Aharonian, Felix A.; Akhperjanian, A.; Beilicke, M.; Bernlohr, K.; Borst, H.; Bojahr, H.; Bolz, O.; Coarasa, T.; Contreras, J. L.; Contina, J.; Denninghoff, S.; Fonseca, M. V.; Girma, M.; Gotting, N.; Heinzelmann, G.; Herman, G.; Heusler, A.; Hofmann, W.; Horns, D.; Jung, I.; Kankanyan, R.; Kestel, M.; Kohnle, A.; Konopelko, A.; Kornmeyer, H.; Kranich, D.; Lampeitl, H.; Lopez, M.; Lorenz, E.; Lucarelli, F.; Mang, O.; Meyer, H.; Mirzoyan, R.; Moralejo, A.; Ona-Wilhelmi, E.; Panter, M.; Plyasheshnikov, A.; Puhlhofer, G.; Reyes, R. de los; Rhode, W.; Ripken, J.; Robrade, J.; Rowell, Gavin Peter; Sahakian, V.; Samorski, M.; Schilling, M.; Siems, M.; Sobzynska, D.; Stamm, W.; Tluczykont, M.; Vitale, V.; Volk, H. J.; Wiedner, C. A.; Wittek, W.
Detection of TeV gamma-rays from the BL Lac 1ES 1959+650 in its low states and during a major outburst in 2002
Astronomy and Astrophysics, 2003; 406 (1):L9-L13

A&A 406, L9–L13 (2003)
DOI: 10.1051/0004-6361:20030838

Astronomy & Astrophysics

Letter to the Editor

Detection of TeV gamma-rays from the BL Lac 1ES 1959+650 in its low states and during a major outburst in 2002★

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Received 16 May 2003 / Accepted 4 June 2003

Abstract. TeV γ-rays from the BL Lac object 1ES 1959+650 have been measured during the years 2000 and 2001 with a significance of $5.2\,\sigma$ at a value of 5.3% of the Crab flux and in May 2002 during strong outbursts with $>23\,\sigma$ at a flux level of up to 2.2 Crab, making 1ES 1959+650 the TeV Blazar with the third best event statistics. The deep observation of 197.4 h has been performed with the HEGRA stereoscopic system of 5 imaging atmospheric Cherenkov telescopes (IACT system). 1ES 1959+650 is located at a redshift of $z = 0.047$, providing an intermediate distance between the nearby Blazars Mkn 421 and Mkn 501, and the much more distant object H1426+428. This makes 1ES 1959+650 an important member of the class of TeV Blazars in view of the absorption of TeV photons by the diffuse extragalactic background radiation (DEBRA). The differential energy spectrum of 1ES 1959+650 during the flares can be fitted by a power law with a spectral index of $2.83 \pm 0.14_{\rm stat} \pm 0.08_{\rm sys}$ or by a power law with an exponential cut-off at $(4.2^{+0.8}_{-0.6\ \rm stat} \pm 0.9_{\rm sys})$ TeV and a spectral index of $1.83 \pm 0.15_{\rm stat} \pm 0.08_{\rm sys}$. The low state differential energy spectrum obtained with lower statistics can be described by a pure power law with a spectral index of $3.18 \pm 0.17_{\rm stat} \pm 0.08_{\rm sys}$.

Key words. γ-rays: observations – BL Lacertae objects: individual: 1ES 1959+650

1. Introduction

Active Galactic Nuclei (AGN) are known to be sources of extragalactic TeV γ-radiation. Except for a recent report of a significant TeV excess from the radio galaxy M 87 observed with the HEGRA Cherenkov telescopes (Aharonian et al. 2003b) all TeV AGN detected so far are of the BL Lac class. In these objects the very high energy photons are believed to originate (possibly due to inverse Compton scattering) in the relativistic jets oriented at small angles to the observer's line of sight. To these TeV γ-ray emitters belong the well studied BL Lac objects Mkn 421 ($z = 0.030$) and Mkn 501 ($z = 0.034$).

Recently, the much more distant BL Lac H1426+428 ($z = 0.129$) has been firmly established as an emitter of TeV γ-radiation by the VERITAS (Horan et al. 2002; Petry et al. 2002), HEGRA (Aharonian et al. 2002; Aharonian et al. 2003a), and CAT (Djannati-Ataï et al. 2002) collaborations. Possible further TeV detections of BL Lac objects have been reported by different collaborations for 1ES2344+514 ($z = 0.044$) (Catanese et al. 1998), the BL Lac PKS2155-304 ($z = 0.117$) (Chadwick et al. 1999) and the very distant object

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★ Table 4 is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.125.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/406/L9

Table 1. Individual periods of 1ES 1959+650 observations with the HEGRA IACT system. Listed are the total observation times and mean zenith angles $\langle\vartheta\rangle$. Typically, each night comprises about 1 h of observation time.

Date	Year	Obs. Time [h]	$\langle\vartheta\rangle$ [°]
July 28–August 2	2000	8.2	40.0
August 28–September 6	2000	10.2	40.7
May 18–June 1	2001	13.0	37.4
June 22–June 28	2001	15.5	38.1
July 11–July 22	2001	8.5	38.1
August 9–August 25	2001	17.5	37.2
September 6–September 19	2001	15.0	37.3
October 11–October 21	2001	19.9	40.1
May 18–May 21	2002	10.0	41.8
June 3–June 18	2002	34.4	38.5
July 1–July 18	2002	18.7	39.5
July 31–August 16	2002	20.2	38.4
September 3–September 11	2002	6.3	38.6
Sum		197.4	38.8

3C 66A ($z = 0.444$) (Neshpor et al. 1998), but no confirmation by any other group was stated so far.

The object 1ES 1959+650 (Elvis et al. 1992) with a redshift of $z = 0.047$ was classified as a BL Lac in 1993 using a specially developed radio/optical/X-ray technique (Schachter et al. 1993). A first detection at TeV energies was reported by the Utah Seven Telescope Array collaboration for the 1998 observational season (Nishiyama et al. 1999). An excess with a statistical significance of $3.9\,\sigma$ above 600 GeV was obtained after 57 h. There was no independent confirmation until the year 2001, when the HEGRA collaboration reported a detection of 1ES 1959+650 with a significance of $>4\,\sigma$ (Götting et al. 2001), resp. $>5\,\sigma$ with a larger data set (Horns et al. 2002).

In May 2002, 1ES 1959+650 underwent a strong TeV outburst, detected by the VERITAS (Holder et al. 2002), HEGRA (Horns et al. 2002; Kranich et al. 2002) and CAT (Vorobiov et al. 2002) collaborations. Strong variations with flux levels of up to 3 times the Crab flux have been measured.

In this Letter the results of extensive observations of 1ES 1959+650 using the HEGRA IACT system (Daum et al. 1997) during the years 2000/2001 and 2002 are reported. Astrophysical conclusions concerning the nature of this fourth established TeV Blazar regarding possible influence by the DEBRA absorption are briefly discussed.

2. Observations and results of analysis

For the following analysis, a total of 18.4 h of data from the year 2000, 89.4 h from 2001, and 89.6 h from 2002 were used taken with the HEGRA IACT system. The dates of the HEGRA observation periods are listed in Table 1. The mean zenith angle of all observations was 38.8°, resulting in a mean energy threshold (defined as the peak detection rate for γ-showers) of 1.4 TeV for a Crab-like spectrum (Konopelko et al. 1999). The 1ES 1959+650 data were mainly taken with the complete 5-telescope setup of the IACT system. A few data runs were taken with only 4 telescopes due to technical reasons. Individual runs were accepted, if well-defined quality criteria were fulfilled (see, e.g. Aharonian et al. 2003b). About 8% of all data were rejected due to this selection.

All observations of 1ES 1959+650 were carried out in the so-called *wobble* mode allowing for simultaneous estimation of the background ("OFF") rate induced by charged cosmic rays (Aharonian et al. 1997). This analysis uses for the signal search the so-called ring segment background model as explained in Aharonian et al. (2003b) providing a small ratio of ON to OFF-source solid angle areas $\alpha = A_{\rm ON}/A_{\rm OFF}$ (resulting in improved background statistics). For the spectral analysis a set of 7 independent background regions is used (Aharonian et al. 2001).

The general shower reconstruction and the event selection cuts for the image analysis have been described in previous publications (e.g. Aharonian et al. 1999). For the signal search, the stereo air shower direction reconstruction algorithm #3 (Hofmann et al. 1999) and a tight shape cut (parameter $mscw <$ 1.1) (Konopelko et al. 1999) for an effective γ-hadron separation have been applied. Because of the relatively large zenith angles more usable shower images per event are recorded compared to observations close to the zenith. Therefore, a minimum number of 3 images per event is required for the whole reconstruction chain rejecting all 2-telescope events, which only provide a poor resolution. The optimum angular cut was derived using γ-ray events from the Crab nebula on the basis of a nearly contemporaneous data set at similar zenith angles. The procedure of spectral evaluation – with an energy resolution of ≤12% for a single event – is discussed in Aharonian et al. (2003a). The energy spectrum is derived from a background subtracted photon count spectrum using an effective area on an event by event basis, depending upon the number of active telescopes, the reconstructed energy, the zenith angle and the assumed spectral shape. In order to take into account the slightly varying detector performance, the effective areas are determined on a monthly basis along with the mirror reflectivities, photocathode efficiencies and conversion factors from digitized photomultiplier signals to photoelectrons (Pühlhofer et al. 2003).

The relevant direction reconstruction algorithms, event selection cuts, resulting event numbers, and significances for the individual HEGRA 1ES 1959+650 data sets used for the signal search and the spectral analysis are summarized in Table 2. Figure 1 shows the event distribution for the ON-source and the OFF-source regions from the May 2002 flare and the year 2000/2001 quiescent state data sets, respectively, as a function of the squared angular distance to the source position. The statistical significance of the excess from the direction of 1ES 1959+650 amounts to $5.2\,\sigma$ in the year 2000/2001 observations, calculated using formula 17 in Li & Ma (1983). The evidence for TeV γ-rays from 1ES 1959+650 during this quiescent state at a value of $(5.3\pm1.1_{\rm stat})$% of the flux of the Crab nebula (Aharonian et al. 2000) already confirms the tentative detection of 1ES 1959+650 by the Utah Seven Telescope Array. The HEGRA detection during the strong outburst in May 2002

Table 2. HEGRA IACT system direction reconstruction algorithms and cuts used for the 1ES 1959+650 signal search and for the spectral analysis, respectively. The resulting numbers for 4 selected subsets are given: "2000/2001" including all data used for the first $5.2\,\sigma$ detection, "May 2002" only using data from the nights May 18/19 and May 19/20, 2002 (see Fig. 1). The "low state" resp. "high state" data sets are used for the spectral analysis (see text and Fig. 3).

	signal	spectrum
stereo algorithm	#3	#3
number of images per event	≥3	≥3
shape cut on *mscw*	<1.1	<1.1
angular distance cut Θ^2	<0.012 deg^2	<0.014 deg^2
$\alpha = A_{\rm ON}/A_{\rm OFF}$	0.0758	0.1429
	2000/2001	*"low state"*
$T_{\rm obs}$	93.8 h	149.6 h
$N_{\rm ON}$	354	585
$N_{\rm OFF}$	3441	1960
$N_{\gamma\text{-candidates}}$	93 ± 19	305 ± 25
significance (σ)	5.2	14.6
	May 2002	*"high state"*
$T_{\rm obs}$	3.6 h	8.5 h
$N_{\rm ON}$	179	275
$N_{\rm OFF}$	131	141
$N_{\gamma\text{-candidates}}$	169 ± 13	255 ± 17
significance (σ)	23.4	25.5

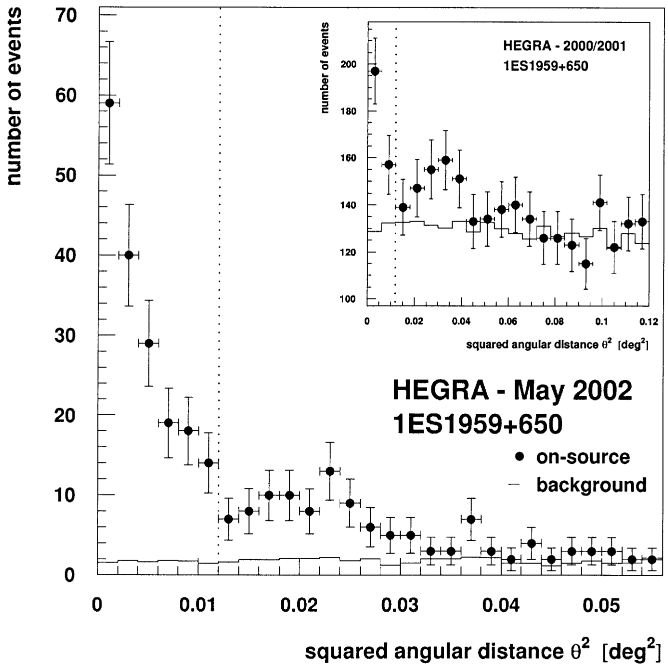

Fig. 1. Number of events vs. squared angular distance Θ^2 to the position of 1ES 1959+650, observed on May 18/19 and 19/20, 2002, with the HEGRA IACT system. The dots show the ON-source events, the histogram gives the background estimate determined from a ring segment as explained in the text. The statistical error for the background estimate is much smaller than the error of the ON-source distribution. Upper right: Similar distributions for the year 2000/2001 observations yielding a significance of $5.2\,\sigma$.

is obvious at a very high significance of greater than $23\,\sigma$. The diurnal integral flux levels above 2 TeV observed in the year 2002 are shown in Fig. 2 (Table 4 containing the complete lightcurve for the years 2000–2002 is available at the CDS, see note to the title). The strong outburst in May 2002 is followed by a post-flare low state in June. During July, the source has exhibited more activity again followed by a period of diminishing TeV flux in August and September 2002.

The spectral investigation of the 1ES 1959+650 "high state" was performed using the data of the 6 nights in May and July 2002 with the object's integral flux being larger than 1 Crab above 2 TeV (see Table 3). Within the limited statistics, the single nights of these 8.5 h of observations show the same spectral shape. A fit of a pure power law $\mathrm{d}N/\mathrm{d}E = N_0 \times (E/1\,\mathrm{TeV})^{-\alpha}$ to the differential energy spectrum results in $N_0 = (7.4 \pm 1.3_{\rm stat} \pm 0.9_{\rm sys}) \times 10^{-11}$ phot. cm^{-2} s^{-1} TeV^{-1} and $\alpha = 2.83 \pm 0.14_{\rm stat} \pm 0.08_{\rm sys}$ with $\chi^2_{\rm red.}$(d.o.f.) = 1.9 (6). A fit of a power law with an exponential cut-off $\mathrm{d}N/\mathrm{d}E = N_0 \times (E/1\,\mathrm{TeV})^{-\alpha} \times \exp(-E/E_{\rm c})$ with $N_0 = (5.6 \pm 0.9_{\rm stat} \pm 0.7_{\rm sys}) \times 10^{-11}$ phot. cm^{-2} s^{-1} TeV^{-1}, $\alpha = 1.83 \pm 0.15_{\rm stat} \pm 0.08_{\rm sys}$, $E_{\rm c} = (4.2^{+0.8}_{-0.6\,\rm stat} \pm 0.9_{\rm sys})$ TeV, $\chi^2_{\rm red.}$(d.o.f.) = 1.7 (5), is also an adequate description of these data (see Fig. 3).

Figure 3 also shows the spectral energy distribution of the 1ES 1959+650 "low state". Nearly 150 h of observations during nights with 1ES 1959+650 emitting TeV γ-rays at a flux level below 0.5 Crab have been used for this purpose. The spectrum can be described by a pure power law with $N_0 = (7.8 \pm 1.5_{\rm stat} \pm 1.0_{\rm sys}) \times 10^{-11}$ phot. cm^{-2} s^{-1} TeV^{-1} and $\alpha = 3.18 \pm 0.17_{\rm stat} \pm 0.08_{\rm sys}$ with $\chi^2_{\rm red.}$(d.o.f.) = 0.22 (3). A power law with an exponential cut-off and a spectral index fixed at $\alpha = 1.8$ fits the data with $N_0 = (6.0 \pm 1.4_{\rm stat} \pm 0.8_{\rm sys}) \times 10^{-12}$ phot. cm^{-2} s^{-1} TeV^{-1} and $E_{\rm c} = (2.7^{+0.6}_{-0.4\,\rm stat} \pm 0.6_{\rm sys})$ TeV with $\chi^2_{\rm red.}$(d.o.f.) = 0.65 (3).

3. Summary and conclusions

The BL Lac object 1ES 1959+650 has been observed with the HEGRA IACT system for a total of 197.4 h. The object has been detected at TeV energies during its low flux state in the years 2000 and 2001 at a value of $(5.3 \pm 1.1_{\rm stat})$% of the Crab flux and during flaring states in 2002, reaching a flux level as high as 2.2 Crab. Extensive HEGRA observations in 2002 show strong changes in the absolute flux level.

The time averaged energy spectrum of the high state observations is well described by a pure power law with spectral index $\alpha = 2.83 \pm 0.14_{\rm stat} \pm 0.08_{\rm sys}$ or by a power law with an exponential cut-off at $E_{\rm c} = (4.2^{+0.8}_{-0.6\,\rm stat} \pm 0.9_{\rm sys})$ TeV. Within the synchrotron self-Compton (SSC) model the TeV γ-ray emission of a BL Lac type object corresponds to the Inverse Compton (IC) component. Costamante & Ghisellini (2002) have predicted the IC flux above 1 TeV in a flaring state of 1ES 1959+650 to be 1.74×10^{-11} phots. cm^{-2} s^{-1} using a phenomenological parametrization of the spectral energy distribution by Fossati et al. (1998). Taking into account the

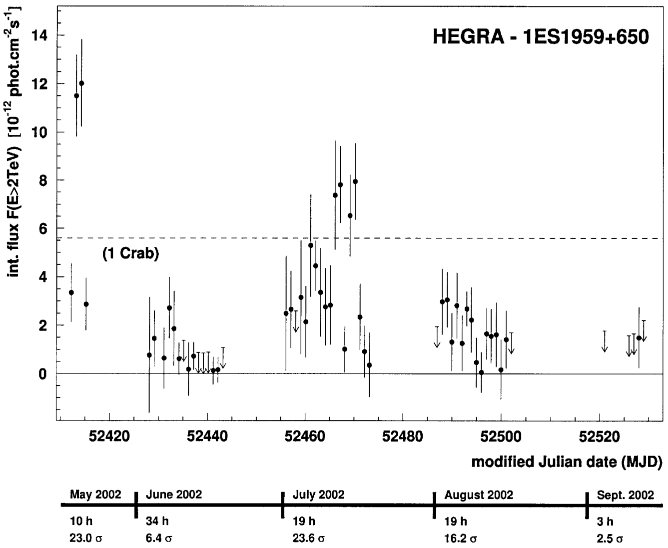

Fig. 2. Diurnal integral flux values resp. upper limits (99% c. l.) observed above 2 TeV vs. the modified Julian date (MJD) for the year 2002 HEGRA IACT system data. Strong flux variations are visible in May and July. The level of the flux of the Crab nebula is indicated by the horizontal dashed line. The time gaps between the individual observation periods are due to the full moon periods when no observations were possible.

Table 3. HEGRA IACT system event statistics and values of the differential photon flux of 1ES 1959+650 in the high state for the individual energy bins as shown in Fig. 3.

Energy (TeV)	N_{ON}	N_{OFF}	Sign. (σ)	diff. Flux (phot. cm^{-2} s^{-1} TeV^{-1})
1.52	42	21	10.0	$(2.5 \pm 0.5) \times 10^{-11}$
2.02	44	43	8.6	$(8.5 \pm 1.6) \times 10^{-12}$
2.68	44	25	10.0	$(4.0 \pm 0.7) \times 10^{-12}$
3.55	54	12	12.9	$(3.0 \pm 0.4) \times 10^{-12}$
4.70	34	9	10.0	$(1.3 \pm 0.3) \times 10^{-12}$
6.23	16	3	7.1	$(4.5 \pm 1.2) \times 10^{-13}$
8.25	6	4	3.5	$(1.1 \pm 0.5) \times 10^{-13}$
10.94	5	1	4.0	$(0.7 \pm 0.3) \times 10^{-13}$

strong variations of 1ES 1959+650 in 2002 the observed flux values can be easily accommodated.

Due to the absorption of TeV photons by the pair production process $\gamma_{TeV} + \gamma_{DEBRA} \longrightarrow e^+ + e^-$ with the DEBRA the observed spectrum differs from the source spectrum. In the range from 1 to several TeV however, the spectral shape remains nearly unchanged since the optical depth in this energy range is rather constant for most of the DEBRA candidate spectra in the relevant wavelength range of 1 to 10 μm (Aharonian 2001). Using a "model of choice" prediction of the DEBRA spectral energy density (Aharonian 2001), the attenuation coefficients for the HEGRA 1ES 1959+650 high state data points have been calculated and applied to unfold the measured spectrum as shown in Fig. 3. The cut-off energy is only marginally shifted to $(4.5^{+1.2}_{-0.8\,\mathrm{stat}} \pm 0.9_{\mathrm{sys}})$ TeV. The low event statistics at the

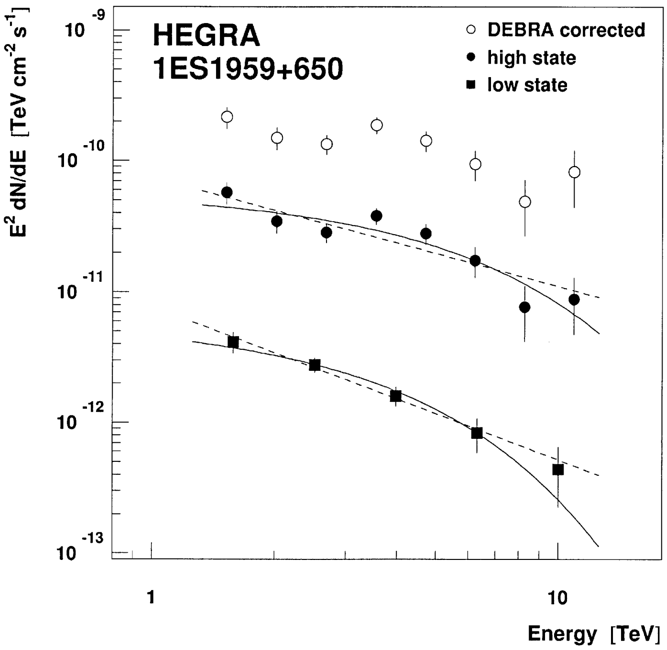

Fig. 3. Time averaged spectral energy distributions (SED) of 1ES 1959+650 as measured with the HEGRA IACT system. The filled circles show the spectrum during 6 high state nights in 2002, while the filled squares show the SED for the combination of all low state nights (<0.5 Crab). The results of fits of a power law with an exponential cut-off (solid lines) resp. a pure power law (dashed lines) are indicated. The open circles show the high state spectrum corrected for the DEBRA absorption (see text).

highest energies observed around 10 TeV and above (Table 3) do not allow one to see the strong deformation of the spectral shape, which is expected from the energy dependence of the attenuation coefficients (e. g. see Fig. 9 in Aharonian 2001).

The fact that 1ES 1959+650 is about 1.5 times more distant than the nearby TeV Blazars Mkn 421 and Mkn 501 and bridges the distance gap to H1426+428 makes it a very important object for future DEBRA probing in the optical to near-infrared region.

Acknowledgements. The support of the German Federal Ministry for Research and Technology BMBF and of the Spanish Research Council CICYT is gratefully acknowledged. G. Rowell acknowledges receipt of a von Humboldt fellowship. We thank the Instituto de Astrofísica de Canarias (IAC) for the use of the HEGRA site at the Observatorio del Roque de los Muchachos (ORM) and for supplying excellent working conditions on La Palma.

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