TeV/X-ray observations of Mkn 501 during 1997 and 1998

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Abstract. The stereoscopic Cherenkov telescope system of HEGRA was used in 1997 and in 1998 to observe the BL Lac object Mkn 501 on a regular basis. After a period of exceptional activity in 1997 of continuous flares and a mean flux roughly one order of magnitude stronger than in the preceding years the source returned in 1998 to a state of moderate flux levels with only very sparse flaring activity. In this paper we summarize the TeV characteristics of Mkn 501 as deduced from the 1997 and 1998 HEGRA observations. Furthermore, we describe a joint HEGRA/RXTE campaign which we organized in June 1998.

INTRODUCTION

In the northern hemisphere two BL Lac objects have firmly been established as emitters of TeV γ-rays: Mkn 421 and Mkn 501. Due to the extreme conditions needed for the production of TeV photons, this TeV blazars can be revealing laboratories for the understanding of the nonthermal high energy emission of blazars in general. Furthermore, observations of TeV blazars contribute to the field of *Observational Cosmology*: the extinction of TeV photons due to pair production processes of the TeV γ-rays on photons of the Diffuse Extragalactic Background Radiation (DEBRA) [1,2] is expected to rapidly increase with γ-ray energy; the TeV energy spectra henceforth constrain the DEBRA intensity in the notoriously difficult wavelength region from 1μm-50μm. The DEBRA spectrum in this wavelength region is very interesting since it depends on the star formation history during the evolution of the universe and the cosmological parameters [3].

The stereoscopic HEGRA system of five identical Imaging Atmospheric Cherenkov Telescopes [4,5] is located on the Canary Island of La Palma (Spain) and is characterized by a large effective area of $\sim 10^5\,\mathrm{m}^2$ and excellent spectroscopic capabilities with an energy resolution better than 20% for individual TeV photons. The simultaneous observations of the Cherenkov light produced by air showers with several Cherenkov telescopes results in an unprecedented angular resolution of 0.1°

per individual γ-ray and a reduction of the background of hadronic cosmic rays by O(100) based on the analysis of the stereoscopic air shower images. The telescope system achieves an energy flux sensitivity of $\nu\,\mathrm{F}_\nu$ at 1 TeV of 10^{-11} $\mathrm{erg\,cm^{-2}s^{-1}}$ (S/N $= 5\sigma$) for one hour of observation time which is ideally suited for the study of the rapid variability which is characteristic for blazars in general and especially for TeV blazars.

Multiwavelength observations of blazars promise to provide enough information to constrain the emission mechanism and the jet structure. In this context simultaneous TeV/X-ray observations are of special interest since both radiation components are believed to be produced by a population of high energy electrons producing synchrotron photons at longer wavelengths (X-rays) and Inverse Compton photons at shorter wavelengths (TeV γ-rays). In the following we first describe the TeV and TeV/X-ray observations; subsequently we discuss the results.

THE 1997/1998 TEV CHARACTERISTICS OF MKN 501

The HEGRA telescope system was used in 1997 and 1998 to extensively monitor the two TeV blazars Mkn 501 and Mkn 421. The 1997 Mkn 501 observations as well as the standard analysis tools and the methods to determine the systematic error on spectral estimates are described in [6,7]; interested readers can find a detailed account of the Mkn 421 observations in [8]. The results presented in this paper for Mkn 501 are based on 200 h of high quality, low zenith angle ($\theta < 30°$) data taken from March 16th, 1997 to Aug 25th, 1998.

The 1997/1998 light curve is shown in Fig. 1. During 1997 the source was extremely bright and variable. The integral fluxes above 1 TeV reached (during flares) 10 times the flux level of the Crab Nebula. Flux variability was found on time scales smaller than one day: from the flux measurements of different days shortest exponential flux increase/decrease time-constants of about 12 h were derived; on shorter time scales some evidence was found for substantial variability within several hours. For 63 days *diurnal* differential γ-ray spectra could be determined with a median accuracy of 0.2 in the 1-5 TeV photon index. In Fig. 2 (left side) an example of a diurnal differential spectrum is given (May 8th, 1997). After 1.9 h of observation time, the curvature of the spectrum can clearly be recognized and the 1-5 TeV

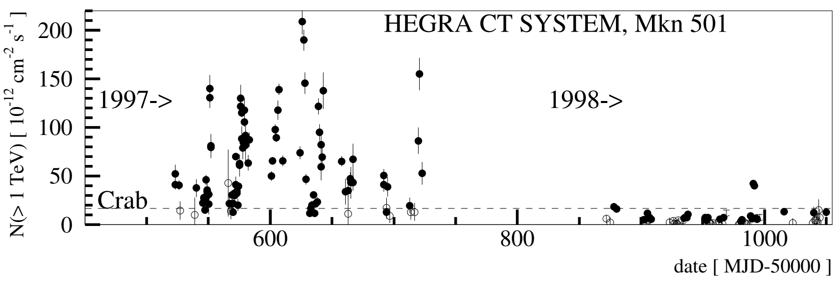

FIGURE 1. The 1997-1998 Mkn 501 light curve (1 day binning). MJD 50600 corresponds to June 1st, 1997.

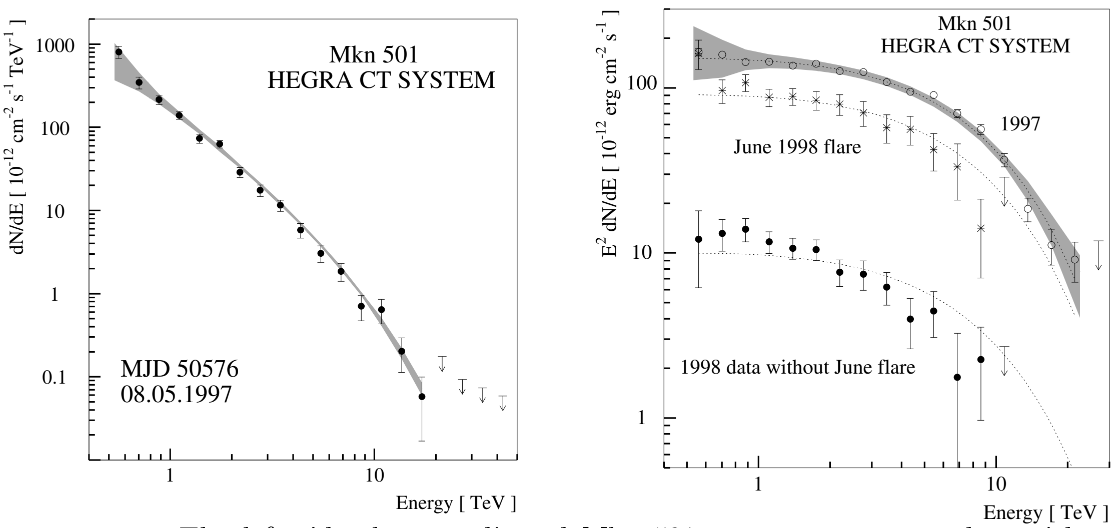

FIGURE 2. The left side shows a diurnal Mkn 501 energy spectrum taken with an integration time of 1.9 hours (data with $<30°$ zenith angle). The right side shows the Spectral Energy Distribution (E^2 dN/dE) averaged over 1997 (open symbols), for the 2 days of maximum flux during the June 1998 flare (asterisks), and for the rest of the 1998 data (full symbols). The systematic error on the curvature of the spectra is represented by the hatched region. Additionally, there is a 15% systematic error on the absolute energy scale. All flux upper limits are on a 2σ confidence level.

photon index could be determined to be $2.24 \pm 0.11_{\rm stat} \pm 0.05_{\rm syst}$. Remarkably, the HEGRA 1997 observations showed that the drastic flux variability was accompanied by at most modest variations in the TeV photon index. Only marginal evidence was found for spectral variability, i.e. two days (April 13th, 1997 and September 3rd, 1997) showed a spectrum harder than the time averaged spectrum on the $\sim 3\sigma$ confidence level.

The stability of the spectral shape justified a determination of the time averaged energy spectrum which is shown in Fig. 2 (right side). From 500 GeV to 24 TeV, the spectrum could be described by a power law model with an exponential cutoff: $d{\rm N}/d{\rm E} \propto ({\rm E}/1\,{\rm TeV})^{-\beta} \exp(-{\rm E}/{\rm E}_0)$, with $\beta = 1.92 \pm 0.03_{\rm stat} \pm 0.20_{\rm syst}$, and ${\rm E}_0 = (6.2 \pm 0.4_{\rm stat}\ (-1.5\ +2.9)_{\rm syst})$ TeV. Note that the errors on β and ${\rm E}_0$ are strongly correlated. A dedicated χ^2-analysis yielded a very conservative lower limit on the maximum γ-ray energy in the signal of 16 TeV.

In 1998 the source showed very modest flux levels with only one flare with a flux clearly above the level of the Crab Nebula (June 26th/27th and 27th/28th). While the shape of the energy spectrum during the maximum of the June 1998 flare is rather similar to the shape of the 1997 spectrum, the time averaged 1998 energy spectrum (excluding the two days of the flare) seems to be noticeably softer (Fig. 2, right side). A fit of a power law model to the ratio of the two spectra gives $(d{\rm N}/d{\rm E})_{1997}/(d{\rm N}/d{\rm E})_{1998,{\rm lowstate}} \propto {\rm E}^{\beta}$ with $\beta = 0.36 \pm 0.10$.

HEGRA/RXTE OBSERVATION DURING JUNE 1998

In June 1998 we organized a HEGRA/RXTE multiwavelength campaign which was characterized by exactly simultaneous TeV/X-ray observations with long integration times per day for approximately two weeks [9]. The results of the campaign are summarized in Fig. 3. A strong flare was observed in both, the TeV and the X-ray bands. Mkn 501 showed very low TeV flux levels of about 1/10 the flux of the Crab Nebula. Only during a flare of approximately two days the TeV flux increased to about two times the Crab level. The X-ray flux varies synchronously; a time delay between the the TeV and the X-ray variability is surely smaller than one day. Remarkably, the TeV flux changed during the flare by a factor of $\sim$20 but the 10-20 keV X-ray flux changed only by a factor of $\sim$4. The TeV hardness ratios indicate that the TeV spectrum was already rather hard during the first days of observations, stayed hard during the flare, but substantially softened after the flare. However, the statistical significance for the softening after the flare is only about 2σ. In the X-ray band a simple correlation of the flux level and the spectral hardness is observed. Note that for the day of maximum TeV emission (June 26th/27th) we found evidence on the 0.5% chance probability level for a flux increase and subsequent decrease by a factor of 2 on a 1 h timescale.

DISCUSSION

The implications of the observations of the Mkn 501 spectrum on the DEBRA intensity have been discussed in detail in [7]. Here we focus on the evolution of the source from 1997 to 1998. Mkn 501 returned after 1997 – a year of high activity – to a state of moderate activity, both in the TeV and the X-Ray energy

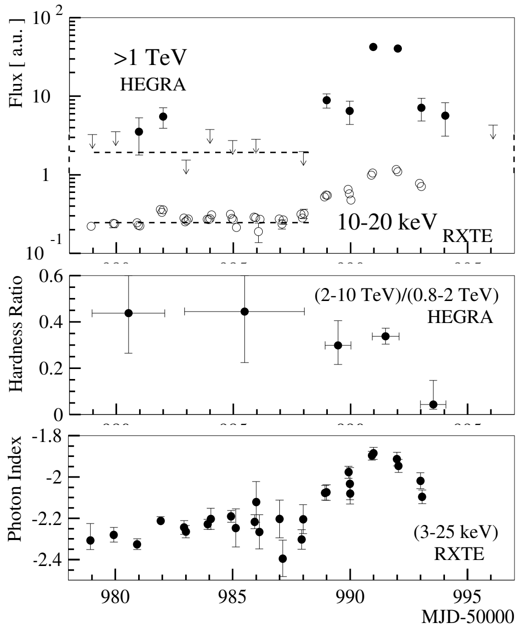

FIGURE 3. The temporal evolution of the TeV/X-ray fluxes and spectra during the RXTE/HEGRA campaign of June 1998. The upper panel shows the integral flux above 1 TeV as measured by HEGRA and the 10-20 keV count rate as determined from RXTE data. The dashed lines show the mean flux levels during the first 10 days of the campaign. The HEGRA flux upper limits are at the 1σ confidence level in order to facilitate the comparison with the 1σ error bars on the flux points. The second and third panels show the HEGRA hardness ratio and the RXTE 3-25 keV photon index (β from $d\mathrm{N}/d\mathrm{E}\propto\mathrm{E}^{\beta}$), respectively.

bands. The decrease in flux is accompanied by a softer average TeV spectrum. Also the X-ray photon indices typically observed with RXTE are softer in 1998 than in 1997: between -1.7 and -2.1 were observed in 1997 [10], and between -1.9 to -2.3 during the observations of 1998 (this work). The BeppoSAX observations of April 1997 and April/May 1998 [11,12] show a similar trend. The softer 1998 X-ray and TeV spectra can easily be understood in terms of the high energy cutoff of accelerated particles moving towards lower energies. Certainly also the other parameters characterizing the production of the γ-ray radiation, as for example a softer spectrum of accelerated particles, could contribute to the evolution of the mean spectra. A decreasing bulk Lorentz factor of the emission region would account not only for a shift of the peaks of the X-ray and γ-ray spectral energy distributions towards lower energies, but also for the decrease of the mean flux level. Interestingly, the relation between the simultaneously observed X-ray and TeV fluxes did not change drastically (by much less than an order of magnitude), neither during 1997 [10] nor from 1997 to 1998. In most models, including Inverse Compton models, the TeV/X-ray flux relation is very sensitive to the model parameters as e.g. the magnetic field or the radius of the emission volume. It is thus puzzling that the source exhibits dramatic flares on a time scale of days or less while maintaining a rather constant TeV to X-ray flux relation on a time scale of two years. In Inverse Compton models this means that the magnetic field and/or the radius of the source have to stay very constant during all these flares or that they are connected to each other by a fixed relationship.

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