TeV Flare Spectra of Mkn 421 and Mkn 501

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Abstract

The BL Lacertae objects Mkn 501 and Mkn 421 have shown several episodes of γ-ray flaring activity over the last four years. Their energy spectra in the range between 260 GeV - 12 TeV have been measured using the Whipple Observatory 10 m telescope. Despite a large variety of γ-ray fluxes and time profiles of the flares, the energy spectra of Mkn 501 and Mkn 421 do not exhibit significant spectral changes during prominent bursts.

1 Introduction:

Two blazars have been detected at TeV energies with a statistical significance exceeding $> 10\sigma$: Mkn 421 (Punch et al. 1992) and Mkn 501 (Quinn et al. 1996). Mkn 501 was detected only recently at GeV energies with EGRET(Kataoka, 1999). Also, Mkn 421 was a weak source for EGRET. (Thompson et al. 1995). TeV γ-ray flares of Mkn 421 and Mkn 501 have been detected with sufficiently strong fluxes that we were able to derive energy spectra on time scales as short as 30 minutes. This allows the study of spectral energy distributions for flaring activity over a wide range of time scales.

Blazar emission for X-ray selected BL Lac objects at lower energies (up to about 1-100 keV) is almost certainly due to synchrotron emission from a beam of highly relativistic electrons. The GeV/TeV emission forms a second component which is usually attributed to inverse Compton scattering of relatively low energy photons by the electron beam (see, e.g., Sikora, Begelman & Rees 1994) or perhaps to pion photoproduction by a proton component of the beam (see, e.g., Mannheim 1993). The inverse Compton models predict typical blazar γ-ray energy cutoffs of 10 GeV to about 30 TeV whereas proton beam models allow γ-ray energies exceeding 100 TeV. Spectrum measurements at the low energy end (perhaps probing the energy onset of the second component) and the high energy end (perhaps showing an energy cutoff) are both important for constraining models.

Multiwavelength observations of Mkn 421 and Mkn 501 showing γ-ray/X-ray correlations (Buckley et al. 1996; Catanese et al. 1997) indicate that synchrotron-inverse Compton models could accomodate the observations. However, a smoking gun, either ruling out or confirming proton beam or synchrotron-inverse Compton models has not yet been provided. Complications in interpreting multiwavelength spectra arise from the absorption of the highest energy photons by the extragalactic IR background radiation. However, variations in the X-ray/TeV spectra can be directly attributed to the emission mechanism. Therefore, detailed energy spectra of flares at γ-ray and X-ray energies might provide the strongest constraints for emission models addressing spectral variability.

Mkn 421/Mkn 501 observations are particularly interesting because both have nearly the same redshift. Absorption due to intergalactic infrared photons should affect the energy spectral shapes (spectral index and curvature) in the same way and spectral differences can be attributed to the emission process. We present a summary of observations of Mkn 421 and Mkn 501 taken during 1995 - 1998 showing energy spectra from strong flaring states between fluxes of 1 - 10 Crab.

2 The 1995 - 1998 observations:

The observations presented here were made with the Whipple Observatory 10 m imaging Cherenkov telescope. The camera consisted of 109 (until 1996 December 4), 151 (after 1996 December 4) or 331 (after 1997 September 30) photomultiplier tubes (PMTs) placed on a 0.25° hexagonal matrix. These cameras covered fields of view of about 3.0°, 3.4° and 4.8°. The data were normally taken in an on-off mode in which the source is tracked for typically 28 minutes, and then the same range of elevation and azimuth angles is tracked for another 28 minutes giving a background comparison region. The Crab Nebula serves as a standard candle for TeV γ-ray astronomy, and it was observed using the same camera configurations and ranges of zenith angles that were used for the blazar observations.

The Mkn 421 data consists of observations in June 1995, on May 7 and May 15 1996 and on April 21 1998. The first flare (1995) was detected using large-zenith angle (LZA) observations. The details of the analysis are described in Krennrich et al. (1999). The second data set consists of 2 hours of observations showing the largest flux from Mkn 421 observed (Gaidos et al. 1996). The γ-ray rate increased steadily giving a count rate at the end of the run of about 15 γ's/min at $\mathrm{E} > 350$ GeV which is 10 times the rate from the Crab Nebula. The average rate during the runs was 7.4 Crab units. The third data set (May 15 1996) consists of an extremely short flare lasting for only 1/2 hour including the rise and fall. A fourth data set consists of an observation as part of a multiwavelength campaign including X-ray observations (flare on April 21 1998). Again a rising γ-ray flux but also a decrease of the flux within 4 hours was observed. Simultaneous X-ray observations using the BeppoSAX X-ray satellite are reported by Maraschi et al. (1999).

The Mkn 501 data reported here consists of observations which were made in between February 14 to June 8 of 1997 during a high state of emission (Protheroe et al. 1997), resulting in an averaged spectrum. A total of 16 hours of small-zenith angle (SZA) on-source data were taken at 8° to 25° and 5.1 hours of LZA data were taken at 55° to 60° (Samuelson et al. 1998). These observations showed that the flux for the 1997 observing season varied from about 0.2 to 4 times the flux from the Crab Nebula with an average value of 1.4 (c.f. Quinn et al. 1999). A second observation (March 5 1998) showing the strongest flare observed by the Whipple Observatory γ-ray telescope is used to measure the spectrum during a state of high but nearly constant emission (5 Crab) lasting for at least 84 minutes.

3 Analysis

The analysis of the Mkn 501 and Mkn 421 data prior to 1998 has been described in (Samuelson et al. 1998; Krennrich et al. 1999; Zweerink et al. 1997). For the analysis of flares using the 331-PMT camera, we followed an established procedure (Mohanty et al. 1998) in deriving energy spectra. The telescope is triggered when any two of the 331 PMTs give pulses within a triggering gate of 20 ns with 50 or more photoelectrons. We have added the additional software requirement that a signal corresponding to at least 80 photoelectrons is present in at least two pixels. This raises the telescope energy threshold, but the collection area can be readily calculated. The energy threshold for the 331-PMT camera was higher than in previous years, because lightcones, which compensate for the dead-space between PMTs and reduce albedo, were not yet installed. As a check on extraction of energy spectra we have analyzed data for the Crab Nebula taken with the 331-PMT camera, showing a spectral shape consistent with previous measurements.

4 Results: Mkn 421

The spectra derived for Mkn 421 are shown in Figure 1. To the left the energy spectra are shown and to the right the rate (in Crab units) versus time is shown. The flares in Figure 1 are different in time history and average flux level:

a) In June 1995 (triangles) flares that occured within a week involving data taken on three different nights are shown. The observations in June 1995 were taken at LZAs where the telescope operates at a higher energy threshold. The average flux level was 3.3 Crab above 1.3 TeV.

b) On May 7 1996 (circles) a rising flare shows the highest flux observed from Mkn 421 over a period of 2 hours. The flux doubled within one hour (Gaidos et al. 1996). The average flux was 7.4 Crab, however, rising from 3 Crab to 10 Crab.

c) On May 15 1996 a flare shows a fast rise and fall (boxes), over a time of 30 minutes. The average flux was 2.8 Crab. Observations 30 minutes before and continuous monitoring of the source after this flare (solid circles) show a low level of emission, constraining the short time scale of this flare.

d) On April 21 1998 a flare rising from about 1 Crab to 2.5 Crab over a time scale of 2 hours and falling off afterwards was observed. The spectrum is based on small-zenith angle data only and therefore just the rise of the burst is included.

Despite the different flaring profiles, either rising (b), rising and falling (c) or relatively constant (a), no significant variations of the spectral indices are found. Also the two rising flares, b) rising from 3.5 - 10 Crab and d), rising from 1.2 to 2.5 Crab, show different flux levels, but consistent spectral indices. It should be emphasized that short flares such as in b), c) and d) provide strong constraints on the size of the emission region and consequently on the Doppler factor. These should be relevant for modeling the time evolution of the energy spectral distribution. Contemporaneous X-ray observations during flares d), showing for the first time a TeV/X-ray correlation on short time-scales (Maraschi et al. 1999), supports synchrotron-inverse-Compton models.

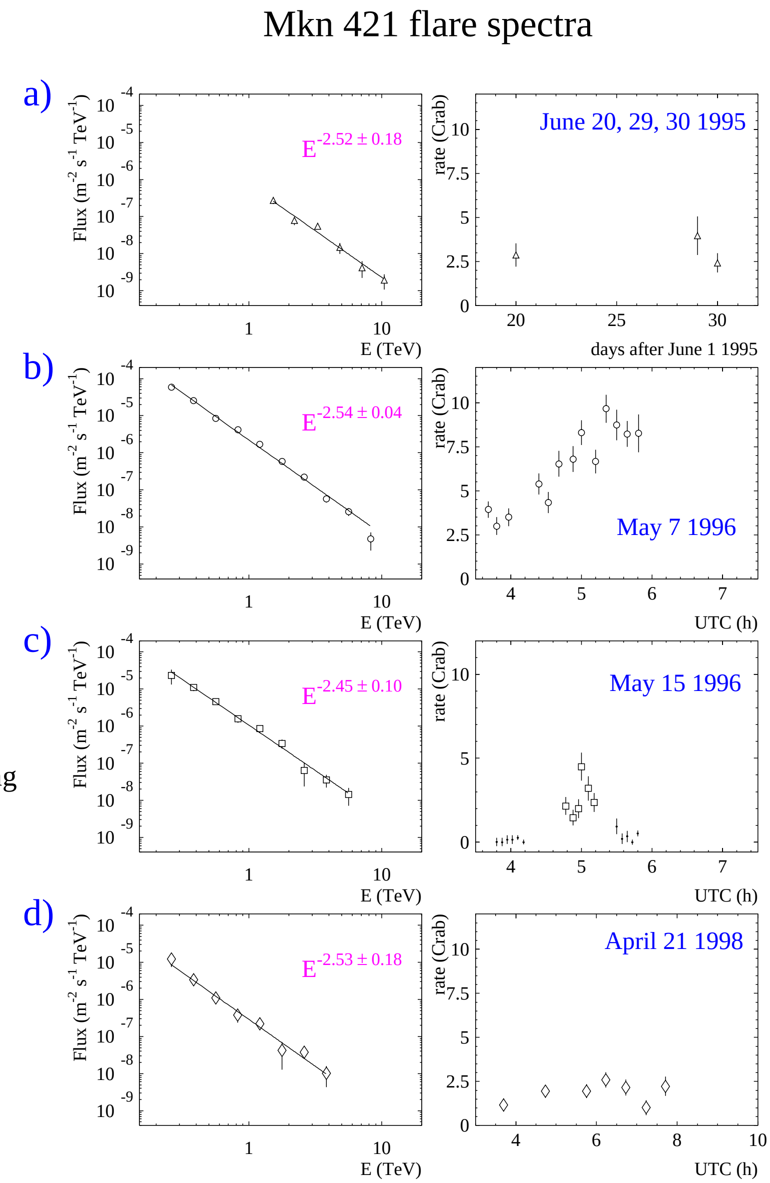

Figure 1: Mkn 421 spectra of flares between June 1995 through April 1998 are shown. The energy spectra are shown to the left and their corresponding flux history (only same marker type) is shown to the right.

5 Results: Mkn 501

The average energy spectrum of Mkn 501 for data taken during a period of strong flaring activity between February - June 1997 (Samuelson et al. 1998) shows, that the data cannot be fit by a straight power-law (probability of 2.5×10^{-7}). Including a curvature term yields a good fit, indicating significant curvature

(Figure 2 a)) in the spectrum of Mkn 501 (confirmed by Aharonian et al. 1999a). In 1998 the average emission level decreased considerably from that of 1997 (to $\sim$ 20% of the Crab Nebula flux) but showing also two significant (Quinn et al. 1999) flaring events. The strongest one (84 minutes) occured on March 5 1998, showing $\sim$ 5 Crab, the largest flux detected to date from Mkn 501 by the Whipple Observatory 10 m telescope. Figure 2 b) shows its energy spectrum, which consistent with the 1997 spectrum.

A straight power-law fit shows a spectral index of 2.38 ± 0.07 also showing good agreement with the averaged spectrum (2.41 ± 0.025) from 1997.

The energy spectra of Mkn 421 and Mkn 501, which show different spectral energy distributions (Krennrich et al. 1999), have been studied to search for spectral variability. No significant spectral variability during high levels of flaring activity (1 - 10 Crab for Mkn 421; 0.5 - 5 Crab for Mkn 501) has been found neither for Mkn 421 nor Mkn 501. This is in agreement with studies of Mkn 501 reported by Aharonian et al. 1999b. However, it is clear that spectral variability needs to be studied over a larger range of flux levels. Also contemporaneous measurements of corresponding X-ray - hard-X-ray spectra are necessary to constrain emission models (see Maraschi et al. 1999).

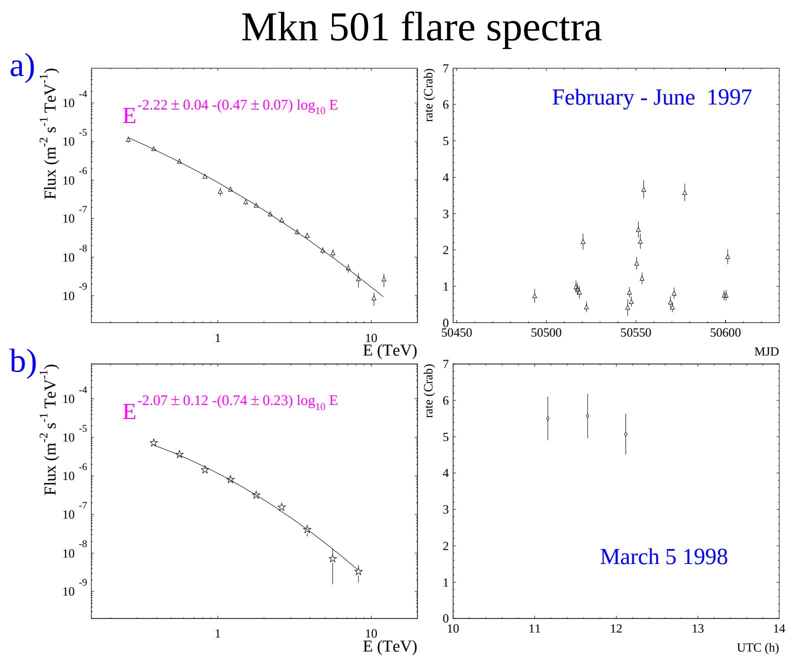

Figure 2: a) average spectrum in 97' b) flare spectrum from March 5 98'

References

Aharonian, F.A., et al. 1999a, A & A, in press,
Aharonian, F.A., et al. 1999b, A & A, in press,
Buckley, J.H., et al. 1996, ApJ, 472, L9
Catanese, M., et al. 1997, ApJ, 487, L143
Kataoka, J., et al. 1999, ApJ, 514, 138
Krennrich, F., et al. 1999, ApJ, 511, 149
Mannheim, K. 1993, Astron. Astrophys., 269, 67
Maraschi, L., et al. 1999, Astroparticle Physics, in press
Mohanty G., et al. 1998, Astroparticle Physics, 9, 15
Protheroe, R. J., et al. 1998, Proc. of 25th ICRC (Durban), eds. M. S. Potgieter et al. 8, 317
Punch, M., et al. 1992, Nature, 358, 477
Quinn, J., et al. 1996, ApJ, 456, L83
Quinn, J., et al. 1999, ApJ, in press
Samuelson, F. W., et al. 1998, ApJ, 501, L17
Sikora, M., Begelman, M. C., & Rees, M. J. 1994, ApJ, 421, 153
Thompson, D. J., et al. 1995, ApJS, 101, 259; Thompson, D. J., 1996, private communication
Zweerink, J, et al. 1997, ApJ, 490, L170