TeV OBSERVATIONS OF THE VARIABILITY AND SPECTRUM OF MARKARIAN 421

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ABSTRACT

Markarian 421 was the first extragalactic source to be detected with high statistical certainty at TeV energies. The Whipple Observatory gamma-ray telescope has been used to observe the Active Galactic Nucleus, Markarian 421 in 1996 and 1997. The rapid variability observed in TeV gamma rays in previous years is confirmed. Doubling times as short as 15 minutes are reported with flux levels reaching 15 photons per minute. The TeV energy spectrum is derived using two independent methods. The implications for the intergalactic infra-red medium of an observed unbroken power law spectrum up to energies of 5 TeV is discussed.

INTRODUCTION

Markarian 421, a nearby (z=0.031), X-ray selected BL Lacertae object was the first extragalactic object to be detected at energies greater than 30 GeV (Punch et al, 1992). BL Lacertae objects are a subset of a broader class of Active Galactic Nuclei (AGN) known as blazars. It is widely believed that the characteristic properties of blazars (rapid variability over a wide range of energies, flat radio spectrum and high and variable polarization) result because the jets in these AGN are closely aligned to the line of sight (Blandford and Königl, 1979). The rapid γ-ray variability reported in this paper supports this interpretation since relativistic beaming is necessary to avoid absorption of the highest energy radiation.

The TeV γ-ray emission from Markarian 421 has been monitored from December through May in 1996 and 1997. The observations were made with the 10 meter γ-ray telescope at the Whipple Observatory. The camera was significantly upgraded during Autumn 1996 to 151 pixels increasing the field of view of the telescope from 3° to 3.5°. The imaging atmospheric technique uses information on the angular shape and orientation of individual Čerenkov images to reject more than 99.7% of the cosmic-ray induced showers while retaining over 50% of the possible source γ-ray initiated events (Reynolds et al, 1993). Since the instrument has changed significantly between the 1996 and 1997 observing seasons, the γ-ray flux for each season is quoted as a fraction of the γ-ray flux from the Crab Nebula so that data from the two seasons may be meaningfully compared.

FLUX VARIABILITY: DECEMBER 1995-MAY 1997

The γ-ray emission averaged over each observing season has gradually decreased since the 1995 observing season from 0.35 Crab in 1995 to 0.2 Crab in 1997. The γ-ray emission from Mrk421

Mrk421 in 1996 was constant about the average rate is 3×10^{-36}. A similar test applied to data from the Crab Nebula taken in 1996 gives a probability of 0.86 for steady emission. This result shows that the emission from the Crab Nebula is constant and indicates that fluctuations due to systematic effects are negligible compared to the statistical errors. Figure 1 shows the γ-ray flux from Mrk421 as a fraction of the Crab Nebula flux for the 1996 and 1997 observing seasons.

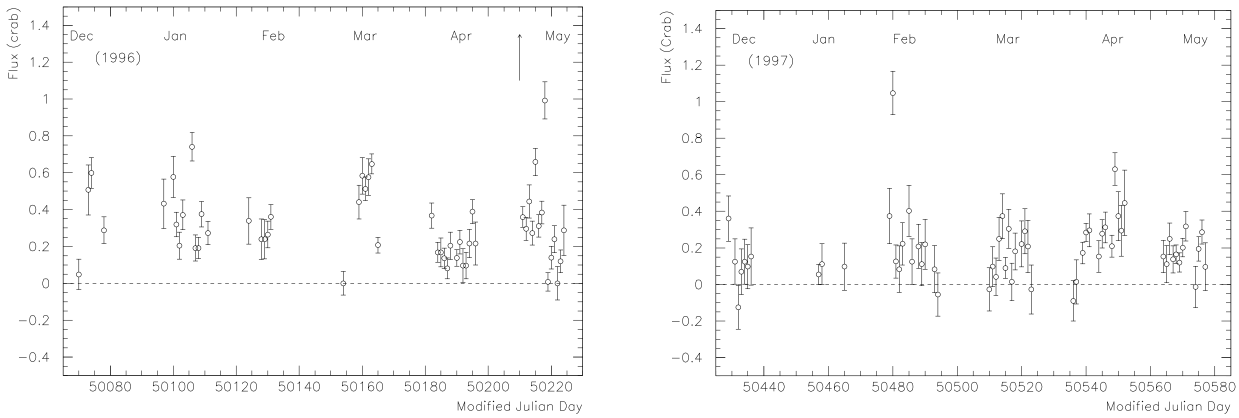

Fig. 1: The daily γ-ray rates during 1996 and 1997 as a fraction of the rate from the Crab Nebula, data from May 7, 1996 (6.2 Crab) is supressed and is represented here by an arrow.

A number of well defined flares can be seen in these data. On February 1, 1997, the γ-ray emission increased by a factor of 5.5 above the average flux for the 1997 observing season. No evidence for hourscale variability within the 1 hour of observations on this night was found. The most impressive variations observed occurred in May 1996 when, in addition to an increase of dayscale flickering, two dramatic hourscale flares were observed. These are shown in Figure 2 (Gaidos et al, 1996). The first occurred on May 7, where the flux increased by a factor of 5 in the 2.5 hours of observations and reached a maximum rate ∼10 times the Crab, becoming the most intense source of TeV γ-rays ever observed. The second, on May 15, was only ∼ 30 minutes in duration, with a peak TeV flux of about 14 times the average for 1996.

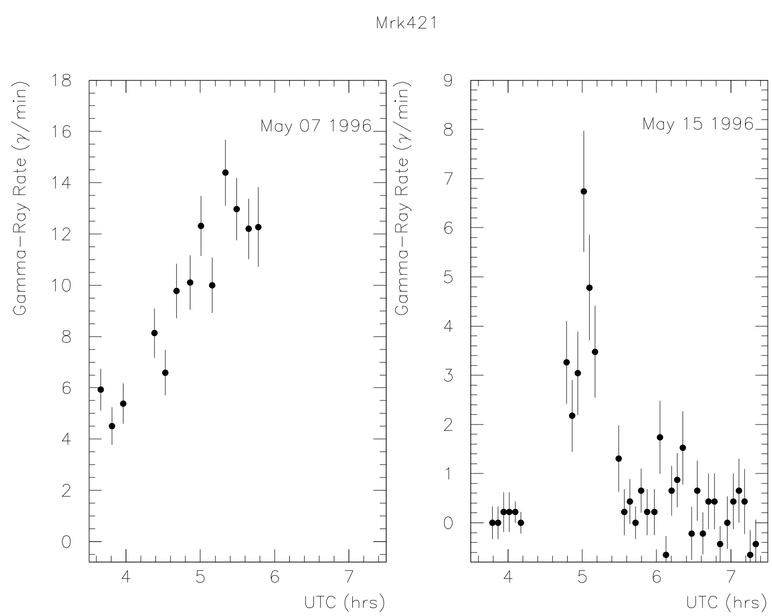

Fig. 2: Light curves of two Mrk 421 flare events of 1996 May 7 and 1996 May 15.

The extremely large γ-ray flux observed on May 7 from Mrk421 provides a very pure sample of γ-rays from which we can extract an energy spectrum and search for evidence for a spectral cutoff. The spectrum of Mrk421 was obtained using two independent analysis methods described in detail as method 1 and method 2 of Mohanty et al (1997). Method 1 isolates γ-rays from the dominant background of cosmic-ray induced images using parameter cuts which have a slight energy dependence. This compensates for the fact that showers from higher energy γ-rays have slightly larger images. Method 2 uses a "cluster" or "spherical" approach in which a single parameter is used to characterize the γ-ray-like nature of an image and correlations between image parameters are incorporated naturally. Figure 3 shows a plot of the γ-ray flux versus energy using method 1 (filled circles, Zweerink et al. 1997) and method 2 (open circles, Rodgers 1997) along with the best fit power law of:

$$F(E) = (2.24 \pm 0.12 \pm 0.7) \times 10^{-6} E^{-2.56 \pm 0.07 \pm 0.1} \mathrm{photons/s/m^2/TeV}. \quad (1)$$

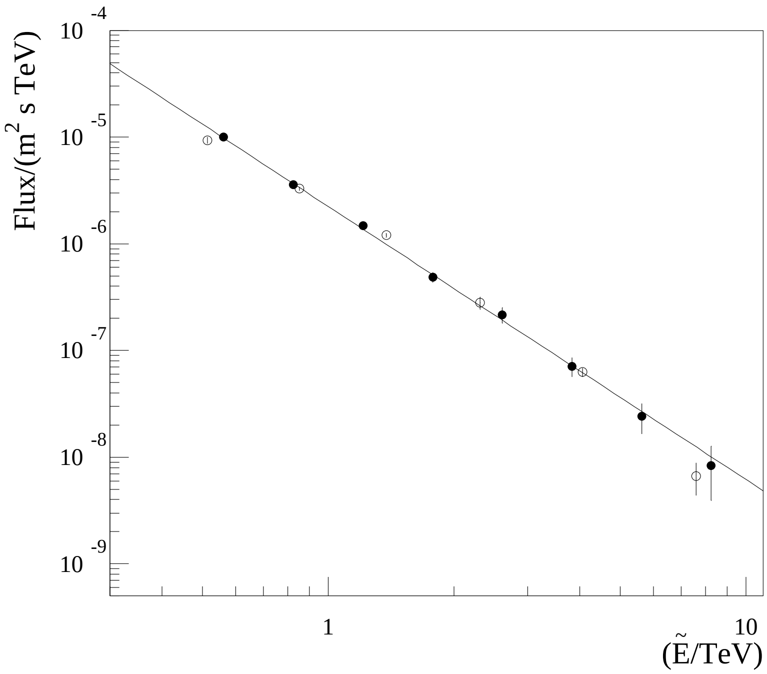

Fig. 3: Differential energy spectrum of Markarian 421 fom observations taken on May 7 1996. The filled circles are calculated using method 1 (Zweerink et al 1997) and the open circles using method 2 (Rodgers et al, 1997)

In June 1995, a considerable amount of data was taken at large zenith angles while Mrk421 was in a high γ-ray state. The large zenith angles cause the energy region covered by the observations to shift to significantly higher energies relative to the standard small zenith angle observations. Monte Carlo simulations were used to determine the energy threshold, collection area and optimal parameter cuts at a variety of large zenith angles. Large zenith angle observations of the Crab Nebula were used to perform a consistency check of the predictions of the Monte Carlo simulation regarding the energy threshold and collection areas at different zenith angles. (Krennrich et al, 1997)

Observations at zenith angles of 45°-50° on June 20, 21 and 28 and 55°-60° on June 20 were used to search for a spectral cut-off in the very high energy γ-ray emission from Mrk421. Table 1 shows the excess events at different energy thresholds, it is evident that the spectrum of Mrk421 extends beyond 5 ± 1.5 TeV. Although the statistical significance above 8 ± 2.4 TeV is marginal (3.1σ), a hint that the emission extends beyond 8 ± 2.4 TeV is present in the data.

DISCUSSION

The extremely rapid γ-ray variability observed in May 1996 implies, by relativistic causality, a very

Table 1: Number of excess events from June 20,21,28 at large zenith angles (Krennrich et al, 1997)

Energy Threshold (TeV)	Excess Events	significance (σ)
2.0 ± 0.6	109	9.3
4.0 ± 1.2	41	6.0
5.0 ± 1.5	25	5.0
8.0 ± 2.4	11	3.1

compact emission region. A significant degree of Doppler boosting is required to avoid absorption of the γ-rays by pair production off low energy photon fields. A lower limit of 9.9 can be derived for the Doppler boost factor of the γ-ray emission region in the jet by considering the simultaneous optical U-band flux (Buckley et al, 1996b).

Gamma-ray emission with $E \geq 5$ TeV from Mrk421 has been detected using two independent methods and datasets; no evidence for a cutoff in the energy spectrum is seen in the data. This result conflicts with the interpretation of a previously reported energy spectrum (Mohanty et al, 1993) by De Jager, Stecker, and Salomon (1994), where they attributed a non-detection at energies above 5 TeV to a cutoff by extragalactic IR background radiation.

ACKNOWLEDGEMENTS
This research is supported by grants from the U.S. Department of Energy and by NASA, by PPARC in the UK and by Forbairt in Ireland.

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