Observation of gamma-rays greater than 10 TeV from Markarian421

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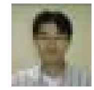

Abstract

We have observed Markarian 421 during an extraordinarily high state in January and March 2001 with the CANGAROO-II imaging Cherenkov telescope. From 14 hours observations at a very large zenith angle of ~70°, a signal of ~300 gamma-ray-like events was detected at E>10TeV with more than 5σ significance. Under the assumption of power-law spectrum, we derived a steep energy spectrum of photon index ~4.0. Although the derived spectrum was not inconsistent with the exponential cutoff reported by other experimental groups, we have obtained the 4.0 σ excess above 20TeV more than expected from a simple extrapolation of the cutoff spectrum.

Introduction

Markarian 421 (Mrk421 J1104+3812)

- Near-by BL Lacertae object (z=0.031) (Punch et al. 1992)
- Multi-wavelength observations support SSC mechanism
- Variable TeV gamma-ray flux on time-scales of less than an hour (Gaidos et al. 1996)

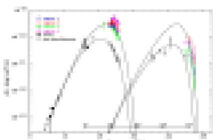

Fig 1. multi-wavelength spectrum of Markarian 421 (Takahashi et al. 2000)

CANGAROO observation in 2001

- Observations for 10 nights in January and March in 2001 during extremely strong flare (Boerst, Goetting & Remillard 2001)
- Large zenith angle (LZA) observation of 69.3 - 71.5 deg.

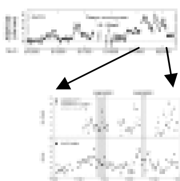

Fig 2. Lightcurve spectrum of X-ray (RXTE) and TeV gamma-ray (HEGRA) intensity. Observation period of CANGAROO is shown with hatched region.

Attenuation of TeV γ-rays with CIB

- Energy spectrum in multi TeV region is important for studying the absorption of TeV gamma-ray due to cosmic infrared photon background (CIB).
- E>10TeV gamma-rays from Mrk421 are expected to be suppressed, since they interact with mid- to far-infrared photons of ~100mm. (Primack et al. 1999, de Jager & Stecker 2001, Totani & Takeuchi 2002)

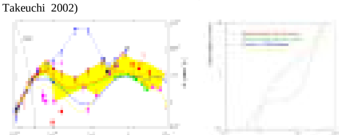

Fig 3. Summary of cosmic infrared photon measurement (Hauser & Dwek 2001) (Left) and expected optical depth of TeV gamma-ray from Mrk421 (Right).

Results

Alpha distributions

- 298±52 gamma-ray-like events (5.7 σ) was obtained with alpha<20 degrees
- Broad alpha peak is due to deterioration of pointing resolution caused by image shrinkage, and consistent with simulations.
- 4.0 σ excess (103±26 events) was observed at E>20TeV.

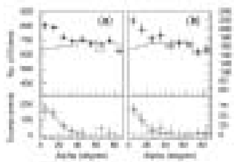

Fig. 8 Image orientation angle (alpha) distributions for gamma-ray-like events. The left figure (a) shows the distributions for all energies, and the right figure (b) for those with reconstructed energies above 20 TeV.

Energy spectrum

- Energy spectrum was derived with the assumption of power-law spectrum:

$$\frac{dN}{dE} = (3.3 \pm 0.9_{stat.} \pm 0.3_{syst.}) \times 10^{-13} \left(\frac{E}{10TeV}\right)^{-(4.0^{+0.9}_{-0.6 stat.} \pm 0.3_{syst.})} ph/cm^{-2}/\sec/TeV$$

- Our spectrum is not inconsistent with cutoff spectrum measured by Whipple and HEGRA-CT groups.
- However, considering the excess at E>20TeV, our result favored a higher cutoff energy of ~8 TeV rather than 4 TeV, which is at the high end of the range allowed for Mrk 501 (Aharonian et al. 1999)

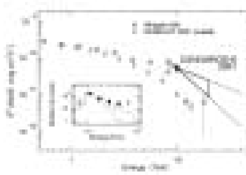

Fig 9. The observed gamma-ray fluxes (main panel) and the energy spectrum of gamma-ray events (inserted panel). The fluxes observed by Whipple (Krennrich et al. 2001) and HEGRA-CT (Aharonian et al. 2002) were also shown.

Light curves

Consistent with flat curve, though the statistics is limited.

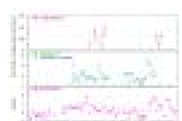

Fig 10. Light curve spectrum of Mrk421 observed by CANGAROO telescope, associated with those of X-ray (RXTE) and TeV (HEGRA) fluxes.

Simulations

Effective area

For LZ angle of 70°, gamma-ray shower cascade develops ~3 times further than that of normal observation at zenith, which provides ~10 times larger effective area. (Sommers & Elbert 1987, Tanimori et al. 1994), though with a higher energy threshold of ~10 TeV.

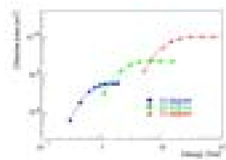

Fig 4. Calculated effective collecting area of gamma-ray (including cut efficiency) for different observation zenith angle of 15, 55, and 70 degrees.

Simulation for LZA observation

- Cherenkov shower image is shrunk for LZA observation.
- Hadron simulations well agree with data
- High resolution camera helpd to to separate the smaller images of gamma-ray events from those of background events

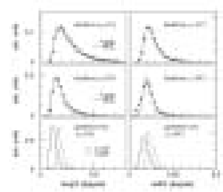

Fig 5. Distributions of the image-centroid parameters (length and width) observed at the large (~70) and small (~15) zenith angles. In the upper and middle panels, the observed background data (dots with error bars) and hadrons simulations (solid lines) are shown for the large and small angles. In the bottom panels, those of the gamma-ray simulations, with different camera pixel spacings (0°.115 and 0°.230), are shown for large angle observations.

To appear in ApJL (astro-ph/0209487)

Analysis

Likelihood method

- The likelihood method (Enomoto et al. 2002a,2002b) uses a single parameter,

$$R_{prob} = \frac{\text{Prob}(\gamma)}{\text{Prob}(\gamma) + \text{Prob}(B.G.)}$$

Prob(γ) and Prob(B.G.) are the probabilities for γ-ray or background events, which were estimated from *width*, *length*, and *asymmetry* parameters, considering the energy dependence.

- We adopted a relatively loose cut of

$$R_{prob} > 0.4$$
$$0.2 < distance < 1.1$$

where 86 % rejection of background events and 63 % acceptance of γ-ray events are expected.

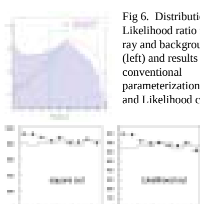

Fig 6. Distributions of Likelihood ratio for gamma-ray and background events (left) and results with conventional parameterization (square) cut and Likelihood cut. (bottom)

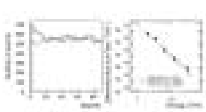

Fig 7. Crab results (alpha plot and energy spectrum)

Calibration with Crab nebula

Crab observed for the confirmation of the analysis method and the estimation of the systematic error in the absolute energy scale, at relatively large zenith angles of 55° in November and December 2000. Derived energy spectrum in 2-20TeV agrees well with other experiments.

Summary

Owing to the large effective area and the high resolution performance of the Cherenkov imaging camera, E>10TeV gamma-rays from Mrk421 were detected at a high confidence level at zenith angles of ~70 degrees with 14 hours of observations. The derived spectrum in the region of 10-30 TeV is steeper than that around 1TeV, which supports the cutoff spectrum of Mrk 421 measured in the 0.2-10TeV range by other groups. The excess observed above 20 TeV is strongly suggestive of a higher cutoff energy, ~8TeV, compared to the lower energy observations. These observations confirm, with the support of detailed simulations, the viability of the large zenith angle technique.

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