Measurement of TeV γ-rays from Markarian 501 during a state of high activity

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Abstract

From March 15, 1997 to April 14, 1997, a high count rate level of about 25 mHz γ-rays above 1 TeV was observed from Mrk 501, using the HEGRA system of four imaging Cherenkov telescopes. The average count rate level is about twice the count rate of γ-rays observed from the Crab Nebula. The energy spectrum of the radiation was measured from 1 TeV to beyond 10 TeV, and follows a power law. For Mrk 501, the value of the differential spectral index of $2.49 \pm 0.11 \pm 0.25$ is comparable to that of the Crab Nebula, $2.71 \pm 0.17 \pm 0.25$. The time variation of the γ-ray flux was studied on time scales between 5 min. and days.

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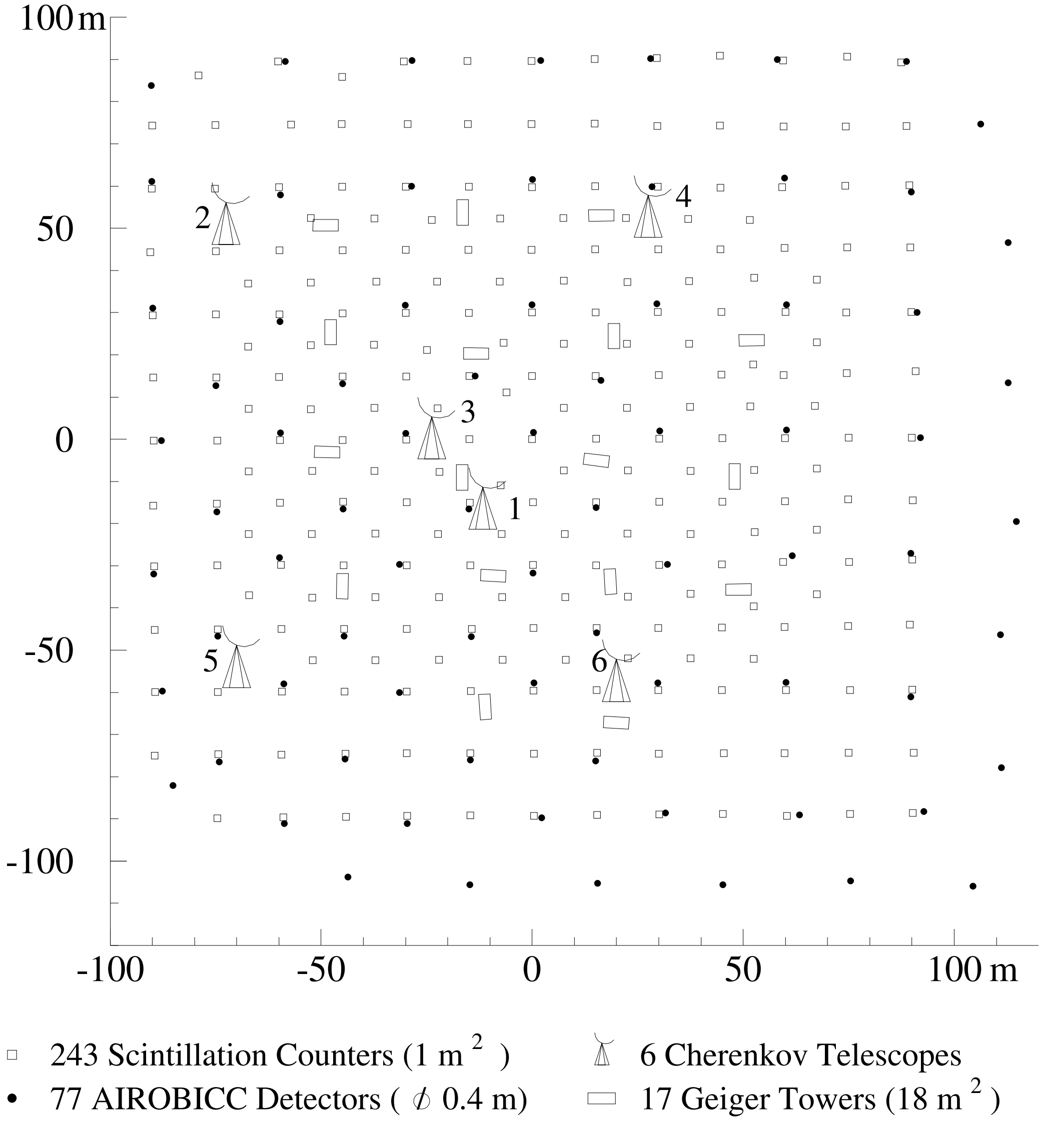


Layout of the HEGRA experiment

Observatorio del Roque de los Muchachos

Canary Island La Palma (2200 m a.s.l.)

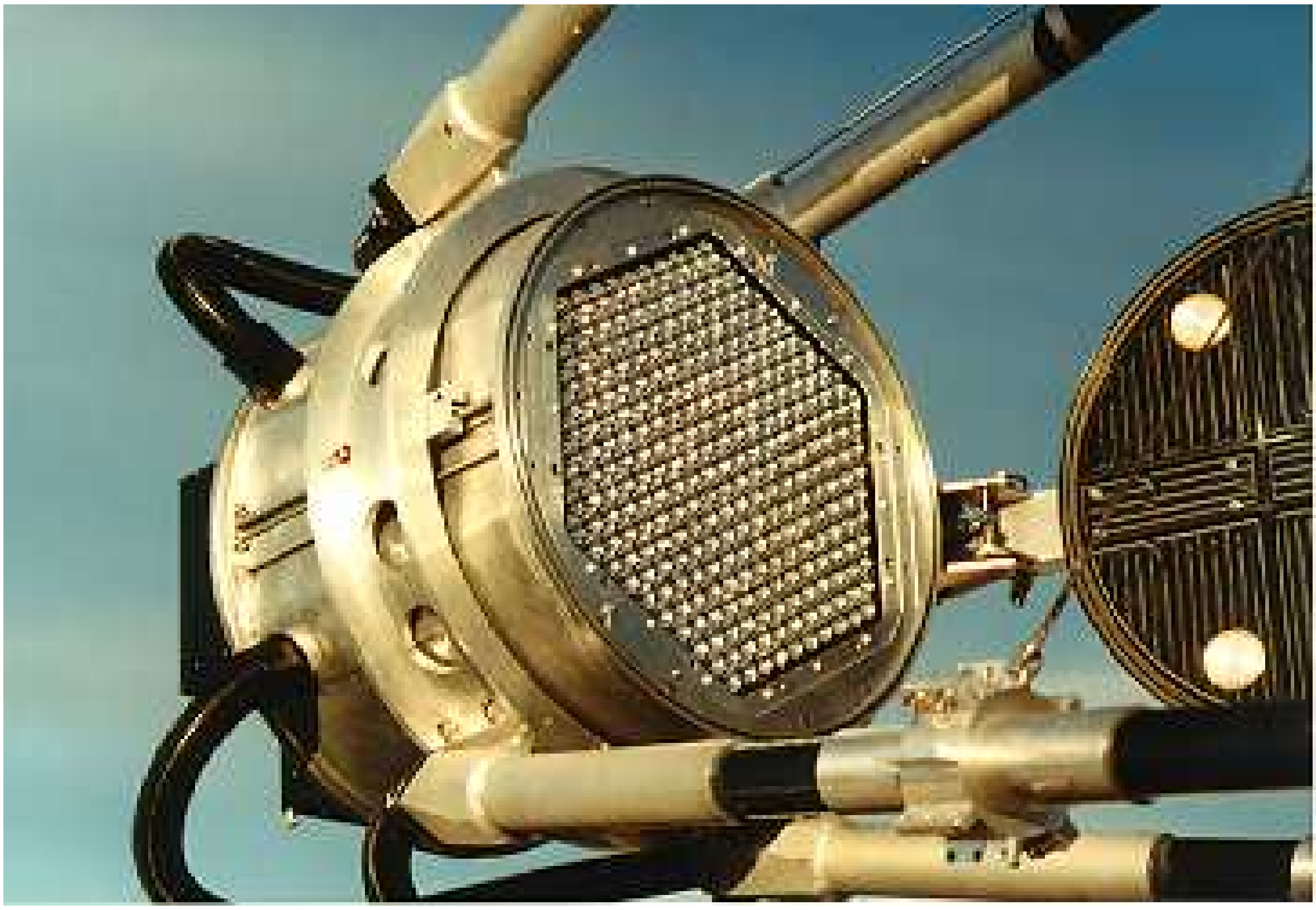
28.75° N, 17.89° W

The HEGRA Telescope System

Central Telescope: CT3

The HEGRA System of IACTs: 5 *identical telescopes*

- **reflector** 30 (front aluminazed & quartz coated) 60 cm diameter spherical glass mirrors; $S_0 = 8.5\,m^2$; $F = 5\,m$; $\sigma \approx 3$ arcmin
- **mount** alt-azimuth; pointing accuracy ≈ 20 arcsec
- **camera** close-packed cluster of 271 PMTs (EMI 9083) faced with hollow hexagonal light guids; pixel size=0.25°, FoV $\simeq 4.6°$
- **electronics** in VME standard; 120 MHz FADCs
- **triggers** local – '2 pixesls from 271' ($q_{min} \sim 10\,ph. - e.$)
  system – 'n IACTs from 5' ($n \geq 2$)



The HEGRA Telescope System: Camera

Performance of the HEGRA 5-IACT array

- Energy Threshold: $\mathrm{E_{th}} \sim 500\,\mathrm{GeV}$
- Angular Resolution: $\delta\theta < 0.1^\circ$
- Energy resolution: $\delta\mathrm{E}/\mathrm{E} \leq 25\%$
- Flux sensitivities:

Point Sources:

SURVEY mode: 'background-free' $\sim 10\ \gamma$'s in effective FoV=$1.5^\circ \times 1.5^\circ$

$$\mathrm{J_{min}} = 0.2\,\mathrm{Crab}\,(\mathrm{t}/1\,\mathrm{h})^{-1} \qquad \text{for} \quad \mathrm{t} \leq 1\mathrm{h}$$

TARGET mode: '5σ' detection

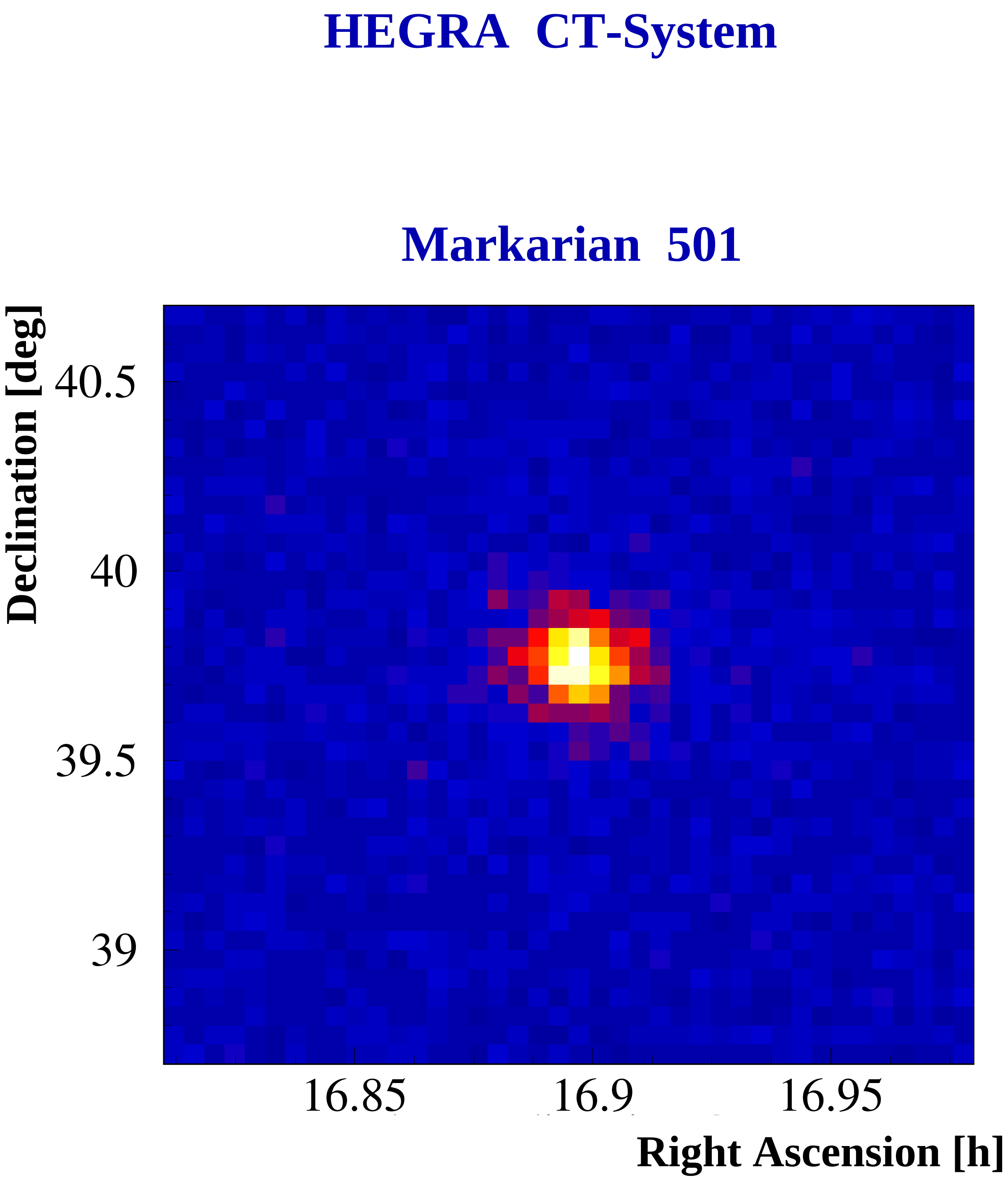
$$\mathrm{J_{min}} = 0.04\,\mathrm{Crab}\,(\mathrm{t}/25\,\mathrm{h})^{-1/2} \qquad \text{for} \quad \mathrm{t} \geq 1\mathrm{h}$$

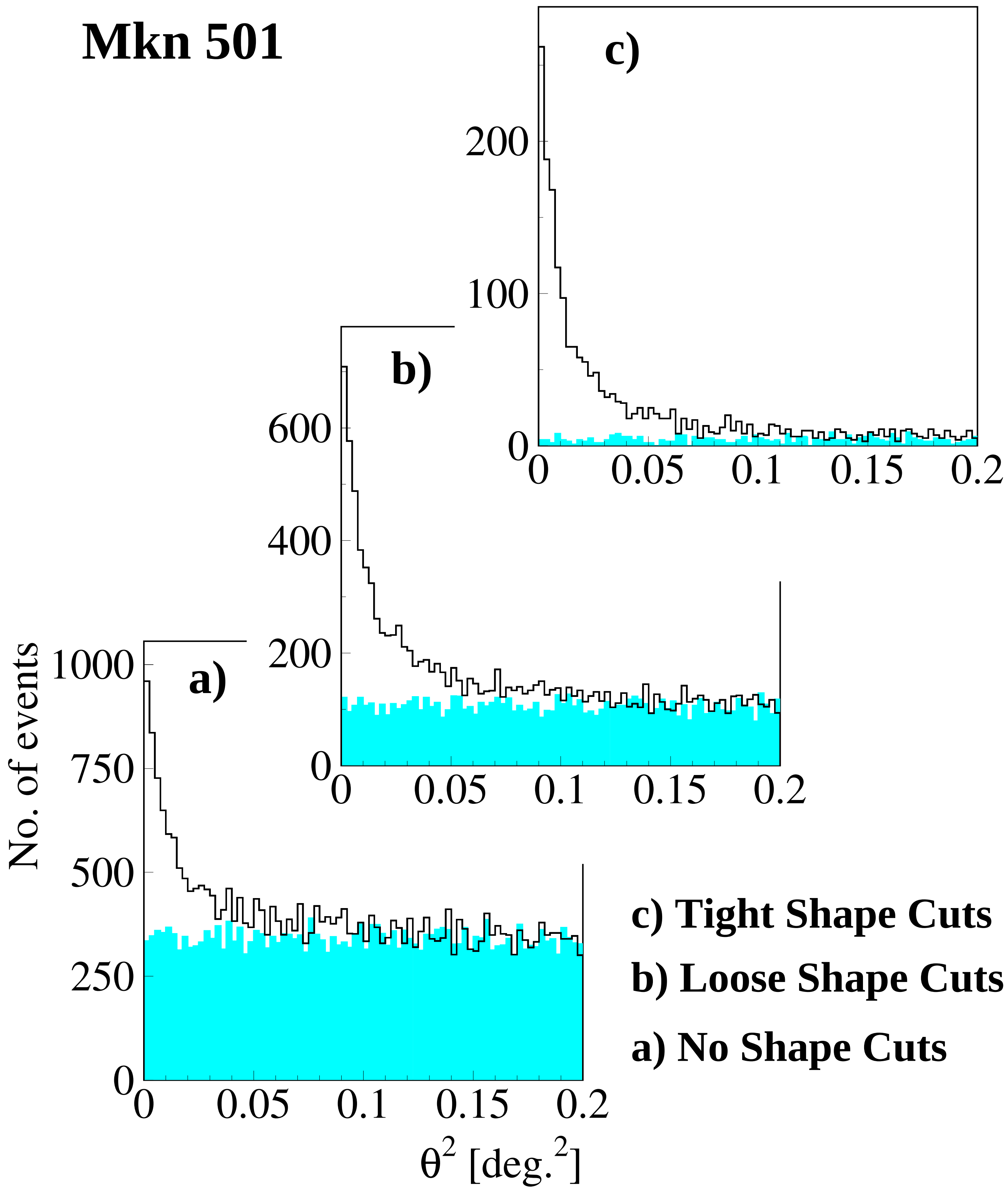
Extended Sources

$$\mathrm{J_{min}} = 0.15\,\mathrm{Crab}\,(\phi/1^\circ)\,(\mathrm{t}/100\,\mathrm{h})^{-1/2}$$

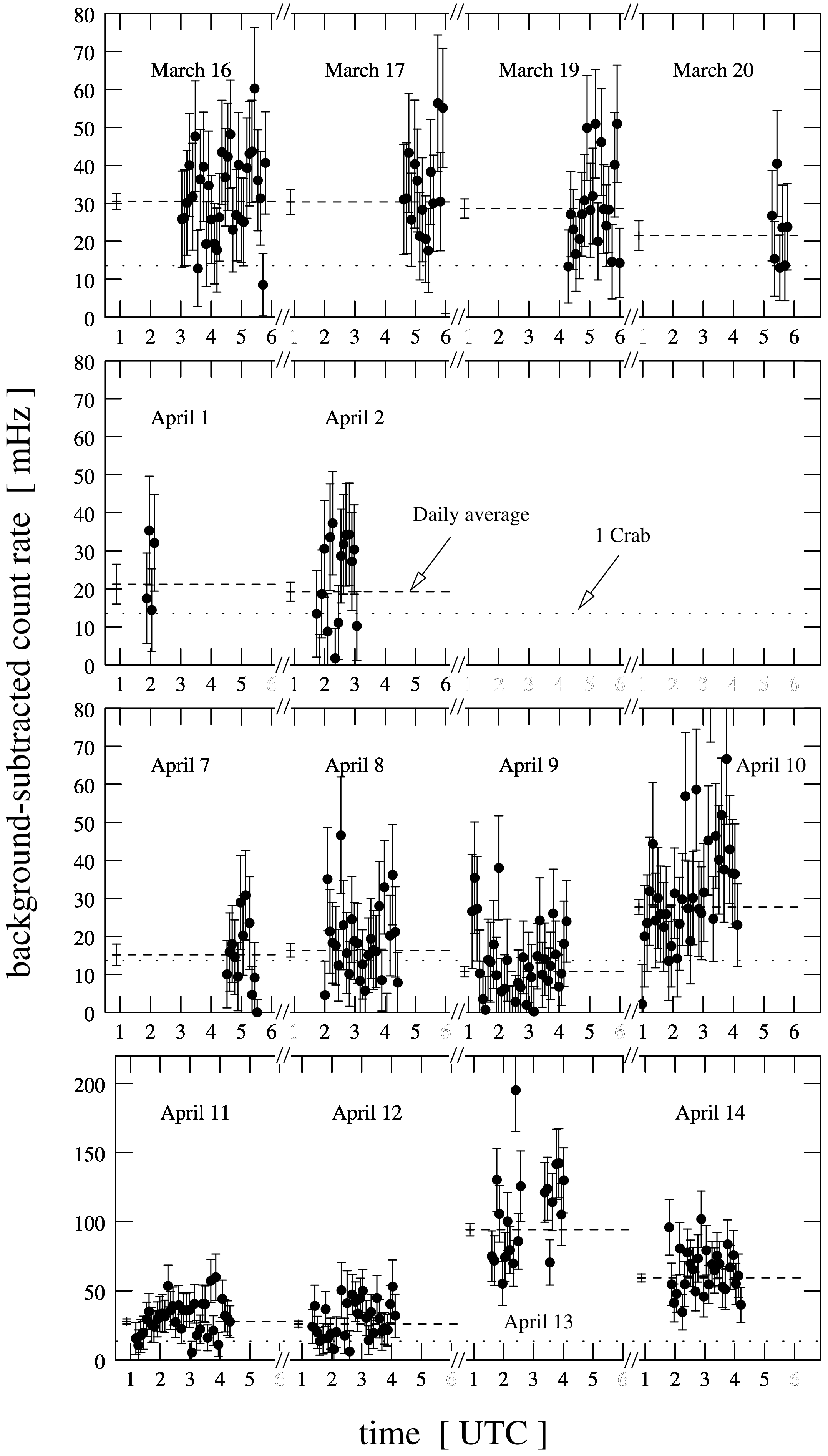
Transient Sources:

$$\text{Fluence} \simeq 3 \times 10^{-8}\,\mathrm{erg/cm^2} \qquad \text{for } \Delta\mathrm{t} \leq 1\,\mathrm{h}$$

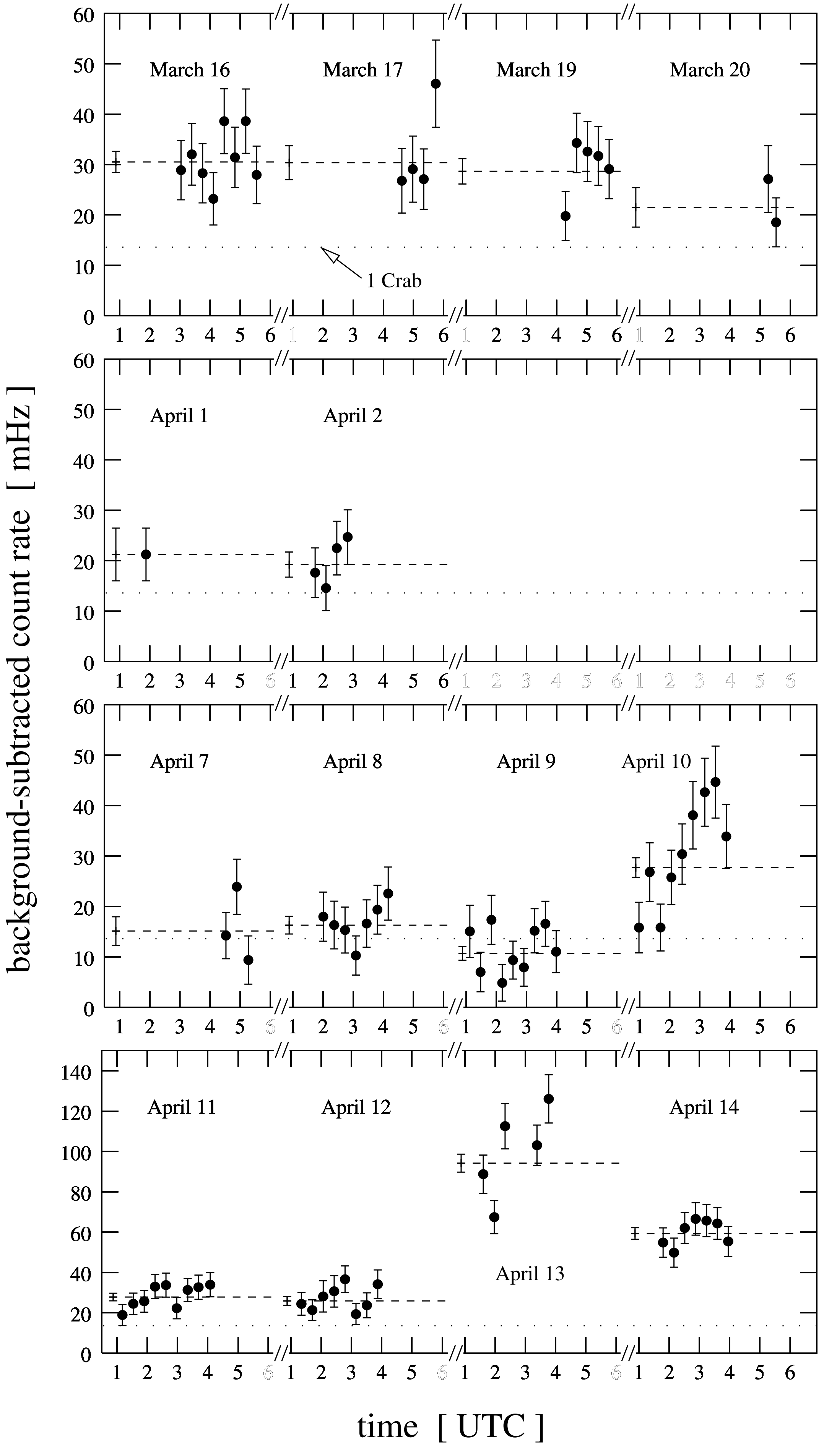

HEGRA CT-System
Markarian 501
Declination [deg]
40.5
40
39.5
39
16.85
16.9
16.95
Right Ascension [h]


Mkn 501
c)
b)
a)
No. of events
θ^2 [deg.^{2}]
c) Tight Shape Cuts
b) Loose Shape Cuts
a) No Shape Cuts

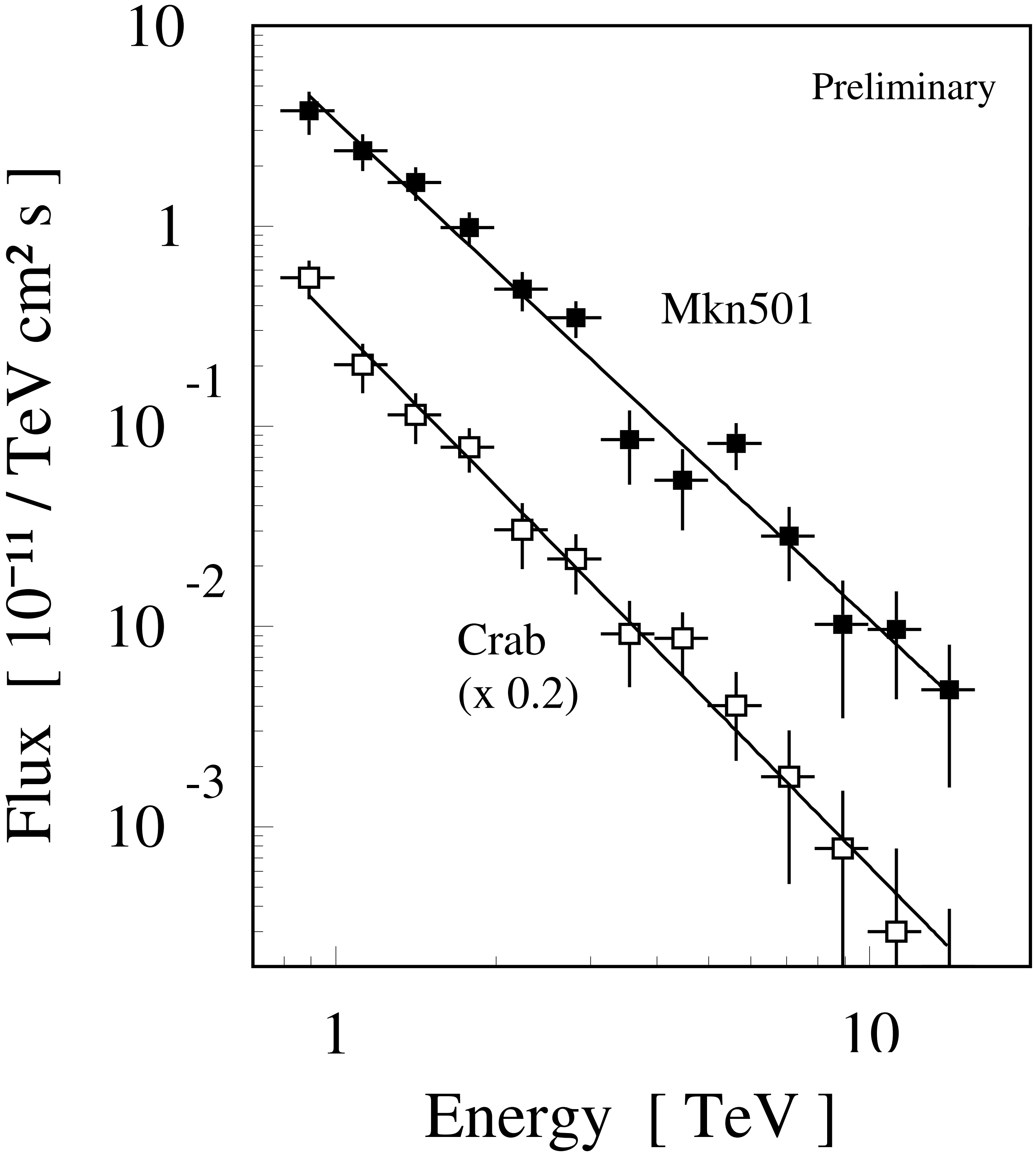
page



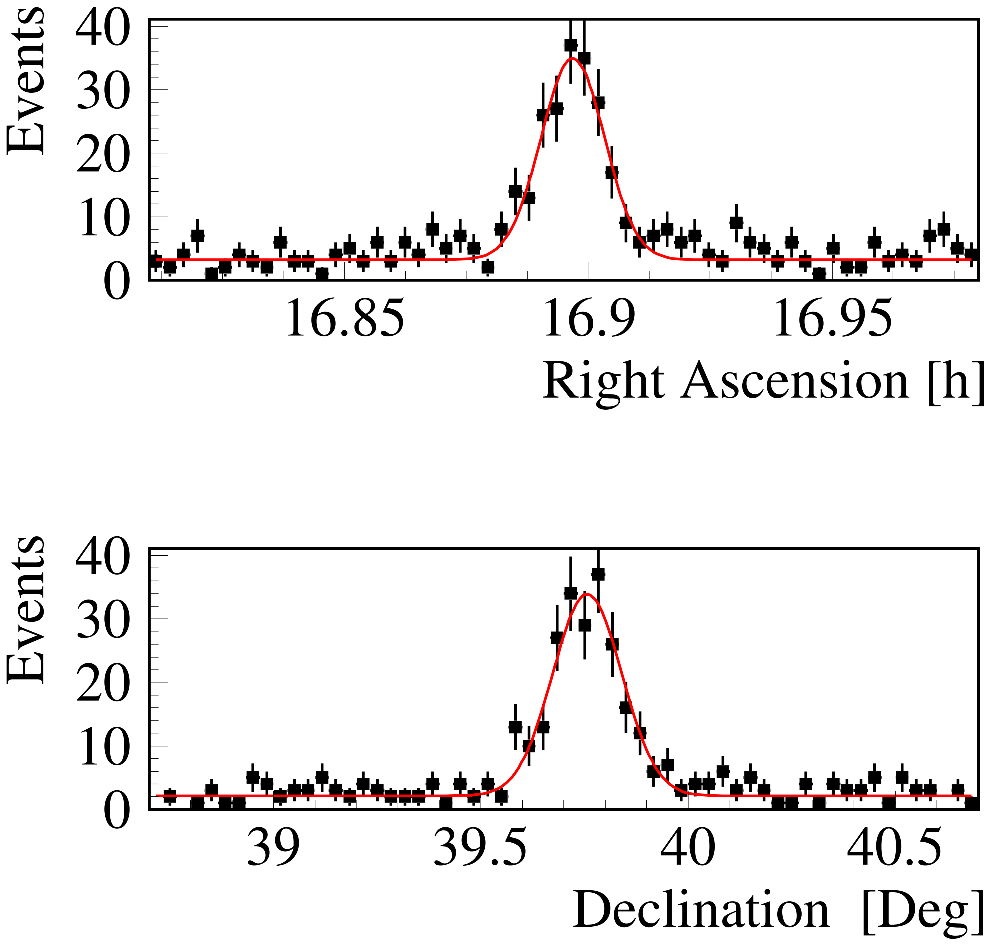
background-subtracted count rate [mHz]
time [UTC]
March 16
March 17
March 19
March 20
April 1
April 2
Daily average
1 Crab
April 7
April 8
April 9
April 10
April 11
April 12
April 13
April 14



March 16
March 17
March 19
March 20
1 Crab
April 1
April 2
April 7
April 8
April 9
April 10
April 11
April 12
April 13
April 14
background-subtracted count rate [mHz]
time [UTC]


Preliminary
Mkn501
Crab
(x 0.2)
Flux [10^{-11} / TeV cm^2 s]
Energy [TeV]
10
1
10^{-1}
10^{-2}
10^{-3}
1
10

Markarian 501: Source Position



Ra = 16.8978 h , Dec = 39.757 [Deg]

The distribution in the angle θ between the shower axis and the source location is plotted; shown is $dN/d\theta^2$.

• For the uniform background from charged cosmic rays one expects a flat distribution in θ^2. A γ-ray source causes an excess around $\theta \approx 0$. The background is shown as a shaded histogram; it is flat in θ^2. In the region out to $\theta = 0.7°$ on average about 90 excess events per 1 h are counted. Thus already in the raw data, before selection cuts, a clear signal is visible (**a**).

• The shapes of Cherenkov images can be used to suppress cosmic-ray background relative to γ-ray showers; γ-rays generate narrower and more compact images. As selection parameter, the width of each image in a given event is scaled to the Monte-Carlo expected width of γ-ray images as a function of image amplitude and distance to the shower core, and an average scaled width is calculated for all telescopes participating in an event. To maintain high efficiency and to minimize corrections, a very loose cut is applied (**b**). While the background is reduced by a factor of about 3 the number of events in the peak is almost unchanged.

• At the expense of signal statistics the background can be reduced much further. Case (**c**) illustrates the effect of tight cuts which almost completely eliminates the background.

The **source position** is determined from the two-dimensional distribution of the reconstructed shower directions relative to the direction to Mrk 501, after application of the loose cuts. The accuracy achieved is about 0.01°.

To investigate **time variability**, data were grouped in different time bins, ranging from about 5 min., to entire nights. We required that at least two telescopes triggered, and applied a loose angular cut at $\theta = 0.22°$ as well as a loose shape cut of images.

Shown in the *left panel* is the detection rate as a function of time **in bins of 5 min.**, over the observation period of 14 days. The errors given are statistical only; the dashed lines show daily averages.

The *right panel* shows **bins of 20 min.** over the entire observation period.

The HEGRA IACT system with its energy resolution of about 25% allows detailed studies of the **spectrum of γ-ray sources**. To derive the flux F(E) only events where at least **three** telescopes triggered were used, to guarantee good stereoscopic reconstruction. Events were counted within a radius of $0.22°$ from the source, and the background determined from the average yield of events around a virtual source on the opposite site of the camera were substracted. In the determination of spectra, only runs with zenith angles below $30°$ were included. The resulting **Mrk 501 fluxes for the first four days of observation** are shown together with the spectrum of the Crab Nebula analyzed in identical fashion. Both spectra are compatible with pure power laws up to at least of 12 TeV, with a differential spectral index of 2.71 ± 0.17 in case of the Crab Nebula, and 2.49 ± 0.11 for Mrk 501 (statistical errors only; at this moment the systematic errors are estimated within ± 0.25; the integral flux above 1 TeV is $1.0 \pm 0.1 \cdot 10^{-11}/\mathrm{cm}^2\mathrm{s}$ and $2.25 \pm 0.2 \cdot 10^{-11}/\mathrm{cm}^2\mathrm{s}$, respectively (systematic errors $\pm 25\%$).

For the first twelve nights of the observation period, the **average daily excess count rates** were around 25 mHz, corresponding to about 90 γ-rays/h, whereas on night 14 the rate had increased by about a factor of 4, coming down to about 200 γ-rays/h on the last night, still about 2 times higher than the average rate.

The **average daily differential spectral indices** have an average value of 2.5 ($\pm 0.11 \pm 0.25$) over the observation period.

Temporal Behaviour of Flux and Spectral Index