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The light curve and spectrum of Mkn 421 as measured with the HEGRA CT1 telescope during its 2001 flare

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Abstract. In the first months of 2001 the AGN Mkn 421 exhibited high activity at flux levels well above 1 Crab. Here we present this object's light curve and energy spectrum for this time period as measured with the HEGRA stand-alone CT1 Cherenkov telescope.

1 Introduction

At $z = 0.031$ Mkn 421 is the closest known BL Lac. It was the first extragalactic source found to emit TeV γ-rays ((Punch et al., 1992) and confirmed by HEGRA (Petry et al., 1996)). Mkn 421 is the source with the up to now fastest observed flux changes reported from TeV γ-ray emitters. With 15 minutes flux doubling time the emission region must be of the size of our solar system (assuming a γ-factor of ~ 10 (Gaidos et al., 1996)).

CT1, the first telescope in HEGRA, has regularly monitored this source since 1994 and produced the light curve with the highest time coverage of all TeV instruments. Exceptionally large and persistent flaring has been observed in the 2000-2001 season. Several multi wavelength campaigns have been carried out, Their results are expected to further clarifiy the physics of AGNi.

Mkn 501, at a similar redshift ($z = 0.034$), shows TeV emission with a cutoff around 6 TeV in its energy spectrum from 1997. This cutoff might be intrinsic to the source or caused by an absorption process due to the possible interaction with the up to now unquantified infrared (IR) background. Therefore the detailed study of the TeV spectra of both Mkn 501 and Mkn 421 are of particular interest for cosmology, because TeV γs might provide an efficient probe of the IR background around 10μm wavelength.

While a high significance observation of an unbroken powerlaw spectrum of Mkn 421 would be a proof that the cutoff of Mkn 501 is source inherent, the observation of a cutoff of Mkn 421 at about the same energy would strengthen the evidence for a sizeable IR background around 10μm wavelength but not rule out the source internal limitation.

Here we shall describe the results of the analysis of the 2001 flare data. A light curve is presented and compared with the X-ray ASM light curve. The high statistics of the sample allow to extract an accurate energy spectrum.

2 Mkn 421 2000-01 data

2.1 Description of the CT1 hardware and MC simulation

The HEGRA collaboration operates the standalone Imaging Atmospheric Cherenkov telescope HEGRA CT1 at the IAC site at La Palma (Canary Islands, Spain) since 1991 (Cortina et al., 1999).

A refined Monte Carlo simulation has been used for this analysis (see (Sobczyńska and Lorenz, 2001) for a full description). The most important improvement with respect to earlier simulations is that single photo electron pulses are now simulated with a variable pulse height and time shape according to the measured distributions, whilst previous simulations were based on simple photo electron counting within trigger coincidence windows. The resulting effective areas are smaller compared to those obtained with the previously used simulations. This is especially important close to the telescope threshold, where the old simulation overestimated the trigger efficiencies, leading to too low flux estimates in the first few energy bins of the derived energy spectra.

CT1 has a threshold of ≈700 GeV. The trigger rate on cosmic ray events close to the zenith is around 3.5 Hz and decreases to ∼2 Hz at 45° ZA.

2.2 2000-2001 period dataset

Roughly 300 hours have been taken on Mkn 421 during dark nights in the 2000-01 period. Additional data under the presence of moonlight (with reduced PM high voltage (HV) and higher energy threshold) were also taken but are not included

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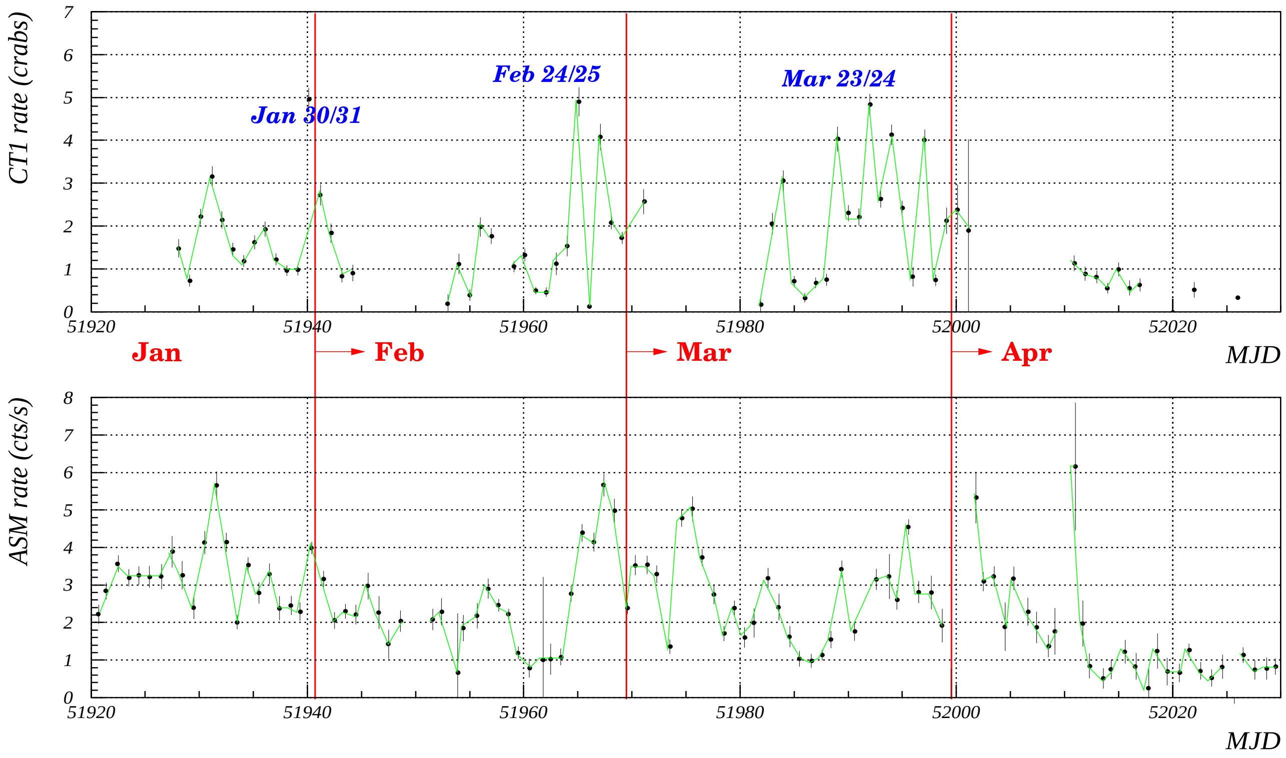

Fig. 1. Integral average daily flux curve of Mkn 421 as measured with HEGRA CT1 and the X-ray detector ASM on board RXTE through the year 2001. Nights where the source flared close to 5 crab levels are indicated. Flux points have been joined with lines to guide the reader and do not indicate a fit to the data. The TeV data point at Feb 25/26 must actually be excluded due to bad weather.

HV Setting	Moonshine	Hours	Significance
Nominal	No	301.9	75
Nominal	Yes	43.4	18
-4%	Yes	21.5	8.6
-8%	Yes	13.4	7.6
-12%	Yes	12.4	7.0

Table 1. The observation times of Mkn 421 with HEGRA CT1 in the 2000-01 observation period for the different HV settings.

yet in this analysis. Table 1 provides an overview over the observation times and results with different HV settings.

The minimum zenith angle (ZA) for the observation of Mkn 421 is around 9°. The maximum ZA considered in the analysis is 45°, corresponding to the highest ZA in the Monte Carlo study.

In total 2.9×10^6 moonless events were recorded with nominal HV after rejecting events triggered by night sky background noise. Around 7×10^5 additional events were recorded under moonlight.

3 Data analysis

A number of quality cuts have been applied to the raw data.The cosmic ray rate as a function of ZA was required to be close to the nominal one under the best atmospheric conditions. Proper functioning of the electronics was checked and any coherent noise (e.g. from the steering motors) has been corrected in the data. The calibration of the raw ADC information to photo electrons and the calculation of the Hillas parameters have been done as described e.g. in Petry (1997).

Significant variations of the night sky background with a significant impact on the image parameters were observed during the run period. A new method (described in Kestel et al. (2001)) to correct the Hillas image parameters for the influence of variable night sky background light was applied to the data.

A set of Crab data, recorded from October 2000 through March 2001, was subjected to the same image parameter correction and used to derive a set of γ-hadron separation cuts. The procedure is described in more detail in Kranich (2001a). Using these cuts an excess γ-rate of ≈24 γ/hour on a background of 16 events/hour from Crab is achieved.

The initial γ-energy has been estimated from the showers combining information of the Hillas parameters *WIDTH*, *LENGTH*, *DIST* and *SIZE* and the reconstructed impact parameter. The method is described in more detail in Kranich (2001a). A comparison of reconstructed Monte Carlo energy with the input energy shows that a small fraction of high energy events are underestimated while the energy resolution is typically 20-30% RMS. The method to derive the energy spectrum is described in Kranich et al. (2001b).

4 Results

4.1 Light curve of Mkn 421

HEGRA CT1 has managed to collect the most complete light curve of Mkn 421 in the TeV range. It can be found in (Kestel et al., 2001). Mkn 421 has been rather quiet since its discovery save for a few daily flares and seldom reached the Crab level until the end of the 1998-99 season. During the 1999-2000 observation season two flares were recorded with fluxes reaching around two times that of the Crab.

Figure 1 shows the integral flux curve for the first four months of 2001 along with the X-ray light curve recorded by ASM (1.5-12 keV) on board the RXTE satellite. Both in the TeV and X-ray range the source displays enhanced activity in the first three months of the year at an average level of 1.6 crab and 33 mcrab respectively. As indicated in the figure, the source exhibited a daily average flux close to 5 crabs for several nights. On February 24/25 the emission peaked for an hour at around 8 crabs. The activity has been observed to decrease in May.

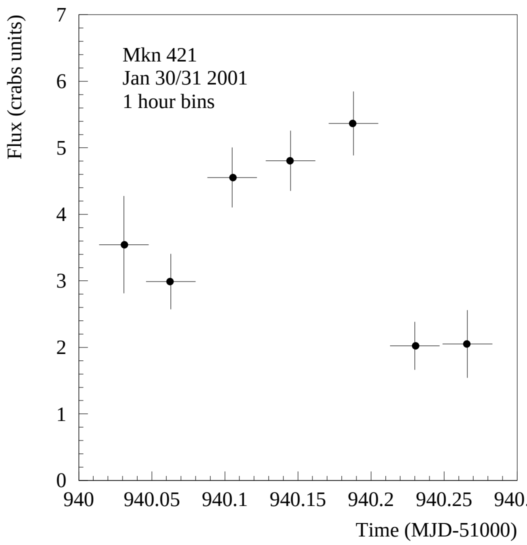

Fig. 2. The intranight light curve of Mkn 421 measured on January 30/31 2001. The integral fluxes above 1 TeV are drawn in bins of 1 hour observation time windows. The horizontal error bars correspond to the measured on-time within the 1 hour window.

Mkn 421 had been reported earlier to be highly variable on very short timescales down to ≈15 minutes (Gaidos et al., 1996). An example of intranight variability is shown in figure 2, where the integral flux for the night of January 30/31 is displayed in 1 hour time bins. A flux of ≈5.5 crabs was reached at the beginning of the observation. The flux is observed to halve in less than one hour during the night. This variability is much faster than that observed in Mkn 501. It can be used to severely constrain the size of the TeV emission region in Mkn 421.

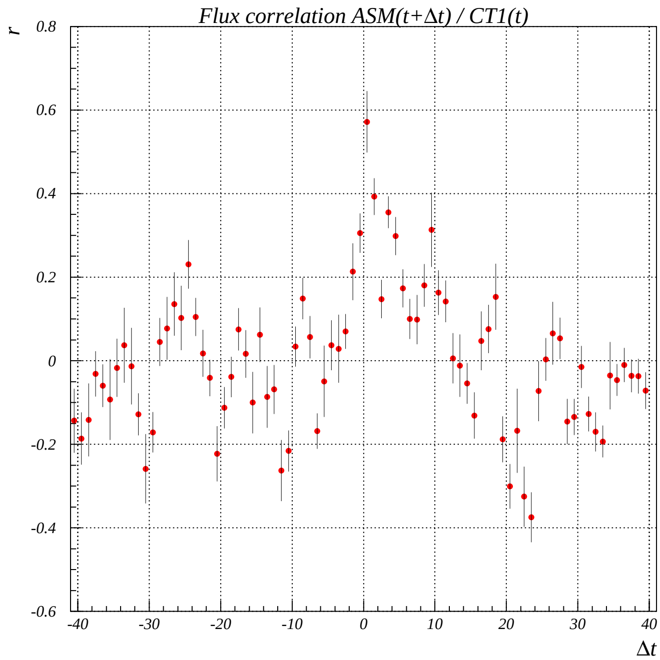

Fig. 3. The discrete correlation function r corresponding to the correlation between the ASM and CT1 daily average fluxes for different time shifts (Δt, in days) of the ASM data points. A maximum correlation is observed for synchronous variability of both samples (time shift shorter than 1 day).

The correlation coefficient r of the X-ray and TeV samples has been calculated. The X-ray data have been shifted on time with respect to the TeV data and the resulting correlation coefficient r has been plotted in figure 3 for time shifts between -40 and +40 days. The X-ray and TeV flux variations have been found to be significantly correlated (with a correlation coefficient equal to 0.6) for a time shift shorter than 1 day. This result is partly influenced by the very rapid ($\ll$1 day) changes and incomplete daily overlap. More precise studies should take these variations and the restricted observation period into account. For this preliminary study only moonless data were taken into account. Adding the daily averages obtained under moonlight may result in a more significant correlation.

4.2 Energy Spectrum

The time-averaged differential energy spectra of Mkn 421 in 1999-2000 (from Kestel et al. (2001)) and 2000-2001 are shown in figure 4. They have been calculated from data up to 45° ZA, the highest available in the Monte Carlo dataset. Only moonless data have been considered up to now.

The 1999-2000 spectrum can be fitted to a power law with $dN/dE = (0.94\pm0.23)\cdot10^{-11}\ (E/TeV)^{-3.33\pm0.35}\ cm^{-2}\ s^{-1}\ TeV^{-1}$. In fact the limited statistics prevents to significantly test any energy cutoff.

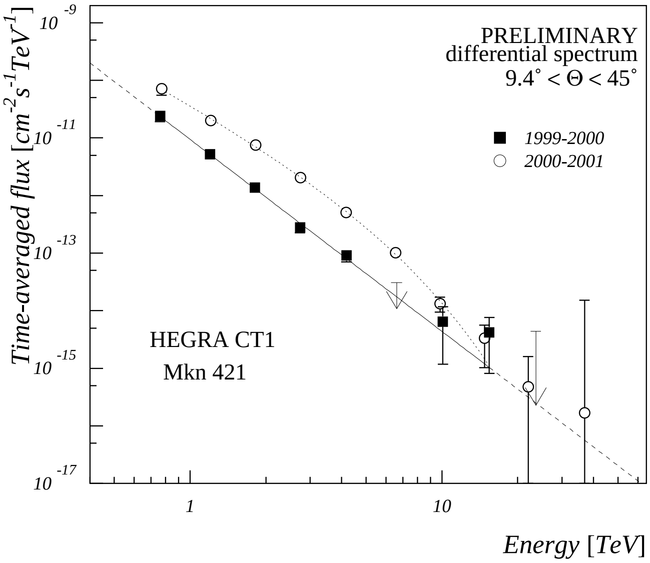

Fig. 4. The HEGRA CT1 Mkn 421 spectra in 1999-2000 and 2000-2001. The limited γ-statistics does not allow to distinguish between a pure power law and a curved energy spectrum in 1999-2000 whereas a fit to a curved spectrum is significantly better than a fit to a power law in 2000-2001. The points above 20 TeV have not been included in the fit.

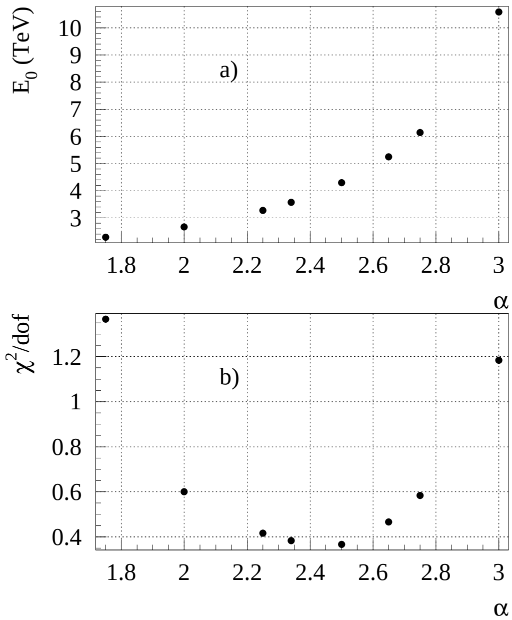

Fig. 5. a) Cutoff energy E_0 as a function of differential index α. b) Reduced χ^2 as a function of α. Both E_0 and χ^2/dof are obtained in a fit with fixed α.

On the contrary the 2000-2001 spectrum is significantly curved. A fit to a power law in the 0.7-15 TeV energy range shows a reduced chi-square χ^2/dof=2.8 whereas a fit to a power law with an energy cutoff yields χ^2/dof=0.52. The power law can thus be ruled out at the 2.3σ level. The result of the second fit is:
dN/dE = $(4.69\pm0.86)\cdot10^{-11}$ $(E/TeV)^{-2.34\pm0.48}$ $\exp(-E/E_0)$ cm^{-2} s^{-1} TeV^{-1} with a cutoff energy E_0=3.62$\pm$1.91 TeV. It should be noted that changes in E_0 are strongly correlated with changes in α. Figure 5a shows E_0 as resulting from a fit where α is fixed. E_0 is found to grow steadily with α. Figure 5b illustrates the point that any α in the 1.9-2.8 range can be fitted with an acceptable χ^2/dof.

5 Discussion

Mkn 421 has been in a high state of TeV γ emission in the first months of 2001. Integral fluxes above 700 GeV in excess of 5 crabs have been observed for several nights.

The high statistics allowed to extract a detailed light curve showing very fast variability with doubling times shorter than one hour. The time variations are significantly correlated to the 1.5-12 keV X-ray time variations with less than 1 day time delay.

An accurate energy spectrum up to energies above 10 TeV could also be extracted. In contrast to the 1999-2000 data a simple power law can be ruled out. The spectrum is compatible with a power law with differential index 2.3$\pm$0.5 combined with an energy cutoff at 3.6$\pm$1.9 TeV. This is in good agreement with the cutoff observed at Mkn 501 in 1997 and provides strong evidence for TeV attenuation in the infrared extragalactic background. We would like to stress again the strong correlation between α and E_0 requiring a careful interpretation of the results.

Further analysis of the moonlight data sample shall allow to increase the statistics and more thoroughly cover the light curve of the source.

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