THE VARIATIONS OF VERY-HIGH ENERGY γ-QUANTA FLUX FROM THE BLAZAR 3C 66A IN 2002

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The extra-galactic source blazar 3C 66A was observed in 2002 with the aid of the air Cherenkov telescope GT-48 dedicated for stereoscopic measurements of extensive air showers (EAS). The analysis of the observational data obtained during the period November–December with a total exposure time of 6^h40^m revealed a γ-ray flux at $E > 1$ TeV $\approx 93\%$ of the steady flux from the Crab Nebula at $5.03\,\sigma$ level. The observations have shown variations of flux intensity from source in the very-high energy (VHE) band which may be interpreted as low and high states of the object during the observing period. The temporal properties of object are correlated well with quasi-simultaneous observations in the 2–10 keV energy band as measured by the All Sky Monitor onboard RXTE.

INTRODUCTION

Observation of VHE cosmic γ-rays at different redshifts is a means to probe the intergalactic infrared radiation field (IIRF) and to test cosmological models [16, 20]. Propagating in intergalactic medium, VHE γ-rays interact with IR photons through the pair-production mechanism and attenuate the high-energy ends of blazar spectra. Thus, looking for cutoffs in the γ-ray spectra of distant blazars, one may judge about the energy density of IIRF.

Another aspect of VHE cosmic γ-rays observations arises with the problems of empirical and theoretical research of radiation processes in blazars and of the understanding their structure. Blazars emit an essential part of their power in the high energy and VHE bands. Their fundamental feature is the beamed continuum, caused by relativistic jets ejected from the central engine [5].

According to commonly adopted models, the γ-ray emission from blazars may be explained by two main mechanisms – the synchrotron and inverse Compton (IC) radiation. Among them, the most popular model is the Synchrotron-Self Compton one (SSC) in which the Compton scattered photons by relativistic electrons emitting the synchrotron radiation have energies in some cases in the TeV range [13]. Due to the synchrotron and IC radiation, the spectral energy distribution (SED) of γ-bright blazars is marked by two broad peaks, the first of them is extending from the radio to UV/X-ray band and the second one may reach TeV energies [18].

Emission in two peaks, correlated in different ways, may be studied by quasi-simultaneous X-ray and TeV observations of blazars. Usually, these radiation processes are studied in the extreme states of blazars such as flaring with the highest seed photon densities and highest energy of electrons. Timing analysis of observing data and resolving characteristic time-scales of blazars may be used to constrain the geometry and spatial structure of emitting regions on different scales.

VHE γ-rays may be observed with the aid of the ground-based technique detecting Cherenkov light from induced EAS. Some γ-ray sources which have been detected by the EGRET detector onboard the Compton Gamma-Ray Observatory, covering the energy band from about 30 MeV to above 20 GeV [19], have displayed the fluxes in the VHE band too. Among them are Mrk 421 at $z = 0.031$ [14], Mrk 501 at $z = 0.033$ [15], 1ES 2344+514 at $z = 0.044$ [4], 1ES 1959+650 at $z = 0.047$ [2], BL Lac at $z = 0.069$ [11], H 1426+428 at $z = 0.129$ [1], and 3C 66A at $z = 0.444$ [12].

The last object has the highest redshift in comparison with the others which makes the increasing order of redshift. Thus, its observations are of great interest. The blazar 3C 66A was also classified as a BL Lac object owing to its high optical polarization and the brightness variability with an amplitude of about 2 mag [9]. Its flux in the 0.2–4 keV range reached 10^{-11} erg cm^{-2} s^{-1} in the flaring period according to X-ray observations onboard the Einstein Observatory [8].

In this paper, we present our observations of 3C 66A at $E > 1$ TeV in comparison with flux variations in X-rays.

CHERENKOV TELESCOPE AND OBSERVATION

The second generation γ-ray telescope GT-48 is situated at an altitude of 600 m above sea level. It consists from two identical alt-azimuth mountings, or sections, separated apart by 20 m in the North–South direction. Four telescopes, which we call "elements", are mounted on each section. The optics of each element consists of four mirrors with diameters of 1.2 m with a common 5-meter focus. In the focal plane of each element, there is a camera consisting of 37 photomultipliers (cells) with a hexagonal grid pattern which organize 37 channels. Each camera has field of view equal to 2.6° and records images of Cherenkov flashes in the visible band (300–560 nm). The signals from the cells from the four elements on each section are linearly added, channel by channel.

Flashes are registered only when the amplitudes of the signals for any two of the 37 channels exceed a certain threshold. The time resolution for the coincidence scheme is 15 ns. Flashes are recorded in a digitized form. The total area of mirrors on both sections is 36 m^2. The mountings are geared by a control system with a pointing accuracy of 0.05°. The effective threshold energy for the detection of γ-rays is approximately 1 TeV. The telescope was described in detail in [21].

Observations were made in the ON/OFF mode, when ON runs (source exposure) are followed by OFF runs of the background registration with a 30 minutes shift on right ascension. Both ON and OFF runs were 25 minutes in duration and carried out in the same range of elevation. In all 21 ON/OFF pairs were taken in two dark moon periods. By processing of observing data, the weather conditions and apparatus noises were taken into account, and 5 ON/OFF pairs were disregarded. 16 pairs with a total exposure time of $6^h 40^m$ and the same time of background observations were taken for processing of Cherenkov light images from EAS produced by γ-ray primaries and cosmic ray (CR) primaries.

DATA REDUCTION AND ANALYSIS

Parameters of the remaining flashes were processed using formal mathematical methods. The first and second moment of the brightness distribution was calculated and used for deriving of the centres of the brightness distribution and effective dimensions of flash images. The parameters of flashes recorded simultaneously at each section were determined independently using the data for each section.

All the registered showers, coming from the source direction (ON runs) as well as from the surrounding sky region (OFF runs) are induced by a hadronic component of CR, mainly protons. Candidates for γ-rays are selected using differences in the shape and dimensions of images and their orientation concerning the source position in the field of view of camera. The images of γ-ray showers have the less effective dimensions and compact forms and are aligned in the direction of source, while the images from proton showers are greater, have more fragmented forms and an isotropic orientation.

Firstly, for the shape cut, we have used the so-called IPR parameter. It was assigned to the zero value for images having the most compact form and to 1–7 for more fragmented images. Usually, the IPR parameter did not exceed 1, in other words, is was assigned to 0, 1. The IPR parameter set may be different for each section and, also, for each object under analysis. For the 3C 66A data, parameter IPR was equal to 0 for both sections.

For selection of γ-like events from their images, their effective dimensions – *length, width*, orientation parameters *miss* (the perpendicular distance of the centre of the field (the source) from the major image axis), and *dist* (the distance of image centroid from source) – were used [6] (Fig. 1).

Flashes were also selected taking into account amplitudes of detected signals because the parameters of flashes with low amplitudes are defined with high errors.

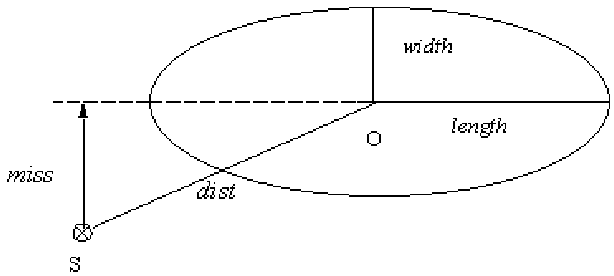

Figure 1. The main selection parameters of flash image. O is the centre of the brightness distribution, S is source position in the field of view of camera

THE RESULTS OF ANALYSIS

The selection statistics is summarized in Table 1. Results are given in terms of the parameter *miss* accompanied with selection of events by parameter *dist*. The mean counting rate for observing period is equal to (0.163 ± 0.032) γ-quanta min^{-1}. To convert this counting rate to flux, we have expressed it as a fraction of the steady counting rate of VHE γ-quanta from the Crab Nebula observed in the same season, equal to (0.176 ± 0.033) γ-quanta min^{-1} [10]. Comparison of two quantities for count rates gives a value of flux of VHE γ-quanta for 3C 66A, which is equal to (0.926 ± 0.355) Crab.

Table 1. Recorded and selected events

Selection algorithm	Number of events on source	Number of events on background	Resulting events number	Significance, σ
No selection	5811	5709	102	0.95
Selection by amplitude, form and dimension	402	347	55	2.01
Selection by *miss* $< 0.175°$	116	51	65	5.03

During four years of observations in CrAO (1996–2000), the blazar 3C 66A had exhibited an averaged flux of VHE γ-quanta equal to $(2.8 \pm 0.4) \cdot 10^{-11}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at $E > 1$ TeV [17]. From the calculations of the flux from the Crab Nebula with the same energy threshold we derived the value of $(1.5 \pm 0.3) \cdot 10^{-11}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. This quantity is in accordance with our observations of the Crab Nebula in 2002 [10] and a commonly accepted value [7]. Thus, the average flux of VHE γ-quanta from 3C 66A in 1996–2000 is equal to (1.9 ± 0.6) Crab. On the basis of this reanalysis of the early reported data, we may conclude that the source was in 2002 in full in a low state.

Using the method of trial sources [3] based on the orientation difference of images from γ-ray and CR primaries, the distribution of selected flashes over the detector's field of view was calculated, and the position of the true γ-ray source was determined. Figure 2 shows a three-dimensional histogram, and Figure 3 shows isophotes of this distribution. The precision of the determination of coordinates from the Cherenkov data is $\pm 0.1°$. ($\Delta\alpha$, $\Delta\delta$) are deviations from the source in right ascension and declination. $N\gamma$ is the number of selected events. The form of histogram confirms that the detected VHE γ-quanta were emitted by a point source in the direction of the object with the coordinates of 3C 66A.

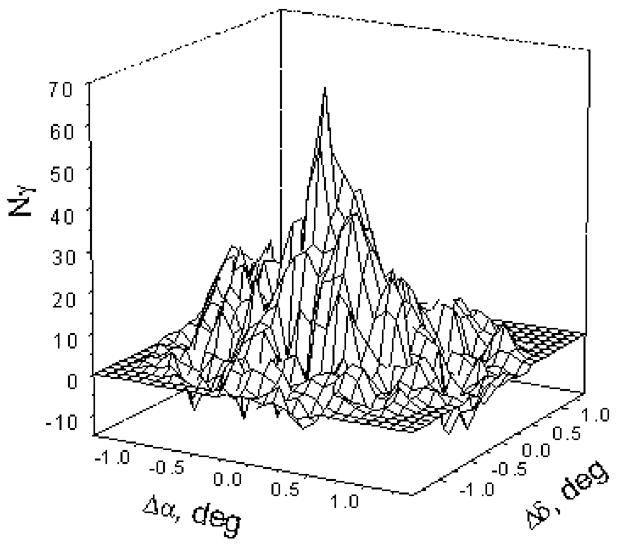

Figure 2. Stereo "map" of the distribution of γ-ray arrival directions from 3C 66A

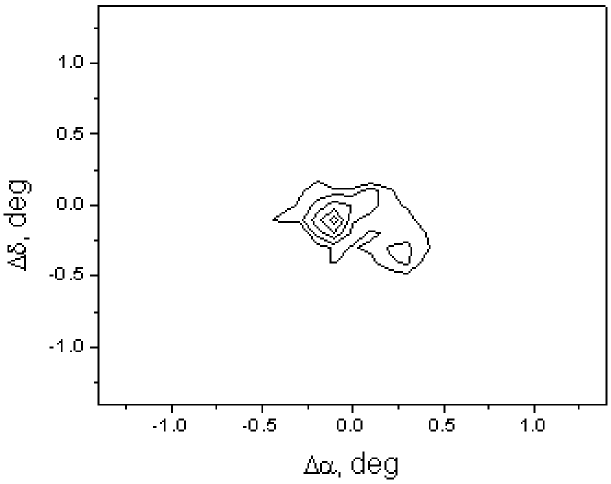

Figure 3. The “map” of isophotes for γ-ray source 3C 66A. The highest excess of γ-like events appears at $(-0.1, -0.1)$. The external isophote corresponds to 28 events. The isophotes step is 8 events

SOURCE VARIABILITY

The flux from the blazar 3C 66A at $E > 1$ TeV in observing period was variable. There may be seen two small flares (Fig. 4). In the first flare, occurred on November 29 (MJD52607.8), the flux rose up to 2 Crab at $2.7\,\sigma$ level. In the next night, the flux decreased up to 0.9 Crab at $1.51\,\sigma$ level. In the second flare, occurred on December 2 (MJD52611), the source come to the flux maximum for the observed period, equal to 2.3 Crab at $3.43\,\sigma$. In the next night, the source also was in the high state approximately on the level of 1.7 Crab ($2.69\,\sigma$). The summed flux of these two nights approached to 2 Crab ($4.34\,\sigma$).

If we represent the behaviour of the source by two states – below and above the Crab level, – then the summed flux in the high state will have value of ≈ 2 Crab at $5.05\,\sigma$ level and a low one – ≈ 0.43 Crab at $2.2\,\sigma$ level (Fig. 4).

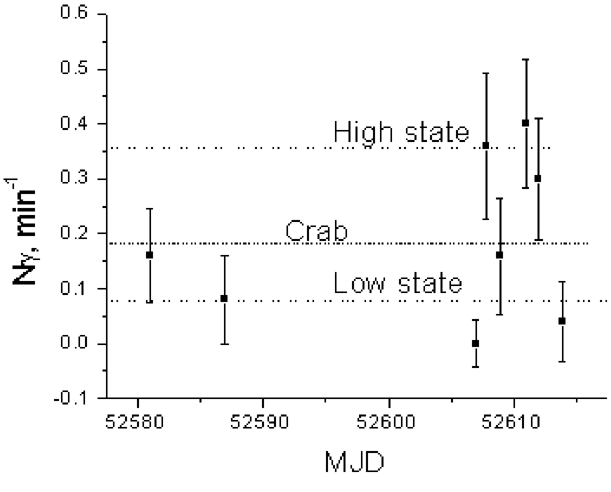

Figure 4. Light curve for 3C 66A at $E > 1$ TeV. Error bars are purely statistical. The short dash line shows the average count rate of VHE γ-quanta from the Crab Nebula

So that, the flux of VHE γ-quanta at high state was two times greater than the average flux in observing period and ≈ 4.7 times greater than the flux in the low state. This is a good accordance with the common property of γ-bright blazars – a strong variability in the VHE band.

X-RAY/γ-RAY CORRELATION

From Fig. 5 it can be seen that the X-ray/γ-ray flux variations are similar. Their most dominant feature is a simultaneous rising on November 28–29 (MJD52607 − 52608) and decreasing by the end of observations. These flux features may also be seen more distinctly in Fig. 6.

The keV counterpart of the second TeV flare coincides with it within 2 days. In both flares, the leading role of the IC emission is seen.

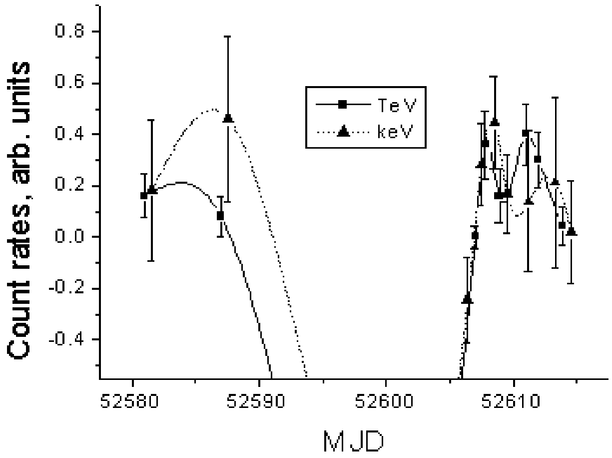

Figure 5. Light curves for 3C 66A at $E > 1$ TeV and in the 2–10 keV energy band (quick-look results provided by the ASM/RXTE team)

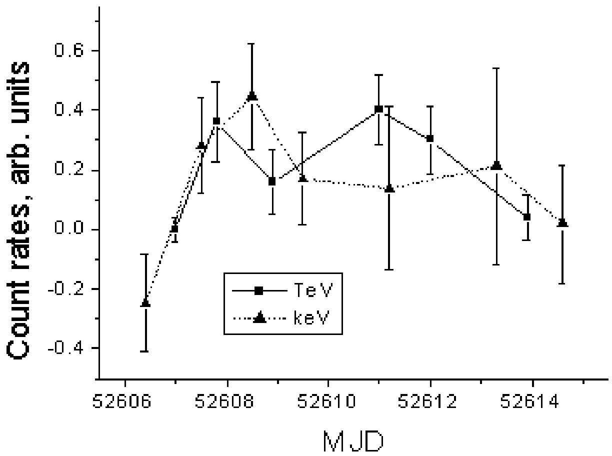

Figure 6. TeV/keV light curves in the dark moon period from November 28 till December 5, 2002

DISCUSSION

The analysis of our data obtained in 2002 with the GT-48 telescope confirms the existence of the TeV emission from the blazar 3C 66A comparable with the flux from the Crab Nebula at a confidential level $\approx 5\,\sigma$. The comparison with our early reported data for the 1996–2000 epoch shows the variability of the source in the VHE band on the yearly scale.

In the observing period, the behaviour of the source at $E > 1$ TeV may be represented by two states with a flux ratio of about 4.6. The increasing keV activity which is nearly coincided with the occurrence of the TeV flares and the light curves in both energy bands display the common tendency to decrease the activity by the end of observations.

Thus, our observations reveal the similar behaviour of 3C 66A in both energy bands.

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