Large zenith angle observations of flares from Mkn 421 in 2004 with H.E.S.S.

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Abstract.
Mkn 421 was observed during a high flux state for nine nights in April and May 2004 with the fully operational High Energy Stereoscopic System (H.E.S.S.) in Namibia. The observations were carried out at zenith angle distances of 61-64°, which result in an increased average threshold of 1.5 TeV. Observations of the Crab nebula at similar zenith angles are used to check on the reliability of the large zenith angle observation technique. Roughly 7000 photons from Mkn421 were accumulated with an average gamma-ray rate of 11 gammas/min. The overall significance of the detection exceeds 80 standard deviations. The light curve shows night-by-night variations by a factor of 2. The energy spectrum is curved and may be fit with a power law with an exponential cut-off at 2.1 TeV.

INTRODUCTION

Mkn 421 is a 'BL Lac' type active galactic nuclei. The broad-band spectral energy distribution is dominated by non-thermal emission that is believed to be produced in a relativistic jet pointing towards the observer. The object is well-studied by previous observations carried out from northern hemisphere ground based Cherenkov telescopes. Observations from southern hemisphere at large zenith angles show considerable improvement in the collection area at higher energies which results in a better temporal resolution of variations at high energies and a better sampling of the high energy part of the energy spectrum.

Observations of fast ($<$ 1 hr) variability at gamma-ray energies indicate that the emitting plasma is moving with a relativistic Doppler factor of at least 5 in order to reduce the opacity for the gamma rays to escape from the compact emission region. Besides the general interest of understanding the physics of the highly relativistic plasma and its interaction with the ambient medium, the proximity of Mkn421 (z=0.031) makes it an interesting target to observe the effect of pair-production of gamma-rays with soft (thermal) background photons as part of the extragalactic background light.

OBSERVATIONS AND DATA ANALYSES

The H.E.S.S. experiment [1] is an imaging atmospheric Cherenkov detector dedicated to the ground based observation of VHE gamma rays. Situated in Namibia, the array of four telescopes is operational since December 2003. Each telescope has a mirror area of 107 m^2 and is equipped with a camera consisting of 960 photomultiplier tubes [2]. The system has a field of view of 5° and allows to reconstruct the direction of individual showers with a precision of better than 0.1°.

H.E.S.S. Observations of Mkn 421 in 2004 were triggered by increased levels of activity observed by the All-Sky-Monitor onboard the RXTE satellite. Online analysis of H.E.S.S. data revealed that the source was also active at TeV energies during observations in April motivating extensions of the campaign for roughly one week. In the beginning of May, H.E.S.S. participated in a multi-wavelength campaign with overlap with pointed X-ray observations with the RXTE satellite.

The H.E.S.S. observations were carried out for typically 1 hour per night over a period of 1 week in April and one night in May. The observation mode was employing all four telescopes in coincidence, pointing with 0.5° offset in declination with alternating sign from run to run (28 minutes per run). The runs were selected according to general quality checks like absolute value of the rate, changes in the rate and performance of the cameras (number of broken pixels, homogeneity of the acceptance, trigger rate). In total 11.2 hours of good data were selected for the analyses. The zenith angle of the observations ranges from 61.3° at culmination to 64.4°.

Observations of the Crab nebula at similar zenith angles were subjected to an identical analysis procedure to check the procedure applied to the data taken from Mkn 421.

The data were calibrated following the general procedure [3] of identifying and excluding broken pixels, to matching the high/low gain ratios, subtracting the pedestal, fixing the conversion coefficients (ADC counts to photo-electrons) and flat-fielding the camera-response. The data are subject to a conventional image analysis using *Hillas*-parameters [4] to describe the images after cleaning of night-sky background contamination with a two-stage tailcut. The first and second moments and the orientation of the images are calculated and used for the stereoscopic reconstruction of event direction, core impact distance, energy, and scaled image width and length. Cuts are imposed on the events to select gamma-like events while rejecting a large fraction of the charged cosmic ray events. Finally, in order to get the energy spectra, collection areas are calculated from simulated air showers which are used to calculate differential energy spectra [5].

The analysis method used here is not fully employing the potential of the fine pixelation of the H.E.S.S. cameras. More advanced techniques will be applied in the future and an improvement mainly in the angular resolution and background rejection is expected (Lemoine et al., these proceedings).

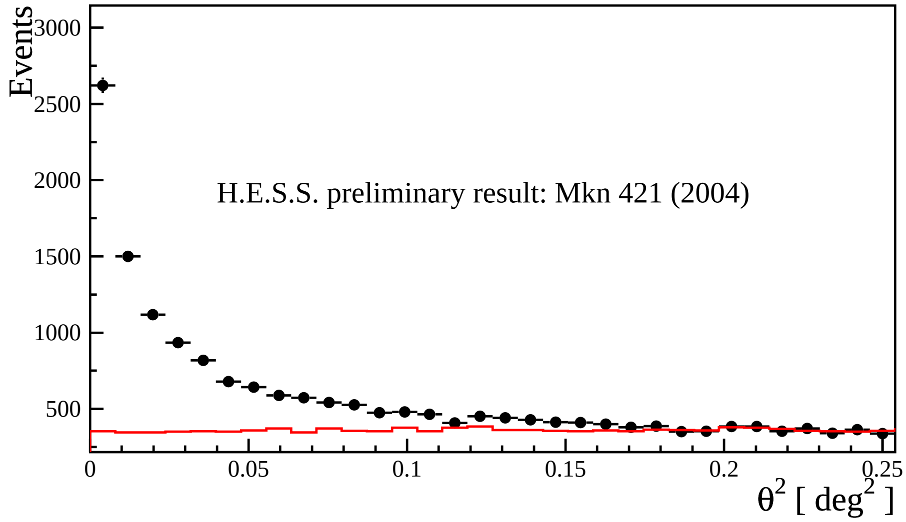

FIGURE 1. The signal of gamma rays from Mkn 421. In total, $N_{\mathrm{on}} = 10\,667$ events are detected when applying an angular cut of $\theta^2 < 0.05\ (^\circ)^2\,(\theta < 0.224^\circ)$ with an averaged background expectation of $N_{\mathrm{off}} = 3\,744.8$ events. This corresponds to a significance of the signal of $S = 81\ \sigma$ with an observation time of 11.2 hrs.

PRELIMINARY RESULTS

Signal from Mkn 421

Employing a Hillas-type stereoscopic analysis to the Mkn 421 data-set, a signal in excess of 80 standard deviations is detected with about 7000 gamma-events. Invoking a loose cut on the space angle between the position of Mkn 421 and the reconstructed arrival direction of events to be less than 0.224°, in total $N_{\mathrm{on}} = 10667$ events are detected with an expected background of $N_{\mathrm{off}} = 3744.8$ averaged over 5 background regions displaced to the center of the camera by 0.5° to mimick the acceptance of the region from which the signal events are extracted. The resulting distribution of arrival direction in bins of squared angular distance (corresponds to equal solid angles per bin) to the position of Mkn 421 is shown in Fig. 1. The distribution is strongly peaked towards the direction of Mkn 421 whereas the background distribution is flat indicating homogeneous acceptance. Moreover, the signal and background distribution are in very good agreement when comparing suffi ciently far from the signal region.

Energy spectrum from the Crab nebula at large zenith angles

In order to check the procedure of the reconstruction of energy spectra at large zenith angles, a small (1.8 hrs) data set taken on the Crab nebula at zenith angles ranging from 57° to 67° is analysed. The energy reconstruction is based upon tabulated values for varying zenith angles of energy for intervals of size and core distance. Monte Carlo simulations are used to derive collection areas as a function of reconstructed energy (see

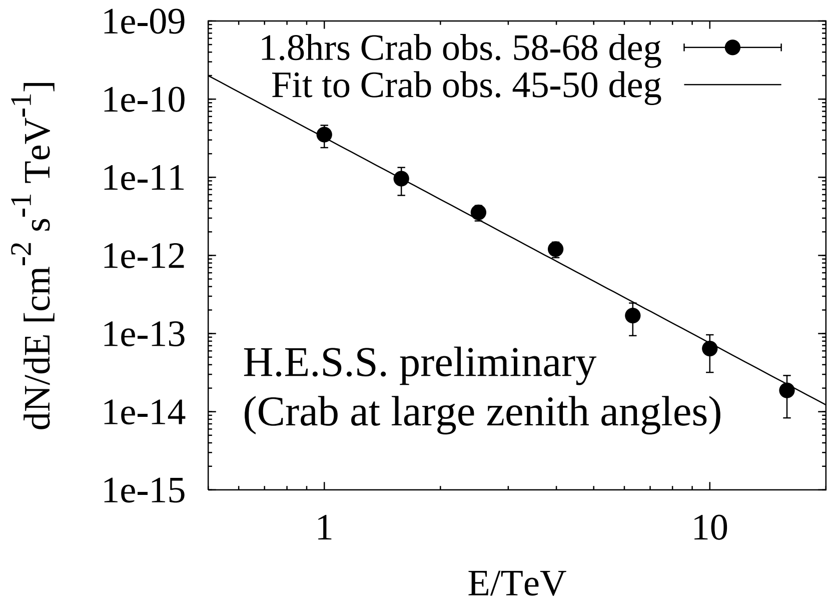

FIGURE 2. For the standard candle in TeV astronomy (Crab nebula), large zenith angle data has been taken. Applying the analysis described in the text results in a differential energy spectrum which is consistent with observations around culmination.

also [5] for details).

The collection area derived for individual events (using log linear interpolation between energy and linear interpolation between zenith angles) are used as weights to calculate exposure in bins of energy by summing over the events in the on and off regions. The resulting differential energy spectrum for the Crab nebula is shown in Fig. 2 together with the fit result of the Crab spectrum observed at culmination. The agreement is quite good. The χ^2 for the data compared to the power law spectrum from smaller zenith angles as given in [6] with $\Phi_0 = 3.2\,10^{-11}\,(cm^2\,s)^{-1}$ and $\Gamma = 2.63$ is 1.2 for 7 degrees of freedom.

The analysis method is identical to that applied to Mkn421 data giving confidence in the reliability of the instrument's response and reconstruction technique at large zenith angles.

Light curve and energy spectrum from Mkn 421

The nightly integral fluxes above 1 TeV are calculated by summing over all events above 1 TeV. The resulting light curve is shown in Fig. 3. The solid line indicates the integral flux observed from the Crab nebula. The light curve exhibits night-by-night variability in the first observing week and resumes a lower flux in the later observation. The corresponding gamma-rate is sufficiently high to probe intra-night variability (not shown here) of the high energy end of the spectrum with unprecedented accuracy. The peak flux reaches a value of about 5 times the flux observed from the Crab nebula.

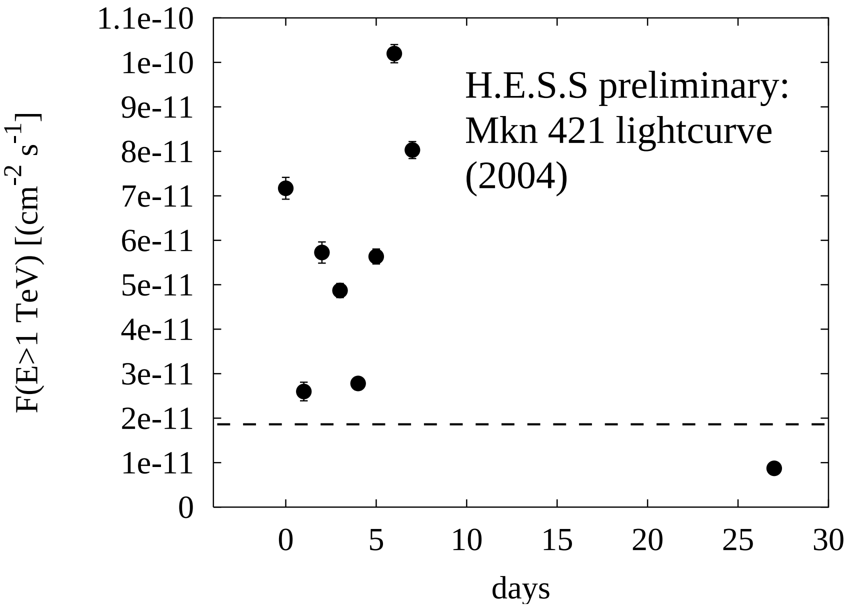

FIGURE 3. For the time between March and May 2004, the light curve shows strong variability. The flux values are nightly averages. For comparison, the horizontal line indicates the flux observed from the Crab nebula.

The differential energy spectrum for Mkn 421 is calculated in the same way as described above for the Crab nebula. The entire data set is combined even though in principle temporally resolved spectroscopy is easily achievable and will be presented in a forthcoming paper. As the energy spectrum shows clear evidence for curvature, the collection areas are calculated iteratively until the parameters of the model fit function converge. Different models have been applied, the best fit is found to be a power law modified by an exponential cut-off. As described in [5], the effect of spill-over is compensated by using collection areas as a function of reconstructed energy and iterating the collection areas as the fit parameters converge.

The preliminary result is shown in Fig. 4. The differential energy spectrum of Mkn 421 is well sampled between 1 and 10 TeV. The spectrum is clearly curved and the line gives a best fit among the tested functions employing a power law with an exponential cut off with a reduced $\chi^2 = 2.6$ (8 d.o.f.) - a power law fit produces a reduced $\chi^2 = 20.8$ (9 d.o.f.), a parabola in log(dF/dE) vs. log(E) gives a reduced $\chi^2 = 4.3$ (8 d.o.f.).

The cut off energy E_c and the photon index Γ derived from the fit are highly correlated (correlation coefficient -0.955 between E_c^{-1} and photon index Γ). The confidence region for the fit is shown in Fig. 5 for different confidence levels as contours. The best-fit value is marked with a cross ($E_c = 2.4$ TeV, $\Gamma = 1.83$). Since the energy coverage is mainly in the region of the exponential cut off, the uncertainty region is comparably large. The cut-off appears to be smaller than during previous observations by HEGRA of 3.6 ± 0.4 TeV ([5] and VERITAS ≈ 4.3 TeV [7] in 2001 and 2002. Combining data with a simultaneous low threshold observation (MAGIC) would greatly improve the constraint from the data.

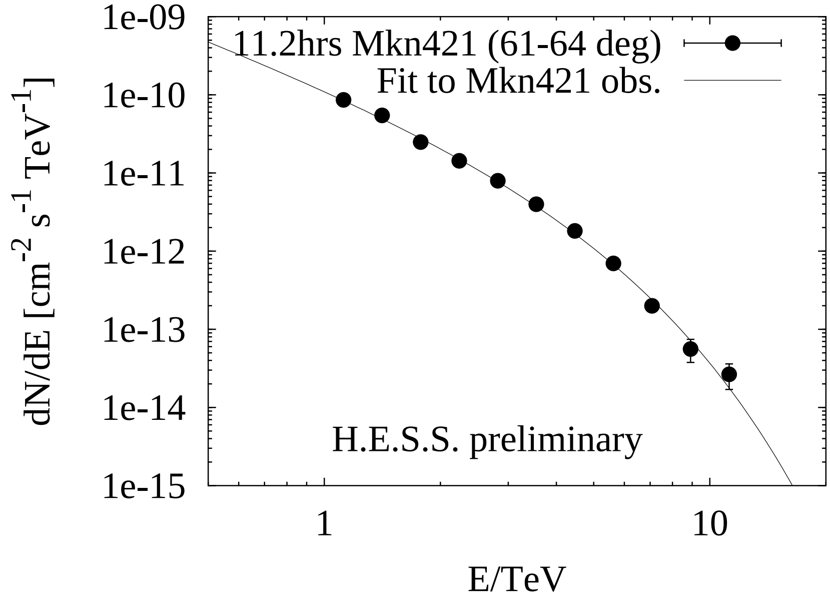

FIGURE 4. Differential energy spectrum of Mkn 421: The curvature is evident and described by a power law with an exponential cut-off (solid line).

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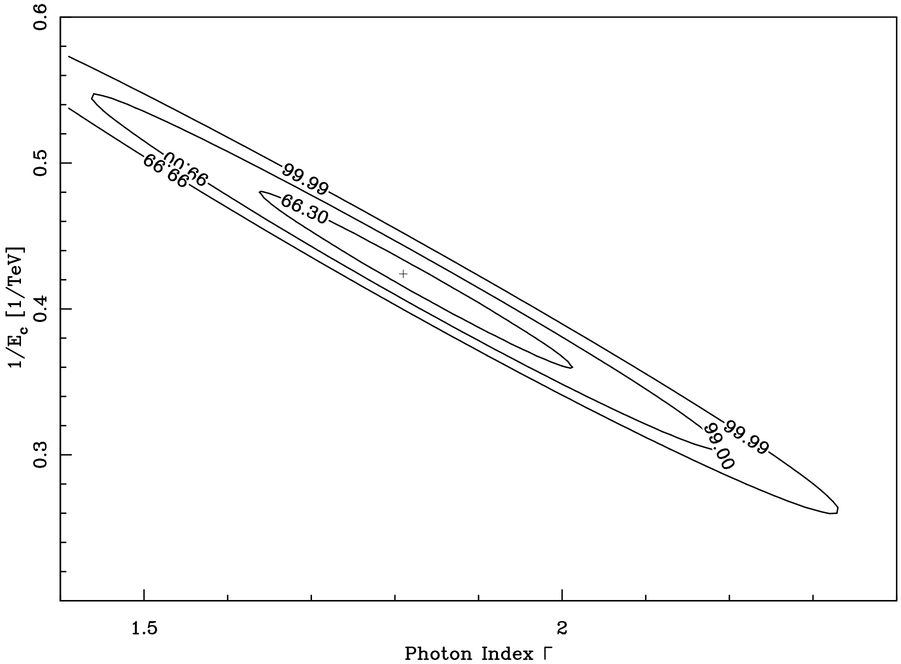

FIGURE 5. The contours (labelled with the confidence level given in per cent) indicate the confidence region for a slice in the 3-dimensional parameter space of the power law with exponential cut-off fit to the data. The cross indicates the best fit value.

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