TeV Gamma-ray Observations of Markarian 421 using TACTIC during 2009-10

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Abstract. We have observed the blazar Markarian 421 with the TACTIC γ-ray telescope at Mt. Abu, India, from 22 November 2009 to 16 May 2010 for 265 hours. Detailed analysis of the data so recorded revealed presence of a TeV γ-ray signal with a statistical significance of 12.12σ at Eγ ≥ 1 TeV. We have estimated the time averaged differential energy spectrum of the source in the energy range 1.0 - 16.44 TeV. The spectrum fits well with the power law function of the form \( \frac{dF}{dE} = f_0 E^{-\Gamma} \) with \( f_0 = (1.39 \pm 0.239) \times 10^{-11} \text{cm}^{-2} \text{s}^{-1} \text{TeV}^{-1} \) and \( \Gamma = 2.31 \pm 0.14 \).

1. Introduction

Markarian 421 falls in the blazar category of Active Galactic Nuclei (AGN) which are the most extreme and powerful variable sources of photons with energies ranging from the radio to the γ-ray regimes. Blazars are believed to have their jets more aligned towards us as compared to any other class of radio loud AGN, are quite bright, have irregular amplitude variability in all accessible spectral bands and a core-dominated radio morphology with flat radio spectra, which join smoothly to the infrared (IR), optical and ultra-violet spectra. The observed high variability and broadband emission from such objects make long-term multiwavelength observations of blazars very important for understanding their emission mechanisms and other jet related properties[34, 62]. The Spectral Energy Distributions (SEDs) of these violent objects have double-peaked structure in the \( \nu F_\nu \) versus frequency plot. The first peak is usually referred to as the synchrotron peak, both in leptonic and hadronic models for blazar emission. Further, it is generally believed to be the result of incoherent synchrotron emission from relativistic electrons and positrons, which are conjectured to be present in the magnetic fields of the jet. The origin of the second peak, usually referred to as
the inverse-Compton peak, is less well determined. In synchrotron self-Compton (SSC) models\cite{18, 40, 43, 57} it is assumed that the synchrotron photons are up-scattered to higher energies by the electrons while in external Compton (EC) models\cite{16, 24, 31, 64}, these seed photons can come from the accretion disk, broad-line region, torus, local infrared background, cosmic microwave background, ambient photons from the central accretion flow or some combination of these sources. In the framework of hadronic models \cite{4, 42, 46}, the X-ray to $\gamma$-ray emission is believed to be due to synchrotron radiation from protons accelerated in highly magnetized compact regions of the jet. In another scenario it is proposed that the proton-proton collisions, either within the jet itself or between the jet and ambient clouds, give rise to neutral pions which decay to gamma rays \cite{14, 22, 49}.

The blazar Mrk 421($z=0.031$) was the first extragalactic source detected at TeV energies in 1992 using imaging atmospheric Cherenkov telescopes \cite{51, 53}. The source has been observed extensively by various groups since then \cite{1, 6, 7, 10, 13, 19, 23, 44, 47, 48, 52, 56, 66, 68}. These observations have shown that the TeV $\gamma$-ray emission from Mrk 421 is highly variable with variations of more than one order of magnitude and occasional flaring doubling time as short as 15 mins \cite{5, 30}. Since its detection in the TeV energy range, Mrk 421 has also been the target of several multiwavelength observation campaigns \cite{1, 11, 13, 17, 20, 27, 60, 61, 63}. Several groups have also determined the energy spectrum of Mrk 421 at various flux levels and some of these results are cited and discussed in section 6. Differences in the energy spectrum of Mrk 421 and Mrk 501 have also been addressed to understand the $\gamma$-ray production mechanisms of these objects and absorption effects at the source or in the intergalactic medium due to interaction of $\gamma$-rays with the Extragalactic Background Light (EBL) \cite{25}. In this paper, we present TACTIC results obtained from our observation campaign on this source during the period 2009-10.

2. **TACTIC telescope**

TACTIC (TeV Atmospheric Cherenkov Telescope with Imaging Camera) $\gamma$-ray telescope is located at Mt. Abu (24.6° N, 72.7° E, 1300m asl), Rajasthan, India. It deploys a F/1 type tracking light collector of $\sim$9.5 m² area which is made up of 34 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 has a 349 photomultiplier tubes (ETL 9083UVB) -based imaging camera with a uniform pixel resolution of $\sim$0.3° and a field-of-view of $\sim$6°x6° to record images of atmospheric Cherenkov events. Data used in the present work have been collected with the inner 225 pixels and the innermost 121 pixels were used for generating the event trigger. The trigger is based on the 3NCT (Nearest Neighbour Non-Collinear Triplets) logic \cite{37}. The safe anode current ($\leq$ 3 $\mu$A) operation of the photomultipliers (PMT) has been ensured by implementing a gain control algorithm \cite{15}. The data acquisition and control system of the telescope \cite{67} have been designed around a network of PCs with the QNX (version 4.25) real-time
operating system. 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 single pixel threshold was set to $\geq 14$ photoelectrons (pe). The detailed description of the telescope related hardware and software has been given in [39]. The telescope is sensitive to $\gamma$-rays above 1 TeV and can detect the Crab Nebula at $5\sigma$ significance level in 25 hours of observation.

3. Mrk 421 Observations

| Year  | Month | Observation dates | Total data (hrs.) | Data Selected (hrs.) |
|-------|-------|-------------------|-------------------|---------------------|
| 2009  | Nov.  | 22-27             | 5.6               | 5.6                 |
| 2009  | Dec.  | 13,15-16,18-19,21,23-27 | 21.1             | 16.9               |
| 2010  | Jan.  | 10,13-24          | 47.8              | 41.0                |
| 2010  | Feb.  | 6,10-20,22-23     | 54.2              | 50.2                |
| 2010  | Mar.  | 7-22              | 60.5              | 59.4                |
| 2010  | Apr.  | 2,4-7,9-18        | 50.2              | 38.5                |
| 2010  | May   | 2,4,6-13,15-16    | 26.0              | 18.3                |
| 2009-2010 | Nov.-May |                | 265.4             | 229.9               |

Very High Energy (VHE) $\gamma$-ray observations of Mrk 421 presented here were made with the TACTIC $\gamma$-ray telescope during 22 November 2009 to 16 May 2010 for 265.4 hours. The observations were carried out in tracking mode, where the source is tracked continuously without taking off-source data [54]. This mode improves the chances of recording possible flaring activity from the candidate source direction. Details of these observations with the TACTIC $\gamma$-ray telescope during 2009-10 are given in Table 1. We have used the standard data quality checks to evaluate the overall system behaviour and the general quality of the recorded data, including conformity of the Prompt Coincidence (PC) rates with the expected zenith angle trend, compatibility of the arrival times of PC events with the Poissonian statistics and the steady behaviour of the chance coincidence rate with time [65]. After applying these cuts, we have selected good quality data sets as per details given in Table 1.
4. Data Analysis and Results

The analysis of data recorded by the ground based atmospheric Cherenkov gamma-ray telescopes, involves a number of steps including filtering of night sky background light, accounting for the differences in the relative gains of the PMTs and finding Cherenkov image boundaries, image parameterization, event selection, energy reconstruction etc. We have characterized each Cherenkov image using a moment analysis methodology given in [36, 55, 65, 2, 8, 9], wherein the roughly elliptical shape of the image is described by the LENGTH and WIDTH parameters and its location and orientation within the telescope field of view are given by the DISTANCE and ALPHA(\(\alpha\)) parameters respectively. In addition, the two highest amplitude signals recorded by the PMTs (max1, max2) and the amount of light in the image (SIZE) are also obtained for each recorded image. Further, another parameter FRAC2 which is the addition of two largest amplitude signals recorded by PMTs divided by the image size, is also estimated [65].

The standard Dynamic Supercuts [35, 45] procedure is then used to separate \(\gamma\)-ray like images from the overwhelming background of cosmic-rays. This procedure uses the image shape parameters LENGTH and WIDTH as a function of the image SIZE so that energy dependence of these parameters can be taken into account. The \(\gamma\)-ray selection criteria used in this analysis is given in Table 2 and has been obtained on the basis of Monte Carlo simulations carried out for the TACTIC telescope [26, 38].

| Parameters       | Cuts Value                                      |
|------------------|-------------------------------------------------|
| LENGTH (L)       | \(0.11 \leq L \leq (0.235 + 0.0265 \times \ln S)^0\) |
| WIDTH (W)        | \(0.065 \leq W \leq (0.085 + 0.0120 \times \ln S)^0\) |
| DISTANCE (D)     | \(0.5 \leq D \leq (1.27 \cos^{0.88} \ln \Theta)^0\) (\(\Theta=\)zenith angle) |
| SIZE (S)         | \(S \geq 485 \text{ dc} \) (6.5 digital counts = 1.0pe) |
| ALPHA (\(\alpha\)) | \(\alpha \leq 18^0\)                             |
| FRAC2 (F2)       | \(F2 \geq 0.38\)                                |

VHE \(\gamma\)-ray signal processing is done by using the histogram of the \(\alpha\) parameter (defined as the angle between the major axis of the image and the line between the image centroid and camera center, when the source is aligned along the optical axis of the telescope) after applying the set of image cuts given in Table 2. The distribution of the \(\alpha\) parameter is expected to be flat for the isotropic background of cosmic ray events, whereas for the \(\gamma\)-ray signal events, the distribution is expected to show a peak at smaller \(\alpha\) values. This range for the TACTIC telescope is \(\alpha \leq 18^0\). The contribution of the background events is estimated from a reasonably flat \(\alpha\) region of \(27^0 \leq \alpha \leq 81^0\). The number of \(\gamma\)-ray events is then calculated by subtracting the expected number of background
events, calculated on the basis of the background region [21], from the \(\gamma\)-ray domain events. The reason for not including the \(\alpha\) bins 18°-27° and 81°-90° in the background region is to ensure that the background level is not overestimated because of a possible spill over of \(\gamma\)-ray events in the third bin and the truncation of the Cherenkov images recorded at the boundary of the imaging camera [21] in the last bin. The significance of the excess events is calculated by using the maximum likelihood ratio method of Li and Ma [41].

Next, we present data analysis results of Mrk 421 observations made using the TACTIC telescope during the year 2009-10. When all the data are analyzed together, the corresponding results obtained are shown in Figure 1. In this figure the histogram of the \(\alpha\) parameter has been shown after having applied shape and orientation related imaging cuts given in Table 2. It shows the presence of the VHE \(\gamma\)-ray signal with a total number of \(\gamma\)-ray like events of 1932.7 ± 159.4. The statistical significance of the detected signal stands at 12.12\(\sigma\) level, thereby indicating that the source was in a relatively high TeV emission state during the period of observations. When these data were divided into seven monthly spells as depicted in Table 3 and analyzed by using the same data analysis procedure, the number of \(\gamma\)-ray like events obtained was highest during February 2010 observations. The details of these results have been given in Table 3.
Table 3. Monthly spell wise analysis of Mrk 421 data recorded during 2009-10 with only statistical errors.

| Spell | Observation Period     | Time (hrs.) | γ-rays           | Significance |
|-------|------------------------|-------------|-----------------|--------------|
| 1     | 22-27 Nov. 2009        | 5.6         | 37.0 ± 20.2     | 1.83         |
| 2     | 13-27 Dec. 2009        | 16.9        | 105.7 ± 38.4    | 2.75         |
| 3     | 10-24 Jan. 2010        | 41.0        | 285.0 ± 62.7    | 4.54         |
| 4     | 06-23 Feb. 2010        | 50.2        | 711.7 ± 88.6    | 8.03         |
| 5     | 07-22 Mar. 2010        | 59.4        | 432.7 ± 88.6    | 4.88         |
| 6     | 02-18 Apr. 2010        | 38.5        | 264.7 ± 52.9    | 5.00         |
| 7     | 02-16 May 2010         | 18.3        | 96.0 ± 33.1     | 2.90         |
| Total | 22 Nov. 2009-16 May 2010| 229.9      | 1932.7 ± 159.4  | 12.12        |

Figure 2. Mrk 421 light curves for 2009-10 TACTIC observations.

These data have also been analyzed on nightly basis in order to look out for the possibility of a strong episodic TeV emission. The results so obtained are depicted in Figure 2b, which shows a day-to-day variations of the γ-ray rate (γ-rays/hour) for Mrk
Figure 3. Distribution of image parameter $\alpha$ for the TACTIC observations of Mrk 421 during February 2010. Vertical dashed line represents the $\alpha$ parameter cut used for $\gamma$-ray like events. Horizontal line represents the mean background level per 9° bin derived by using the reasonably flat $\alpha$ region of $27^\circ \leq \alpha \leq 81^\circ$. Error bars shown are for statistical errors only.

421 during 2009-10 observations. This light curve is characterised with a reduced $\chi^2$ value of 83.26/69 with respect to the mean level of $7.4 \pm 0.65$ photons per hour, with corresponding probability of 0.12 which is consistent with the no variability hypothesis.

Next we compare the TeV light curve obtained which is shown in Figure 2a with those of the source with the Swift/Burst Alert Telescope (BAT) \textsuperscript{58}( 15-50 KeV), Rossi X-ray Timing Explorer (RXTE)/All-Sky Monitor (ASM) \textsuperscript{12}( 2-10 KeV) and Fermi/Large Area Telescope (LAT) \textsuperscript{28}(1-300 GeV) detectors. The Swift/BAT contemporary light curve of the source obtained from its archived data \textsuperscript{58} is shown in Figure 2b. It is characterised with a reduced $\chi^2$ value of 1594/168 (probability is close to zero which is consistent with the variability hypothesis) with respect to the mean level of $0.00349 \pm 7.4e-05$ counts $cm^{-2}s^{-1}$. Next the RXTE/ASM contemporary light curve shown in Figure 2c which has been plotted by using the daily average count rates of the ASM from its archived data \textsuperscript{12}. The ASM light curve is characterised with a reduced $\chi^2$ value of 2825/174 ( probability obtained is very low which is consistent with the variability hypothesis) with respect to the mean level of $2.15 \pm 0.025$ counts/sec.

The Fermi/LAT contemporary light curve shown in Figure 2d has been plotted by using the daily counts $cm^{-2}s^{-1}$ of the LAT from its archived data \textsuperscript{28}. The LAT light curve is characterised with a reduced $\chi^2$ value of 291/156 ( probability obtained is very low which is consistent with the variability hypothesis) with respect to the mean level of $6.17e-08 \pm 1.25e-9$ counts $cm^{-2}sec^{-1}$. 

As already mentioned above and is also clear from Table 3 that we have detected a statistically significant TeV $\gamma$-ray signal at 8.03$\sigma$ level during February TACTIC observations of the source. It was observed for 12 nights and a total of 50.2 hours of on-source observations were possible during this month. Total number of TeV $\gamma$-rays detected during this month are $711.7 \pm 88.6$ which is clear from the corresponding alpha plot shown in Figure 3. Further, we find that the source was at higher TeV emission state during three nights of 15-17 February, 2010 (MJD 55242.73913-55244.98546). Details of these results are given in Table 4. On 16th February, 2010 we detected 177.7 $\pm$ 30.8 $\gamma$-ray photons of TeV energies at more than 5$\sigma$ statistical significance level. During other two nights of 15th and 17th February, 2010 again we detected statistically significant number of TeV $\gamma$-rays with greater than 4$\sigma$ level. Using these results we believe that the source had possibly switched to an intense flaring state during 15-17 February, 2010 observations. Further, in order to compare the February 2010 TeV results with those at lower energies, we have depicted the February source light curves of TACTIC, Swift/BAT, RXTE/ASM and Fermi/LAT in Figures 4a,b,c and d respectively. As is clear from these figures the daily variations in the number of counts

Figure 4. Mrk 421 light curves for February 2010 observations.
Table 4. Details of Mrk 421 data analysis results of TACTIC observations made during 15- 17 February 2010.

| Obs. Date (Feb. 2010) | Start MJD  | End MJD   | γ-rays       | Sig.(σ) | Obs. Time(hrs) |
|-----------------------|------------|-----------|--------------|---------|----------------|
| 15                    | 55242.73913| 55242.99233| 93.3 ± 27.5  | 3.39    | 4.9            |
| 16                    | 55243.77758| 55243.98686| 177.7 ± 30.8 | 5.76    | 5.0            |
| 17                    | 55244.75948| 55244.98546| 143.0 ± 30.2 | 4.73    | 5.2            |
| 15, 16, 17            | 55242.73913| 55244.98546| 414.0 ± 51.2 | 8.09    | 15.1           |

detected by these four experiments are such that when we fit zero degree polynomials to these light curves the reduced χ² values obtained are 33.46/11, 353.8/15, 484.1/14 and 22.38/14 (χ²/dof) for TACTIC, Swift/BAT, RXTE/ASM and Fermi/LAT respectively. Fermi/LAT’s light curve reduced χ² value of 22.38/14 yields a corresponding probability of 0.07 thereby indicating that the light curve is consistent with a flat distribution. However, the first three light curves yield corresponding probabilities much less than 0.05 thereby indicating in favour of variable signal detection in the TACTIC, Swift/BAT and RXTE/ASM energy ranges. These light curves also indicate a possible correlation between TeV and X-ray emissions from this source direction particularly during 15- 17 February, 2010 observations. This lends possible support to the SSC model in which a unique electron population produces the X-rays by synchrotron radiation and the γ-ray component by inverse Compton scattering.

Further when hourly data runs of these three days are investigated in terms of the detected number of γ-ray like events, we find that on the night of 17th February, 2010, during the hourly run from MJD 55244.812502 to 55244.854161, we have detected 57 ± 14.2 γ-ray photons of TeV energies at 4σ statistical significance as is clear from Figure 5. It may be noted here that TACTIC detects on an average 9 γ-ray like events in one hour of observations from the Crab nebula direction. Therefore, we conclude that the source has possibly exhibited yet another short duration high TeV γ-ray emission state during this period.

5. Differential energy spectrum

In this section we present the differential time-average energy spectrum of the source estimated using its TACTIC observations made during the period 22 Nov. 2009- 16 May 2010. The energy reconstruction procedure employed to unfold it uses an Artificial Neural Network (ANN) with 3:30:1 configuration and resilient backpropagation algorithm. The energy of each γ-ray like event is estimated on the basis of its image SIZE, DISTANCE and zenith angle. This method yields an energy resolution of ~ 26%, the details of which have been given in [26, 66].

The observed Mrk 421 differential energy spectrum so obtained has been tabulated
Figure 5. TACTIC observed hourly light curves of Mrk 421 on three nights of 15, 16 and 17 February 2010 (MJD 55242.73913 to 55244.98546).

Table 5. Differential energy spectrum data for Mrk 421 in 2009-10 with the TACTIC telescope. Only statistical errors are given below.

| Energy (TeV) | Diff. flux $\text{photons cm}^{-2} \text{s}^{-1} \text{TeV}^{-1}$ | Statistical error in flux $\text{photons cm}^{-2} \text{s}^{-1} \text{TeV}^{-1}$ |
|--------------|-------------------------------------------------------------|-------------------------------------------------------------|
| 1.00         | $1.75 \times 10^{-11}$                                     | $6.78 \times 10^{-12}$                                     |
| 1.50         | $5.45 \times 10^{-12}$                                     | $1.11 \times 10^{-12}$                                     |
| 2.22         | $2.15 \times 10^{-12}$                                     | $3.15 \times 10^{-13}$                                     |
| 3.32         | $7.46 \times 10^{-13}$                                     | $1.54 \times 10^{-13}$                                     |
| 4.95         | $3.89 \times 10^{-13}$                                     | $7.98 \times 10^{-14}$                                     |
| 7.38         | $1.85 \times 10^{-13}$                                     | $4.31 \times 10^{-14}$                                     |
| 11.00        | $5.11 \times 10^{-14}$                                     | $2.59 \times 10^{-14}$                                     |
| 16.44        | $1.01 \times 10^{-14}$                                     | $1.24 \times 10^{-14}$                                     |

in Table 5 and also shown in the Figure 6 which extends up to 16.44 TeV. The errors in the flux constant and spectral index are standard errors. A power law function of the
Figure 6. TACTIC observed differential energy spectrum of Mrk 421 derived using the 2009-10 observations (filled circle). De-absorbed source spectra estimated by using various EBL models are also shown for comparison.

The observed differential energy spectrum of the source can be described by a power-law form $dF/dE = f_0 E^{-\Gamma}$ when fitted to the data in the energy range 1-16.44 TeV yields

$$\frac{dF}{dE} = (1.39 \pm 0.239) \times 10^{-11} \text{cm}^{-2} \text{s}^{-1} \text{TeV}^{-1} \left(\frac{E}{1.0 \text{TeV}}\right)^{-2.31 \pm 0.14}$$

for the observed differential energy spectrum of the source with $\chi^2/dof = 3.37/6$ (probability 0.76).

Table 6. Estimated intrinsic differential energy spectrum fitted parameters for three models.

| $\Gamma$  | $\Delta \Gamma$ | $f_0$       | $\Delta f_0$   | Model                  |
|-----------|-----------------|-------------|-----------------|------------------------|
| 2.31      | 0.14            | $1.39 \times 10^{-11}$ | $2.39 \times 10^{-12}$ | Presented observations |
| 2.03      | 0.16            | $1.86 \times 10^{-11}$ | $3.60 \times 10^{-12}$ | Primack [50]           |
| 1.85      | 0.16            | $1.73 \times 10^{-11}$ | $3.16 \times 10^{-12}$ | Stecker Baseline [59]  |
| 1.73      | 0.17            | $2.00 \times 10^{-11}$ | $4.11 \times 10^{-12}$ | Stecker Fast evolution [59] |
| 1.94      | 0.18            | $1.60 \times 10^{-11}$ | $3.43 \times 10^{-12}$ | Franceschini [29]      |
| 1.97      | 0.14            | $1.88 \times 10^{-11}$ | $3.20 \times 10^{-12}$ | Gilmore [32]           |

We have also estimated the source intrinsic $\gamma$-ray spectra by using the SED of the
EBL provided by five models given in Table 6. The resulting intrinsic spectra for five models are shown in Figure 6. A power law fit to the estimated intrinsic data of the type $d\Phi/dE = f_0 E^{-\Gamma}$ in the energy range 1 - 16.44 TeV yields values of $\Gamma$ and $f_0$ listed in Table 6. As is clear from Figure 6, the Primack model yields minimum attenuation of TeV photons, in contrast, Stecker’s fast evolution model yields maximum attenuation as compared to other models used in estimating the intrinsic source spectra.

As mentioned earlier, Mrk 421 is a nearby source with $z=0.031$, so we do not expect significant absorption of intrinsic source spectrum due to EBL in the TACTIC energy range. Another important characteristic feature associated with this source is its relatively higher flaring frequency when compared to other objects of the same class, thereby making it an excellent cosmic laboratory to study VHE $\gamma$-ray emission mechanisms and physics of relativistic jets.

6. Discussion and conclusions

For the reasons mentioned above, we are monitoring Mrk 421 on the long term basis with TACTIC $\gamma$-ray telescope. In this paper, we have presented the results obtained using TACTIC observations made during 2009-10. Detailed analysis of this data shows...
evidence for the presence of a statistically significant VHE $\gamma$-ray signal at 12.12$\sigma$ level. The total number of $\gamma$-ray like events detected are 1932.7 $\pm$ 159.4. These observations suggest that the source had gone into a variable active state in the VHE region during the period of TACTIC 2009-10 observations. During the month of February 2010, TeV signal strength in terms of the number of TeV $\gamma$-ray like events which is 711.7$\pm$ 88.6 highest as compared to results obtained for other months as depicted in Table 3. It is interesting here to mention that the HESS [44], VERITAS [47] and ARGO-YBJ [13, 33] have also detected the source in a high state particularly during February 2010.

We have estimated an observed differential energy spectrum of the detected $\gamma$-ray like events which is shown in Figure 6. The spectrum fits well with the power law function of the form $(dF/dE = f_0E^{-\Gamma})$ with $f_0 = (1.39 \pm 0.239) \times 10^{-11} cm^{-2}s^{-1}TeV^{-1}$ and $\Gamma = 2.31 \pm 0.14$. In comparison with our earlier TACTIC detected high states of this source reported in [66, 23], present observed spectrum is harder and extends up to 16 TeV primary $\gamma$-ray photon energy. We have also used five templates of EBL to estimate $\tau$’s for $z = 0.031$ which have been used to estimate corresponding intrinsic source spectra. The results of this study have been tabulated in Table 6.

A comparison of the observed spectral energy distribution of this source in the VHE range obtained by the HESS, MAGIC, VERITAS, Whipple, HEGRA, CAT, ARGO-YBJ and TACTIC [7, 10, 68, 2, 3] [5, 52, 66, 33, 44] is shown in Figure 7. As is clear from this figure our 2009-10 results are in close agreement with various reported results on this source.

TACTIC, Swift(BAT) and RXTE(ASM) light curves of 15-17 February, 2010 observations (55242.73913 - 55244.98546 ) do indicate a possible correlation of TeV and X-ray emissions of the source as is shown in Figures 4a, b and c. This indicates that the mentioned short TeV $\gamma$-ray flare was not an orphan type as it is also seen at lower energies and possibly supports the SSC model in which a relativistic electrons population produces the X-rays by synchrotron radiation and the $\gamma$-ray component by inverse Compton scattering.

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8. References

[1] Abdo A. A. et al. (2011), arXiv:1106.1348v1, [astro-ph]
[2] Acciari V. A. et al. (2009), ApJ, 703, 169
[3] Aharonian, F. et al. (1999), A&A, 350, 757
[4] Aharonian, F. A. (2000), New Astronomy, 5, 377
[5] Aharonian F. et al. (2002), A&A, 393, 89
[6] Aharonian F. et al. (2003), A&A, 410813
[7] Aharonian F. et al. (2005), A&A, 437, 95
[8] Aharonian F.et al. (2006) A&A, 457, 899
[9] Albert, J., et al. (2008), ApJ, 674, 1037
[10] Albert J. et al. (2007), ApJ, 663, 125
[11] Aleksic J. et al. (2010), A&A, 519, A32
[12] ASM http://xte.mit.edu
[13] Bartoli, B. et al. (2011) ApJ, 734, 110
[14] Beall, J. H. & Bednarek, W. (1999), ApJ, 510, 188
[15] Bhatt, N. et al., Meas. Sci. Technol. (2001), 12, 167
[16] Blandford, R. D. & Levinson, A. (1995), ApJ, 441, 79
[17] Blazejewski H. et al. (2005), ApJ, 630, 130
[18] Bloom, S. D. & Marscher, A.P. (1996), ApJ, 461, 657 309, 95
[19] Boone L.M. et al. (2002), ApJ, 501, 616
[20] Dar, A. & Laor, A. (1997), ApJ, 621, 181
[21] Catanese, M. et al. (1998), ApJ, 501, 616
[22] Chandra, P., et al., et al. (2010), J. Phys. G: Nucl. part. Phys. 37, 125201
[23] Dermer, C. D., Strumberg, S., & Schlickeiser, R., (1997), ApJS, 109, 103
[24] Dwek E. & Krennrich F. (2005), ApJ, 618, 657
[25] Ghisellini, G. & Madau, P. (1996), MNRAS, 280,67
[26] Gilmore R.C., et al. (2009), MNRAS, 399, pp.1694-1708
[27] He H.H. et al. (2011), 32nd ICRC, Beijing, China
[28] Horan D., et al. (2009) ApJ, 695, 596
[29] Kaul, S. R. et al., (2003) Nucl. Instrum. and Meth. A., 496 , 400
[30] Koul, M.K. et al. (2011) Nucl. Instrum. and Meth. A., 646, 1, 204
[31] Koul, R. et al. (2007) Nucl. Instrum. and Meth. A., 578 548
[32] Königl, A. (1981), ApJ, 243, 700
[33] Li, T.P., & Ma, Y.Q. (1983), ApJ, 272, 317
[34] Mannheim, K. (1993), A&A, 269, 67
[35] Maraschi, L. Ghisellini, G., & Celotti, A. (1992), ApJ, 397, L5
[36] Martin Tluczykount 2011, arXiv:1106.1035v2 [astro-ph]
[37] Mohanty,G. et al. (1998), Astropart. Phys., 9, 15
[38] Möckel, A. et al. (2003), Astropart. Phys., 18, 593
[39] Nicola, G. Proc. (2011) 32nd ICRC, Beijing , China; arXiv:1109.6059v1 [astro-ph.HE].
[40] Ong, R. A. for the VERITAS Collaboration; (2010), ATel 2443
[41] Primack, J.R., Bullock, J.S. and Somerville, R.S. (2005), High Energy Gamma-Ray Astronomy, AIP Conference Series, vol. 745, 23
[42] Petry D. et al.(1996), A&A, 311, L13
[43] Piron F. et al. (2001), A&A, 374, 895
[44] Punch M., et al. (1992), Nature, 358, 477
[45] Quinn J. et al. (1996), ApJ, 456, L83
[46] Reynolds, P.T. et al. (1993), ApJ, 404, 206
[47] Smith D.A. et al. (2006), A&A, 459, 453
[48] Sikora, M. & Madsen, G. (2001), in AIP Conf. Proc. 558, High Energy Gamma-ray Astronomy, ed. A.F. Aharonian & H.J. Volk(New York: AIP), 275
[58] http://swift.gsfc.nasa/docs/swift/results/transients
[59] Stecker, F.W. Malkan, M.A. Scully, S.T.(2007), ApJ, 658, pp.1392
[60] Takahashi T. et al.(1996), ApJ, 470, L89
[61] Takahashi T. et al.(2000), ApJ, 542, L105
[62] Urry, C.M. & Padovani, P. (1995), Unified Schemes for Radio-Loud Active Galactic Nuclei, PASP, 107, 803
[63] Wagner, R. M., et al. (2009), 31st ICRC, Lodz, Poland: arXiv e-print (arXiv:0906.5253)
[64] Wagner, S. J., et al. (1995), A & A, 298, 688
[65] Weekes T.C., et al. (1989), ApJ, 342, 379
[66] Yadav, K. K., et al.(2007), Astropart. Phys., 27, 447
[67] Yadav, K. K. et al. (2004), Nucl. Instrum. and Meth. A., 527, 411
[68] Zweerink J.A. et al.(1997), ApJ, 490, L144