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Blazar 3C 66A: Another Extragalactic Source of Ultra-High-Energy Gamma-Ray Photons

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Abstract—The observations of the object 3C 66A which were carried out with the GT-48 gamma-ray telescope at the Crimean Astrophysical Observatory in November–December 1996 revealed a flux of ultra-high-energy ($>10^{12}$ eV) gamma-ray photons from this blazar. According to preliminary estimates, the photon flux is $(3 \pm 1) \times 10^{-11}$ photons cm^{-2} s^{-1}. The blazar 3C 66A is the third extragalactic object from which a flux of ultra-high-energy gamma-ray photons was detected. Fluxes of gamma-ray photons were previously detected from the galaxies Mk 421 and Mk 501 at the Whipple observatory. This result provides further evidence that active processes proceed in blazars which are accompanied by the generation of cosmic rays responsible for the emission of gamma-ray photons.

INTRODUCTION

The search for ultra-high-energy gamma-ray photons ($>10^{11}$ eV) has recently led to the discovery of gamma-ray fluxes from extragalactic objects. The galaxy Mk 421 proved to be the first object of this kind, whose flux has been recorded at the Whipple Observatory (Punch *et al.* 1992), where two years later the flux of gamma-ray photons from the Mk 501 galaxy was also detected (Catanese *et al.* 1995). These objects belong to the Lacertae group. They are distinguished by significant variations in radiation fluxes at all frequencies, from radio waves to X-ray radiation. The characteristic variation time varies from minutes to one year. Lacertae are distinquished by a strong tendency for flare (on a time scale of a few days) and eruption (with a duration of several months) activity. Large amplitudes of variations in the X-ray range coincide in some cases with optical variations (Maccagni *et al.* 1987).

All of this suggests that these objects have many high-energy particles, whose radiation spans from radio waves to high- and ultra-high-energy gamma-ray photons. Gamma-ray fluxes with energies >100 MeV from a large number of active galaxies were revealed in the satellite observations with the aid of the EGRET instruments. The flux of high-energy gamma-ray photons was recorded with these instruments in the direction close to the direction toward 3C 66A. In the second EGRET catalog, the source named 2EG J0220 + 4228, with the coordinates $\alpha = 35\overset{\circ}{.}01$ and $\delta = 42\overset{\circ}{.}48$, is given. 3C 66A is an object of the BL Lac type. Its radiation in the optical region is strongly polarized (up to 15% or, occasionally, to 30%) (Takalo 1991). The spectrum in the optical range is continuous, with very weak lines. The results obtained stimulated observations of the 3C 66A object on the ground-based GT-48 gamma-ray telescope at the Crimean Astrophysical Observatory with the aim of revealing a gamma-ray flux in the ultra-high-energy region ($>10^{12}$ eV). Observations were made in the period from November 13 to December 12, 1996.

A BRIEF DESCRIPTION OF THE GT-48 GAMMA-RAY TELESCOPE AND OBSERVATIONAL TECHNIQUE

The detection of gamma-ray photons with energies $E > 10^{11}$ eV is performed with the aid of ground-based instrumentation. The fact is used that ultra-high-energy gamma-ray photons, while interacting with atomic nuclei, produce a so-called wide atmospheric shower consisting of high-energy electrons and positrons, which emit Cerenkov photons in the optical range at a small angle (~1°) to the direction of motion of the initial photon. This allows one to determine the region where the gamma-ray flux comes from. The area illuminated by a Cerenkov flash is fairly large: ~ 10^4 m^3. Because of this circumstance, the detection of low (about 10^{-11} photons cm^{-2} s^{-1}) gamma-ray fluxes is possible. The main impediment to the detection and study of sources of ultra-high-energy gamma-ray photons is the presence of a significant cosmic-ray background, whose particles produce Cerenkov flashes in the Earth's atmosphere, which are difficult to distinguish from flashes caused by gamma-ray photons. The use of multielement cameras makes it possible to cut off the predominant portion of flashes produced by the charged cosmic-ray component. The setup consists of two identical alt-azimuthal mountings (sections)—northern (1) and southern (2)—spaced at a distance of 20 m in the north–south direction at a height of 600 m above sea level. Six telescopes were mounted in parallel in each section. Optics of each telescope comprises four 1.2-m mirrors. The light detector positioned in the

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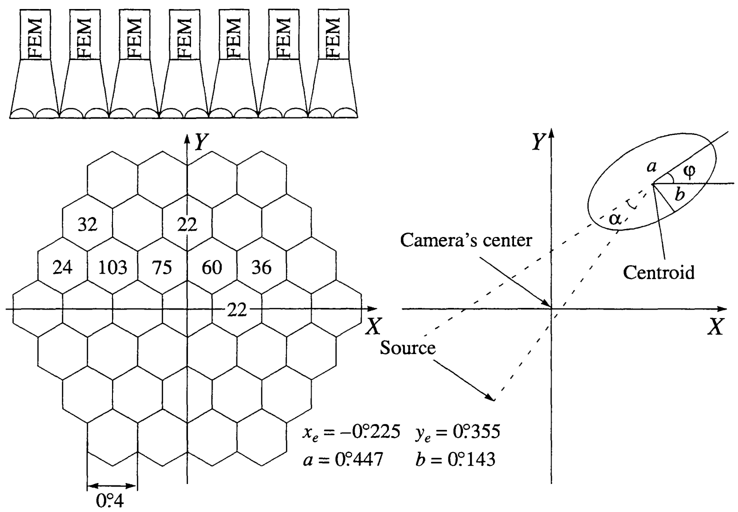

Fig. 1. The schematic view of the light detector and parameters of Cerenkov flash. The numbers in the cells give the amplitude of the light flash in a given channel expressed in discrete units of the analog–code convertor. The flash parameters are: the effective "length" (a) and the effective "width" (b) of the flash image; the azimuthal angle α; and the orientation angle φ.

telescope's focal plane consists of 37 photoelectron multipliers (FEMs) which are used to record images of Cerenkov flashes in the visible region (300–600 nm). A conical lightguide is mounted in front of each FEM. The mean diameter of the light-guide entrance window corresponds to the linear angle of the field of view of one cell 0.4° (Fig. 1). The overall field of view of the light detector is 2.6°. Signals from FEMs positioned in the same way in the field of view of light detectors, i.e., the FEMs which are able to pick up the Cerenkov radiation from the same part of the sky, are added linearly and transferred through the corresponding channel into the amplitude–code converter with subsequent recording on the PC disk. We obtain in this way the discrete image of the flash consisting of 37 numbers (according to the number of channels). For greater clearness, we do not show in Fig. 1 the flash amplitudes in the channels where their value is less than the preset threshold level. Flashes are recorded only in the case where the amplitudes of synchronous signals in any two of 37 channels are greater than the preselected threshold. The time resolution of the coincidence circuit is 15 ns. The total area of mirrors in both sections is 54 m^2. The setup motion is accomplished by the control system with a position accuracy of ±1′. Observations can be made either in the two-section coincidence mode or independently by each section. The effective threshold energy for detecting gamma-ray photons is 0.9 TeV. The detailed description of the GT-48 telescope, as well as the observation and processing technique, can be found in Vladimirskii *et al.* (1994).

OBSERVATION AND DATA REDUCTION

Observations of the 3C 66A object ($\alpha = 2^h22^m40^s$, $\delta = 43°02'08''$, 1996) were carried out with the use of two parallel sections in the coincidence mode with a time resolution of 100 ns. The use of a double setup in the section coincidence mode, instead of single telescopes (Cawley *et al.* 1990), almost completely eliminates the events caused by individual charged particles. The gamma-ray telescope can detect an individual charged particle if it passes through two or more FEMs and produces in them signals with amplitudes above the threshold level. This fact was established in foreign studies and in our works: the signals are recorded even with closed covers of light detectors. However, in our setup such events are fully excluded when we work in the coincidence mode (see for details the work by Neshpor *et al.* 1997).

Observations of the 3C 66A object were performed by the object monitoring method, comparing the results of observations of the gamma-ray source and the background. The time shift was 30 min. The background observations were made at the same azimuthal and zenith angles as the source observations. A total of 12 sessions, of 25-min length each, was made so that the total duration of the source observations was 300 min. The data obtained were processed as follows: (1) we removed the data in which the overall signal from light detectors of three telescopes caused, at least in one channel, the saturation of the analog–code converter; (2) the signal amplitudes in channels were corrected using the calibration coefficients; (3) the flashes, whose maximum amplitude was in the outer ring of the cells of the light detector, were discarded; (4) the events whose recording was accompanied by the mulfunctioning of the telescope guidance system were removed (i.e., if the departure of the telescope's optical axis from the preselected direction was in excess of 3'). Our study showed that the parameters of flashes with the overall amplitude less than 50 photoelectrons are severely dis-

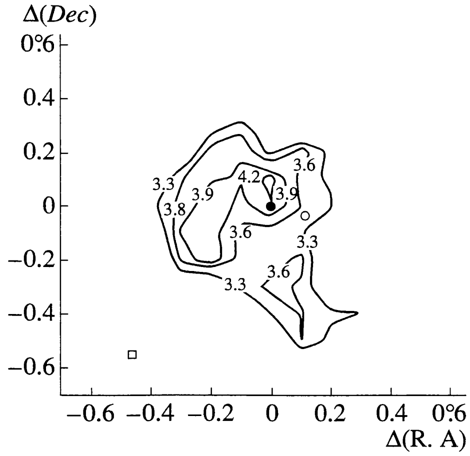

Fig. 2. Isophotes of the distribution of the quantity A/σ for the 3C 66A gamma-ray source. The position of the blazar 3C 66A is marked by the filled circle. The open circle indicates the position of the powerful radio galaxy 3C 66B. The square denotes the position of the high-energy gamma-ray source 2EG J0220 + 4228. The deviation in declination from the coordinate of 3C 66A is plotted on the vertical axis, the deviation in right ascension is given on the horizontal axis.

torted; these flashes have, therefore, been excluded from consideration. As a result of primary processing, there remained 5708 events recorded in the source observations and 5671 events recorded in the background observations. Then we determined the flash parameters: the first and second moments of the light brightness distribution, from which all remaining parameters were found. The numerical values of parameters for analysis were determined as follows. Let x_i, y_i ($i = 1, \ldots, n$) be the coordinates of the axes of the ith FEM in the light detector plane (Fig. 1); and I_i be the signal amplitude in the ith FEM. The longitudinal and the transverse (a and b, respectively) size of the Cerenkov flash image and the orientation angle φ, which characterizes the direction of maximum flash extent, i.e., the flash orientation, can then be determined from the expressions

$$a = \sqrt{k_{11}\cos^2\varphi - k_{12}\sin 2\varphi + k_{22}\sin^2\varphi},$$

$$b = \sqrt{k_{11}\sin^2\varphi + k_{12}\sin 2\varphi + k_{22}\cos^2\varphi},$$

$$\varphi = \frac{1}{2}\arctan\frac{2k_{12}}{k_{22} - k_{11}},$$

where $k_{11} = \min(k'_{11}, k'_{22})$, $k_{22} = \max(k'_{11}, k'_{22})$, and

$$k_{12} = \sum_{i=1}^{n} I_i(y_i - y_c)(x_i - x_c)/\sum_{i=1}^{n} I_i.$$

$$k'_{11} = \sum_{i=1}^{n} I_i(x_i - x_c)^2/\sum_{i=1}^{n} I_i,$$

Here

$$x_c = \sum_{i=1}^{n} I_i x_i/\sum_{i=1}^{n} I_i \quad \text{and} \quad y_c = \sum_{i=1}^{n} I_i x_i/\sum_{i=1}^{n} I_i$$

are the coordinates of the centroid of the flash image. Upon determining the sizes a and b, the orientation angle, and the centroid position, we can find all other parameters (Vladimirskii *et al.* 1994). The parameters a and b are coordinate-independent because they do not depend on the source position relative to the flash.

SELECTION OF GAMMA-RAY PHOTONS

As noted above, the parameters of Cerenkov flashes produced by ultra-high-energy photons differ slightly from the parameters of flashes generated by charged cosmic-ray particles. The problem lies in the fact that the distributions of parameter values from flashes produced by gamma-ray photons and charged particles are broad and overlap to a significant degree. However, the multidimensional distributions over various parameters permit us to remove up to 99% or more flashes caused by the charged component of cosmic rays. It is necessary for this purpose to fit the critical (or boundary) values of the parameters involved in order to obtain the optimal signal-to-noise (S/N) ratios $= (N_s - N_b)/\sqrt{N_s + N_b}$, where $(N_s - N_b) = N_\gamma$ is the number of flashes identified as gamma-ray photons, and the noise $\sqrt{N_s + N_b}$ is the statistical error in signal determination.

We use the effective length and the effective width of the flash image, and the flash orientation with respect to the direction to the gamma-ray source candidate (specified by the angle α; see Fig. 1) as parameters for separating gamma-ray showers against the background of charged-particle showers (p-showers). The angle α depends on the source position and is called the coordinate-dependent parameter. Determinations of Cerenkov flash parameters are described in detail by Vladimirskii *et al.* (1994).

Images of flashes produced by gamma-ray photons have smaller sizes and are directed toward the source. A simultaneous detection of flashes by the two sections of the instrument makes it possible to use another parameter, DRO, which is called the stereoeffect magnitude and is simply the angular distance between the centroids of Cerenkov flash images recorded by different sections of the GT-48 setup:

$$\mathrm{DRO} = \sqrt{(x_c(1) - x_c(2))^2 + (y_c(1) - y_c(2))^2}.$$

Here $x_c(1)$, $y_c(1)$, $x_c(2)$, and $y_c(2)$ are the coordinates of the centroids of Cerenkov flash images at the northern and southern sections of GT-48, respectively. Since the showers produced by gamma-ray photons develop at higher altitudes than p-showers (produced by charged particles), they have, on the average, a larger DRO parameter. This provides the selection of gamma-ray showers.

In our case, gamma-ray showers were selected in the following manner. From further analysis, we ruled out the showers for which the image width $b > 0\overset{\circ}{.}175$ for both sections, as well as the showers with DRO > $0.85\overline{\mathrm{DRO}}$ (where $\overline{\mathrm{DRO}}$ is the background DRO value, mean in the given observing session). In addition, we removed the showers for which the angle α made with the direction to the candidate source is in excess of 20°. The parameter values used for selecting gamma-ray showers were determined from the maximum S/N ratio, i.e., the ratio of the number of selected events to the statistical error of determination of this number. We took into account the results of previous studies of this problem (Neshpor *et al.* 1995).

As a result, after selection procedure there remained 387 events at the source and 258 events at the background. The excess number of events in the source observations, equal to 5.1 standard deviations, can be considered as an indicator of the presence of the ultra-high-energy gamma-ray flux from the 3C 66A object.

The multielement light detectors of second-generation gamma-ray telescopes permit us to determine more accurately the region in the sky where the gamma-ray source is located. To do this, we used the trial source method (Akerlof *et al.* 1991; Neshpor *et al.* 1994; Fomin *et al.* 1994) based on the fact that images of gamma-ray photons in the telescope's focal plane are pointed, within the accuracy of determination of the α angle, to the source, i.e., normally to the camera's center, whereas the major axes of the ellipses of p-shower images are oriented uniformly in all directions. Therefore, if we select flashes using an arbitrary point with coordinates (x_i, y_j) in the focal plane to indicate the source direction and if the selection is done over the α angle, the number of the remaining p-showers will not depend, to the first approximation, on the position of the source candidate. On the other hand, the number of images produced by gamma-ray showers substantially depends on the position of the source candidate and has a maximum in the direction of the genuine source. We can construct the distribution of the number of selected flashes within the field of view of the light detector as a function of the position of the source candidate, $N(x_i; y_j)$, where x_i and y_j are the coordinates of the point. In other words, we construct the "map" and can therefore find the position of the real gamma-ray source. To eliminate instrumental effects (for details, see Kornienko *et al.* 1993), the maps are constructed both for the data obtained from the source observations, $N_s(x_i; y_j)$, and for the background observational data, $N_b(x_i; y_j)$. We used the flashes selected on the basis of the coordinate-independent parameters b and DRO. As a result, we found 1901 flashes at the source and 1659 at the background. By subtracting the number of background events from the number of source events, we obtained the map for the quantities $A_{ij}/(\sigma)_{ij}$, where $A_{ij} = N_s(x_i; y_i) - N_b(x_i; y_i)$ and $\sigma_{ij} = \sqrt{N_s(x_i; y_i) + N_b(x_i; y_i)}$. Obviously, the source direction coincides, within an error of ($\pm 0\overset{\circ}{.}3$), with the maximum of the A/σ value. The error was determined from the half-width of the spatial distribution of the $A_{ij}/(\sigma)_{ij}$ quantity.

Figure 2 shows the isophotes of A/σ for the α criterion, which were constructed on the basis of data collected by the southern section of the instrument. We also plotted on this figure the most probable position of the high-energy gamma-ray source 2EG J0220+4228 established by the EGRET instrument (Thompson *et al.* 1995), as well as the position of the blazar 3C 66A and of the powerful radio galaxy 3C 66B. The error in determining the source position with the EGRET instrument was in this case ~1°.

CONCLUSION

The coincidence of the coordinates of the gamma-ray source found by the method of trial sources with the coordinates of the radio source 3C 66A and the data analysis based on the coordinate-independent parameters strongly suggest (at confidence $>5\sigma$) that an ultra-high-energy gamma-ray source (with $E_{\mathrm{thresh}} > 0.9$ TeV) is observed in the direction of the blazar 3C 66A. Note that the powerful radio galaxy 3C 66B is located in the immediate vicinity to this source, and, therefore, it is not inconceivable that the gamma-ray source found by us coincides with this object. According to our estimates, the flux of gamma-ray photons with energy > 0.9 TeV is $(3 \pm 1) \times 10^{-11}$ photons cm^{-2} s^{-1}. If we assume that for 3C 66A $z = 0.444$ (Takalo, 1991), the gamma-ray energy flux will then be 10^{46} erg s^{-1}, provided that radiation is isotropic. In reality, the isotropy of gamma-ray radiation is hardly probable. It is worth noting that the apparent brightness of the galaxy 3C 66A increased during our observations (Efimov 1997). Recently, the ultra-high-energy gamma-ray radiation from the galaxies Mk 421 and Mk 501 was found to be highly variable (Mc Enery *et al.* 1997; Quinn *et al.* 1997). It is, therefore now too early to do estimates of the possible contribution of extragalactic sources to the diffuse background of ultra-high-energy gamma-ray photons, which, moreover, cannot be assumed known. No doubt, it is desirable to support the result obtained in this study by complementary measurements. Astrophysically, 3C 66A is a very interesting object, and it is desirable to observe it in the future using both the EGRET instruments and Cerenkov detectors.

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