

# Observations of the Crab Nebula, Mkn 501 and Mkn 421 using the TACTIC Imaging Element

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## Abstract

The results of our observational campaigns on the two extragalactic sources Mkn 501 and Mkn 421, carried out with the Imaging Element of the TACTIC array, during March-May, 1998 and April-May, 1999, are presented. The results indicate that the two BL Lac objects (Mkn 501 and Mkn 421) were in a ‘low’ gamma-ray emission state during both epochs of our observations.

## 1 Introduction:

The Imaging Element (IE) of the 4-element TACTIC array (Bhat, 1996) has seen first light in March 1997, when it was used to observe the Crab Nebula and the two BL Lac objects, Mkn 421 and Mkn 501, with a prototype 81-pixel Cerenkov Light Imaging Camera. The results of these observations, including the successful detection of a TeV gamma-ray signal from the Mkn 501, were reported at the 25th ICRC (Bhat et al, 1997; Protheroe et al, 1997). The prototype camera is in the process of being upgraded to its full complement of 349 pixels and is presently operational with a 169-pixel camera. During March - May, 1998, the IE was redeployed, whenever available, for observations on the two BL Lac objects, with its 81-pixel camera, as a part of the international multiwavelength observation campaign, while for the 1999 observations the augmented 169-pixel camera was used in order to improve the statistics.

As referred to in Koul et al, (1997), the IE employs  $32 \times 0.6$  m spherical mirrors mounted on a Davies-Cotton structure, giving an overall collection area of  $\sim 9.5m^2$ . During the 1998 observations, the central  $9 \times 9$  pixels of the camera were activated, leading to a field-of-view of  $2.8^\circ \times 2.8^\circ$  with a pixel resolution of  $\sim 0.31^\circ$ . The camera size was increased to 169 pixels ( $13 \times 13$ ) for the 1999 observations leading to a field-of-view of  $\sim 4^\circ \times 4^\circ$ . The charge-to-digital (CDC) counts of all the active pixels are logged following a master system trigger which is derived from the innermost 36/144 pixels (for 1998/1999 observations) by demanding a prompt coincidence (resolving time  $\sim 10$  ns) through the 3 NCT proximity hardware trigger (Bhat et al, 1994). The details about observational methodology, system calibration and data reduction and analysis technique are available in Bhat et al (1997).

## 2 Observations and Data Treatment:

During the 1998 observational spell, it became possible to use the IE to observe the Crab Nebula for only  $\sim 10$  h in the on-off mode of observations. The resulting poor statistics and the low flux sensitivity of the  $9 \times 9$  pixel interim camera, used for the Crab observations does not allow a meaningful analysis of the Crab data base and is, therefore, not discussed further. The two extragalactic sources Mkn 421 (34.8 h) and Mkn 501 ( $\sim 52$  h) were tracked upto source zenith angle  $\theta \leq 45^\circ$ . No off-source scans were made in order to maximize the on-source observation time and to improve the chances of recording possible flaring activity from these sources. During the observational spell in March-May 1999, the augmented TACTIC Imaging Element, with a 169 pixel camera, was again deployed to observe the extragalactic sources Mkn 421 (20 h) and Mkn 501 ( 16.2 h). The daily data stretches were subjected to the standard image-processing treatment in which each raw image was first cleaned to minimize the noise component in the event, using a graded noise-filter cut (Bhat et al, 1997). The CDC counts of the surviving ‘clean pixels’ were flat-fielded by normalizing

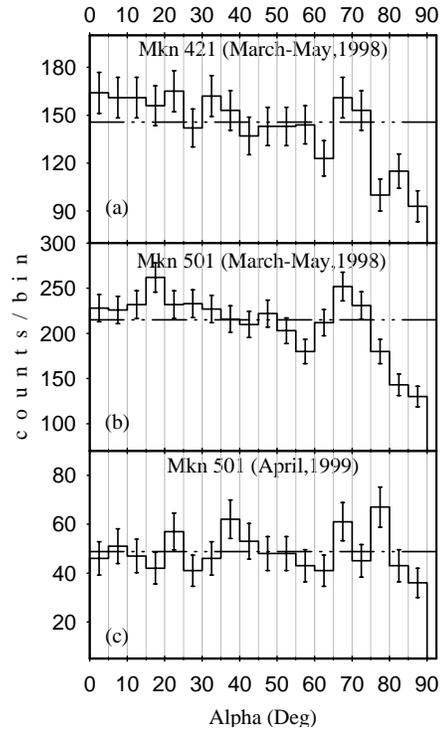
their noise-subtracted CDC counts using the calibration data. All images with  $\leq 4$  ' active ' pixels with non-zero flat-fielded counts or with  $\geq 1$  pixel with saturation-level CDC counts ( $\geq 4090$ ) were rejected. For the surviving events, the image parameters Length (L), Width (W), Azwidth (A), Distance (D) and orientation parameter ( $\alpha$ ) were calculated and the total normalized count, (size S), determined for each processed image. Based on detailed Monte Carlo simulations of the TACTIC system (Sapru et al, 1997), the following filters were used for  $\gamma/h$  separation:  $0.10^\circ \leq L \leq 0.31^\circ$ ;  $0.08^\circ \leq W \leq 0.17^\circ$ ;  $0.55^\circ \leq D \leq 1.10^\circ$ ; size  $\geq 500$ .

### 3 Results:

The minimum image size value of  $S_0=500$  CDC counts ( $\sim 80$ -100 photoelectrons) was demanded to ensure a robust image quality and the numbers of processed images surviving the above mentioned image parameter cuts determined. Table given below gives a summary of the results obtained for Mkn 421 and Mkn 501, for the 1998 data set.

Parameter	Mkn501(I)	Mkn501(II)	Mkn421
1. Epoch of obsv.	April 23	April 12	March 23
- -	- May 29, 98	- April 22, 99	- May 27, 98
2. # Observation days	18	11	21
3. Total Observation Time ( h )	3124.0	973.7	2089.2
4. Total Processed images	461796	254978	182963
5. # Selected Events	3820	877	2576
6. # Events in $\gamma$ domain ( $\alpha < 15^\circ$ )	$686.00 \pm 26.19$	$144.00 \pm 12.00$	$486.0 \pm 22.05$
7. # Background Events ( $\alpha < 15^\circ$ )	$645.00 \pm 14.66$	$146.33 \pm 6.98$	$437.33 \pm 12.07$
8. # Excess Events	$41.00 \pm 30.02$	$-2.33 \pm 13.88$	$48.67 \pm 25.14$
9. Significance ( $\sigma$ )	1.37	-0.17	1.94

Defining  $\alpha < 15^\circ$  as the  $\gamma$ -ray domain and  $20^\circ \leq \alpha \leq 65^\circ$  as the control region, the event excess in the  $\gamma$ -ray domain with respect to the average background value in the region  $0 \leq \alpha \leq 15^\circ$ , determined from the control region data, was estimated, both, on a day-to-day basis and over the entire data-set. Figs. 1a and 1b represent the  $\alpha$ -distribution of the image-parameter selected events for the two sources for the overall data. In both the cases, no significant excess of events is observed in the gamma-ray domain ( $\alpha < 15^\circ$ ). The implied null results lead to  $3\sigma$  confidence level upper limits of  $1.76 \times 10^{-12}$  photons  $cm^{-2} s^{-1}$  for Mkn 421 and  $1.4 \times 10^{-12}$  photons  $cm^{-2} s^{-1}$  for Mkn 501, above  $E_\gamma > 2$  TeV, during April-May, 1998, after taking due account of the restricted field-of-view ( $2.8^\circ \times 1.2^\circ$ ) of the  $4 \times 9$  pixel trigger generator used in the 1998 observations. Mkn 501 was observed for a total on-source observation time of  $\sim 16.2$ h over a period of 11 days spanning the period April 12 - 22, 1999. The same analysis procedure, as outlined above, was followed to search for a TeV gamma-ray signal from the source during the period of our observations. The results are again summarized in the Table . The  $\alpha$  plot of the image parameter-selected events is shown in Fig.1c; again no enhancement is evident in the  $\gamma$ -ray event domain . As seen from the Table , the total number of events in the  $\gamma$ -domain ( $\alpha \leq 15^\circ$ ) is  $144.00 \pm$



**Figure 1:** On source alpha-distributions for Mkn421 and Mkn501

12.00 as compared to a background rate (RBL) of  $146.33 \pm 6.98$ , indicating the absence of a TeV signal from the source during our epoch of observations. Based on these results a  $3\sigma$  upper limit of  $1.57 \times 10^{-12}$  photons  $\text{cm}^{-2}\text{s}^{-1}$  above 2 TeV can be set on the source emission during the 1999 epoch of observations. The analysis of the 1999 Mkn 421 data-set is currently on.

#### 4 Discussion and Conclusions:

Mkn 421 was first detected as a TeV gamma-ray source by the Whipple system in 1991/92 (Punch et al, 1992) at a flux level of  $(1.59 \pm 0.20) \times 10^{-11}$  photons  $\text{cm}^{-2}\text{s}^{-1}$  above 500 GeV and subsequently confirmed from observations carried out during 1993/1994 when its average flux had dropped to  $\sim 50\%$  of the 1992 level. The most remarkable observation concerning the TeV gamma-ray emission from Mkn 421 was the detection of an intense burst between May 11-15, 1994 and a second burst on June 7, 1994 by the Whipple system (Kerrick et al, 1995). During the 1997 observing season, Mkn 421 was reported to be in a low state by a number of imaging systems (Petry, 1997). Although Mkn 421 is now considered to be a firmly established TeV gamma-ray source, the nature of its short-term variability and the exact shape of its energy spectrum in the VHE region remain unclear due to mainly its relatively low intensity in the quiescent state and the large systematic errors of spectral measurements with Cerenkov telescopes. The present observations indicate a continuation of the low TeV activity state during the 1998 observation cycle. Mkn 501 was first discovered as a VHE source by the Whipple system in 1995 at a level of 80 mCrab above 300 GeV (Quinn et al, 1996), and was subsequently confirmed by the HEGRA system during observations carried out in 1996 (Bradbury et al, 1997) above 1.5 TeV. A large number of VHE detections of Mkn 501 were reported at the 25th ICRC (Bhat, 1997 ; Protheroe et al, 1997) including the first-ever near simultaneous detection of short-term flaring activity by 5 imaging telescopes located across the globe. The present observations indicate that the source has relapsed into a low activity state during March - April, 1998 after the unusually active phase witnessed in 1997 when it became the brightest object in VHE gamma-ray sky. As in the case of Mkn 421, the origin of short-term variability and the prolonged phases of 'low' activity remains unclear at present.

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