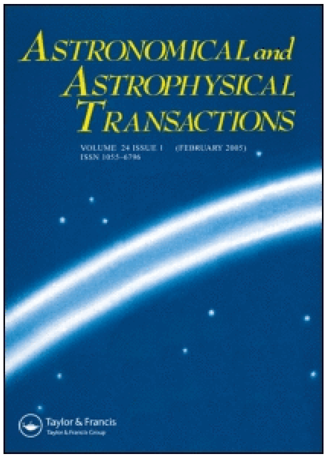

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On teraelectronvolt γ-ray emission from Markarian 501 in 2004

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Galaxy Markarian 501 was observed with the Cerenkov telescope GT-48 at the SRI Crimean Astrophysical Observatory. A total of about 18 hr of source exposure in good weather conditions for 20 nights in the period between May and July 2004 were used for processing the Cerenkov light images induced by extensive air showers. Discrimination analysis has shown the excess number of detected very-high-energy photons in the direction of the observed object at the 5.6σ level. The emission from the object was characterized by the variability of its intensity on a monthly scale. The analysis of X-ray data has also shown enhanced activity from the object in the observation period.

Keywords: γ sources; Active galactic nuclei; Markarian 501

1. Introduction

Detection by the EGRET detector onboard the Compton Gamma-Ray Observatory of the number of point sources of high energy ($E > 100$ MeV) γ-rays, identified with active galactic nuclei (AGNs) [1], has stimulated the search for very-high-energy (VHE) ($E > 10^{11}$ eV) photons from them. Unfortunately, VHE γ-rays are undetectable at present by space-based instruments. They may be detected by means of the ground-based Cerenkov technique. On entering the Earth's atmosphere, a VHE γ-ray initiates an extensive air shower (EAS) that may be detected on the ground by their Cerenkov radiation. The EASs propagate in a direction that coincides with the incident directions of the primary γ-rays. The Cerenkov light from EASs triggered by photons with an energy of 1 TeV covers an area of the Earth's surface of about 10^4 m^2 with a density of optical photons of 50–100 m^{-2} [2] and provides information about the angular dimensions of the EASs and their total energy proportional to the energy of the primary γ-ray. So it is possible to detect very weak fluxes of VHE γ-rays (about 10^{-11} photons cm^{-2} s^{-1}) and to derive the direction of the γ-ray sources.

Since the flux of VHE γ-rays is so weak, the efficiency of the ground detectors depends on the collecting areas of their reflectors which collimates Cerenkov light on the light receivers.

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Using two or more spaced multichannel Cerenkov detectors viewing EASs at different angles, the efficiency of the operation of the instrument may be essentially improved [3].

Unfortunately EASs may be initiated in the atmosphere not only by the VHE γ-rays but also by cosmic rays of such energies. Using a discrimination analysis of Cerenkov light images based on their characteristics the γ-ray showers may be separated from the prevailing background.

All VHE γ-rays from extragalactic objects detected so far (with the exception of that recently reported by Aharonian *et al.* [4] in radio galaxy M 87) are related to the BL Lacertae type of active galactic nuclei. The relativistic jets of these objects which consist of a magnetized plasma are in a direction close to the observer's line of sight. So the emitted power in the VHE band in this direction may be maximal, which may explain the detection of fluxes from distant BL Lacs [5].

BL Lacs show a wide variety of active phenomena in the VHE band on different timescales (up to a ten fold flux increase above the quiescent state for Markarian (Mrk) 421 on a daily scale [6] and the flaring activity of Mkr 501 (see, for example, [7]).

The primary goal of AGN investigation in the VHE band is to examine theoretical models of γ-ray acceleration in their environment [8]. An important aspect of this research is understanding the nature of space–time phenomena and examining their relations.

Galaxy Mrk 501 ($z = 0.033$) is the second object of this type after Mrk 421 [9], a nearby BL Lac object from which was flux of VHE γ-quanta was detected [10]. Observation of Mrk 501 in the VHE band is an exclusive way investigating the γ-rays from it because detection is below the level of EGRET sensitivity.

Mrk 501 was observed by different ground-based experiments (see [11] and references therein). In 1997 this object was in an exclusively high state in the teraelectronvolt band. A number of high-intensity flares were detected in the VHE band between March and October by different ground-based observatories. Observations of Mrk 501 with the stereoscopic system HEGRA with an energy threshold of about 0.5 TeV revealed an averaged flux over the whole period of activity as high as three times the flux of the Crab Nebula [12].

Observations of Mrk 501 at the Crimean Astrophysical Observatory were carried out from 1997 [13]. In this work we present the results of observations of this object with the Cerenkov telescope GT-48 in 2004.

2. Cerenkov telescope and observations

The Cerenkov telescope GT-48 is situated at an altitude of 600 m above sea level. It consists of two identical altitude–azimuth mountings (sections), north and south, separated by 20 m. Each section is equipped with four cameras, consisting of 37 photomultiplier tubes (PMTs) that organize 37 channels. Each camera, which is mounted in the focal plane of four mirrors of diameter 1.2 m, registers the images of Cerenkov flashes from air showers.

Each PMT in the camera has a field of view $0^\circ.4$; the total field of view of each camera is $2^\circ.6$. Both sections of the telescope operate in the coincidence mode. Cerenkov flashes are detected in the optical band and only when the amplitudes of the signals for any two of the 37 channels exceed a certain threshold. The total area of the mirrors on both sections is $36\,\mathrm{m}^2$. The mountings are geared by a control system with a pointing accuracy of $0^\circ.05$. The effective threshold energy for the detection of the γ-rays was estimated by digital modelling of EAS development and equals about 1 TeV. The telescope has been described in detail by Vladimirsky *et al.* [14].

Galaxy Mrk 501 ($\alpha = 16\,\mathrm{h}\,53\,\mathrm{m}\,59\,\mathrm{s}$ and $\delta = 39^\circ\,45'\,14''$) was observed between May and July 2004. Observations were made in the ON–OFF mode, when ON runs (source exposure)

Table 1. Mrk 501 observation log.

Dark moon period	Modified Julian date	Source exposure (min)
17–23 May 2004	53143–53149	200
10–20 June 2004	53167–53177	600
9–21 July 2004	53196–53208	300
Total		1100

were followed by OFF runs (background recording). Both ON and OFF runs were 25 min in duration and were carried out at the same level of elevation. In ON runs the source was in the centre of the field of view of the camera; in OFF runs the observed sky region was shifted by 30 min. A total of 62 ON–OFF pairs were taken at zenith angles of 29° on less. After 'cleaning' of observational runs with respect to weather conditions and detector stability, 18 ON–OFF pairs were disregarded from the analysis. The remaining 44 ON–OFF pairs with the total of about 18 h of source exposure (table 1) and the same time of background recording were used to process the Cerenkov flash images from the EASs triggered by VHE γ-rays and cosmic rays.

3. Data reduction

The 'cleaned' data were followed by the next reduction process.

(i) Events which were registered in the distorted telescope guiding process (i.e. deviation of the optical axes of the telescope mountings from the specific direction more than $3'$) were disregarded.
(ii) Data in which of the analogue–digital converter maximum (255 discrete units, or 180 photoelectrons) was exceeded in at least one channel were discarded.
(iii) The amplitudes of signals in all channels were corrected using calibration coefficients estimated in each run.
(iv) Flashes whose maximum amplitudes were in the outer ring of the camera were disregarded.

The remaining data were processed further. The centres of the brightness distributions and the effective dimensions of the flash images were calculated using a mathematical method [14]. The parameters of flashes recorded simultaneously at each section were determined independently using the data for each section. Most of the recorded showers from the source direction (ON runs) as well as from the surrounding sky region (OFF runs) are induced by the hadronic component of cosmic rays (mainly protons). Candidates for γ-rays were selected using the differences in the shapes and dimensions of the flash images and their orientation concerning the source position in the field of view of the camera.

The images of γ-ray showers have less effective dimensions and compact forms and are aligned in the direction of the source, while the images from proton showers are greater, have more fragmented forms and are of isotropic orientation. To characterize roughly the shapes of γ-ray and cosmic-ray shower images we have used the imaging pattern ratio (IPR). It was assigned as $\mathrm{IPR} = 0$ for images having the most compact form (simple flash) and $\mathrm{IPR} = 1 - 7$ for more distorted and fragmented images. In this selection, flashes on both sections were chosen with $\mathrm{IPR} = 0$.

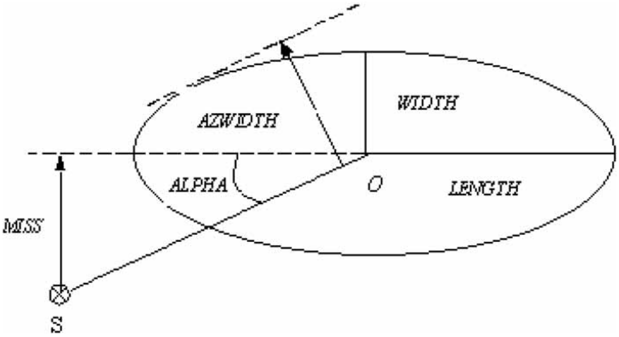

Figure 1. The schematic representation of the main parameters of flash image: O, centre of the brightness distribution; S, position of the source. The length OS corresponds to parameter DIST.

To select γ-like events the following were used [15]: the effective dimensions of flash images (length and width) and their orientation parameters, namely α, which is the angle between the direction towards the source from the image centroid and the direction of the major axis of the flash image, MISS, which is the perpendicular distance of the centre of the field of view (the source) from the major image axis, AZWIDTH which is the rms image width relative to a new axis which joins the source to the centroid of the image, and DIST, which is the distance of image centroid from source (figure 1).

Because the parameters of flashes with low energy are derived with high error, limits were introduced for their detected amplitudes. The boundary parameters for selection of any criteria were estimated by the maximum value of the signal-to-noise ratio $Q = (N_s - N_b)/(N_s + N_b)^{1/2}$, where N_s and N_b are the numbers of γ-like events in ON and OFF runs respectively. The difference $N_s - N_b = N_\gamma$ is interpreted as the number of γ quanta and $(N_s + N_b)^{1/2}$ is the statistical error in this number. The events having values of selection criteria that do not fall in the given interval are disregarded.

4. Results of the analysis

The selection statistics are summarized in table 2. Results are given for the MISS, AZWIDTH and α distributions accompanied by the selection of events using the parameter DIST. The selection by each orientation parameter was fulfilled independently of the selection of two other parameters.

Table 2. Selection statistics.

Selection method	N_s	N_b	$N_s - N_b$	Q
Without selection	14 461	13 991	470	2.79
Selection by amplitude, form and dimensions	556	422	134	4.28
Selection by orientation				
AZWIDTH <0°.22	351	238	113	4.66
MISS <0°.32	263	152	111	5.45
α <34°	280	162	118	5.61

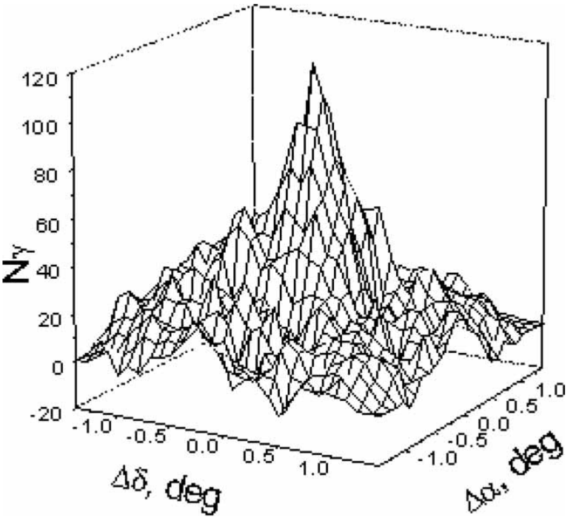

Figure 2. The stereoimage of distribution of γ-ray arrival directions. $\Delta\alpha$ and $\Delta\delta$ are the deviation from the source position in the field of view of the camera on the right ascension and declination respectively. N_γ is the number of γ-quanta.

From table 2 it can be seen that the values of $N_\gamma = N_\mathrm{s} - N_\mathrm{b}$ selected by orientation parameters differ little from each other (by not more that 6%), which confirms the appropriateness of the obtained results.

Using the method of trial sources [16, 17] the distributions of the number of selected events over the detector's field of view were constructed and the position of the true γ-ray source determined. Figure 2 shows a two-dimensional histogram of this distribution with the parameter α and figure 3 shows isophotes of this distribution. The maximum of the distribution ($\Delta\alpha = 0.0$; $\Delta\delta = 0.0$) coincides with coordinates of Mrk 501.

Figure 4 shows the average count rates of detected γ-quanta in dark moon periods with the parameter α (the total γ-ray rate for the observation period is $(0.107 \pm 0.019) N_\gamma\,\mathrm{min}^{-1}$). It may be seen that from Mrk 501 in May enhanced activity was observed at teraelectronvolt

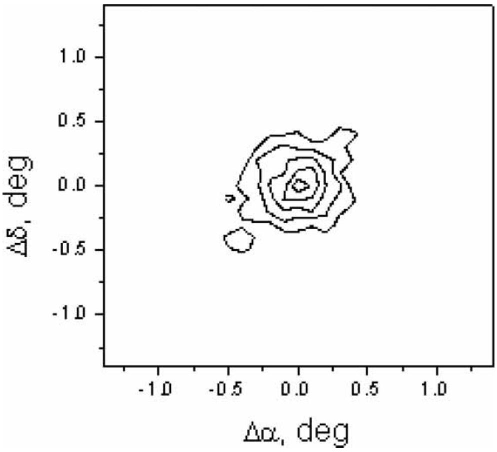

Figure 3. Isophotes of the distribution of the γ-quanta arrival directions. The external isophote equals 50 events; the isophotes step is 14 events.

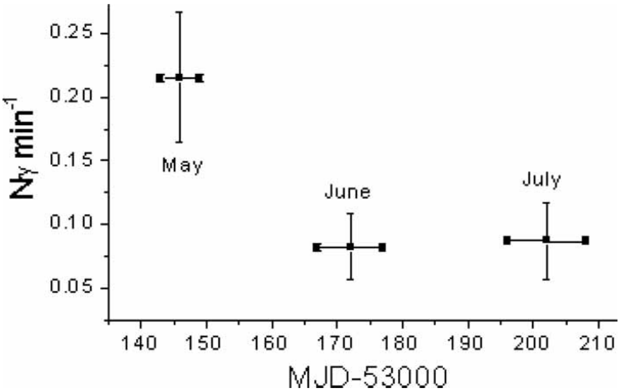

Figure 4. Distribution of the mean detection rates of VHE γ-quanta for different dark moon periods. The error bars are purely statistical.

Table 3. Behaviours of X-ray (2–10 keV) and teraelectronvolt γ-rays of Mrk 501 in different observation periods.

Observation period	Modified Julian date	ASM count rate (counts s^{-1})	GT-48 count rate (γ-quanta min^{-1})
May–June 1997	50569–50609	1.54 ± 0.03	0.300 ± 0.027
May–July 2004	53140–53210	0.46 ± 0.03	0.11 ± 0.02
July–September 2004	53211–53281	0.32 ± 0.03	–

energies. The May period contributed about 36% to the total number of detected VHE γ-rays. It is also apparent that the event rate for the May data set was about 2.5 times greater than the event rates for the June and July data sets, which nearly coincided within the errors.

The confidence levels of the detected fluxes in May, June and July are 4.2σ, 3.2σ and 2.6σ respectively. The flux from Mrk 501 in May was greater than the average flux in the observation period and less than the detected flux for 1 May–10 June 1997 [13].

It is interesting to compare the behaviour of the Mrk 501 in X-ray and VHE γ-ray in different periods. The correlation of teraelectronvolt emission of Mrk 501 with the flux measured by the RXTE All Sky Monitor in the energy range 2–12 keV was revealed during the 1997 observation campaign by Aharonian *et al.* [12].

We have also compared our data with the source intensity in X-rays. Table 3 shows the average count rates of the ASM detector (quick-look results provided by the ASM–RXTE team) and GT-48 in different epochs. It is apparent that the object was in a more quiescent state in 2004 in comparison with the 1997 data for both X-rays and VHE γ-rays. Accordingly, from the behaviour of the source in X-ray in the next 70 days, one may suppose that Mrk 501 was more active in May–July 2004 (see table 3).

5. Conclusion

The flux from galaxy Mrk 501 at $E \geq 1$ TeV was detected at the 5.6σ level. The reliability of VHE γ-ray selection was confirmed by near-coincidence of excess events for different orientation parameters.

The comparison of the source behaviour in the X-ray and VHE γ-rays showed that the object was in a more quiescent state in the 2004 observation period in comparison with the 1997 data in both energy bands. The relationship between X-ray and teraelectronvolt data also assumes that Mrk 501 was in a more active state in May–July 2004 than in the next period of the same duration.

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