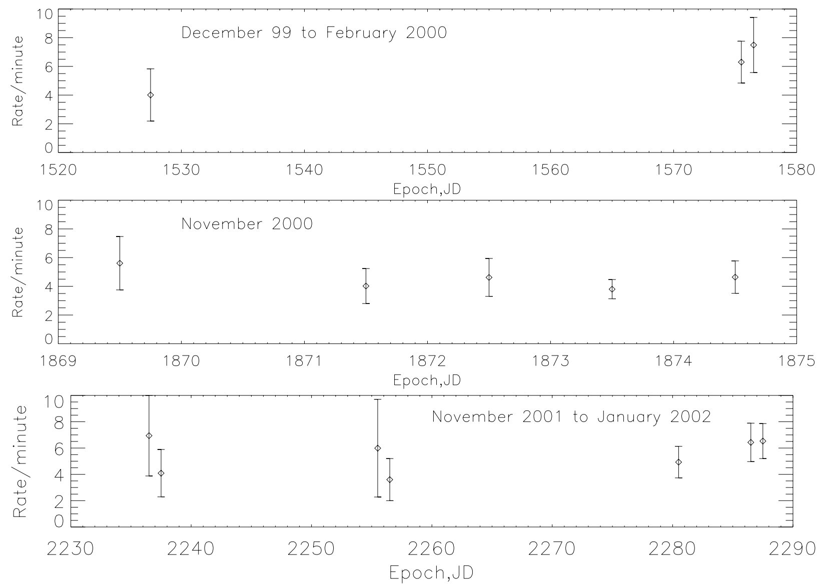

Fig. 3. Excess event rate per minute from Crab as a function of Julian Day

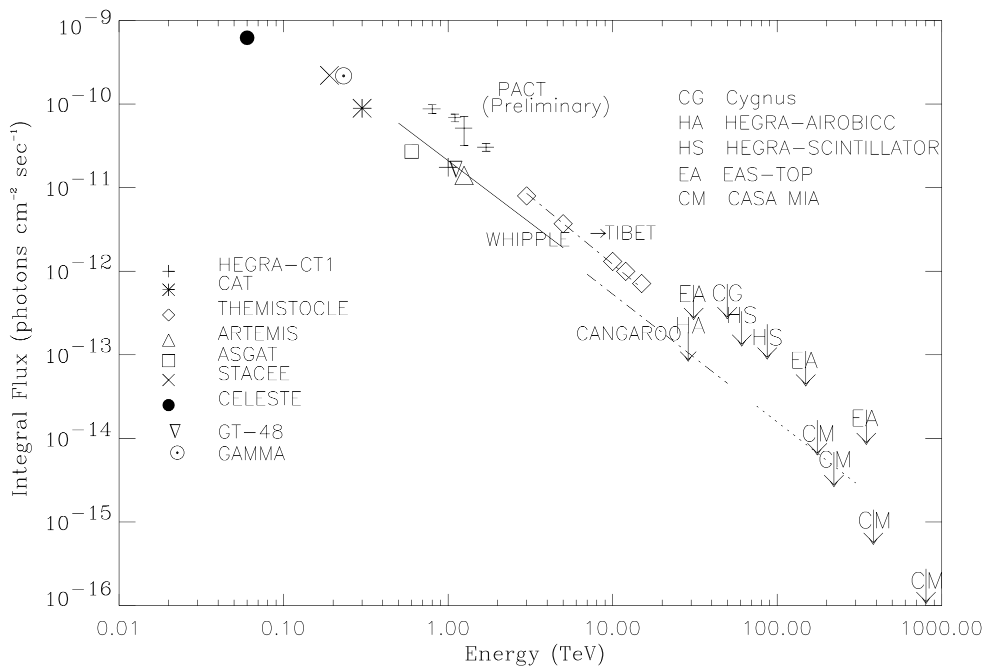

Fig. 4. Integral Energy spectrum of VHE $\gamma-$ rays from Crab Nebula