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On the Correlation between the Very-High-Energy Gamma-Ray and X-ray Fluxes from the Blazar 3C 66A

V. V. Fidelis*

Crimean Astrophysical Observatory, p/o Nauchnyĭ, Crimea, 98409 Ukraine

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Abstract—We consider the very-high-energy (VHE) gamma-ray observations of the blazar 3C 66A with the GT-48 Cherenkov telescope in the period 2002–2004 in comparison with the quasi-simultaneous ASM/RXTE observations in the energy range 2–10 keV. We show that there are positive correlations between the VHE gamma-ray and X-ray fluxes from this object recorded in the observing periods of 2002–2004.

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INTRODUCTION

The blazar 3C 66A ($z = 0.444$) exhibits a strong polarization and a variability of the optical flux coincident with the X-ray flux variations (Takalo 1991). Variations in the optical flux from 3C 66A were observed on time scales from one hour to several months; the magnitude of the variability can change from $0\overset{m}{.}14$ for daily variations to 2^m for long-term variations (Miller and McGimsey 1978). The variability of the X-ray 1.2–10 keV flux was corroborated by the observations of the blazar 3C 66A onboard the Einstein orbiting observatory (Maccagni *et al.* 1983a). In July–August 1979, this observatory recorded a strong burst from the object with a peak luminosity of $L_X \geq 10^{46}$ erg s^{-1} in the energy range 0.2–4.0 keV (Maccagni *et al.* 1983b). Observations of the 3C 66A blazar onboard the BeppoSAX orbiting observatory in January 1999 and July 2001 showed similar 2–10 keV fluxes of $2.0\,^{+0.3}_{-0.5} \times 10^{-12}$ and $(2.0 \pm 0.6) \times 10^{-12}$ erg cm^{-2} s^{-1}, respectively. The bolometric flux from the synchrotron radiation component was estimated to be $F_s \approx 3 \times 10^{-10}$ erg cm^{-2} s^{-1} (Perri *et al.* 2003).

Multiwavelength observations of the blazar 3C 66A, from radio waves to gamma rays (EGRET), during several years (since 1991) revealed concurrent variations of the flux from the object (Takalo and Sillanpaa 2001). Although the object has been studied at a number of wavelengths, the data on the correlation between its fluxes at high and very high energies are still scarce. The accumulation and systematization of these data can elucidate the nature and mechanisms of the radiation from this object in the two energy ranges under consideration.

At present, several radiation models have been suggested to explain the spectral energy distribution of blazars. These models differ by both the geometry of the emitting region (single-zone homogeneous models or inhomogeneous jet models) and the nature of the photons that increase their energies during the inverse Compton scattering (Ghisellini *et al.* 1998). The inverse Compton scattering may involve both the synchrotron photons proper and the photons injected

Table 1. Observing periods for the blazar 3C 66A

Year	Beginning of observations	End of observations	Effective source exposure time, min
2002	2.11	30.11	225
	2.12	5.12	175
2003	23.9	30.9	300
	1.10	5.10	250
	2.11	25.11	200
2004	12.9	20.9	750
	22.10	22.10	50
	4.11	13.11	250
Total			2200

*E-mail: fedelis@crao.crimea.ua

Table 2. Selection effect for various observing periods

Year	Parameter	ON	ON-OFF	Q, standard deviations	$(\Delta\alpha; \Delta\delta)$
2002	MISS < 0°.175	116	65	5.0	−0°.1; −0°.1
2003	0°.142 < AZWIDTH < 0°.24	466	172	6.2	0.0; 0.0
2004	ALPHA < 35°	250	107	5.4	0.2; 0.1
2002–2003	0°.16 < AZWIDTH < 0°.24	237	125	6.7	0.0; 0.0
2002–2004	0°.16 < AZWIDTH < 0°.24	727	212	6.0	0.0; −0.1

into the emitting region from outside (from an accretion disk, a gas–dust torus surrounding the nucleus of the blazar). The actual blazar radiation mechanism can be dominated by one of the models or combine several models.

Whereas estimates of the correlation between TeV and X-ray fluxes are already available for less distant blazars, such as 1ES 1959+650 (Fidelis 2004), Mrk 421, and Mrk 501 (Katarzyński *et al.* 2005), these data for 3C 66A are limited (Fidelis 2005). Observations of this object over a wide energy range become particularly topical, because the spectral energy distribution for the blazar 3C 66A differs from that for the Markarian galaxies Mrk 421 and Mrk 501.

The synchrotron radiation for Mrk 421 and Mrk 501 peaks at X-ray energies, while the peak for the blazar 3C 66A is shifted to radio wavelengths (Weeks 2003). Accordingly, the peak of the inverse Compton scattering must be shifted to the lower frequencies.

The blazar 3C 66A has been observed at the Crimean Astrophysical Observatory since 1996 (Neshpor *et al.* 1998, 2003). The recorded very-high-energy energy (VHE) gamma-ray flux from this object averaged over the 1996, 1997, 1998, and 2000 observing periods is $(2.8 \pm 0.4) \times 10^{-11}$ cm^{-2} s^{-1} (Stepanyan *et al.* 2002). The VHE gamma-ray fluxes were shown to correlate with the optical fluxes. In this paper, we present our observations of the blazar 3C 66A with a GT-48 Cherenkov telescope in combination with the ASM/RXTE data.

VHE GAMMA-RAY OBSERVATIONS

The observations were performed with a GT-48 Cherenkov telescope consisting of two identical sections spaced 20 m apart, each of which is equipped with four 37-pixel light detectors (Vladimirskiĭ *et al.* 1994). Cherenkov radiation was recorded at optical wavelengths. We determined the threshold energy of the telescope by numerically simulating the development of a photon-electromagnetic cascade, 1 TeV. The total area of the composite mirrors on both sections is 36 m^2. Flashes were recorded only when they coincided on both sections and when the signal amplitude from any 2 of the 37 cells on each section of the telescope exceeded the established threshold.

The observations were performed in the ON mode with a duration of 25 min followed by OFF measurements of the same duration with a shift of 30 min in right ascension α. The observations in both modes were made at the same zenith distance. The center of the camera was directed to the blazar 3C 66A in the ON mode. For our analysis, we chose paired observing sessions carried out under good weather conditions. We selected a total of 88 paired observing sessions in the period 2002–2004 (see Table 1).

ANALYSIS OF OBSERVATIONAL DATA

The procedure for selecting the extensive air showers (EASs) produced by VHE gamma-ray photons from the showers triggered by cosmic rays is based on the difference between the parameters of the flash images in the field of view of a multipixel camera (Hillas 1985). The selection is additionally made by the amplitude of the detected signal. The gamma-ray flash selection procedure, as applied to the GT-48 gamma-ray telescope, was described in detail by Andreeva *et al.* (2000).

The selection effect is characterized by the signal-to-noise ratio $Q = (N_s - N_b)/\sqrt{N_s + N_b}$, where N_s and N_b are the numbers of gamma-ray-like bursts in the source and background observational data, respectively. The difference $N_s - N_b = N_\gamma$ is interpreted as the number of gamma-ray photons, and $\sqrt{N_s + N_b}$ is the statistical error of this number. Events with selection parameters outside a given

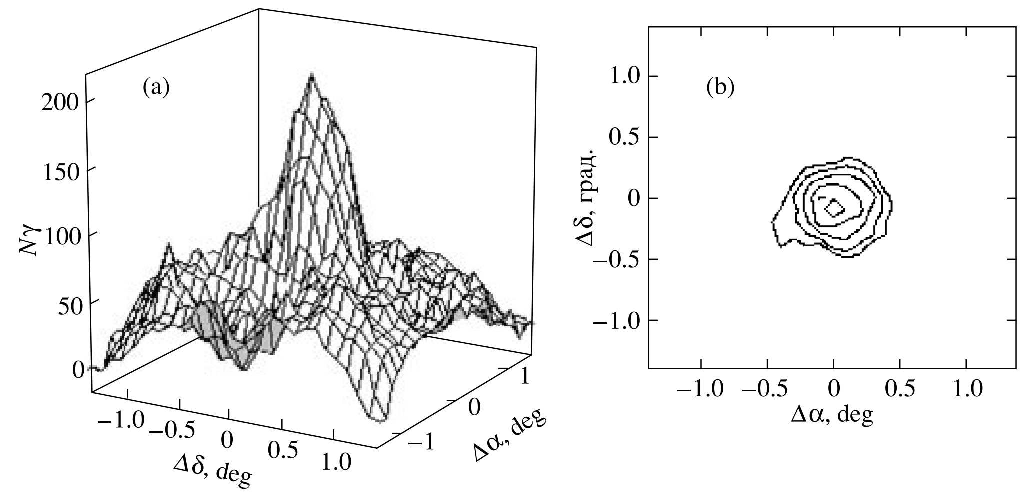

Fig. 1. (a) Stereo image of the distribution of VHE gamma-quanta arrival directions for the observing period 2002–2004. (b) Isophotes of this distribution. The outer isophote corresponds to 100 events; the subsequent isophotes correspond to 120, 150, 170, and 200 events.

range are excluded from the analysis. We also take into account the deviations of the maximum of the arrived VHE gamma-quanta from the coordinates of the observed object in right ascension ($\Delta\alpha$) and declination ($\Delta\delta$). Table 2 lists the results of the selection of EASs (each flash corresponds to one EAS) triggered by VHE gamma-quanta in various observing periods of 2002–2004. The selection by one of the parameters, ALPHA, MISS, or AZWIDTH, was combined with the selection by DIST parameter.

We see from Table 2 that the combined reduction of the observational data for 2002 and 2003 yielded the best selection effect with zero deviations from the coordinates of the object. Most of the selection variants (their parameters differ) have similar signal-to-noise ratios and insignificant deviations from the source's coordinates. Note that the total selection effect in the reduction of the data for several years is smaller than that for a simple addition of events through the loss of some of the gamma-ray-like events that do not satisfy the new selection criteria, because the selection parameters for observing periods of different years differ.

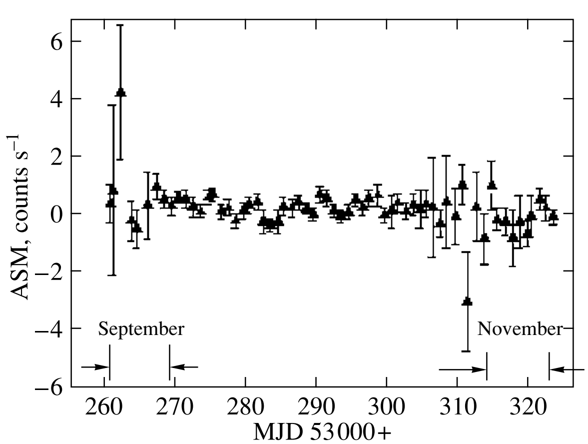

Fig. 2. Time dependence of the flux from the blazar 3C 66A in the energy range 2–10 keV (quick-look results provided by the ASM/RXTE team).

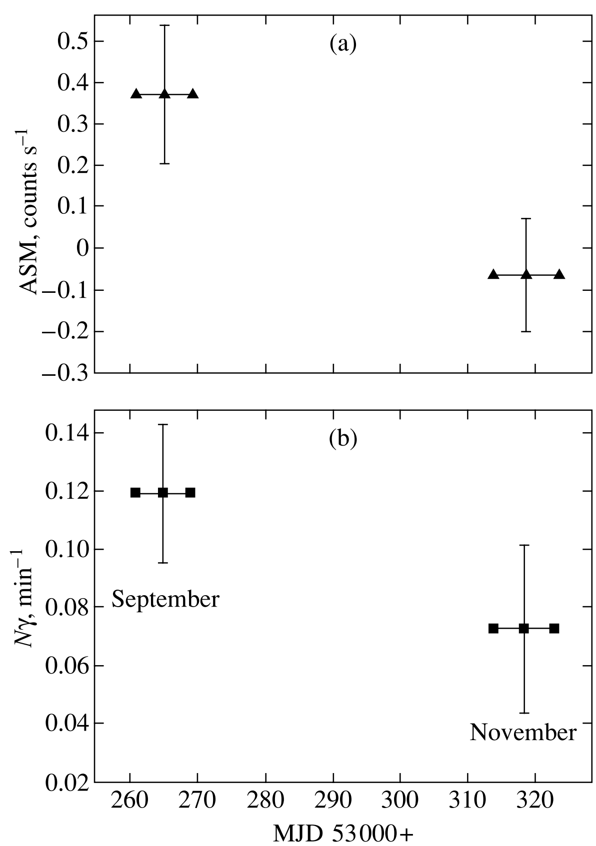

Fig. 3. Mean fluxes from the object in the energy range 2–10 keV (a) and above 1 TeV (b) recorded in September and November 2004.

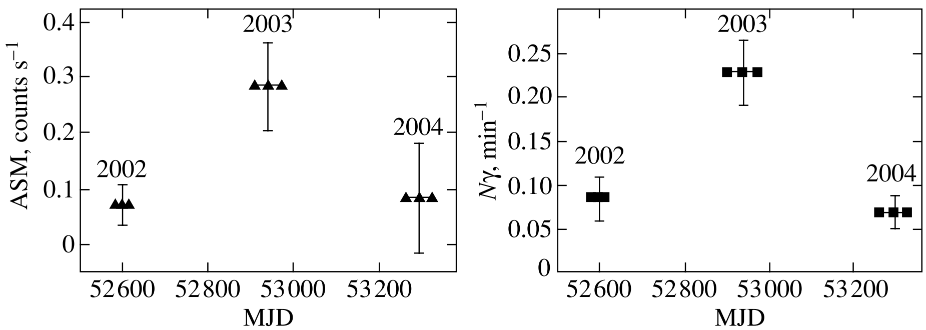

Fig. 4. Mean fluxes from the object in the observing periods of 2002–2004. Statistical errors are shown.

Figure 1 shows a three-dimensional distribution (histogram) of the number of selected gamma-ray bursts across the field of view of the detector and the isophotes of this distribution for the observing period 2002–2004 constructed using the method of trial sources (Akerlof *et al.* 1991). The accuracy of determining the source's coordinates using this method is $\approx 0^\circ.1$. The maximum of the arrived gamma-quanta is located almost at the center of the field of view of the camera (see Table 2 and Fig. 1b).

COMPARISON WITH X-RAY DATA

Figure 2 shows the light curve of the daily mean X-ray fluxes from the blazar 3C 66A in the energy range 2–10 keV for the period from September 12 through November 13, 2004. The mean 2–10 keV flux for the entire period covered by Fig. 2 (MJD 53260.8–53325.6) is 0.22 ± 0.04 s^{-1}, which is equivalent to ≈ 3 mCrab. Such a flux is typical of the blazar Mrk 421, which has a low luminosity in this energy range (quick-look results provided by the ASM/RXTE team) and which is located at a much smaller distance ($z = 0.031$).

We see from Fig. 2 that the period from November 4 (MJD 53314) through November 13 (MJD 53323), 2004, which coincides with the gamma-ray observations, is distinguished by reduced activity. This trend is also traceable for the mean VHE gamma-ray fluxes (Fig. 3). The statistical significance of the results obtained in September and November is ≈ 5 and ≈ 2.5 standard deviations, respectively.

Figure 4 shows the mean fluxes in two energy ranges for the observing periods of 2002–2004. The data for comparison in 2002 and 2004 were taken at zero deviations from the object's coordinates corresponding to the selection results in 2003. The correlation coefficient between the fluxes in the two energy ranges is ≈ 0.67.

The presence of a positive correlation between the fluxes in the two energy ranges is most clearly reflected in Fig. 5, which shows an increase in the TeV flux from the blazar 3C 66A with rising activity at keV energies. We also used the data for the three-year observing period. For our analysis, we used the quasi-simultaneous observations in the two ranges and, where necessary, interpolated the X-ray data on two adjacent observing nights. We estimated the correlation coefficient between the two fluxes to be 0.45 ± 0.11. The lower correlation coefficient than that in Fig. 4 is attributable to the choice of quasi-simultaneous data.

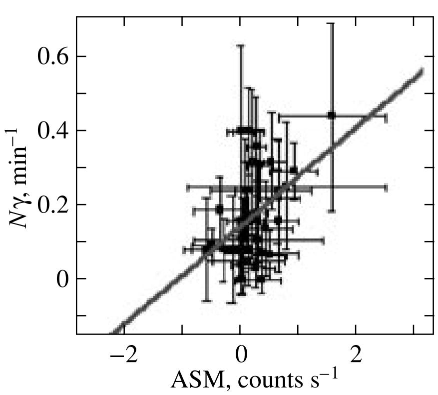

Fig. 5. Correlation between the daily main count rates in two ranges. The dashed line was drawn by least squares.

CONCLUSIONS

The VHE gamma-ray observations of the blazar 3C 66A over three continuous years allowed us both to confirm the existence of VHE gamma-ray radiation from it and to compare this radiation with the X-ray radiation in various observing periods. The presence of a positive correlation between the VHE gamma-ray flux and the X-ray flux may be evidence for a common electron nature of the synchrotron and inverse Compton radiation mechanisms. Since the fluxes in the two energy ranges are significantly correlated, they may be generated by charged particles (electrons) of similar energies.

Most of the radiation at the synchrotron and inverse Compton peaks for 3C 66A is emitted at electron Lorentz factors of $\gamma = 4.7 \times 10^3$ (Costamante and Ghisellini 2002). At such large Lorentz factors, the photons will be scattered by electrons in the Klein–Nishina mode. Photons with keV energies will then be upscattered to peak energies of $E \sim \gamma mc^2 \sim$ 2 GeV.

The shift of the inverse Compton component to the low-energy region can also result in its presence at keV energies, which can explain the observed correlation.

The actual nature of the radiation from the object studied is much more complex and may combine various mechanisms, including the simplest ones considered here.

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