Study of the TeV Emission from Mkn 501 with the Stereoscopic Cherenkov Telescope System of HEGRA

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Abstract. The HEGRA system of 4 Imaging Atmospheric Cherenkov Telescopes (IACTs) has been used since March 1997 for a comprehensive study of the gamma-ray emission from the BL Lac object Mkn 501 in the energy range above 500 GeV. Taking advantage of the unique capabilities of the IACT system, i.e. an unprecedented flux sensitivity in the TeV energy range and an unique energy resolution of better than 20% for individual TeV photons, detailed information about the temporal and spectral characteristics of the source during its spectacular bright phase in 1997 is reported. Furthermore, using the large HEGRA and Rossi X-Ray Timing Explorer All Sky Monitor (RXTE ASM) data bases, the correlation of the X-ray and the TeV activity of the source is discussed. Finally, an outlook over present and future activities is given.

1. Introduction

In the first two years after its discovery as a TeV γ-ray source, the BL Lac object Mkn 501 showed fluxes well below the persistent flux of the Crab Nebula (Quinn et al. 1996, Bradbury et al. 1997). In 1997 the source went into a state of surprisingly high activity and dramatic variability, outshining during several nights the brightest known source in the TeV sky, the Crab Nebula, by factors as large as ~10. In this paper we report on detailed studies of this spectacular bright phase performed with the HEGRA IACT system. The IACT system (Daum et al. 1997) is located on the Roque de los Muchachos on the Canary Island of La Palma, (lat. 28.8° N, long. 17.9°, 2200 m a.s.l.). It is formed by 5, during 1997 by 4, identical IACTs - one at the center and 4 (during 1997, 3) at the corners of a 100 m by 100 m square area. Each telescope is equipped with a segmented 8.5 m² mirror and a 4.3° field of view high resolution camera consisting of 271 pixels of 0.25° diameter. Exploiting the stereoscopic observation technique (simultaneous observation of air showers under widely differing viewing angles with two or more Cherenkov telescopes, see Aharonian et al. 1997) the system achieves a low energy threshold of 500 GeV, an excellent angular resolution of 0.1°, an energy resolution of better than 20% (all for individual photons), and a flux sensitivity \( \nu F_\nu \) at 1 TeV of \( 10^{-11} \text{ergs/cm}^2\text{sec} \) \( \simeq 1/4 \text{Crab for 1 hour of observation time (S/}\sqrt{B}=5\sigma \text{ with a system of 4 IACTs).} \)

The 4 IACT system started operation in fall 1996.
2. Data sample and analysis method

The analysis of this paper is based on 110 hours of Mkn 501 data acquired between March 16th, 1997 and October 1st, 1997 under optimal weather conditions, with the optimal detector performance, and with Mkn 501 being more than 45° above the horizon. Altogether about 38,000 Mkn 501 photons were recorded, making it possible to verify the source location with an accuracy of 35 arcsec (Pühlhofer et al. 1997). Since the IACT system provides an unprecedented signal to noise ratio, loose $\gamma$/hadron-separation cuts can be used to extract the Mkn 501 signal and to suppress the background of charged cosmic rays which accept a large fraction of $\sim 80\%$ of the $\gamma$-rays at all energies above 1 TeV. By this means, the systematic uncertainties associated with uncertainties in energy dependent cut efficiencies are minimized. The analysis, i.e. the cut optimization and the calculation of effective detection areas and cut efficiencies, is based on detailed Monte Carlo simulations which have been checked experimentally using cosmic ray data (hadron induced showers) and Mkn 501 and Crab data (photon induced showers). A more detailed description of the analysis tools and also of the temporal characteristics of Mkn 501 can be found in (Aharonian et al. 1998).

3. Time-averaged 1997 Mkn 501 energy spectrum

The time-averaged Mkn 501 energy spectrum is shown in Fig. 1 (left side) over the energy region from 500 GeV to 25 TeV. For determining the spectrum down to energies below 800 GeV, the analysis is restricted to the 80 h of low energy threshold data taken with Mkn 501 at altitudes $> 60^\circ$. The systematic error on
the absolute energy scale is 15%. The shaded region shows our current conservative estimate of the additional systematic error on the shape of the spectrum. It is mainly caused by uncertainties in the effective areas near detection threshold. The error bars in vertical direction show the statistical errors and the error bars in horizontal direction indicate the energy resolution of the IACT System. The spectrum is smooth over the whole energy range and it is clearly curved. Although the exact shape of the spectrum above 10 TeV is still preliminary, the Mkn 501 emission clearly extends into the energy range well above 10 TeV. A $\chi^2$-analysis yields a $2\sigma$ lower limit on the minimum photon energy of the signal of 18 TeV. A fit of the data over the energy region of small systematic errors, i.e. from 1.25 TeV to 50 TeV, with a power law model with an exponential cut off gives:

\[
dN/dE = 9.7 \pm 0.3 \text{(stat)} \pm 2.0 \text{(syst)} \cdot 10^{-11} E^{-1.9 \pm 0.06 \text{(stat)} \pm 0.07 \text{(syst)}} \cdot \exp \left[ -E / (5.7 \pm 1.1 \text{(stat)} \pm 0.6 \text{(syst)} \text{ TeV}) \right] \text{cm}^{-2}\text{s}^{-1}\text{TeV}^{-1}.
\]

In Fig. 1 (right side) the spectral energy distribution (SED) $\nu F_{\nu}$ is shown for the mean spectrum and for all days with a differential flux at 2 TeV below 1.6 and above 3 times $10^{-11}$ cm$^{-2}$s$^{-1}$TeV$^{-1}$. Seemingly, the SEDs peak in the energy range between 500 GeV and 2 TeV, although, due to the systematic uncertainties, a peak in the energy range below 500 GeV cannot be excluded. The three SEDs have within the statistics the same shape. Thus we do not find any evidence for a correlation of the emission strength at 2 TeV and the spectral shape in the energy range from 500 GeV to 20 TeV. Most interestingly, as described further below, the time-averaged spectrum also fits the diurnal energy spectra statistically satisfactorily. The observed spectral shape is invariant during the whole 1997 observation period.

4. The temporal characteristics of the 1997 Mkn 501 emission

The stereoscopic IACT system makes it possible to determine differential TeV spectra even on diurnal basis. Figure 2 (upper panel) shows the differential spectra obtained for 8 exemplary individual nights in the energy range from 1 to 10 TeV. We do not find any diurnal spectrum with a shape which deviates significantly from the time-averaged 1997 spectrum. The temporal evolution of emission intensity and spectral steepness have been studied by fitting power law models to the diurnal spectra in the energy range from 1 to 5 TeV. In Fig. 2 (2 lower panels) the results are shown. As before, the error bars show the statistical errors only. The systematic error on the flux amplitude deriving from the 15% uncertainty in the energy scale is approximately 20% and the systematic uncertainty on the spectral index is 0.1. The emission intensity, i.e. the differential flux at 2 TeV, varies dramatically from a fraction of a Crab unit to ~ 10 Crab units, the peak emission being recorded on MJD 50625/50626. In contrast, the differential spectral indices from 1 to 5 TeV are rather stable. Only two $3\sigma$-deviations from the mean value -2.25 have been found, namely for the night MJD 50550/50551 the spectral index is $-1.87 \pm 0.13 - 0.14$ and for the night MJD 50694/50695 it is $-1.05 \pm 0.30 - 0.38$.

A dedicated search for the shortest time scales of flux variability has been carried out. The time gradient of the flux computed with adjacent diurnal
Figure 2. The upper panel shows the γ-ray spectra of eight individual nights. For each of the four data periods March/April, April/May, May/June, and June/July, 1997 a night of weak emission and a night of strong emission has been chosen (upper limit has 2σ confidence level). The two lower panels show the diurnal diff. fluxes at 2 TeV and spectral indices (1-5 TeV) for the 1997 Mkn 501 data. Spectral indices are shown only for the days with sufficient statistics, i.e. with errors on the spectral index <0.5. Measurement gaps are due to bad weather or shining moon. All three plots: only statistical errors, see text for systematic errors. (MJD 50550 is April 12th, 1997)

5. Correlation X-ray / TeV

The RXTE ASM (Remillard & Levine 1997) data have been used to study the correlation between the 2 to 12 keV and the TeV emission intensities. Figure 3 (left side) shows the Discrete Correlation Function DCF (Edelson & Krolik 1988) as function of the time lag ∆t between X-ray and TeV variability, as computed from the HEGRA diurnal flux amplitudes at 2 TeV and the ASM 2-12 keV count rate, the latter for each day averaged over all measurements within...
a 24 h interval centered close to 0:00 UTC. The DCF shows evidence for a weak correlation between X-ray and TeV activity with a time lag between X-ray and TeV emission smaller than or equal to one day. The DCF computed for $\Delta t = 0$ with 50 pairs of data is $0.37 \pm 0.03$. Due to the limited number of $\approx 50$ pairs of data entering the determination of the DCF, the significance of the correlation is modest. Depending on the assumptions about the autocorrelation properties of the X-ray and TeV emission, the chance probability for larger DCF values is computed to lie between $0.43\%$ and $8\%$. In Fig. 3 (right side), the correlation between the diurnal X-ray and TeV fluxes is shown for $\Delta t = 0$. The straight line fit to the data indicates a much larger relative flux variability in the TeV energy range than in the 2 to 12 keV energy band.

6. Outlook

The 1997 high emission phase of Mkn 501 made it possible to study this BL Lac object in the TeV energy range with unprecedented signal to noise ratio during a long time period of more than 6 months. The IACT system of HEGRA has been used to obtain a wealth of detailed spectral and temporal information. Most interestingly, within the statistical accuracy, the shape of the energy spectrum is constant during the whole observation period and extends well into the energy range above 10 TeV. A deep understanding of the spectral properties is rendered difficult since several effects combine to give the observed spectrum, e.g. the spectrum of the emitting electrons, the spectrum of possible Inverse Compton seed photons, internal $\gamma_{\text{TeV}}$, $\gamma_{\text{O,UV}}$ absorption of the TeV photons in the source, and intergalactic absorption of the TeV photons in $\gamma_{\text{TeV}} \gamma_{\text{IR}} \rightarrow e^+ e^-$ processes by the Diffuse Extragalactic Background Radiation (DEBRA). Note that already the pure fact of the registration of TeV photons with energies exceeding
10 TeV yields a sensitive upper limit on the largely unconstrained DEBRA in the wavelength region from 1 to 20 microns. Due to very general arguments concerning the emitted $\gamma$-ray luminosity, the optical depth $\tau$ of the DEBRA for TeV photons cannot exceed 1 by much more than one order of magnitude. The condition $\tau < \tau_0 \simeq 10$ yields for the DEBRA density $n(\varepsilon)$ at energy $\varepsilon$ the upper limit $\varepsilon^2 n(\varepsilon)/(10^{-3} \text{eV/cm}^3) < (\tau_0/5) (H_0/(60 \text{km/s/Mpc})) / (\varepsilon/\text{eV})$ where $H_0$ is the Hubble constant, with only small corrections depending on the shape of the spectrum.

Models will further be constrained by intensive multiwavelength campaigns and by studying more sources. The analysis of the Mkn 501 and Mkn 421 multiwavelength campaigns performed during 1997 and 1998 with participation of the HEGRA IACT array is underway. Further more, the IACT system has extensively been used to search for new TeV emitting BL Lac sources, although, up to now, without positive evidence. Members of the HEGRA collaboration pursue the installation of two next generation IACT installations aiming at a sensitivity increase by one order of magnitude. HESS, a stereoscopic system of at first 4, in the second stage 16 IACTs of the 10 m diameter class for $\gamma$-ray astronomy at energies above 40 GeV (Hofmann 1997) will probably start operation in the year 2001. MAGIC will be a dedicated “low energy threshold” stand alone IACT for $\gamma$-ray observations above an energy threshold of 10 GeV (Lorenz 1997).

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