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Long-Term Observations of the Blazar 1ES 1426+428 with the GT-48 Cerenkov Telescope

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Abstract—Ultra-high-energy gamma-rays have been detected from the Active Galactic Nucleus 1ES 1426+428 with a high significance level (8σ) in observations with the GT-48 Cerenkov telescope in 2002–2010. Four-day flare activity was detected in 2009, as has been confirmed by observations by the Fermi LAT space telescope at 1–300 GeV. The growth in TeV activity just before 2008 detected with the Crimean Astrophysical Observatory GT-48 telescope is consistent with the increased activity at energies >350 GeV indicated by data from the Whipple observatory Cerenkov detectors. It is proposed that the presence of more substantial variations at ultra-high gamma-ray energies compared to lower energies is related to more efficient particle acceleration in the jets of Active Galactic Nuclei associated with the generation of hard gamma-rays.

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1. INTRODUCTION

The blazar 1ES 1426+428 ($z = 0.129$) is a BL Lac object—one of the classes of Active Galactic Nucleus (AGN) that has been detected at ultra-high energy (UHE) above 50 GeV [1]. The radiation from these objects is characterized by variability over a wide range of wavebands, which has been explained as radiation emitted from jet outflows oriented roughly toward the observer.

Different models can explain the generation of the gamma-rays in different ways. In leptonic models, the main mechanism for the emission of UHE gamma-rays is inverse Compton scattering of relativistic electrons on low-energy photons, emitted, for example, by the accretion disk [2]. In so-called hadron models, the gamma-ray emission is associated with collisions between relativistic protons and low-energy ("soft") photons [3]. A model in which high-energy photons are created via inverse Compton scattering of energetic electrons on their own synchrotron radiation (so-called synchrotron self-Compton radiation) was considered earlier in [4–6]. Other models have also been considered, but the mechanism for the generation of the UHE radiation remains a subject of discussion. Observations of BL Lac objects are of considerable interest for studies of mechanisms for both the emission of the gamma-rays and their variability.

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2. OBSERVATIONS OF 1ES 1426+428 AT ULTRA-HIGH ENERGIES

The blazar 1ES 1426+428 was first detected at UHE by the Whipple Observatory [7]; this detection was then confirmed by HEGRA [8] and CAT [9] observations in 1999–2000 and 1998–2000, respectively. The total duration of the HEGRA observations was 42.6 h, and the significance of the detection was 6.1σ, with a count rate of $N_s = 2.4 \pm 0.4$ photons/h. The CAT telescope observed a total of 26 h, yielding a count rate of $N_s = 0.21 \pm 0.04$ photons/min and a significance level for the detection of 5.2σ. Starting in 2002, 1ES 1426+428 was also observed at the Crimean Astrophysical Observatory (CrAO) on the GT-48 second-generation Cerenkov telescope, whose operation and technical characteristics are described in detail in [10]. Note that the detection of UHE gamma-rays using ground-based detectors is based on the fact that UHE gamma-rays produce secondary electrons during interactions with atoms in the air, which emit optical Cerenkov radiation at a small angle ($1°$) to the direction of the motion of the primary gamma-ray. Thanks to this effect, it is possible to determine the direction from which a gamma-ray has arrived. The threshold energy is of order 1 TeV.

Table 1 presents all years in which the source was observed on the GT-48 telescope (MJD is Modified Julian Date, and Δ is the total duration of the observations of the source). The observations were carried

Table 1. Observations of 1ES 1426+428 on the GT-48 telescope

Year	Observing period	MJD	Number of scans	Δ, min
2002	30.04–17.05	52 394–52 411	19	855
2004	16.04–26.04	53 111–53 121	8	360
2008	30.04–07.05	54 586–54 593	7	315
2009	22.04–27.05	54 943–54 978	11	495
2010	04.05–16.05	55 320–55 332	8	360

out by tracking the object, and comparing observations of the gamma-ray source with observations of the background, with a time shift between them such that the observations of the source and background (a so-called observing session, or scan) were carried out at the same azimuth and zenith angles. Thus, each session included source and background observations with equal durations. Observing sessions that took place under poor weather conditions were excluded. The preliminary reduction of all the data included the exclusion of events with poor pointing (when the deviation of the optical axis of the telescope from the specified direction exceeded 3′), correction of the signal amplitudes in the channels, taking into account calibration coefficients, and the exclusion of flashes whose maximum amplitudes were in the outer ring of light-detectors. After this initial processing, about 30% of the registered events remained for further analysis [1].

The main problem that arises in the detection of UHE gamma-ray sources is the presence of background cosmic-ray particles, which also lead to Cerenkov flashes in the Earth's atmosphere. These are fairly difficult to distinguish from flashes initiated by gamma-rays, but there are differences between them, and the two are characterized by a set of parameters that can be used to tell them apart. Coordinate-independent and coordinate-dependent parameters have been used for this purpose [10]. The distributions of these parameters for flashes from both gamma-rays and charged cosmic-ray particles are broad, and overlap considerably. However, considering the distributions for several parameters enables the exclusion of up to 99% or more of flashes from charged cosmic rays [1]. The boundary values for the parameters were chosen so as to optimise the signal-to-noise ratio (SNR). The difference $N_{\rm on} - N_{\rm off}$ is interpreted as the number of gamma-rays, and the square root of their sum as the statistical error in this number, where $N_{\rm on}$ and $N_{\rm off}$ are the number of gamma-ray-like flashes (events) from the source and the background, respectively. The SNR is the standard deviation; i.e., the significance of the detection of the gamma-ray flux from the observed object.

Table 2. Observational data of 1ES 1426+428 obtained with the GT-48 without data selection (see text for details)

Year	$N_{\rm on}$	$N_{\rm off}$	$N_{\rm on}-N_{\rm off}$
2002	13 524	13 509	15
2004	4883	4851	32
2008	5999	5938	61
2009	6708	6802	−94
2010	3368	3245	123

Table 2 presents the observational data without any selection. The results of selecting gamma-ray events using the parameters referred to above are shown in Table 3, where N_γ (min^{-1}) is the count rate (number of gamma-rays detected per minute). The mean flux from 1ES 1426+428 over the entire GT-48 observing period from 2002 through 2010 was $N_\gamma = 0.129 \pm 0.016$ photons/min, corresponding to a significance of 8σ.

3. DISCUSSION OF THE RESULTS

Table 3 shows that the fluxes obtained through our data reduction have fairly high significances, apart from the results for 2008. It became clear during the reduction and analysis of these results that flare activity of the blazar 1ES 1426+428 was detected during a short interval from May 14–17, 2009, when there were three observing sessions. Table 4 presents these data in more detail. After summing taking into account the weights, the derived flux exceeded the mean for the entire observing period by a factor of 4.1.

Thanks to the ability of multi-channel light detectors to determine the region of the sky where the

Table 3. Observations of 1ES 1426+428 obtained with the GT-48 with data selection (see text for details)

Year	$N_{\rm on}$	$N_{\rm off}$	N_γ flux with its error, min^{-1}	Significance σ
2002	505	389	0.138 ± 0.035	3.9
2004	116	58	0.161 ± 0.036	4.5
2008	1105	997	0.342 ± 0.145	2.4
2009	106	63	0.086 ± 0.026	3.3
2010	85	36	0.136 ± 0.030	4.5

Table 4. Interval of enhanced activity of 1ES 1426+428 observed on the GT-48

Date	MJD	N_γ flux with its error, $\min^{-1}$	Significance σ
14.05.2009	54 965	0.711 ± 0.222	3.2
15.05.2009	54 966	0.6 ± 0.176	3.4
17.05.2009	54 968	0.466 ± 0.175	2.65
14–17.05.2009	54 965–54 968	0.525 ± 0.114	4.6

Table 5. Yearly mean Whipple fluxes for 1ES 1426+at energies >350 GeV

Year	Observing interval, MJD	Flux with its error, Crab ($= 10^{-11}$ phot. cm^{-2} s^{-1})	Significance σ
2006	53 763–53 907	0.154 ± 0.028	5.5
2007	54 116–54 271	0.196 ± 0.03	6.5
2008	54 476–54 593	0.519 ± 0.091	5.7

gamma-ray source is located [11], it is possible to apply the test-source method [12–14] to construct a stereo image of the distribution of the number of selected gamma-ray-like events in the field of view of the light detector, which can be shown as a series of isophotes. The stereo image presented in Fig. 1 was obtained from the difference of the stereo images for the source and background. Figure 2 shows this image in the form of isophotes, which demonstrates the coincidence of the maximum in the distribution and the coordinates of 1ES 1426+428 in 2009 (which correspond to the coordinate origin in the images). Figure 1 shows a well defined peak whose maximum coincides with the direction toward the source. The stereo image itself directly supports the detected flux from the blazar.

The enhanced activity of 1ES 1426+428 was confirmed by observations with the Fermi Gamma-ray Space Telescope at 100 MeV–300 GeV. These data have high significance levels, and can be considered to be very trustworthy. Figure 3 presents a plot of the flux variations recorded by the GT-48 and Fermi LAT telescopes (the latter monitoring data are openly available at the site `http://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermilasp.html`).

The maximum activity at TeV energies apart from the flare of May 14–17, 2009 occurred in 2008, followed by a decay in activity. Since the presented fluxes are averages over the intervals in which the blazar was observed, the mean value for 2009 (observing period from April 22, 2009 through May 27, 2009) includes all scans in this interval. As a result, information about the flare is lost, and the mean value for 2009 seems to suggest reduced activity. To show the presence of the flare in this period and its enhancement above the mean flux over the entire interval 2002–2010, the flare is labeled in the plot. Note that the Fermi monitoring data for 1ES 1426+428 at 1–300 GeV shows enhanced activity: the daily mean flux for May 15, 2009 is 4.56×10^{-8} phot. cm^{-2} s^{-1} with a significance of about 4σ, which exceeds the mean flux for the entire monitoring period (October 9, 2008–October 10, 2013), 9.07×10^{-9} phot. cm^{-2} s^{-1}, by a factor of five. The coincidence of this value with the daily flux value obtained on the GT-48 during the flare of May 14–17, 2009 (to within a day) is of interest. The main contribution to this value was made by scans 12 and 13 of May 14 and 15, respectively (Table 4). The flux for the interval May 14–May 17, 2009 in Table 4 was obtained after a weighted sum. This confirms the presence of enhanced UHE activity in this time interval.

Figure 4 presents the yearly mean fluxes in two different energy ranges. The stars show the yearly mean UHE gamma-ray fluxes obtained with the Fermi Observatory at 0.3–1 GeV. The errors are small ($\sim 10^{-11}$ phot. cm^{-2} s^{-1} or less), and the corresponding error bars are not shown. The circles show the yearly mean fluxes at 1–300 GeV. Note that no enhanced activity was registered in this four-day interval at the lower energies (0.3–1 GeV), and the mean daily value in this range for May 15, 2009 (2.54×10^{-8} phot. cm^{-2} s^{-1}) is even lower than the mean flux for the entire Fermi LAT observing period (2.75×10^{-8} phot. cm^{-2} s^{-1}).

Moreover, it is of interest to estimate the flux variations measured by other Cerenkov detectors. The only group whose monitoring data are freely available (for energies >350 GeV) is the Whipple collaboration (http://veritas.sao.arizona.edu/component/content/article/43-agn-monitoring/48-lightcurves-for-agn). These data were obtained over three years (from 2006 through 2008), when the total flux from 1ES 1426+428 was 0.19 ± 0.02 Crab (10^{-11} phot. cm^{-2} s^{-1}).

Figure 5 presents the monthly averaged Whipple data. The stright line indicates the trend for growth in activity over the three-year interval. It is of interest to compare these data with the GT-48 results; this is done in Fig. 6, where the Whipple yearly mean data (>350 GeV) are shown by the circles (these values are presented in more detail in Table 5). Note the increase in UHE activity of 1ES 1426+428 from year to year. The flux for 2008 exceeded the mean value over the three-year interval by a factor of 2.73, reflecting

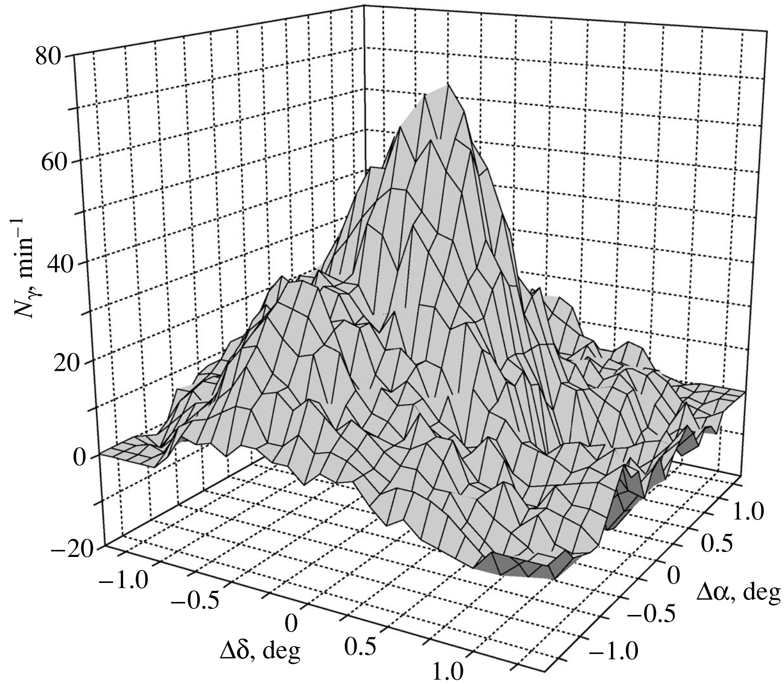

Fig. 1. Map of the probable arrival directions of the gamma-ray events for the flare of May 14–17, 2009. The axes plot the coordinates relative to the source coordinates in right ascension $\Delta\alpha$ and declination $\Delta\delta$ and the number of events N_γ.

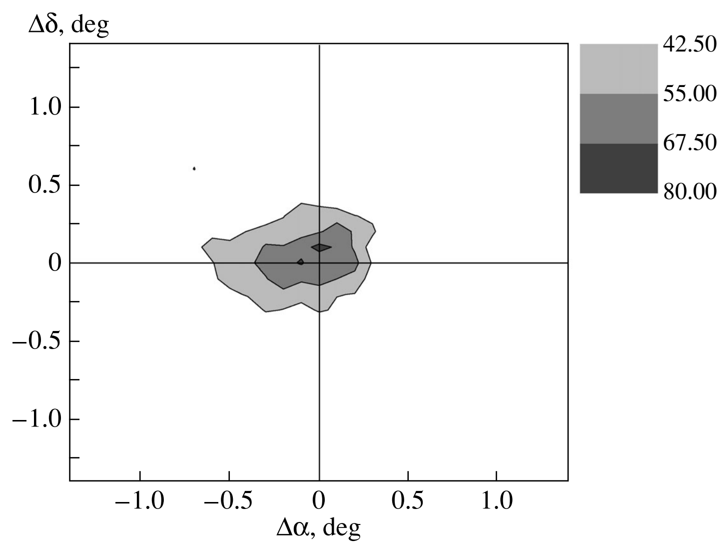

Fig. 2. Isophotes of the distribution of the arrival directions of the gamma-rays used to construct the plot Fig. 1. The axes plot the coordinates relative to the source coordinates in right ascension $\Delta\alpha$ and declination $\Delta\delta$. A gray scale for the event count rate (in min^{-1}) is shown to the right.

a sharp growth in the flux, which coincided with the enhanced activity at TeV energies. The GT-48 and Whipple light curves are presented in Fig. 6. Since the observations on the two telescopes were carried out at different times, the dates for the mean fluxes in the two energy ranges derived from the weighted sums are different. The Whipple data themselves agree well with the CrAO results.

It is appropriate to recall here certain characteristic properties of the activity of BL Lac objects, of which 1ES 1426+428 is a representative. BL Lac objects are characterized by flux variations over a broad range of frequencies, from radio to UHE

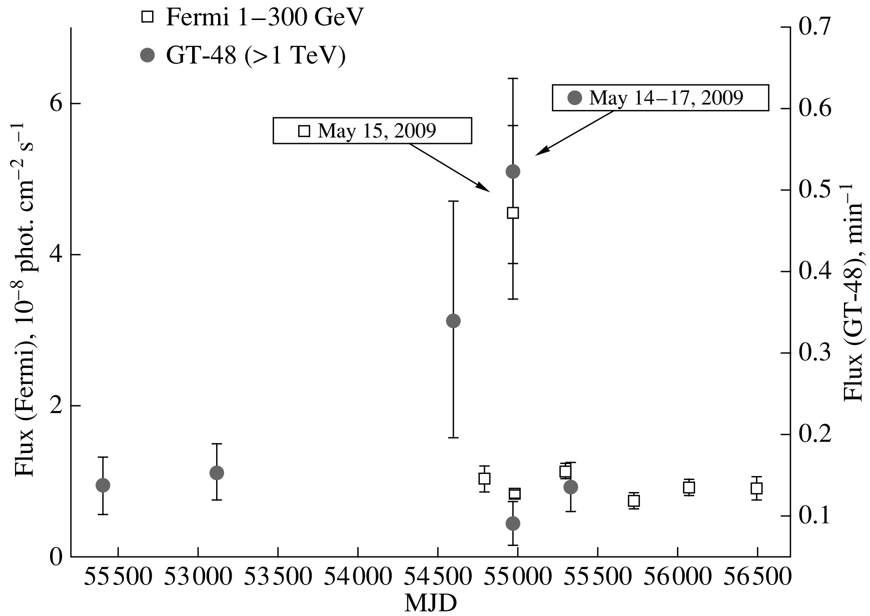

Fig. 3. Light curve of 1ES 1426+428 at energies above 1 TeV (GT-48) and at 1–300 GeV (Fermi LAT). Points corresponding to the flare are labeled.

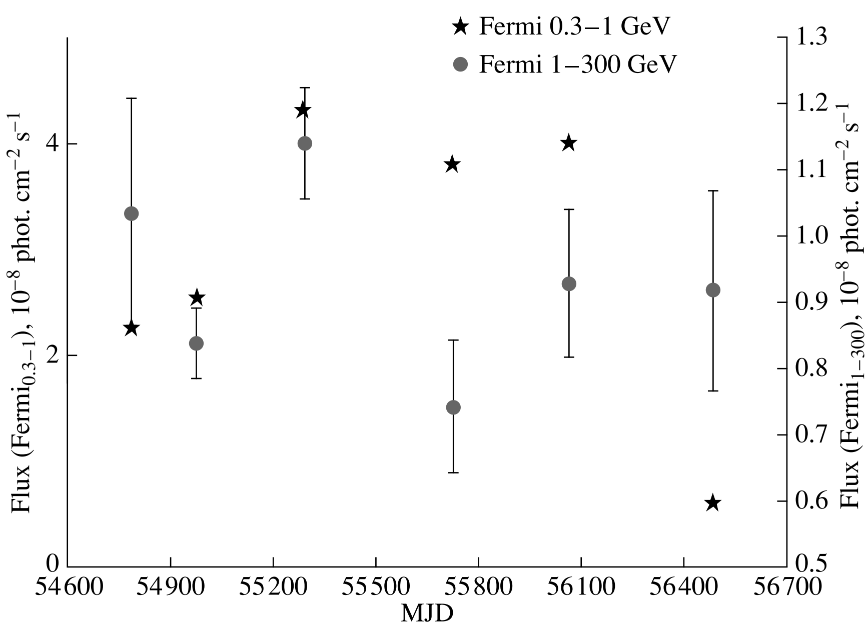

Fig. 4. Mean annual UHE gamma-ray fluxes obtained by the Fermi Observatory at 0.3–1 GeV (stars) and at 1–300 GeV (circles).

gamma-ray. The AGNs themselves display a strong tendency for flare (time scales of several days) and outburst (time scales of several months) activity [1]. The observations of 1ES 1426+428 show that the UHE activity of the source appreciably exceeds the activity at somewhat lower energies. In addition, more substantial variations were observed at higher energies, with the flux exceeding the mean value obtained with the GT-48 during 2002–2010 by a factor of four during four days. If we do not distinguish the flare from the overall flux for 2009 and take the flux for 2008 to represent the maximum activity, the mean flux level for the entire nine-year interval is exceeded by a factor of 2.67. It is interesting that the maximum flux for the Whipple data also occurrred in 2008. The situation is different for the Fermi Observatory, since

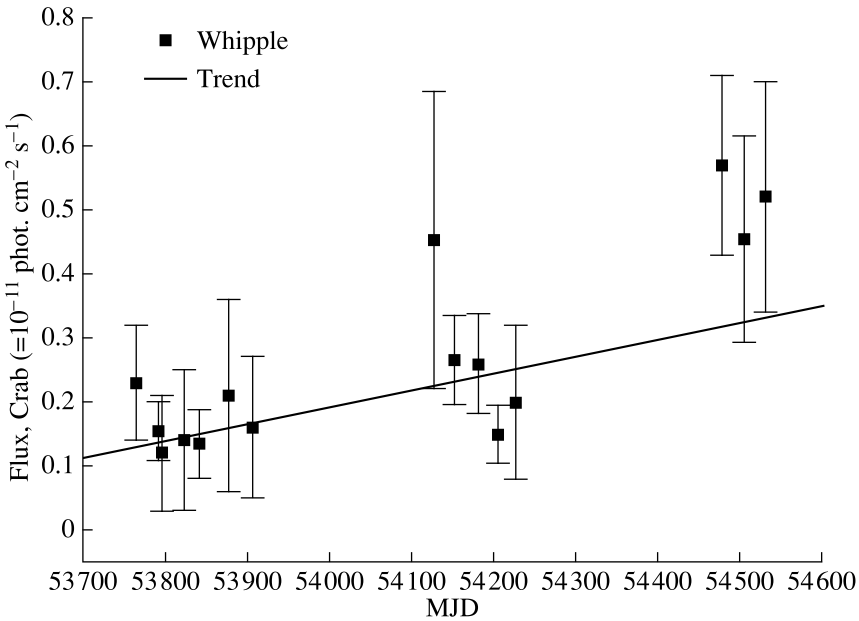

Fig. 5. Variations in the activity of 1ES 1426+428 at energies >350 GeV from January 30, 2006 through March 6, 2008 (see text for more detail).

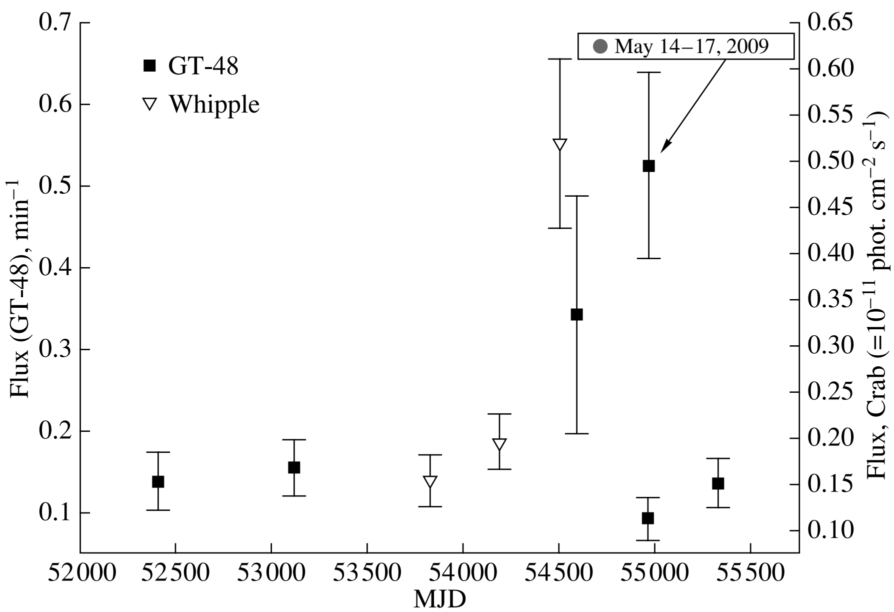

Fig. 6. Yearly average fluxes for the GT-48 (>1 TeV) and Whipple (>350 GeV) data. The flare of May 14–17 detected on the GT-48 in 2009 is marked with an arrow.

it's monitoring began in mid-2008, so that we can compare the mean fluxes only for later years.

4. ACTIVITY OF 1ES 1426+428 AND PARTICLE ACCELERATION IN ITS JET

We can draw the following conclusions based on these results. The data for 1ES 1426+428 show that no enhancement in activity was observed at lower energies (0.3–1 GeV) during the growth in hard gamma-ray activity (1–300 GeV and >1 TeV). This means that the differential spectral index of the radiation α should be decreasing. This is supported by the earlier conclusions of [15], and is consistent with the idea that the spectrum of the IHE gamma-ray emission becomes flatter in periods of increased activity of the blazar, with particles with higher energies being accelerated more efficiently during perturbations in the AGN. It is possible that this can explain the properties of the UHE variations.

However, since a key role in the formation of the gamma-rays is played by particles accelerated to relativistic energies (with Lorentz factors $\gamma \gg 1$), what is the mechanism for this acceleration? One possible mechanism was proposed by Fermi [16], whose essence is the statistical acceleration of particles at shock fronts during supernova flares or ejections from AGN [17]. In the case of multiple random collisions of particles with massive clouds moving with relative velocities $V \ll c$, the energy of the particles grows. With each head-on (most efficient) collision, the relative increase in the particle energy is $\langle \Delta E/E \rangle$ ($\sim V/c$); this corresponds to so-called first-order Fermi acceleration. This mechanism occurs when a particle crosses a shock front multiple times due to scattering on inhomogeneities in the magnetic field ahead of and behind the shock front.

However, this acceleration mechanism is not efficient in relativistic shocks moving at speeds close to the speed of light [18, 19]. Derishev et al [18, 19] have suggested so-called conversion acceleration, whose essence lies in the interaction of the accelerated particles with photon fields in the jets of AGNs, which are usually treated as either noise or an additional energy-loss mechanism. Under certain conditions, collisions with photons can be treated like a mechanism for the random "switching off" and "switching on" of the electrical charge of the particles. A charged particle increases its energy in passing through a shock front and being reflected from inhomogeneities in the magnetic field, then becomes neutral after interacting with a photon, making it possible for the particle to return to the front without being deflected by the magnetic field. When it is ahead of the shock front, the particle again becomes charged, and the entire acceleration cycle is repeated.

Estimates suggest that the energy of a particle that has passed through this entire acceleration cycle will increase by about a factor of γ^2, where γ is the Lorentz factor of the shock front. This corresponds to 10^2-10^3 for AGN jets and 10^5-10^6 for gamma-ray bursts; i.e., a particle could be accelerated to energies of 10^{20} eV after only two to four conversion cycles. This is appreciably more efficient than the Fermi mechanism, which requires tens of "approaches" toward a shock front. It is possible that interactions of particles accelerated in this way with low-energy photons, leading to the generation of hard gamma-ray radiation, could explain to some extent the increase in the variations and activity of blazars as a whole in the higher-energy gamma-ray range compared to lower energies. For example, according to [20, 21], during scattering on isotropically distributed relativistic electrons (the inverse Compton effect), the frequency of the scattered photons should increase by, on average,

$$E_\gamma \approx \frac{4}{3}\epsilon_{ph}\gamma^2,$$

where ϵ_{ph} is the energy of the photon before scattering and γ is the Lorentz factor of the relativistic electrons.

Thus, if we take, for example, an optical photon with an energy of $\sim$1 eV that is scattered by a particle with a Lorentz factor of ten (corresponding to the Lorentz factors of AGN jets) that has passed through at least two acceleration cycles (i.e., $\gamma = 10^4$), its energy should be increased by a factor of $4/3(10^4)^2 \approx 1.33 \times 10^8$, which corresponds to high-energy gamma-rays. This means that the energy acquired by such photons via Comptonization could be much higher if the particles have passed through a large number of cycles.

Note that obtaining more exact estimates requires knowledge of the probability of a single conversion cycle for a particular type of particle, which is much less than unity. As is pointed out in [19], the conversion mechanism achieves its highest efficiency when the product of the probability for passing through a cycle and the energy-increase factor ($\sim\gamma^2$) exceeds unity. Consequently, the higher the particle energy, the higher the energy acquired by a photon when it scatters off this particle. It is possible that the efficiency of this conversion mechanism could answer the question of why the variations of the UHE gamma-rays are larger than those of the lower-energy gamma-rays. Although a number of questions about this proposed conversion mechanism remain, its possible relationship to properties of the activity of objects such as 1ES 1426+428 is of interest and requires further study.

5. CONCLUSION

In conclusion, the blazar 1ES 1426+428 was active in the UHE range during the period of our CrAO observations, as has been confirmed by observations with other telescopes. A TeV flare recorded on May 14–17, 2009 was also detected in the Fermi LAT data, which showed a fivefold increase in the 1–300 GeV activity at this epoch, compared to the mean flux over the entiring monitoring interval. The absence of a growth in activity at lower energies during this period suggests that particles with higher energies may be more efficiently accelerated during perturbations, as has been proposed earlier [15]. We cannot rule out the possibility that particles in the jet acquire ultra-high energies via an acceleration mechanism that is more efficient than Fermi acceleration. One possibility here is conversion particle acceleration, but it remains to establish whether or not there is a relationship between this mechanism and the variability properties of BL Lac objects in the gamma-ray range.

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