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Analysis of the Activity of the Blazar BL Lacertae over the Period 1998–2011

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Abstract—In 1998–2011 the blazar (active galactic nucleus) BL Lacertae was observed at Crimean Astrophysical Observatory (CrAO) with the second-generation GT-48 Cherenkov telescope at energies >1 TeV with a total significance of 11.8σ. More than 20 flares and a fourfold change in yearly mean fluxes (>1 TeV) were recorded. The optical (B band) data obtained at CrAO and the TeV data are shown to correlate in some time intervals. The optical data are also compared with the X-ray RXTE/ASM (2–10 keV) data. In addition, the data from GT-48 are compared with the gamma-ray fluxes recorded by the Fermi LAT space telescope (0.1–300 GeV). The 2009 flare at TeV and Fermi energies has been studied. As a result, it has been found that as the activity rises the increase in flux at high energies exceeds its increase at low energies. This conclusion may be related to the conversion mechanism of particle acceleration. This is consistent with the results of studies for a similar object, 1ES 1426+428.

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INTRODUCTION

BL Lacertae (1ES2200+420, $z = 0.069$) is the archetype of a whole class of objects called BL Lac objects in the literature. These, in turn, belong to blazars, one of the most extreme types of active galactic nuclei (AGNs). Electromagnetic radiation from these objects can be observed from radio waves to very-high-energy (VHE) gamma-rays with energies $E > 100$ GeV. The spectral energy distribution of BL Lac objects is characterized by a double-peaked shape. The first peak (low energies) is a consequence of synchrotron radiation from relativistic electrons; the second peak is produced through inverse Compton scattering of high-energy particles by the synchrotron photons themselves (the so-called synchrotron self-Compton). In addition, inverse Compton scattering is possible on other photons, for example, from the region of the accretion disk around a supermassive black hole, which is currently believed to be the source of a colossal luminosity of blazars and other AGNs. When the synchrotron peak lies in the submillimeter to optical band, the objects are classified as low-frequency peaked BL Lacs (LBLs). If the peak is located in the ultraviolet to X-ray band, then these objects are called high-frequency peaked BL Lacs (HBLs) (Hayashida et al. 2007). BL Lacertae itself belongs to LBLs with the synchrotron peak at a frequency of 2.2×10^{14} Hz (Sambruna et al. 1999).

The observations of AGNs, including BL Lac objects, in the range of the highest-energy gamma-ray emission recorded with both ground-based Cherenkov telescopes and orbital ones have been of great interest in recent years. Like the emission at lower energies, the gamma-ray emission in BL Lac objects is characterized by significant variations; in particular, BL Lac objects show a tendency to flare activity on a time scale of several days (Zhovtan et al. 2011). In addition, it has been established that the differential spectral index decreases with increasing activity, i.e., the spectrum becomes flatter, implying that higher-energy particles are accelerated more efficiently during perturbations (Neshpor 2011). These and other peculiarities of the activity of BL Lac objects require a further study.

VHE OBSERVATIONS OF BL LACERTAE

The galaxy BL Lacertae was observed back in the 1970s with first-generation Cherenkov telescopes at Whipple observatory (Fazio et al. 1972) and Crimean Astrophysical Observatory (CrAO) (Srepanian et al. 1975), but no VHE gamma-ray

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Table 1. Observations of BL Lacertae at CrAO with GT-48

Years	Periods of observations	MJD	Number of scans	Duration of observations, min
1998	June 23–Sep. 1	51018–51058	65	2275
2000	July 28–Oct. 17	51754–51866	38	1330
2002	July 8–Dec. 4	52463–52613	17	595
2003	Aug. 24–Nov. 25	52875–52968	33	1155
2004	Sep. 14–Nov. 11	53263–53321	25	875
2006	Aug. 20–Sep. 29	53967–54007	27	945
2007	Aug. 18–Oct. 12	54331–54386	24	840
2008	July 30–Nov. 1	54680–54741	40	1400
2009	Aug. 17–Dec. 9	55060–55174	40	1400
2011	Aug. 26–Sep. 29	55799–55833	8	280

flux was detected. In 1995 BL Lacertae was observed with the Whipple Cherenkov telescope (Horan et al. 2004) for 39.1 h, when an upper flux limit for energies >350 GeV (3.8% of the Crab flux) was obtained in October–November 1995. In addition, BL Lacertae was also observed by the HEGRA collaboration, which obtained an upper limit for energies above 1.1 TeV, 28% of the Crab flux at a duration of observations of 26.7 h (Aharonian et al. 2004). In 1998 BL Lacertae was observed at CrAO at energies >1 TeV, as a result of which a flux was recorded from it at a 7.2σ significance level (Neshpor 2001). The observations were carried out with the second-generation GT-48 Cherenkov telescope, which began to operate in 1989. The principle of operation and technical characteristics of this telescope are described in detail in Vladimirsky et al. (1994). In this paper, we briefly note that the detection of VHE gamma-ray photons with modern ground-based detectors is based on the interaction of these photons with the nuclei of air atoms to produce secondary electrons that emit Cherenkov photons at a small angle ($\sim 1^\circ$) to the direction of motion of the primary gamma-ray photon. This makes it possible to determine the arrival direction of the gamma-ray flux. The threshold energy for GT-48 is 1 TeV. Table 1 lists the years when BL Lacertae was observed at CrAO (in the table, MJD stands for modified Julian date).

The observations were carried out by tracking the object and comparing the observations of the gamma-ray source itself with the background observations with such a time shift relative to each other that the source and background observations (the so-called observing session or scan) were conducted at the same zenith and azimuthal angles. As a result, each session included the source and background observations with equal durations. Besides, the observing sessions conducted under poor weather conditions were excluded from the data reduction. As a result, the data passed the primary reduction that included the exclusion of events with poor pointing, when the deviation of the telescope's optical axis from the specified direction exceeded $3'$. In addition, the signal amplitudes in the channels were corrected by taking into account the calibration coefficients, and the flashes whose amplitudes were at a maximum in the outer ring of light detectors were excluded. After such a reduction, about 30% of the recorded events remained for the subsequent analysis (Neshpor et al. 2007).

The main problem in searching for VHE gamma-ray sources is the presence of an isotropic cosmic-ray (CR) background. CR particles also trigger Cherenkov flashes in the Earth's atmosphere like gamma-rays. It is quite problematic to distinguish gamma-ray and CR flashes from one another, but it has become possible to select the flashes of gamma-ray showers using a number of Cherenkov flash parameters. The selection criteria include the coordinate-independent and coordinate-dependent parameters of a Cherenkov flash (Vladimirsky et al. 1994). The distributions of parameters for the flashes from both gamma-rays and charged CR particles are wide and overlap considerably, but the distributions in several different parameters allow up to 99% or more of the flashes from charged CR particles to be excluded (Neshpor et al. 2007). For this purpose, the boundary values of the selection parameters were chosen so as to obtain an optimal signal-to-noise ratio. The difference $N_{\rm on} - N_{\rm off}$ is interpreted as the

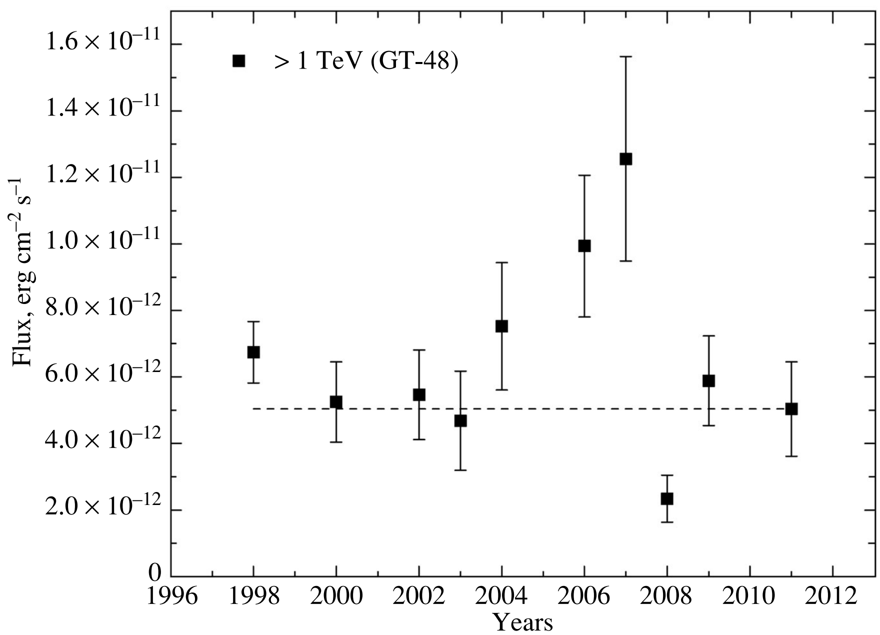

Fig. 1. Light curve of yearly mean fluxes for BL Lacertae (>1 TeV). The horizontal dashed line indicates the mean flux over the entire period of observations ($N_\gamma = (5 \pm 0.42) \times 10^{-12}$ erg cm^{-2} s^{-1}).

number of gamma-ray photons (signal), while the square root of their sum is interpreted as the statistical error of this number (noise), where N_{on} and N_{off} are the numbers of on- and off-source (background) gamma-ray-like flashes (events), respectively. The signal-to-noise ratio is the significance of the detection of the gamma-ray flux from the observed object. Table 2 gives the data without and with selection, respectively. Over the entire period of observations of BL Lacertae with GT-48, the mean flux from it was $N_\gamma = (5 \pm 0.42) \times 10^{-12}$ erg cm^{-2} s^{-1}. More than 20 flares with various significance levels were recorded when BL Lacertae was observed with GT-48 from 1998 to 2011. Their fluxes with errors are presented in Table 3, where MJD stands for modified Julian date. These flares exceed the mean flux by up to a factor of 9.

Table 2. Results of the observations of BL Lacertae at CrAO with GT-48

Years	Without selection			After selection
	N_{on}	N_{off}	$N_{\text{on}}-N_{\text{off}}$	flux, erg cm^{-2} s^{-1}
1998	51206	50452	754	$(6.7 \pm 0.9) \times 10^{-12}$
2000	27820	27424	396	$(5.2 \pm 1.2) \times 10^{-12}$
2002	7714	7831	−117	$(5.4 \pm 1.3) \times 10^{-12}$
2003	16584	16527	57	$(4.7 \pm 1.5) \times 10^{-12}$
2004	13090	12819	271	$(7.5 \pm 1.9) \times 10^{-12}$
2006	17499	17546	−47	$(9.9 \pm 2.1) \times 10^{-12}$
2007	17069	16898	171	$(1.25 \pm 0.3) \times 10^{-11}$
2008	18975	19258	−283	$(2.3 \pm 0.7) \times 10^{-12}$
2009	18164	17840	324	$(5.9 \pm 1.3) \times 10^{-12}$
2011	1011	945	66	$(5 \pm 1.4) \times 10^{-12}$

In addition, Fig. 1 presents the light curve at energies >1 TeV constructed from the GT-48 observational data over the entire interval of observations. It follows from Fig. 1 and Table 2 that the activity was at a maximum in 2007; at the same time, our data analysis shows that the yearly mean fluxes changed by more than a factor of 4 in different years.

The ability of multichannel light detectors to determine the region on the celestial sphere where the gamma-ray source is located (Andreeva et al. 2000) makes it possible to apply the trial source method (Akerlof et al. 1991; Neshpor et al. 1994; Fomin et al. 1994). It is used to construct a stereo image of the distribution of the number of selected gamma-ray-like events over the field of view of the light detector. The stereo image presented in Fig. 2 was obtained as a difference of the source and background stereo images, in which a distinct peak whose maximum points the direction to the source is seen. This

Table 3. Flares recorded from BL Lacertae at CrAO (>1 TeV)

Date (years)	MJD		Flux, erg cm^{-2} s^{-1}	Date (years)	MJD		Flux, erg cm^{-2} s^{-1}
	beginning	end			beginning	end	
1998	51068	51070	$(4.2 \pm 1) \times 10^{-11}$	2004	53319.7	53320.7	$(1.6 \pm 0.55) \times 10^{-11}$
2000	51763	51765	$(1 \pm 0.37) \times 10^{-11}$	2006	53967.88	53967.92	$(2.9 \pm 0.85) \times 10^{-11}$
2000	51821	51823	$(1.3 \pm 0.59) \times 10^{-11}$	2006	54000.76	54005.77	$(1.5 \pm 0.37) \times 10^{-11}$
2000	51863.7	51867.7	$(1 \pm 0.3) \times 10^{-11}$	2007	54332.98	54337.01	$(8.6 \pm 2.5) \times 10^{-12}$
2002	52610.7	52612.7	$(1.6 \pm 0.5) \times 10^{-11}$	2007	54374.7	54374.7	$(1.6 \pm 0.85) \times 10^{-11}$
2003	52874.9	52875.9	$(1.3 \pm 0.56) \times 10^{-11}$	2007	54384.80	54385.75	$(8.8 \pm 3.9) \times 10^{-12}$
2003	52902.7	52906.7	$(8.8 \pm 3.6) \times 10^{-12}$	2008	54706.9	54706.9	$(1 \pm 0.46) \times 10^{-11}$
2003	52912.7	52913.7	$(1.1 \pm 0.6) \times 10^{-11}$	2009	55061.97	55062.98	$(1 \pm 0.35) \times 10^{-11}$
2003	52965.7	52968.7	$(7.1 \pm 5.46) \times 10^{-12}$	2009	55115.69	55115.81	$(8.1 \pm 2.5) \times 10^{-12}$
2004	53262.8	53265.8	$(1 \pm 0.34) \times 10^{-11}$	2009	55122.73	55127.84	$(1 \pm 0.36) \times 10^{-11}$
2004	53268.8	53269.8	$(1.3 \pm 0.5) \times 10^{-11}$				

stereo image confirms the recorded effect from the observed blazar.

BL LACERTAE IN THE OPTICAL AND X-RAY BANDS

The AGN BL Lacertae, like all objects of such a class, is characterized by high variability of its emission in a wide energy range. This necessitates performing a comparative analysis of the temporal variations in the VHE gamma-ray fluxes from the source under discussion with other bands, in particular, with the optical and X-ray ones, over a long period of time. The optical (B band) brightness data for the blazar BL Lacertae obtained at CrAO from 2002 to 2014 were kindly provided by the CrAO researcher G.A. Borman (see Table 4). The optical fluxes are presented in arbitrary units on a linear scale, which were converted from the magnitudes.

Figure 3 shows the light curves at energies >1 TeV and in the optical B band for BL Lacertae in the intervals in which this object was observed with the GT-48 Cherenkov telescope at CrAO (see Table 1). In some years, it can be noticed that there is some correlation between the >1 TeV and optical fluxes, in particular, in 2003 and 2008, in which some decline in activity was observed. However, there are intervals when no correlation is observed. For example, whereas in 2002 the optical flux was higher than the mean, no enhanced activity was observed at TeV energies, and, conversely, in 2007 the gamma-ray flux reached its maximum over the entire period of observations, while there was a distinct decline in the optical band. In addition, no correlation is observed in 2011, when the optical brightness of BL Lacertae increased sharply, while the activity at TeV energies was at the level of the mean flux over the entire interval of observations.

We analyzed the optical and X-ray data. We took the yearly mean fluxes in the optical band and used the RXTE/ASM[1] (2–10 keV) data in the X-ray one. The main problem of using the RXTE/ASM data is that the overwhelming majority of the fluxes measured by this instrument have significant errors.

[1] http://xte.mit.edu/ASM_lc.html

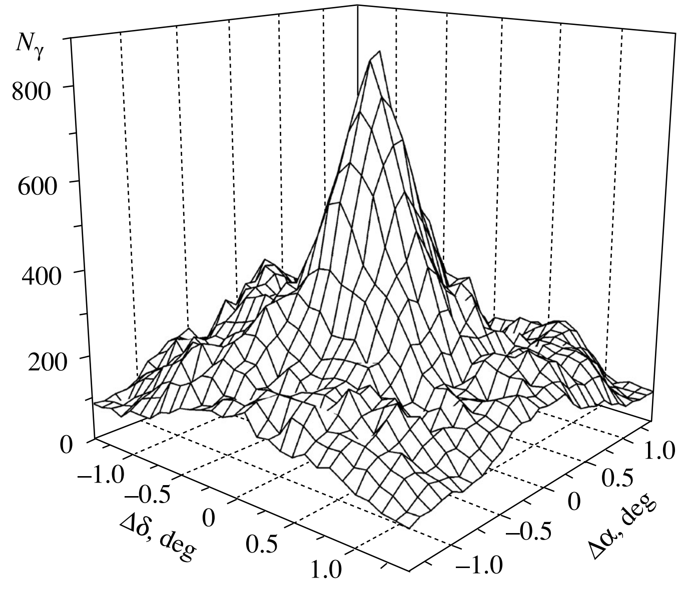

Fig. 2. Map of probable arrival directions for gamma-ray-like events over the entire interval of observations of BL Lacertae with GT-48: $\Delta\alpha$ and $\Delta\delta$ are the deviations from the source coordinates in right ascension and declination, respectively; N_γ is the number of events.

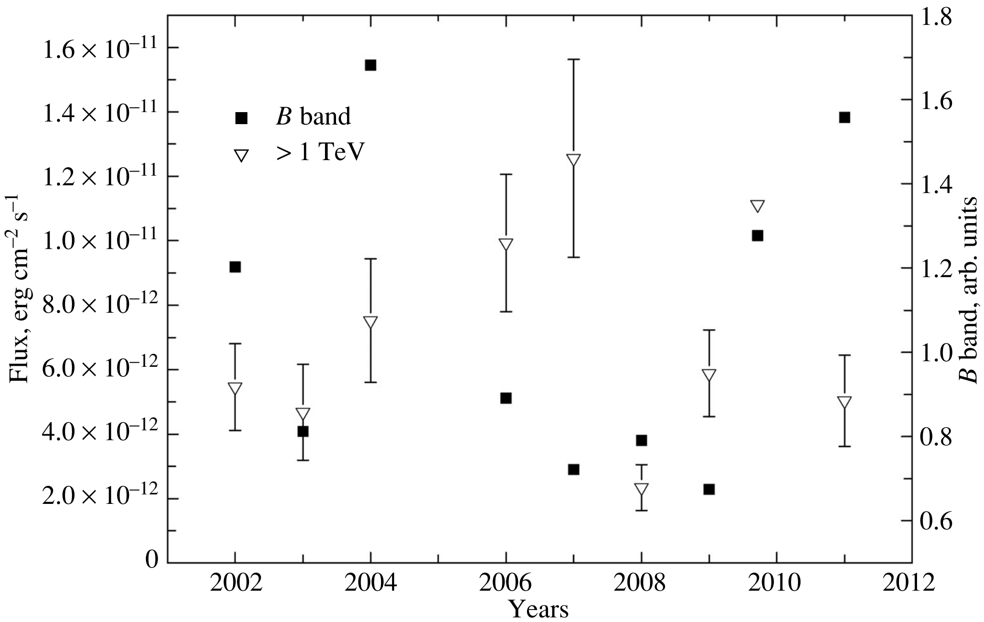

Fig. 3. Two light curves, the optical (B band) and TeV ones, in the intervals of observations of BL Lacertae with GT-48. The data were obtained at CrAO. The optical flux is presented in arbitrary units.

For example, only 437 and 76 of 1529 daily mean fluxes from BL Lacertae with a significance $>1\sigma$ have a significance $>2\sigma$ and $>3\sigma$, respectively. For this reason, for our analysis we break down the data into bins of different lengths to increase the significance. Bins of different lengths, for example, weekly (7 days), monthly (30 days), 100 days, etc., can be used. However, for BL Lacertae these bins turned out to be insufficient for a considerable increase in significance. As a result, we decided to use the yearly mean fluxes

Table 4. X-ray and optical fluxes (see the text)

Years	X-ray N_x, phot./s	B band	B band in GT-48 intervals	Years	X-ray N_x, phot./s	B band	B band in GT-48 intervals
1996	0.371 ± 0.021	–	–	2006	0.454 ± 0.029	0.85743	0.89125
1997	0.39 ± 0.019	–	–	2007	0.45 ± 0.031	0.73383	0.72176
1998	0.405 ± 0.024	–	–	2008	0.48 ± 0.031	0.75997	0.7914
1999	0.448 ± 0.026	–	–	2009	0.516 ± 0.034	0.61488	0.67483
2000	0.407 ± 0.025	–	–	2010	0.71 ± 0.046	0.52819	–
2001	0.465 ± 0.027	–	–	2011	2.078 ± 0.192	1.34774	1.55743
2002	0.433 ± 0.025	1.44148	1.20228	2012	–	1.16736	–
2003	0.423 ± 0.029	1.15346	0.81282	2013	–	1.3766	–
2004	0.481 ± 0.031	1.58493	1.68117	2014	–	1.11893	–
2005	0.461 ± 0.029	0.96205	–				

in the 2–10 keV band. Therefore, we compared the RXTE/ASM X-ray data with the optical (B band) ones not in the GT-48 intervals but based on the data from Table 4, where columns 2 and 3 give the yearly mean X-ray and optical fluxes, while Fig. 4 presents the curves themselves. Note the coincidence of the sharp flux rises in 2011 in both bands. Our analysis of the RXTE/ASM data for the AGN BL Lacertae in the 2–10 keV band revealed no period or correlation with the optical ones.

COMPARISON OF THE GT-48 AND FERMI LAT DATA. DISCUSSION OF RESULTS

Comparing the GT-48 data with the results of gamma-ray detection by other telescopes is of interest. In particular, it is appropriate to make a comparison with the data from the Fermi Gamma-Ray Space Telescope obtained with its LAT (Large Area Telescope) instrument operating at energies 0.1–300 GeV. The light curves constructed from the Fermi LAT Monitored Source List[2] data are presented in Fig. 5. The yearly mean fluxes were obtained by summing, with weights, the daily means rejected by TS = 16, where TS is the test statistic (Mattox et al. 1996) defined as $\mathrm{TS} = 2(\ln L\,(\mathrm{source}) - \ln L\,(\mathrm{nosource}))$, where L quantifies the extent to which the model with a source and without a source (only the background) corresponds to the observational data in a given sky region.

[2]http://fermi.gsfc.nasa.gov/ssc/data/access/lat/msl_lc/

The yearly mean fluxes change from year to year, with the degree of variability being higher in a higher-energy band, by factors of 1.5 and 1.2 for 1–300 and 0.3–1 GeV, respectively. Consequently, the change in yearly mean fluxes at higher energies exceeded the change in low-energy yearly mean fluxes approximately by 25%.

It can be seen from Table 2 that the variability of the TeV gamma-ray flux is even higher, while its yearly means differ from one another by more than a factor of 4. This property is characteristic of not only BL Lacertae itself but also some other BL Lac objects. In particular, more significant variability was noted in Strigunov and Zhovtan (2015) for 1ES 1426+428, which showed a fourfold change in yearly mean fluxes.

Comparing the detection results at high and very high energies involves certain difficulties. The most significant difficulty is a considerable scarcity of data; as a result, it is sometimes impossible or very difficult to perform a comparative analysis of the results

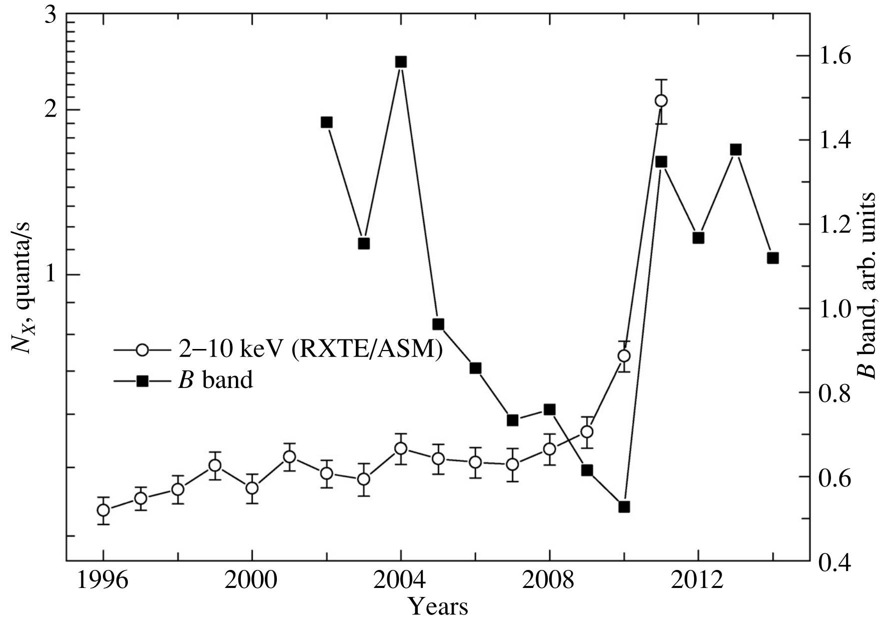

Fig. 4. Optical (B band) light curves obtained at CrAO. The X-ray (2–10 keV) fluxes were recorded with the RXTE/ASM telescope. The optical flux is presented in arbitrary units. The X-ray flux is shown as the event count rate per second.

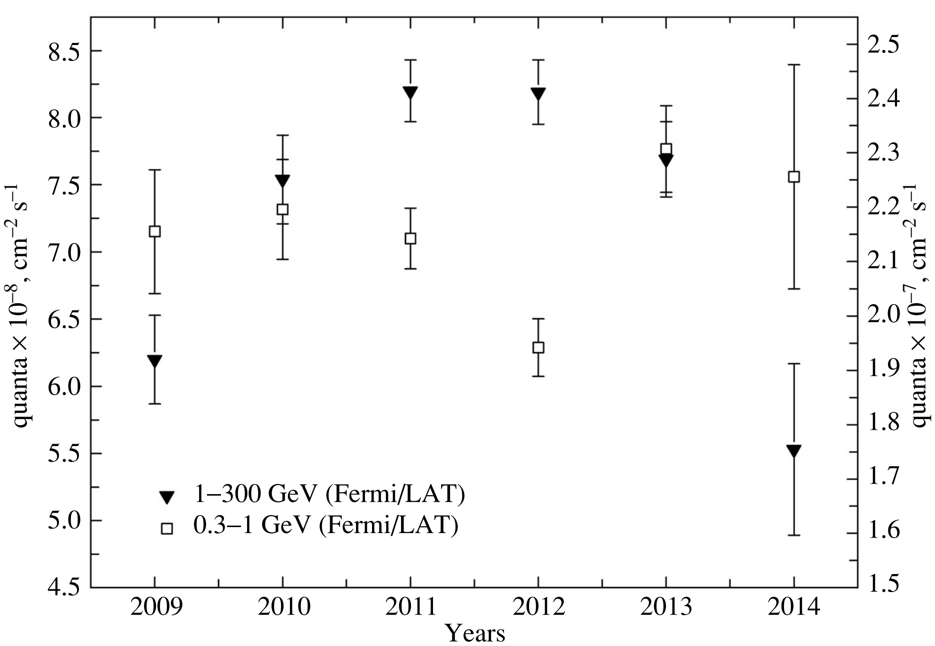

Fig. 5. Light curves of yearly mean fluxes for BL Lacertae obtained from the Fermi LAT data. The triangles mark the yearly mean fluxes at energies 1–300 GeV. The squares indicate the yearly mean fluxes at energies 300 MeV–1 GeV.

obtained with different instruments. In particular, there is little information on the gamma-ray activity of the well-known object BL Lacertae at energies above 100 MeV. Before the launch of the Fermi satellite, an annual monitoring of BL Lacertae at VHE was done only at CrAO with GT-48 at energies above 1 TeV, while the remaining telescopes were pointed toward it only sporadically. As a result, the information about

Table 5. Fluxes and spectral indices for BL Lacertae at Fermi energies (see the text)

Averaged fluxes at Fermi LAT energies			
Over entire interval of Fermi LAT observations (MJD 54833–56917)		Over 2009 flare interval (GT-48) (MJD 55122–55127)	
Flux ($\times 10^{-7}$ cm^{-2} s^{-1})			
(0.1–300 GeV)	(1–300 GeV)	(0.1–300 GeV)	(1–300 GeV)
5.32 ± 0.09	0.765 ± 0.012	2.03 ± 0.61	0.713 ± 0.131
Spectral index, Γ			
1.9 ± 0.1		1.4 ± 0.2	

the activity of BL Lacertae from ground-based and orbital gamma-ray telescopes most often came in different times; as a consequence, the fluxes in different gamma-ray ranges in the same time interval either could not be compared or could be compared rarely and only at random. The situation slightly improved with the launch of the Fermi telescope in 2008, because its LAT instrument had continually monitored quite a few objects active in the range from 100 MeV to 300 GeV. Despite the fact that much of the data provided in the Fermi catalogs are excluded as they are processed, there is likelihood of a coincidence in time between the Fermi LAT observations and the observations with other telescopes. Because of this, it becomes possible to perform a comparative analysis of its data with the observations at other telescopes.

Separate time intervals of blazar activity are also of considerable interest. Previously, Neshpor (2011) noted that the VHE gamma-ray spectrum becomes flatter with increasing blazar activity, while the higher-energy particles responsible for the generation of gamma-ray photons are accelerated more efficiently during perturbations in the AGN jet. This may be responsible for the increase in the relative number of higher-energy photons compared to those at low energies. To test this assumption, we compared the fluxes at Fermi LAT energies (0.1–300 GeV) in the interval of the six-day flare at TeV energies recorded from October 18 to 23, 2009, (MJD 55122–55127) with GT-48, when the rise in flux ($(1 \pm 0.36) \times 10^{-11}$ erg cm^{-2} s^{-1}) was twice the mean flux over the entire interval of observations ($(5 \pm 0.42) \times 10^{-12}$ erg cm^{-2} s^{-1}). At CrAO, for comparison with the above flare, the Fermi LAT data at energies 0.1–300 GeV were fitted by a power-law spectrum:

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0}\right)^{-\Gamma}, \qquad (1)$$

where N_0 is the normalization factor, and Γ is the spectral index. Table 5 gives the fluxes with their errors and the spectral indices at Fermi LAT energies (0.1–300 GeV). We see that the spectral index Γ during the 2009 flare (CrAO, GT-48) was smaller than that over the entire interval of observations of BL Lacertae with Fermi LAT ($\Gamma = 1.9 \pm 0.1$).

Figure 6 shows the spectra of BL Lacertae based on the Fermi LAT data over the complete interval of observations and over the interval of the 2009 flare. In addition, the graph presents the flux from BL Lacertae recorded with the MAGIC telescope (August–December 2005, $E > 200$ GeV) (Hayashida et al. 2007) and the flare observed by VERITAS on June 28, 2011 (MJD 55740, $E > 200$ GeV) (Arlen et al. 2013). The fluxes at TeV energies over the entire interval of observations and over the interval of the six-day flare detected in October 2009 (MJD 55122–55127) are also presented. The mean energies for the ranges were found as follows:

$$E_{\text{mean}} = \sqrt{E_1 E_2}, \qquad (2)$$

where E_1 and E_2 are the lower and upper limits of the energy range, respectively. A twofold increase in flux at TeV energies is seen during the 2009 flare. The spectrum at Fermi energies in the interval of this flare hardened considerably compared to the spectrum constructed from the data over the entire period of Fermi observations of BL Lacertae (dashed line). It can be clearly seen that the fraction of high-energy gamma-ray photons during the flare increased compared to low-energy ones.

An increase in the relative number of hard gamma-ray photons as the activity rose was also observed for the BL Lac object 1ES 1426+428 (belongs to the subclass of HBLs), from which VHE gamma-rays were recorded at CrAO from 2002 to 2010 (Strigunov and Zhovtan 2015). A four-day flare (MJD 54965–54968) that exceeded the mean flux over the entire interval of observations by a factor of 4.1 was detected

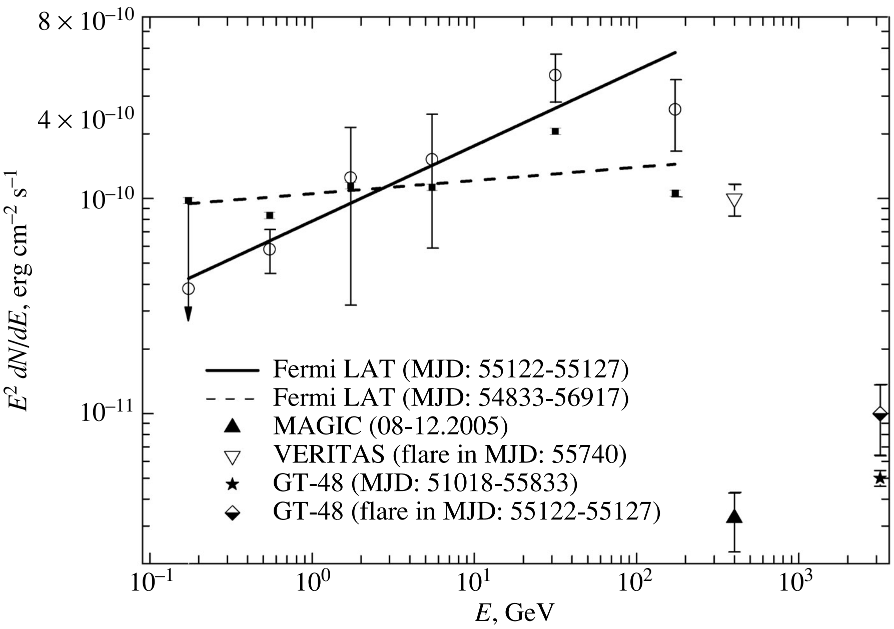

Fig. 6. Spectra of BL Lacertae at Fermi LAT energies over the entire interval of observations of this object (dashed line) and over the interval of its TeV flare (solid line) as well as MAGIC, VERITAS, and GT-48 observations data (for details, see the text).

from this object at energies >1 TeV with GT-48 in 2009. The flare recorded by Fermi LAT at energies 1–300 GeV was observed in the same time interval; it exceeded the mean flux over a five-year interval (MJD 54748–56575) by a factor of 5 with a significance of 4σ, while no growth was observed at low energies. The spectral index Γ for this flare was 1.3 ± 0.2, i.e., it turned out to be smaller than that over the entire five-year interval ($\Gamma = 1.5 \pm 0.1$). The spectral index during the flare from the blazar 1ES 1426+428 observed with GT-48 in 2009 partially overlaps, within the error limits, with that over the entire interval of observations of this object; for this reason, it cannot be unambiguously asserted that its spectrum hardened during the rise in activity. However, the presence of a fivefold rise in highest-energy gamma-ray flux in the Fermi LAT range over the flare interval and the absence of any rise al low Fermi LAT energies suggests that the spectrum of 1ES 1426+428 during this flare became flatter than its spectrum over the entire period of observations. Thus, in the cases of both BL Lacertae and 1ES 1426+428, a rise in activity led to a hardening of the spectrum, while the relative number of higher-energy gamma-ray photons increased significantly.

Strigunov and Zovtan (2015) hypothesized that the increase in the fraction of high-energy gamma-ray photons in the spectrum is related to the so-called conversion mechanism of particle acceleration described by its authors in Derishev et al. (2003, 2007). The classical particle acceleration mechanism that is used to explain the acceleration of particles responsible for the generation of gamma-rays is the first-order Fermi mechanism. However, this type of acceleration cannot explain the changes in the spectrum of gamma-ray emission, which is determined by the spectrum of particles responsible for the generation of gamma-rays. The spectral index for the particles accelerated by the first-order Fermi mechanism (used to explain the particle acceleration) is universal, dependent on the plasma compression ratio at the shock front, and is equal to two (Murzin 2007). The spectral index for the particles accelerated by the conversion mechanism depends on the particle energy gain when passing through the conversion cycle in such a way that the spectral index itself decreases as the energy gained by the particles grows:

$$\alpha = 1 - \frac{\ln k}{\ln g}, \quad (3)$$

where k is the probability of passing through the cycle, and g is the energy gain. In such a mechanism, the particles being accelerated interact with the photon fields in AGN jets; this interaction is usually considered as an additional energy loss channel. Under certain conditions, passing through the shock front and reflecting off the magnetic field inhomogeneities, a charged particle increases its energy and then, after its encounter with a photon, becomes neutral, which allows it to return to the front without any obstacles from the magnetic field. The chain of particle conversions with a gamma-ray photon appears as follows:

$$p + \gamma \rightarrow n + \pi^{+} \quad \text{and} \quad n + \gamma \rightarrow p + \pi^{-} \qquad (4)$$

for the proton cycle,

$$e^{\pm} + \gamma \rightarrow e^{\pm} + \gamma' \quad \text{and} \quad \gamma' + \gamma \rightarrow e^{+} + e^{-} \qquad (5)$$

for the electron cycle. Being ahead of the shock, the particle again becomes charged, whereupon the entire acceleration cycle is repeated. The authors of the mechanism estimated that the particle increases its energy by a factor of γ^2, where γ is the Lorentz factor of the shock. This quantity is 10^2–10^3 for AGN jets. As a consequence, the particle can be accelerated to enormous energies in several cycles and can lead to the generation of a gamma-ray photon when interacting with photons during inverse Compton scattering. The probability of passing through at least one conversion cycle is quite low due to the small cross section for the reactions, but there exist all the necessary conditions for the possibility of their realization in AGNs and gamma-ray bursters. An important feature of the mechanism is that if the product of the probability of passing through one cycle by the energy gain g ($\sim\gamma^2$) exceeds unity, then the conversion mechanism reaches its highest efficiency (Derishev et al. 2007). As a result, the total energy content of the particles increases with each new cycle, while the particles with the energy closest to the maximum achievable one make a major contribution. As the blazar activity rises, when the conditions for the realization of the conversion mechanism become more favorable, the fraction of the energy content is shifted to the region of higher-energy particles during the conversion. Since the particle spectrum determines the gamma-ray spectrum, the higher the energy of the accelerated particles, the more energetic photon is produced through inverse Compton scattering, and we must observed an increase in the contribution of highest-energy photons in the gamma-ray spectrum. Such a mechanism may be able to explain why the fraction of hard gamma-ray photons increases compared to soft ones as the activity rises; as a result, a decrease in the spectral index is observed. In our view, the spectrum of particles accelerated by the Fermi mechanism is unable to explain this feature of the hardening of the gamma-ray spectrum.

CONCLUSIONS

The activity of the blazar BL Lacertae at VHE was observed at CrAO during a thirteen-year period. In addition, this object was recorded at VHE with both ground-based Cherenkov telescopes and orbital gamma-ray telescopes like Fermi LAT, which also conforms the result obtained with GT-48. A synchronous change in fluxes both at TeV energies and in some other energy ranges, the optical and X-ray ones, is observed in some time intervals. At energies 0.1–300 GeV BL Lacertae also exhibited a considerable activity, as confirmed by the observations of the MAGIC and VERITAS collaborations, where a significant difference in fluxes was recorded at different times in comparable energy ranges, being 0.03 Crab in the former case (Hayashida et al. 2007) and 1.25 Crab (Arlen et al. 2013) in the latter one. Besides, the increase in gamma-ray fluxes was shown to be more significant than that at higher energies at the time of brightness rise. Analysis of the spectral characteristics of the fluxes from BL Lacertae at Fermi LAT energies during the flare recorded with GT-48 (MJD 55122–55127) showed quite a sharp increase in the fraction of hard gamma-ray photons (1–300 GeV), as confirmed by the decrease in spectral index, i.e., the spectrum becomes flatter. A similar feature, when the rise in flux during perturbations was most significant in the high-energy range in which the Fermi LAT telescope operates, was noted previously for 1ES 1426+428. This conclusion is also confirmed by the decrease in spectral index during the 2009 flare (MJD 54965–54968) compared to that over the entire period of observations of the blazar 1ES 1426+428.

At present, it is hard to say whether this feature is inherent in blazar-type objects or other VHE gamma-ray sources (for example, galactic ones) also possess it. This requires analyzing the activity of an additional number of various VHE gamma-ray sources to gather statistics that will allow a more definitive conclusion to be reached. It may well be that such a study will help clarify whether the conversion mechanism of particle acceleration has a bearing on the more significant increase in the high-energy gamma-ray flux from blazars and other gamma-ray sources as their activity rises.

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