Search for TeV γ -rays from H1426+428 during 2004-07 with the TACTIC telescope

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Abstract. The BL Lac object H1426+428 ($z \equiv 0.129$) is an established source of TeV γ-rays and detections of these photons from this object also have important implications for estimating the Extragalactic Background Light (EBL) in addition to the understanding of the particle acceleration and γ-ray production mechanisms in the AGN jets. We have observed this source for about 244h in 2004, 2006 and 2007 with the TACTIC γ-ray telescope located at Mt. Abu, India. Detailed analysis of these data do not indicate the presence of any statistically significant TeV γ-ray signal from the source direction. Accordingly, we have placed an upper limit of $\leq 1.18 \times 10^{-12}$ $photons\ cm^{-2}\ s^{-1}$ on the integrated γ-ray flux at 3σ significance level.

1. Introduction

BL Lacertae (BL Lac) objects are a subclass of blazars that are notable for their lack of prominent emission lines. The Spectral Energy Distributions (SED) of these objects extend from radio to γ-ray energies with the double humped shape feature in a νF_ν representation [1, 2, 3]. The broadband SED of the BL Lac objects identified in X-ray surveys are significantly different compared to those identified in radio surveys and have been classified into high frequency peaked BL Lac objects (HBL) and low frequency peaked BL Lac objects (LBL), depending on their X-ray to radio flux densities [4]. The first hump in SED of these objects is expected at X-ray energies and generally accepted as originating from synchrotron radiation of relativistic electrons in the magnetic field around the object. The second peak is expected at γ-ray energies and in the framework of leptonic models [5, 6, 7, 8, 9, 10, 11] is thought to be stemming from inverse Compton scattering of low energy photons to γ-ray energies by the same population of relativistic electrons which produces the synchrotron radiation. Whereas, the hadron based models [12, 13, 14, 15] attribute the second hump and X-ray emission to some extent to processes involving protons which are also accelerated along with the leptons in the relativistic jets.

These objects are extremely variable and are characterized by low emission quiescent states with occasional flaring when the flux can increase by several orders of magnitude. For example, the HESS group detected the activity of the object PKS2155 -304 in July 2006 when its emission reached a flux level more than two orders of magnitude higher than its quiescent flux [16].

Very High Energy (VHE) γ-ray photons are believed to be absorbed by their interactions with the extragalactic background light(EBL) leading to an energy dependent horizon for viewing of VHE γ-ray sources. As a result of this absorption the energy spectrum of such sources may show a cut-off feature or steepening of the spectrum, but at the same time such features can also be attributed to the source itself. The interpretation of such features can be used as a probe for EBL measurements [17]. Interestingly, the recent detections of the AGN 3C 279 (z = 0.536) by the MAGIC group [18] and, H2356-309(z = 0.165) and 1ES 1101-232 (z = 0.186) by the HESS group [19] have incited a lot of interest in the understanding of the γ- ray horizon at very high energies.

H1426+428 was discovered in the 2-6 keV energy band by HEAO 1 [20] and was classified as a BL Lac object in 1989 [21]. In an observation campaign performed by BeppoSAX in 1998-99, this source was identified as an extreme HBL because of its high synchrotron peak frequency, therefore a potential source of VHE γ -rays [22].

The Whipple group reported the first VHE detection of this source in 2002, using the data recorded during 1999 -2001, at a statistical significance of about 6σ [23]. Subsequently it was confirmed by the CAT[24] and HEGRA groups [25, 26] at statistical significance of 5.2σ and 7.5σ respectively. The CELESTE and STACEE groups, both with non-imaging detectors have also observed the source and reported upper limits during the periods 2002- 2004 [27] and 2001- 2002 [28] respectively. However, the Crimean group has reported the detection of VHE γ-rays from this source using their GT-48 system in April 2004 with a statistical significance of 5.8σ[29]. More recently, the VERITAS group observed this source for 12.5 h using their stereoscopic telescope system at Mt. Hopkins. Preliminary results obtained by them indicate a marginal excess of VHE photons at 3.2 σ statistical level and they have placed an upper limit of about 3% of the Crab Nebula flux [30]. In this paper, we report the results of our observations of this source which were made during the period 2004-07 using the TACTIC $\gamma-$ray telescope. In addition, we have also compared the TACTIC light curves with those of RXTE/ASM X-ray in the energy range 2-10 keV.

2. TACTIC telescope

The TACTIC (TeV Atmospheric Cherenkov Telescope with Imaging Camera) γ-ray telescope has been set up at Mt. Abu (24.6° N, 72.7° E, 1300m asl), India for studying the emission of TeV γ-rays from celestial sources. The telescope deploys a F/1 type tracking light collector of $\sim$9.5 m^2 area, made up of 34 x 0.6 m diameter, front-coated spherical glass facets which have been prealigned to produce an on-axis spot of $\sim 0.3°$ diameter at the focal plane. The telescope uses a 349-pixel photomultiplier tube (ETL 9083UVB) -based imaging camera with a uniform pixel resolution of $\sim$0.3° and a field-of-view of $\sim$6°x6° to record images of atmospheric Cherenkov events. The present data have been collected with the inner 225 pixels where the innermost 121 pixels are used for generating the event trigger. The trigger is based on the 3NCT (Nearest Neighbour Non-Collinear Triplets) configuration for 2004 and 2007 data while 2006 data were collected with NNP (Nearest Neighbour Pairs) trigger logic [31]. The safe operation of the photomultipliers (PMT) with anode current $\leq 3\ \mu$A has been ensured by implementing a gain control algorithm [32]. The data acquisition and control system of the telescope [33] have been designed around a network of PCs running the QNX (version 4.25) real-time operating system. The single pixel threshold was set to $\geq 8/25$ pe for 3NCT/NNP trigger logic. The triggered events are digitized by CAMAC based 12-bit Charge to Digital Converters (CDC) which have a full scale range of 600 pC. The sensitivity of this telescope is such that it detects VHE γ-rays from the Crab Nebula direction at a statistical significance of 5σ in 25h above $\sim$1.5 TeV. The details of the telescope can be found in [34].

3. Observations and data analysis

H1426+428 was observed for 244h from 2004 to 2007 with the TACTIC γ-ray telescope. In order to maximize the on-source observation time and to increase the possibility of recording flaring activity from the source, we have made observations in the continuous source tracking mode. This mode of observation is also known as a discovery mode wherein the systematic errors are relatively more as compared to the ON-OFF mode of data taking (where the background is estimated from separate observations). In the observation mode used for the ongoing studies, the source was always placed at the centre of the camera while making observations on it. The zenith angle range covered during these on-source observations was from 18° to 45°. Details of these observations have been given in Table 1.

While analysing, the data were subdivided into 3 spells each corresponding to the observations made in a particular year. Standard data quality checks, e.g. compatibility of the prompt and chance coincidence rates with Poissonian statistics, have been performed in order to evaluate the system behavior and the general quality of the recorded data. As a result of this exercise, 77.9 h of data were rejected and the rest of the data were used for detailed analysis.

While performing detailed analysis of the data, firstly all the data were subjected to pedestal removal by using the standard two-level image 'cleaning' procedure [34] with picture and boundary thresholds of 6.75σ and 3.25σ respectively. The digital counts of each pixel in the clean images were then corrected for inter-pixel gain variation. The image cleaning threshold levels were first optimized on the Crab Nebula data [35] and

Table 1. Details of TACTIC Observations on H1426+428.

Spell	Year	Months	Observation Dates	Total data (h)	Data selected (h)
I	2004	Mar.	22-26, 28,29,31	71.0	44.8
		Apr.	12-15, 18, 20-22, 24-26		
II	2006	Mar.	26-31		
		Apr.	1, 2, 4, 21, 23-30	34.9	18.4
		May	01, 02, 19, 21, 23-24, 29-30		
III	2007	Mar.	16-27		
		Apr.	12-15, 18-20, 22-26	137.7	102.5
		May	06-15, 17-19, 21-22		
		Jun.	07-11		

then applied to the data presented in this paper. The clean Cherenkov images were characterized by calculating their standard image parameters like LENGTH, WIDTH, DISTANCE, ALPHA, SIZE and FRAC2 [36, 37]. The standard Extended Supercuts [38] procedure was then used to separate γ-ray like images from those due to the huge background of cosmic rays. The γ-ray selection criteria based on the imaging cuts, given in Table 2 used in the analysis have been obtained on the basis of Monte Carlo simulations carried out for the TACTIC telescope.

Table 2. Extended Supercuts selection criteria used for analyzing the TACTIC data.

Parameter	Cut Values
LENGTH (L)	$0.11^\circ \leq L \leq (0.235 + 0.0265 \times \ln S)^\circ$
WIDTH (W)	$0.065^\circ \leq W \leq (0.085 + 0.012 \times \ln S)^\circ$
DISTANCE (D)	$0.5^\circ \leq D \leq 1.27^\circ$
SIZE (S)	$S \geq 350 d.c$; (6.5 digital counts $\equiv$ 1.0 pe)
ALPHA (α)	$\alpha \leq 18^\circ$
FRAC2 (F2)	$F2 \geq 0.38$

The next step of the data analysis deals with estimating the number of γ- ray events from the source direction in the presence of overwhelming background of cosmic ray events. This is done by plotting the frequency distribution of the 'Alpha' parameter (defined as the angle between the major axis of the image and the line joining the image centroid with the source position) of shape, size and distance selected events. The γ-rays from a point source have smaller values of the 'Alpha' parameter, whereas the cosmic ray events, because of their isotropic nature, are uniformly distributed in all 'Alpha' values ranging from 0° to 90°. For the TACTIC system we find that the 'Alpha' range for γ-ray events is found to be from 0° $to \leq 18^\circ$.

The flat distribution of 'Alpha' in the range $27^\circ \leq \alpha \leq 81^\circ$ has been used to determine the background events present in the signal region [39]. The number of γ-

ray events is then calculated by subtracting the expected number of background events (calculated on the basis of the background region) from the γ-ray domain events and the significance of the excess events has been finally calculated by using the maximum likelihood ratio method of Li & Ma [40].

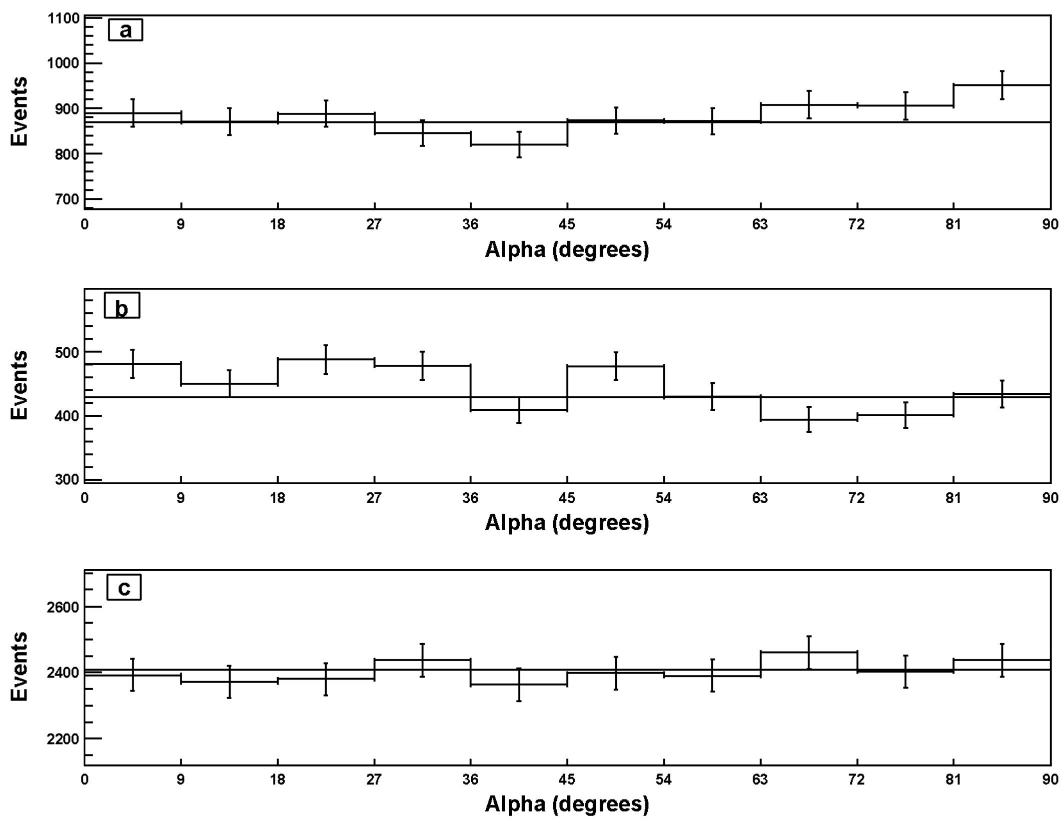

Figure 1. (a) Distribution of image parameter 'Alpha' after applying the cuts given in Table 2 for 44.8h 18.4h and 102.5h of data taken on H1426+428 during (a) 2004, (b) 2006 and (c) 2007 respectively. The horizontal lines in the figure indicate the expected background in the γ-domain obtained by using the background region ($27^\circ \leq \alpha \leq 81^\circ$). The error bars shown are for statistical errors only.

3.1. TACTIC data analysis results

When all the data recorded during the year 2004 are analysed together, the corresponding results obtained are shown in Figure 1a, wherein the histogram of the 'Alpha' parameter has been plotted after having applied shape and orientation related imaging cuts given in Table 2. As is clear from this figure, the distribution is almost flat and the number of gamma-ray like events within the γ- ray domain of the distribution are 19$\pm$48, thereby indicating that the source was possibly in a low TeV emission state (below TACTIC sensitivity level) during the period of these observations. Further the same data were also analysed on a nightly basis to explore the possibility of very strong episodic TeV emissions. The corresponding results obtained are depicted in Figure

3a, which shows the day-to-day variations of the γ-ray rate (γ-rays/hour) for 2004 observations. This light curve is characterised with a reduced χ^2 value of 19.48/12 (here and afterwards the denominator represents the value for the degrees of freedom) with respect to the zero degree polynomial fitted constant value of 0.28$\pm$0.97 photon events, with corresponding probability of 0.11 which is consistent with the no- variability hypothesis. The magnitude of an excess or deficit recorded on different nights is within $\pm$ 2 σ level for 2004 observations and hence indicates the absence of a statistically significant episodic TeV gamma-ray signal from the H1426+428 direction.

In addition, the available TeV light curves reported by different groups upto the year 2004, are also depicted in Figure 4 starting from the Whipple 1999 observations. As is clear from this figure that the GT-48 telescope has recorded the source at more than 200% of the GT-48 detected Crab level on April 19, 2004 (MJD 53115) at 3.9 σ level[29, 41]. It may be noted here that the TACTIC 2004 results discussed above on this source are in agreement with those obtained with the CELESTE system [27] around 100GeV during the same period. However, our results are in conflict with those of GT-48 telescope above 1TeV during the period from April 15 to April 25, 2004, wherein a γ -ray signal at 5.8σ level was reported[29].

We have followed the same data analysis methodology while analysing the data recorded during the years 2006 and 2007 and the corresponding 'Alpha' histograms are shown in Figures 1b and 1c respectively. As is clear from these figures the distributions are almost flat and the number of gamma-ray like events within the γ- ray domain of the distributions are 68$\pm$35 and -54$\pm$80 for the 2006 and 2007 observations respectively, thereby indicating that the source was possibly in a low TeV emission state (below TACTIC sensitivity level) during the period of these observations as well. Further these data were also analysed on a nightly basis and the corresponding results obtained are depicted in Figures 3b and 3c respectively, again showing the day-to-day variations of the hourly γ-ray rate with time. Light curves are characterised with the reduced χ^2 values of 12.66 /13 and 31.31 /34 respectively, with respect to the zero degree polynomial fitted constant value of 2.22 $\pm$1.79 and -0.49$\pm$0.74 photon events with corresponding probabilities of 0.47 and 0.69 respectively which are consistent with the no- variability hypothesis. The magnitude of an excess or deficit recorded on different nights is also within $\pm$ 2 σ level for 2006 and 2007 observations thereby again indicating the absence of a statistically significant episodic TeV gamma-ray signal during these observations as well.

In Figure 2, we have shown the 'Alpha' histogram obtained when the data for all the years were combined together which is also consistent with the flat distribution. There is thus no evidence for the presence of a statistically significant γ-ray signal from the source direction during the period of our observations. We have placed an upper limit of $\leq 1.18 \times 10^{-12}$ $photons\ cm^{-2}\ s^{-1}$ at 3σ level (13.1 % of the TACTIC detected Crab Nebula integrated γ-ray flux) on the integrated TeV γ-ray flux from the source direction, using the method of Helene [42]. In Table 3, we have compiled all results obtained on a yearly spell basis as well as for the case when all the data are considered

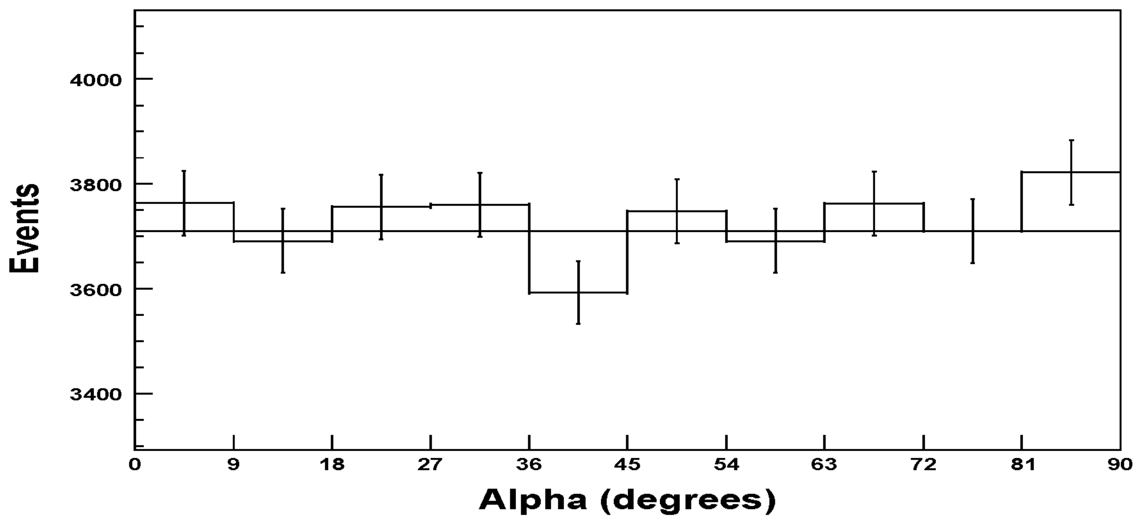

Figure 2. Distribution of image parameter 'Alpha' after applying cuts given in Table 2 for the entire 165.7h of data on H1426+428. The horizontal line in the figure indicates the expected background in the γ-domain obtained by using the background region ($27^\circ \leq \alpha \leq 81^\circ$). The error bars shown are for statistical errors only.

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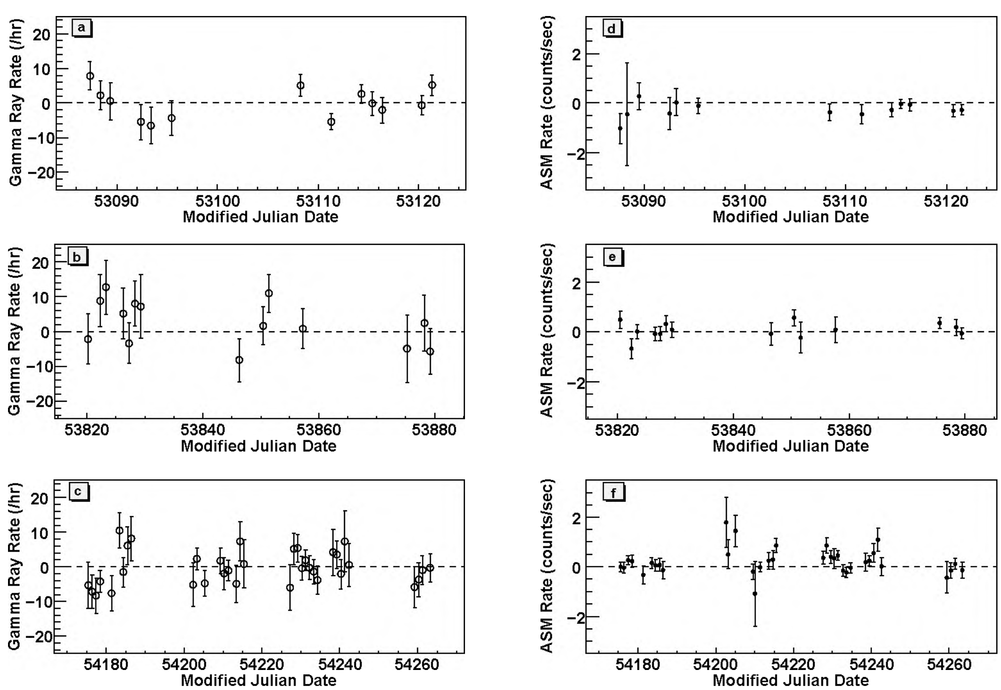

Figure 3. TACTIC light curves for (a) 2004, (b) 2006 and (c) 2007 observations and corresponding ASM light curves are shown in (d), (e) and (f) respectively.

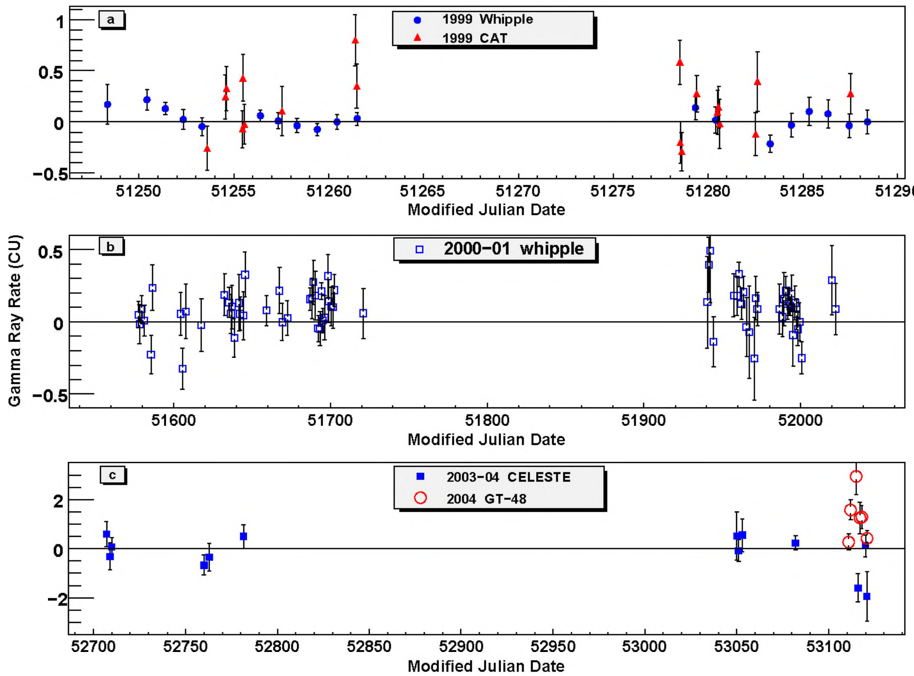

Figure 4. H1426+428 TeV light curves obtained by various groups, namely Whipple[23], CAT[24], CELESTE[27] and GT-48[29].

3.2. ASM X-ray light curves

In order to examine any correlation between VHE γ-ray and X-ray (2-10 keV) source emissions, the Whipple group who discovered this source has done correlation studies for this source and no evidence for significant correlation was found, rather their 2001 data show some evidence for an anticorrelation between the average monthly rates[23]. In the present work we also compare the TACTIC light curves with those of RXTE/ASM X-ray observations in the energy range of 2-10 keV. For this we have used the daily average count rate of ASM from its archived data[43] to obtain the light curves for the contemporary periods. These light curves are shown in Figures 3d, 3e and 3f for the corresponding TACTIC observation periods of 2004, 2006 and 2007 respectively. ASM light curves are characterised with the reduced χ^2 values of 5.27/12, 11.03/13 and 43.78/34 with respect to the zero degree polynomial fitted constant values of -0.2$\pm$0.088, 0.095$\pm$0.082, and 0.152$\pm$0.046 counts and corresponding probabilities of 0.96, 0.60 and 0.17 respectively, thereby indicating that these light curves are consistent with the constant flux hypothesis and no variability is observed in a time scale of a day or more in the RXTE/ASM energy band also. We have not done any correlation studies between the TACTIC and RXTE/ASM observations, mainly because of non detections of the source in the present work.

Table 3. Yearly spell wise and consolidated data analysis results obtained on H1426+428 with the TACTIC telescope.

Year	Obs. time (h)	Excess/Deficit of events from source direction	Significance (σ)	Upper Limit at 3σ level photons cm^{-2} s^{-1}
2004	44.8	19±48	0.39	$\leq 2.13 \times 10^{-12}$
2006	18.4	68±35	1.95	$\leq 3.72 \times 10^{-12}$
2007	102.5	-54±80	-0.68	$\leq 1.54 \times 10^{-12}$
Total	165.7	33±100	0.33	$\leq 1.18 \times 10^{-12}$

4. Discussion and conclusions

We have observed the BL Lac object H1426+428 in the VHE gamma-ray energy range with the TACTIC γ-ray telescope during 2004-2007. We do not find any evidence for the presence of a statistically significant VHE gamma-ray signal either in the overall data or when the data are analysed on a yearly spell basis or a night to night basis during the 2004, 2006 and 2007 observations. An upper limit of I($\geq$1.5 TeV)$\leq 1.18 \times 10^{-12}$ *photons* cm^{-2} s^{-1} (13.1% of the TACTIC detected Crab Nebula flux) has been placed at 3σ confidence level on the integrated γ-ray flux. It may be noted here that we have not used the EBL absorption effect while deriving the upper limit. We conclude that the source was possibly in a low TeV emission state (below the TACTIC sensitivity level) during this period. We have used ASM data [43] in the presented work just to inspect the contemporary RXTE source light curves in the energy band of 2-10keV and to compare with those obtained with the TACTIC observations. In the earlier reported VHE detections, no evidence for the significant correlation between X-ray and VHE γ -ray was found [23] as has been mentioned earlier.

In Figure 4, we show the available light curves of the source from 1999 to 2004 observed by the Whipple, CAT, CELESTE and GT-48 [23, 24, 27, 29] groups. It is interesting to point out here that the TACTIC 2004 results are in close agreement with those obtained by the CELESTE group [27] around 100 GeV threshold energy during the same period. However, these results are in conflict with those obtained with the GT-48 telescope[29] operating above 1 TeV during the same period. At present we do not understand the reason for this conflict between these TACTIC and GT-48 observations.

In Figure 5 we have compared the TACTIC upper limit obtained during 2004-2007 with the source VHE spectra results obtained during different epochs by the Whipple [23], HEGRA [26] and CAT[24] alongwith the upper limits provided by the CELESTE[27], STACEE[28] and VERITAS[30] collaborations. Further, those groups who have reported VHE γ-ray detections their derived source spectra are consistent with the expected signature of absorption of TeV γ-rays by EBL [44, 25, 26, 24].

We feel that the long term multi-wavelength observations of the source are required to possibly record more flaring states of the source to understand it by using the technologically advanced telescopes. These observations in the VHE regime would also

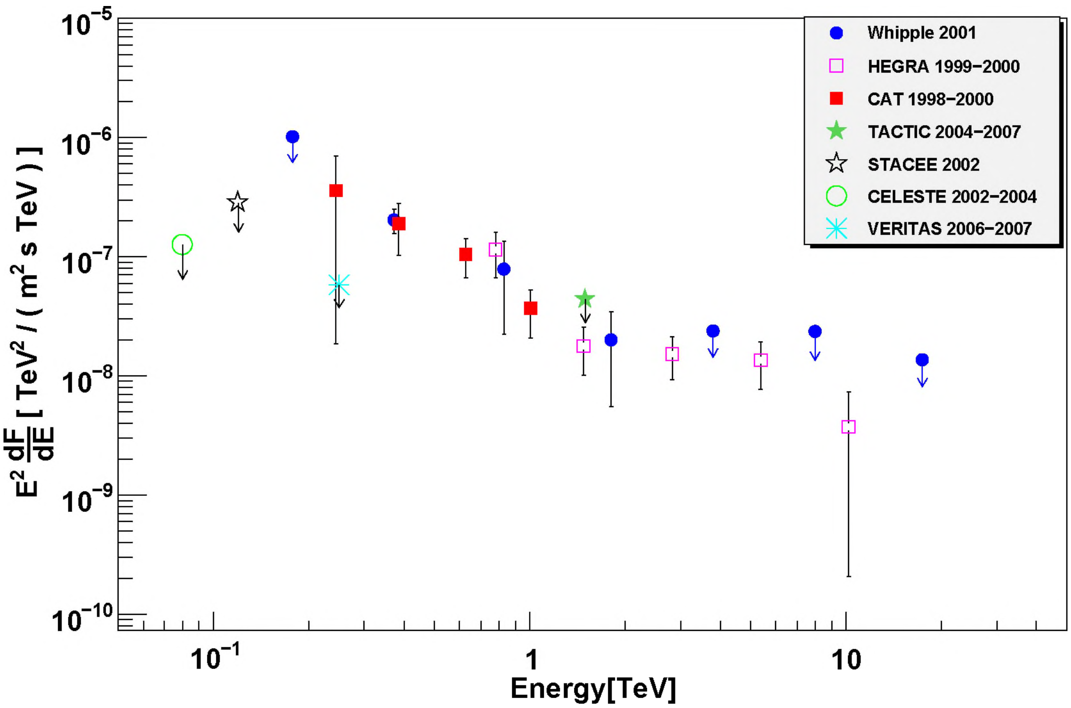

Figure 5. TACTIC upper limit derived using 165.7 h of data has been shown along with results obtained by WHIPPLE[44], HEGRA[26], CAT[24] CELESTE[27], STACEE[28] and VERITAS[30] groups.

possibly record a better statistics of VHE photons to derive the source related observed and intrinsic spectra corresponding to various high states. Indeed this would also help in understanding the particle acceleration and γ-ray production mechanisms in the AGN jets, in addition to the VHE photon horizon and EBL related quest.

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6. References

[1] Bednarek, W., 1997, arXiv astro-ph/9711189
[2] Ulrich, M. H., et al. 1997, Ann. Rev. Astron. and Astroph., 35, 445
[3] Urry, C. M., Padovani,P., 1995, PASP, 107,803
[4] Padovani, P. & Giommi, P. ApJ, 1995, 444, 567.

[5] Bloom, S. D. & Marscher, A.P., 1996, ApJ, 461, 657
[6] Kőnigl, A. 1981, ApJ, 243, 700
[7] Maraschi, L. Ghisellini, G., & Celotti, A. 1992, ApJ, 397, L5
[8] Sikora, M. & Madjeski,G., 2001, in AIP Conf. Proc. 558, High Energy Gamma-ray Astronomy, ed. A.F. Aharonian & H.J. Volk(New York: AIP), 275
[9] Blandford, R. D. & Levinson, A., 1995, ApJ, 441,79
[10] Dermer, C. D., Struner, S.J., & Schlickeiser, R., 1997, ApJS, 109,103
[11] Ghisellini, G. & Madau,P., 1996, MNRAS, 280,67
[12] Bednarek, W., 1993, ApJ, 402, L29
[13] Dar, A. & Laor, A., 1997, ApJ, 478, L5
[14] Aharonian, F. A., et al., 2000, A & A, 353, 847
[15] Mücke, A. & Protheroe, R. J., 2001, APh, 15, 121
[16] Benbow, W. et al., 30th ICRC, Merida, Mexico, 2007
[17] Stecker, F.W. et al., ApJ, 1992, 390, 49.
[18] Albert, J. et al.,2008, Science,320, 1752
[19] Aharonian, F., et al.,2006, Nature 440,20
[20] Wood, K.S., et al., ApJS, 56 (1984) 507.
[21] Remillard, R.A. et al. ApJ, 1989, 345, 140.
[22] Costamante, L., et al.,A&A, 371 (2001) 512.
[23] Horan, D., et al., ApJ, 571 (2002) 753
[24] Djannati-Atai, A., et al., A&A, 391 (2002) L25.
[25] Aharonian, F., et al., A&A, 384 (2002) L23.
[26] Aharonian, F., et al., A&A, 403 (2003) 523.
[27] Smith, D.A. et al.,A&A,459(2006), 453.
[28] The Universe Viewed in Gamma-Rays (Kashiwa, Japan), Sep.2002.
[29] Fidelis, V. V., et al., Astronomy Reports, 49, 11 (2005) 859.
[30] Krawczynski, H. et al., 30th ICRC Merida Mexico (2007).
[31] Kaul, S. R. et al., Nucl. Instrum. and Meth. A., 496 (2003) 400.
[32] Bhatt, N. et al., Meas. Sci. Technol., 12 (2001) 167.
[33] Yadav, K. K. et al., Nucl. Instrum. and Meth. A., 527 (2004) 411.
[34] Koul, R. et al., Nucl. Instrum. and Meth. A., 578 (2007) 548.
[35] Godambe S. V. et al., J. Phys. G: Nucl. Part. Phys. 35 (2008) 065202
[36] Hillas, A. M., 1985, in Proc 19th ICRC, 3, 445
[37] Konopelko, A., et al., Astropart. Phys., 4 (1996)199.
[38] Mohanty, G., et al., Astropart. Phys., 9 (1998)15.
[39] Yadav, K. K., et al., Astropart. Phys., 27 (2007) 447.
[40] Li, T.P., & Y.Q.Ma, ApJ, 272 (1983) 317.
[41] Fidelis, V. V. in a private communication.
[42] Helene, O., Nucl. Instrum. Methods Phys. Res., 212 (1983) 319.
[43] ASM http://xte.mit.edu/
[44] Petry, D., et al., ApJ, 580 (2002) 104.