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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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 σ at a value of 5.3 % of the Crab flux and in May 2002 during strong outbursts with > 23 σ at a flux level of up to 2.2 Crab, making 1ES 1959+650 an important member of the class of TeV γ-ray emitters. 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 1.83 ± 0.10_{stat} ± 0.08_{sys} or by a power law with an exponential cut-off at (4.2±0.8,stat ± 0.9,sys) TeV and a spectral index of 1.83 ± 0.15_{stat} ± 0.08_{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 ± 0.17_{stat} ± 0.08_{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), HEGRA (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) (Cataneo et al. 1998), the BL Lac PKS2155-304 (z = 0.117) (Chadwick et al. 1999) and the
very distant object 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 detected 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 (Vorobiev 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.

### Table 1.

| Date                     | Year | Obs. Time [h] | \(\langle \theta \rangle [\text{'}] \) |
|--------------------------|------|---------------|--------------------------------------|
| 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                                 |

### Table 2.

| signal | spectrum |
|--------|----------|
| \(\alpha = \frac{N_{\text{ON}}}{N_{\text{OFF}}}\) | \(\langle \alpha \rangle &= 0.0758 \pm 0.01429\) |
| \(\theta^2\) | \(<0.0106 \text{deg}^2\) |
| \(\text{shape cut on } m_{\text{SCW}}\) | \(<1.1\) |
| \(\text{number of images per event}\) | \(\geq 3\) |
| \(\text{stereo algorithm}\) | \(#3\) |

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 observations 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 \(\gamma\)-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 \(\text{wobble}\) 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 \(\alpha = \frac{N_{\text{ON}}}{N_{\text{OFF}}}\) (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 \(m_{\text{SCW}} < 1.1\)) (Konopelko et al. 1999) for an effective \(\gamma\)-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 \(\gamma\)-ray events from the Crab nebula on the basis of a nearly contemporaneous data set at similar zenith angles. The proce-
duration of spectral evaluation – with an energy resolution of \( \leq 12\% \) 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 \(\gamma\)-rays from 1ES 1959+650 during this quiescent state at a value of \((5.3 \pm 1.1)\%\) 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 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 Figure 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 \(dN/dE = N_0 \times (E/1\,\text{TeV})^{-\alpha}\) to the differential energy spectrum results in \(N_0 = (7.4 \pm 1.3) \times 10^{-11}\) phot. cm\(^{-2}\) s\(^{-1}\) TeV\(^{-1}\) and \(\alpha = 2.83 \pm 0.14\) with \(\chi^2\) (d.o.f. = 1.9) (6). A fit of a power law with an exponential cut-off \(dN/dE = N_0 \times (E/1\,\text{TeV})^{-\alpha} \times \exp(-E/E_c)\) with \(N_0 = (5.6 \pm 0.9) \times 10^{-11}\) phot. cm\(^{-2}\) s\(^{-1}\) TeV\(^{-1}\), \(\alpha = 1.83 \pm 0.15\) and \(E_c = (4.2^{+0.8}_{-0.7})\) TeV, \(\chi^2\) (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 \(\gamma\)-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 \(N_0 = (7.8 \pm 1.5) \times 10^{-12}\) phot. cm\(^{-2}\) s\(^{-1}\) TeV\(^{-1}\) and \(\alpha = 3.18 \pm 0.17\) with \(\chi^2\) (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 \(N_0 = (6.0 \pm 1.4) \times 10^{-12}\) phot. cm\(^{-2}\) s\(^{-1}\) TeV\(^{-1}\) and \(E_c = (2.7^{+0.6}_{-0.4} \pm 0.6)\) TeV with \(\chi^2\) (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 \((5.3 \pm 1.1)\%\) of the Crab flux and during flaring states in 2002, reaching a flux level as
the relevant wavelength range of 1 to 10 is rather constant for most of the DEBRA candidate spectra in nearly unchanged since the optical depth in this energy range from 1 to several TeV however, the spectral shape remains served spectrum di-
ation process 
AILY accommodated. Fossati et al. (1998). Taking into account the strong variations cal parametrization of the spectral energy distribution by of 1ES 1959 energy density (Aharonian 2001), the attenuation coe-
Fossati et al. 1998). Using a “model of choice” prediction of the DEBRA spectral 
strong changes in the absolute flux level. 

The time averaged energy spectrum of the high state obser-
ations is well described by a pure power law with spectral in-
strong changes in the absolute flux level. 

Due to the full moon periods when no observations were possi-
hich is expected from the energy dependence of the attenuation 
coefficients (e. g. see Figure 9 in Aharonian 2001). 
The fact that 1ES 1959+650 is about 1.5 times more dis-
tant than the nearby TeV Blazars Mkn 421 and Mkn 501 and 
bridges the distance gap to H1426+428 makes it a very im-
potent object for future DEBRA probing in the optical to near-
infrared region.

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