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Observation of Multi-TeV Gamma Rays from Mrk501 during Remarkable Flaring Activity in 1997 with the Tibet Air Shower Array

The Tibet ASγ Collaboration

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ABSTRACT

In 1997, the BL Lac Object Mrk501 entered a very active phase and was the brightest source in the sky at TeV energies, showing strong and frequent flaring. Using the data obtained with a high density air shower array, being successfully operating at Yangbajing in Tibet since 1996, we searched for γ-ray signals from this source during the period from 1997 February through 1997 August. The result shows a 3.7 σ excess for showers with its mode energy 3 TeV. We present the energy spectrum of γ-rays in comparison with those obtained by imaging atmospheric Cherenkov detectors.

1. Introduction

Mrk 501 and Mrk 421 have been well detected as extra-galactic TeV γ-ray sources by Whipple and subsequent ground-based Cherenkov detectors [1]. They are the so-called BL Lac objects, which are radio-loud AGNs (Active Galactic Nuclei) whose relativistic jets are aligned along our line of sight. Flux variability on various scales is a common feature of BL Lac objects as already seen in Mrk 501 and Mrk 421, and spectral variations of γ-rays coming from these sources are considered to be a very powerful tool for understanding the physics of BL Lac objects. When Mrk 501 was first detected by the Whipple Collaboration in 1995, it showed rather low fluxes at a level significantly below the Crab flux. In March of 1997, however, this source went into a state of remarkably flaring activity and lasted for almost half a year with highly variable and strong γ-ray emission and the maximum flux reached roughly 10 times that of the Crab. During this period, several groups [2] observed strong γ-ray emission from this source with imaging atmospheric Cherenkov detectors. Independent measurements of the γ-ray spectrum seem to show a gradual softening towards higher energy, while the systematic uncertainties in the flux estimates remain still large to reach a common understanding. The energy spectrum and its shape are very important quantities to clarify the mechanism of γ-ray production or particle acceleration at the source, and eventually to lead to the actual measurement of the intergalactic infrared or far-infrared background field. Hence, confirmation of the detection of gamma rays with a different technique will be strongly required. Also, note that air shower arrays with wide aperture and high duty cycle are very important to monitor such variable sources.

The Tibet air shower array, operating since 1990, is located at Yangbajing (4,300 m above sea level) in Tibet [3]. This array has a capability of detecting γ-rays in the TeV energy region with high efficiency and high angular resolution. With this array, we succeeded to detect multi-TeV γ-ray flares from Mrk 501 in 1997. The result obtained with well established air shower technique is important to compare with those by atmospheric Cherenkov technique.

2. Experiment

The Tibet air shower array consists of two overlapping arrays (Tibet-II and HD) as described elsewhere [4]. The Tibet-II array comprises 221 scintillation counters of 0.5 m^2 each placed on a 15 square grid with an enclosed area of 36,900 m^2, and the HD (high density) array is operating inside the Tibet-II array to detect cosmic ray showers lower than 10 TeV (some of detectors are commonly used in both arrays). The DAQ system of the HD array manages 109 scintillation counters, each viewed by a fast timing (FT) phototube, placed on a 7.5 m square grid covering an area of 5,175 m^2.

The HD array was constructed in 1996 November and the events have been triggered at a rate of about 115 Hz under any 4-fold coincidence in the detectors, while the Tibet-II array has triggered the events at a rate of about 200 Hz under the same condition. In the following, we used the data obtained during the period from 1997 February through 1997 August. The event selection was done by imposing the following two conditions to the recorded data; 1) Each of any four FT detectors should record a signal more than 1.25 particles. 2) Among the four detectors recording the highest particles, two or more should be within the inner array. After data processing and quality cuts, the total number of events selected were 6.0×10^8 for the HD array and 1.1×10^9 for the Tibet-II array, respectively, with effective running time of 155.3 days.

Since the background cosmic rays are isotropic and gamma rays from a source are apparently centered on the source direction, a bin size for collecting on-source data should be determined based on the array's angular resolution so as to optimize the signal to noise ratio. In the case of the Tibet array, its angular resolution can be easily examined by observing the shadow that the Moon casts in the cosmic rays. Using the HD array, the Moon's shadow was observed with the significance of 15 σ at the maximum deficit position for all events. From this measurement, the angular resolution of the array was estimated to be $0.^\circ 9$. The pointing of the array is inferred from the position of the Moon's shadow by high energy cosmic rays which are not affected by the geomagnetic field and its systematic error is estimated to be smaller than $0.^\circ 1$. It is also shown that the angular resolution scales with the number of hit counters or the sum of the number of shower particles per m^2 detected in each counter, i.e., $\sum \rho$. The angular resolution increases with increasing $\sum \rho$ as $0.^\circ 8 \times (\sum \rho / 20)^{-0.3}$ $(15 < \sum \rho < 300)$. Thus the optimum bin size can be well parameterized in term of $\sum \rho$.

The Moon's shadow was also observed in the direction deflected to the west by about $0.^\circ 4$. The mean energy of protons responsible for casting the shadow is estimated to be about 4 TeV by a Monte Carlo simulation. On the other hand, the deflection angle of protons by the geomagnetic field is expressed as $\Delta\theta \cdot E = 1.6$ (deg $\cdot$ TeV). Then, the observed deflection of the Moon's shadow is consistent with that expected by the geomagnetic effect. This result suggests that the shower size measured by the array can be calibrated by experiment.

3. Results

We use a circular search bin whose size is based on the estimated angular resolution of the experiment. The window size is chosen to maximize the ratio $N_s/N_B^{1/2}$, where N_S is the number of signals and N_B the number of background events, and to contain about 50% of the signals from source. We use the following search bin sizes, i.e. $0.^\circ 9$ radius for showers with $\sum \rho \geq 15$, $0.^\circ 8$ radius for showers with $\sum \rho \geq 50$ and $0.^\circ 5$ radius for showers with $\sum \rho \geq 100$. The signals were searched for by counting the number of events coming from the ON-source window. The background was estimated by averaging over events falling in the ten OFF-source windows adjacent, but excluding the neighborest, to the source.

Figure 1 shows the cumulative excess for all events as a function of mjd. There exist no excess events until the middle of March 1997. However, excess events rapidly increase from April to June and after that it becomes dull. The statistical significance reached the maximum at around the middle of June and its value was a 4.7 σ. These features are consistent with other observations by air Cherenkov detectors. Figure 2 shows the distribution of the opening angles relative to the Mrk 501 direction for all events with $\sum \rho \geq 15$. The excess in the small opening angle region smaller than $0.^\circ 5$ would correspond to the γ-rays from Mrk 501. For the observation period from 1997 February to 1997 August, the statistical significances of the excess events with $\sum \rho \geq 15$, 30 and 50 are 3.7 σ, 2.3 σ and 1.6 σ, respectively.

We also searched for γ-ray emission using the Tibet-II array, but no excess was found in this period and upper limits on the excess number of the events at the 90 % confidence level are obtained.

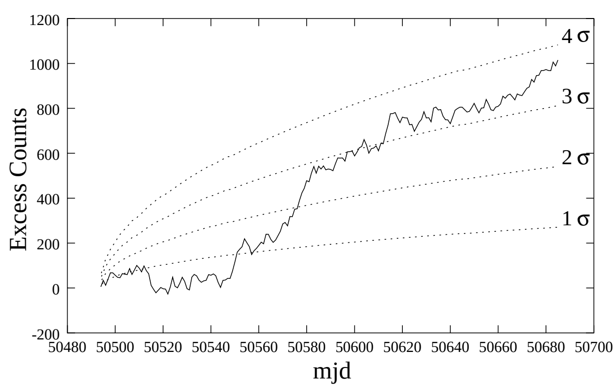

Fig. 1. Cumulative excess of the events with $\sum \rho \geq 15$.

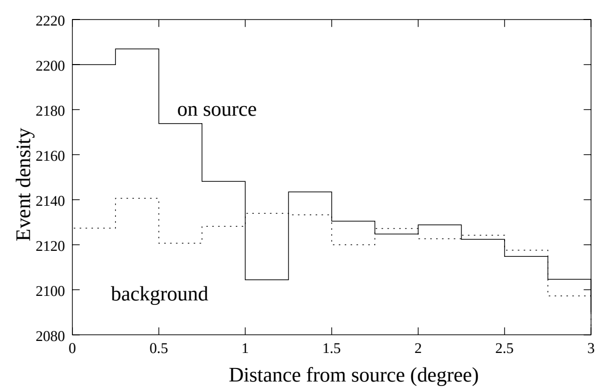

Fig. 2. Opening angle distribution of the events with $\sum \rho \geq 15$.

We tried to estimate the γ-ray spectrum from Mrk 501 by a Monte Carlo simulation, assuming a differential power-law spectrum with the index $-(\beta+1)$ and the cut-off at a certain energy, E_c, where the cut-off means that the spectral slope steepens by -1.0 at E_c. The value of β was changed between 1.4 and 1.7 and also the effect of E_c was examined between 7 TeV and 50 TeV. The primary γ-rays are generated between 0.2 TeV and 30 TeV from the direction of Mrk 501. The detection of simulated events at Yangbajing level was made as done in our experiment. The number of simulated events with respective $\sum \rho$-value was compared with that observed by the experiment. The energy of γ-rays was defined as the energy of the maximum flux of simulated events for respective $\sum \rho$. These steps were repeated until the observed results are well reproduced. A combination of $\beta \cong 1.6$ and $E_c \sim 20 - 30$ TeV seems to reproduce the data well, while the absolute flux value around 3 TeV stays almost unchanged.

Shown in Figs. 3 and 4 are the energy spectra averaged in the period from 1997 February 15 to 1997 August 25 and from 1997 February 15 to 1997 June 8, respectively. The latter observation time corresponds to that of the Whipple Collaboration [5]. It is seen that the observed results by other experiments [5,6,7] are not inconsistent with ours.

4. Summary

Mrk 501 suddenly came into a very active phase from March in 1997, with several large flares and lasted for about half a year. The maximum γ-ray flux during this period reached about 10 times as high as the Crab Nebula. The high resolution Tibet air shower array also succeeded to detect γ-rays during this very active phase. This is the first observation of γ-ray signals from point source with air shower array. The results obtained by well-established air shower technique will be very important to understand the systematic uncertainties inevitably included in the air Cherenkov observations.

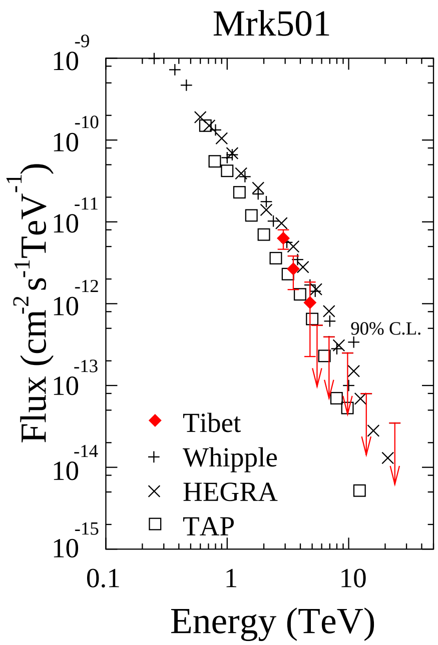

Fig. 3. Energy spectrum of γ-ray from Mrk 501 averaged in the period from 1997 February 15 to 1997 August 25. Upper limits are at the 2 σ confidence level. Our data are compared with other results [5,6,7].

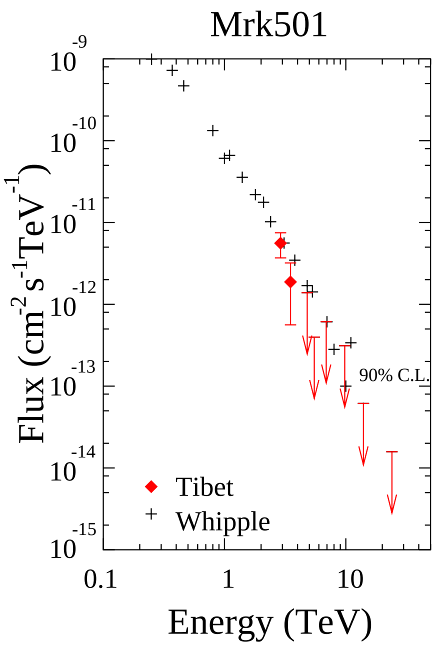

Fig. 4. Energy spectrum of γ-ray from Mrk 501 averaged in the period from 1997 February 15 to 1997 June 9. Upper limits are at the 2 σ confidence level. Our data are compared with the Whipple results.

Acknowledgments

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