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DISCOVERY OF VERY HIGH ENERGY γ-RAYS FROM MARKARIAN 180 TRIGGERED BY AN OPTICAL OUTBURST

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ABSTRACT

The high-frequency–peaked BL Lacertae object Markarian 180 (Mrk 180) was observed to have an optical outburst in 2006 March, triggering a Target of Opportunity observation with the MAGIC telescope. The source was observed for 12.4 hr, and very high energy γ-ray emission was detected with a significance of 5.5 σ. An integral flux above 200 GeV of $(2.3 \pm 0.7) \times 10^{-11}$ cm^{-2} s^{-1} was measured, corresponding to 11% of the Crab Nebula flux. A rather soft spectrum with a photon index of -3.3 ± 0.7 has been determined. No significant flux variation was found.

Subject headings: BL Lacertae objects: individual (Markarian 180) — gamma rays: observations

1. INTRODUCTION

The search for very high energy (VHE, defined as $E \gtrsim 100$ GeV) γ-ray emission from active galactic nuclei (AGNs) is one of the major goals for ground-based γ-ray astronomy. New detections open the possibility of a phenomenological study of the physics inside the relativistic jets in AGNs, in particular, to understand both the origin of the VHE γ-rays as well as the correlations between photons of different energy ranges (from radio to VHE). The number of reported VHE γ-ray–emitting AGNs has been slowly increasing and is currently 12 (2006 June). Six of them have been seen by MAGIC: Mrk 421 (Albert et al. 2006c), Mrk 501 (Mazin 2006), 1ES 1959+650 (Albert et al. 2006a), 1ES 2344+514 (Mazin 2006), 1ES 1218+304 (Albert et al. 2006b), and PG 1553+113 (Albert et al. 2006d).

The known VHE γ-ray–emitting AGNs are variable in flux in all wave bands. Correlations between X-ray and γ-ray emission have been found (e.g., Fossati et al. 2004), although the relationship has proven to be rather complicated, with γ-ray flares also being detected in the absence of X-ray flares (Holder et al. 2003; Krawczynski et al. 2003) and vice versa (Rebillot et al. 2003). The optical-TeV correlation has yet to be studied, but the optical-GeV correlations seen in 3C 279 (Hartman et al. 2001) suggest that at least in some sources, such correlations exist. Using this as a guideline, the MAGIC collaboration has been performing Target of Opportunity observations whenever alerted that sources were in a high flux state in the optical and/or X-ray band.

The AGN Mrk 180 (1ES 1133+704) is a well-known high-frequency–peaked BL Lac (HBL) object at a redshift of $z = 0.045$ (Falco et al. 1999). The spectral energy distribution (SED) of HBL objects exhibits a generic two-bump structure: one peak with a maximum in the X-ray band and the other peak located in the GeV-TeV band. The radiation is produced

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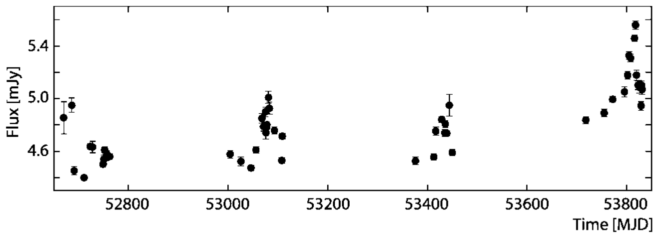

FIG. 1.—*R*-band light curve of Mrk 180 extending from 2003 January to the end of 2006 March as measured by the KVA telescope; 5 mJy is equivalent to 14.47 mag.

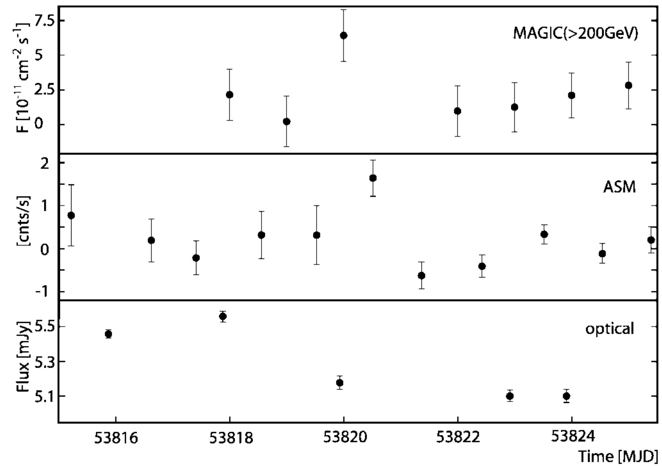

FIG. 2.—Light curve of Mrk 180 for MJD = 53,815–53,825 (March 21–31). *Upper panel*: VHE γ-rays measured by MAGIC above 200 GeV. *Middle panel*: ASM count rate. *Lower panel*: Optical flux measured by KVA.

in a highly beamed plasma jet, which is almost aligned with the observer's line of sight. A double-peaked SED is normally attributed to a population of relativistic electrons, where one peak is due to synchrotron emission in the magnetic field of the jet and where the second peak is caused by inverse Compton (IC) scattering of low-energy photons. The low-energy photons can be external to the jet (external Compton scattering; Dermer & Schlickeiser 1993) or are produced within the jet via synchrotron radiation (synchrotron self-Compton [SSC] scattering; Maraschi et al. 1992). Models based on the acceleration of hadrons can also sufficiently describe the observed SEDs and light curves (Mannheim et al. 1991; Massaro et al. 2004). All of the up to now known AGNs with strong GeV/TeV γ-emission belong to the HBL object class.

In many cases, the second peak of the SED is not observable because of low sensitivity above a few times 100 MeV of satellite-borne detectors and a too high energy threshold of ground-based γ-ray detectors. In case of Mrk 180, HEGRA (Aharonian et al. 2004) and Whipple (Horan et al. 2004) observed this object but were only able to derive flux upper limits, and EGRET did not detect the source (Fichtel et al. 1994; Hartman et al. 1999).

In the optical, Mrk 180 is characterized by a bright host galaxy $R = 14.17 \pm 0.02$ mag and a much fainter (variable) core $R = 15.79 \pm 0.02$ mag (Nilsson et al. 2003). The variations in total optical brightness are therefore small. The source is observed regularly as part of the Tuorla Observatory Blazar monitoring program[22] with the Tuorla 1 m telescope and the KVA 35 cm telescope.[23] To determine the core flux, we had to subtract the flux of the host galaxy and a nearby star within the 5″ aperture radius (together $R = 14.96$ mag, or 3.2 mJy; K. Nilsson 2006, private communication).

After Mrk 180 had been detected in the X-rays by *HEAO-1* (Mufson & Hutter 1981), it was observed by various satellites with fluxes ranging from 6.3 to 22×10^{-12} ergs cm^{-2} s^{-1} (Donato et al. 2001) at around 1 keV and from 5.0 to 9.8×10^{-12} ergs cm^{-2} s^{-1} in the 2–10 keV band (Perlman et al. 2005; Donato et al. 2005). The source is monitored by the all-sky monitor (ASM) on board the *Rossi X-Ray Timing Explorer*.

In this Letter we present the first detection of VHE γ-ray emission from Mrk 180.

2. OBSERVATIONS AND DATA ANALYSIS

The MAGIC telescope (Major Atmospheric Gamma Imaging Cerenkov telescope; Lorenz 2004) is located on the Canary Island La Palma (2200 m above sea level, 28°.45 north, 17°.54 west). MAGIC is currently the largest imaging atmospheric Cerenkov telescope with a 17 m–diameter tessellated reflector dish (Cortina et al. 2005). The 3°.5 field of view camera comprises 576 photomultipliers (PMTs) with enhanced quantum efficiency. The accessible energy range spans from 50–60 GeV (trigger threshold at small zenith angles) up to tens of TeV. The γ point-spread function is about 0°.1.

The observation of Mrk 180 was triggered by a brightening of the source in the optical on 2006 March 23. The alert was given as the core flux increased by 50% from its quiescent level value as determined from over 3 years of data recording, shown in Figure 1. During the MAGIC observation, optical follow-up observations were performed with KVA. The simultaneous MAGIC, ASM, and KVA light curve is shown in Figure 2. Around this time, Mrk 180 was also observed as part of the AGN-monitoring program by the University of Michigan Radio Observatory (UMRAO). No evidence of flaring was found between 2006 January and April.

Mrk 180 was observed in 2006 during eight nights (from March 23 to 31), for a total of 12.4 hr, at zenith angles ranging from 39° to 44°. The observations were performed in the so-called wobble mode (Daum et al. 1997), in which the telescope is pointed alternatively for 20 minutes to two opposite sky positions at 0°.4 off the source. Runs with unusual trigger rates due to detector problems or adverse atmospheric conditions were rejected. The total observation time was thus reduced to 11.1 hr.

The data were analyzed using the standard analysis and calibration programs for the MAGIC telescope (Bretz et al. 2005; Wagner et al. 2005; Gaug et al. 2005). For the γ/hadron shower separation, a multidimensional classification technique based on the Random Forest method was used (Breiman 2001; Bock et al. 2004). The cuts for the γ/hadron separation were trained using a fraction of randomly chosen data to represent the background (hadrons) and were compared to Monte Carlo (MC) γ events with the same zenith angle distribution (CORSIKA ver. 6.023; Knapp & Heck 2004; Majumdar et al. 2005). The cuts were then chosen such that the overall cut efficiency for MC γ events was about 50%. The number of excess events is determined as the difference between the source and background region in the θ^2 distributions, with θ being the angular distance between the source position in the sky and the reconstructed arrival position of the air shower. The latter position is determined for each shower image by means of the so-called DISP method (Fomin et al. 1994; Lessard et al. 2001; Domingo-Santamaría et al. 2005), using image shape parameters (Hillas 1985). In order to determine the background distribution, three

[22] See http://users.utu.fi/kani/1m/.
[23] See http://tur3.tur.iac.es/.

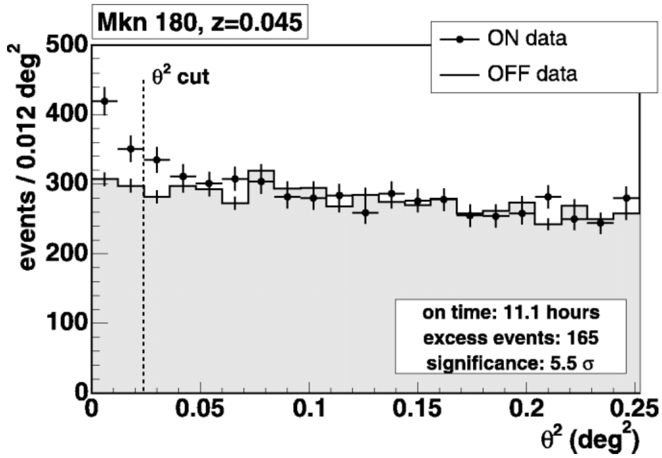

FIG. 3.—The θ^2-distribution for the ON-source data (*filled circles*) and normalized OFF-source events (*gray histogram*) for Mrk 180. The vertical dotted line indicates the θ^2 cut used to determine excess events. The total excess of 165 events corresponds to a significance of 5.5 σ.

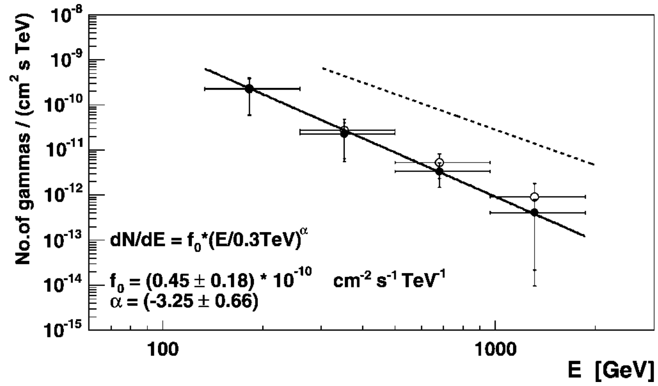

FIG. 4.—Differential energy spectrum of Mrk 180. *Filled circles*: Spectrum measured by MAGIC. *Open circles*: De-absorbed energy spectrum (see text). The horizontal bars indicate the size of each energy bin. The black line represents a power-law fit to the measured spectrum. The fit parameters are listed in the figure. For comparison, the Crab Nebula energy spectrum as derived from MAGIC data (Wagner et al. 2005) is shown (*dotted line*).

background regions of the same size are chosen symmetrically to the on-source region with respect to the camera center. A final cut of $\theta^2 < 0.024$ is applied to determine the significance of the signal and the number of excess events. The energy of the γ-ray candidates was also estimated using the Random Forest technique. The applied cuts were chosen to be looser than the ones in Figure 3 in order to gain statistics on the γ-ray candidates. Due to the large zenith angle of the observation, the corresponding energy threshold (defined as the peak in the differential energy distribution of the MC γ events) after cuts was about 200 GeV. Effects on the spectrum determination, introduced by the limited energy resolution of the detector, were corrected using the "unfolding" methods according to Anykeyev et al. (1991).

3. RESULTS

The distribution of θ^2-values after cuts is shown in Figure 3. The signal of 165 events over 605.2 normalized background events corresponds to a 5.5 σ excess using equation (17) in Li & Ma (1983). The shape of the excess is consistent with a pointlike source seen by MAGIC.

No evidence of flux variability was found. The fit to the nightly integrated flux is consistent with a constant emission ($\chi^2 = 7.1$, 6 degrees of freedom). Figure 2 shows the VHE light curve together with the ASM daily averages and the *R*-band flux data. The X-ray flux of the source is generally below the ASM sensitivity, but on March 25 a 3 σ excess was observed, which suggests that the source was also active in X-rays. The optical flux reached its maximum on the night MAGIC started the observations (March 23) and began to decrease afterward.

The measured energy spectrum of Mrk 180 is shown in Figure 4. Assuming a power-law spectrum, we obtained the following parameterization:

$$\frac{dN}{dE} = (4.5 \pm 1.8) \times 10^{-11} \left(\frac{E}{0.3\ \mathrm{TeV}}\right)^{-3.3 \pm 0.7} \frac{1}{\mathrm{TeV\ cm^2\ s}}.$$

The observed integral flux above 200 GeV is $F(E > 200\ \mathrm{GeV}) = (2.25 \pm 0.69) \times 10^{-11}\ \mathrm{cm^{-2}\ s^{-1}}$, which corresponds to 1.27×10^{-11} ergs cm^{-2} s^{-1}, or 11% of the Crab Nebula flux measured by MAGIC. The errors are statistical only. We estimate the systematic errors to be around 50% for the absolute flux level and 0.2 for the spectral index. The large systematic flux error is a consequence of the steep slope. The main error contributions are the uncertainty in the atmospheric transmission, the reflectivity and focusing uncertainty of the mirrors and light catchers in front of the PMTs, and the uncertainty in the effective quantum efficiency of the PMT and in the photoelectron-to-signal conversion. A second independent analysis gave results in very good agreement with the quoted numbers.

The VHE γ-rays from Mrk 180 are partially absorbed by the low-energy photons of the evolving extragalactic background light (EBL; see Nikishov 1962, Gould & Schréder 1966, Stecker et al. 1992, and Hauser & Dwek 2001). Given the redshift $z = 0.045$ of Mrk 180, the effect is small for photons with energies below 1 TeV. We calculate the optical depth and the resulting attenuation of the VHE γ-rays from Mrk 180 using the number density of the evolving EBL provided by the best-fit model of Kneiske et al. (2004). This state-of-the-art model is consistent with the recently derived upper limits on the EBL inferred from arguments about AGN spectra (Aharonian et al. 2006). The attenuation was determined by the numerical integration of equation (2) from Dwek & Krennrich (2005). The de-absorbed energy spectrum of Mrk 180 is also shown in Figure 4 (*open circles*). A fit with a simple power law to the de-absorbed spectrum reveals a slope with $\alpha = -2.8 \pm 0.7$.

4. DISCUSSION AND CONCLUSIONS

In this Letter we have presented the first detection of VHE γ-ray emission from Mrk 180. The discovery was triggered by an optical flare, but no significant variations in the VHE regime were found. The short observation period and the small signal prevent us from carrying out detailed studies. It is therefore impossible to judge whether the detected VHE flux level represents a flaring or a quiescent state of the AGN.

Earlier observations by other experiments have only set upper limits on the VHE γ-ray emission from Mrk 180. HEGRA observed the source for 9.8 hr, resulting in an upper limit (99% c.l.) at 1.5 TeV of 12% of the Crab Nebula flux (Aharonian et al. 2004). Whipple observed Mrk 180 during three observation periods for a total of 26.8 hr resulting in a flux upper limit at 300 GeV of 10.8% of the Crab Nebula flux (Horan et al. 2004). Both upper limits are above the flux presented in this Letter.

Figure 5 shows the SED of Mrk 180: the radio, optical, and X-ray data are from UMRAO, KVA, ASM, and the NED database, and the VHE data are from this analysis and various

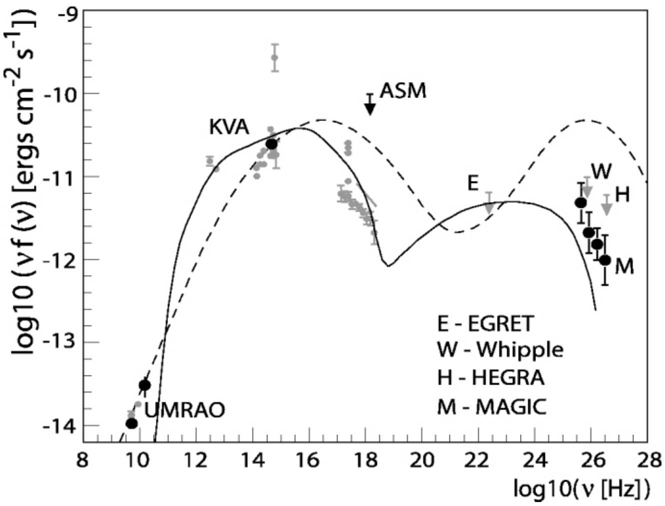

Fig. 5.—SED of Mrk 180. Simultaneous data (UMRAO, KVA, ASM, and MAGIC) are represented as black circles. The gray circles represent historical data (Giommi et al. 2002; Perlman et al. 2005). The arrows denote the upper limits from ASM, EGRET (Fichtel et al. 1994), Whipple, and HEGRA. The solid line is from Costamante & Ghisellini (2002), and the dashed line is from Fossati et al. (2000; see text).

upper limits. Simultaneous data are noted in black, while historical data are noted in gray. The predicted flux by the phenomenological model of Fossati et al. (2000; *dashed line*) is too high, as already emphasized by the nondetection measurements (Aharonian et al. 2004; Horan et al. 2004). A more detailed SSC model from Costamante & Ghisellini (2002; *solid line*) seems to describe the data more closely.

The rather steep slope of the VHE spectrum suggests an IC peak position well below 200 GeV, while the nondetection by EGRET gives a lower limit of ~1 GeV for the peak position. This is in agreement with the SSC model of Costamante & Ghisellini (2002) suggesting that the IC peak position is at around 10 GeV. The overall IC luminosity, however, is underestimated in this model: the observed integral flux above 300 GeV is a factor 30 larger than predicted. An explanation for this discrepancy could be the model's underlying assumption of a quiescent-state synchrotron spectrum to obtain the IC flux. This could indeed suggest that our measurement was made during a high state.

The discovery of VHE emission from Mrk 180 during an optical outburst makes it very tempting to speculate about the connection between optical activity and increased VHE emission. Since Mrk 180 has not been observed prior to the outburst with MAGIC and since the upper limits from other experiments are above the observed flux level, further observations are needed.

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