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DISCOVERY OF VERY HIGH ENERGY γ-RAYS FROM 1ES 1011+496 AT $z = 0.212$

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ABSTRACT

We report on the discovery of very high energy (VHE) γ-ray emission from the BL Lacertae object 1ES 1011+496. The observation was triggered by an optical outburst in 2007 March and the source was observed with the MAGIC telescope from 2007 March to May. Observing for 18.7 hr, we find an excess of 6.2 σ with an integrated flux above 200 GeV of $(1.58 \pm 0.32) \times 10^{-11}$ photons cm^{-2} s^{-1}. The VHE γ-ray flux is >40% higher than in 2006 March–April (reported elsewhere), indicating that the VHE emission state may be related to the optical emission state. We have also determined the redshift of 1ES 1011+496 based on an optical spectrum that reveals the absorption lines of the host galaxy. The redshift of $z = 0.212$ makes 1ES 1011+496 the most distant source observed to emit VHE γ-rays to date.

Subject headings: gamma rays: observations — quasars: individual (1ES 1011+496)

Online material: color figures

1. INTRODUCTION

Known very high energy (VHE defined as >100 GeV) γ-ray emitting active galactic nuclei (AGNs) show variable flux in all wave bands. The relationship between the variability in different wave bands appears rather complicated. The MAGIC collaboration is performing Target of Opportunity (ToO) observations whenever alerted that sources are in a high flux state in the optical and/or X-ray bands. Previously, optically triggered observations resulted in the discovery of VHE γ-ray emission from Markarian 180 (Albert et al. 2006). Here we report the discovery of VHE γ-rays from 1ES 1011+496 triggered by an optical outburst in 2007 March. Previous observations of the source with the MAGIC telescope did not show a clear signal (Albert et al. 2007d).

1ES 1011+496 is a high-frequency-peaked BL Lac (HBL) object for which we now determine a redshift of $z = 0.212 \pm 0.002$ (Fig. 1). Previously, this was uncertain since it was based on an assumed association with the cluster Abell 950 (Wisniewski et al. 1986). The redshift determined here makes 1ES 1011+496 the most distant VHE γ-ray source yet detected with the possible exception of PG 1553+113 (Aharonian et al. 2006a; Albert et al. 2007a) (for which the redshift is $0.09 < z < 0.42$; Sbarufatti et al. 2006; Mazin & Goebel 2007).

The spectral energy distribution (SED) of BL Lac objects

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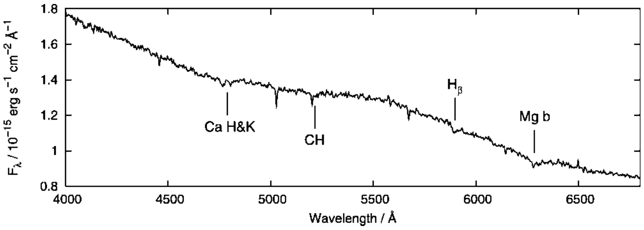

FIG. 1.—Optical spectrum of 1ES 1011+496 obtained with MMT, using the Blue Channel Spectrograph with the 300 line mm^{-1} grating, a 1.5″ slit, and a Loral 3K × 1K CCD. Integration time was 30 minutes. Absorption lines of the host galaxy (Ca H and K, CH G, H_β, and Mg *b*) are clearly visible and indicate a redshift of $z = 0.212 \pm 0.002$.

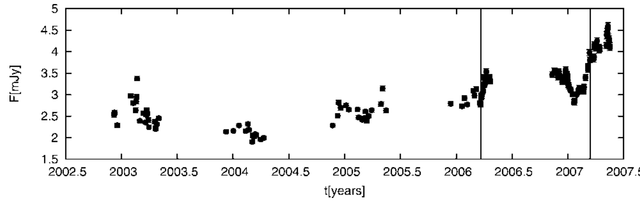

FIG. 2.—Optical *R*-band light curve of 1ES 1011+496 from Tuorla 1 m and KVA 35 cm telescopes. The vertical lines indicate the starting point of the MAGIC observations in 2006 and 2007.

normally shows a two-bump structure. The lower frequency peak is due to synchrotron radiation. Various models have been proposed for the origin of the high-frequency peak; the most popular invoke inverse Compton scattering of ambient soft photons. There have been several suggestions for the origin of the low-frequency seed photons that are upscattered to γ-ray energies: the soft photons may be produced within the jet itself by synchrotron radiation (SSC; Maraschi et al. 1992) or come from outside the jet, perhaps from the accretion disk (EC; Dermer & Schlickeiser 1993). The high-energy peak may, instead, also have a hadronic origin (e.g., Mannheim et al. 1991).

When the synchrotron emission peak is located in the low-energy range from the submillimeter to optical, the objects are called low-frequency-peaked BL Lac objects. HBLs, on the other hand, have the peak synchrotron emission in the UV to X-ray energy range. The peak of the second bump is often not observable because of the low sensitivity above a few hundred MeV of satellite-borne detectors or a too high energy threshold of ground-based γ-ray detectors. With the exception of M87 (Aharonian et al. 2003, 2006b) and BL Lac (Albert et al. 2007b), all known blazar sources detected at TeV energies with Cerenkov telescopes show a synchrotron peak in the UV to X-ray energy range, suggesting that the intensity of the TeV emission is related to a synchrotron component extending to high frequencies.

2. OBSERVATIONS AND DATA ANALYSIS

The MAGIC telescope is located on the Canary Island of La Palma (2200 m above sea level, 28°45′ north, 17°54′ west). The accessible energy range spans from 50–60 GeV (trigger threshold at small zenith angles) up to tens of TeV (Albert et al. 2007c).

The MAGIC observation was triggered by an observed high optical state of 1ES 1011+496 on 2007 March 12 (see light curve in Fig. 2). The source has been monitored for more than 4 years in the optical with the KVA[27] and Tuorla 1 m telescopes as a part of the Tuorla blazar monitoring program.[28] In 2007 March the flux reached the highest level ever observed during the monitoring. The core flux, which is the host-galaxy-subtracted flux (the host galaxy flux is taken from Nilsson et al. [2007] and is 0.49 ± 0.02 mJy), increased more than 50% from the local minimum of the light curve. The high optical state with increasing flux was continuing throughout the MAGIC observations, despite an observation gap of 3 weeks due to bad weather.

1ES 1011+496 is monitored by *RXTE* ASM and *Swift* BAT, but the X-ray flux of the source is below the sensitivity of these instruments and the light curves show no indication of flaring. The source was also observed at Metsähovi Radio Observatory in 2007 May. The source was not detected at 37 GHz, which indicates that it was not in a high state at millimeter wavelengths (A. Lähteenmäki 2007, private communication).

After the alert, MAGIC observed 1ES 1011+496 in 2007 March–May. The total observation time was 26.2 hr and the observation was performed at zenith angles ranging from 20° to 37°. The observation was done in the so-called Wobble mode (Daum et al. 1997). After removing runs with unusual trigger rates, mostly caused by bad weather conditions, the effective observational time amounts to 18.7 hr.

The data were analyzed using the standard analysis and calibration programs for the MAGIC telescope (Albert et al. 2007c). The analysis is based on image parameters (Hillas 1985), the Random Forest (Breiman 2001; Bock et al. 2004), and the DISP methods (Domingo-Santamaría et al. 2005). After cuts for γ/hadron separation, the distribution of the angle θ, which is the angular distance between the source position in the sky and the reconstructed shower origin, is used to determine the signal in the ON-source region. Three background (OFF) regions of the same size are chosen symmetrically to the ON-source region with respect to the camera center. The final cut $\theta^2 < 0.02\ \mathrm{deg}^2$ to determine the significance (Fig. 3) was optimized on nearly contemporaneous Crab data to deter-

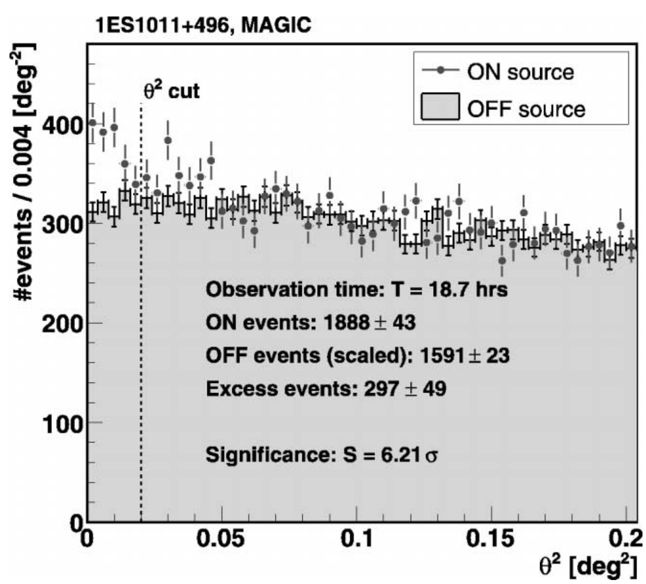

FIG. 3.—Distribution of θ^2 for ON-region data and normalized OFF-region data. The signal region is marked by the dashed line. [*See the electronic edition of the Journal for a color version of this figure.*]

[27] See http://tur3.tur.iac.es.
[28] See http://users.utu.fi/~kani/1m.

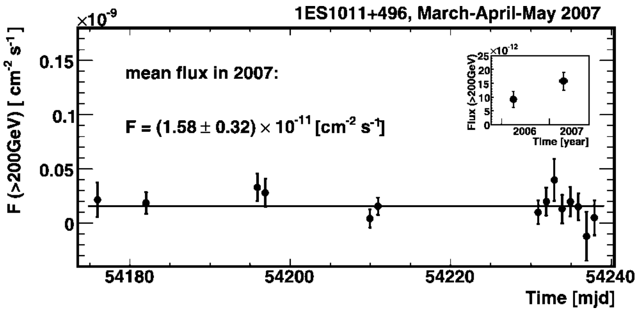

FIG. 4.—Night-by-night light curve of 1ES 1011+496 from 2007 March 17 (MJD 54,176) to 2007 May 18 (MJD 54,238). The year-by-year light curve is shown in the inset; the 2006 data point is from Albert et al. (2007d).

mine the significance of the signal and the number of excess events. The energy threshold was about 160 GeV for this analysis, which, given the soft spectrum of the source, allowed for signal extraction down to 100 GeV. The data were also analyzed with an independent analysis. Within the statistical errors the same significance, flux, and differential spectrum were obtained.

3. RESULTS

The distribution of the θ^2-values, after all cuts, is shown in Figure 3. The signal of 297 events over 1591 normalized background events corresponds to an excess with significance of 6.2 σ using equation (17) in Li & Ma (1983).

To search for time variability the sample was divided into 14 subsamples, one for each observing night. Figure 4 shows the integral flux for each night calculated for a photon flux above 200 GeV. The energy threshold has been chosen to reduce systematic effects arising from a rapidly decreasing effective area for γ-rays for lower energies. The flux is statistically constant at an emission level of $F(>200\ \text{GeV}) = (1.58 \pm 0.32) \times 10^{-11}$ photons $\text{cm}^{-2}\text{s}^{-1}$.

The energy spectrum of 1ES 1011+496 is shown in Figure 5. It extends from ∼120 to ∼750 GeV and can be well approximated by a power law:

$$\frac{dN}{dE} = (2.0 \pm 0.1) \times 10^{-10} \left(\frac{E}{0.2\ \text{TeV}}\right)^{-4.0 \pm 0.5} \frac{1}{\text{TeV cm}^2\ \text{s}}.$$

The errors are statistical only. We estimate the systematic uncertainty to be around 75% for the absolute flux level and 0.2 for the spectral index. The observed spectrum is affected by the evolving extragalactic background light (EBL; Nikishov 1962; Stecker et al. 1992) as the VHE γ-rays are partially altered by interactions with the low-energy photons of the EBL. Therefore, to obtain the intrinsic spectrum of the source, the observed spectrum must be corrected. The optical depth and the resulting attenuation of the VHE γ-rays from 1ES 1011+496 are calculated using the number density of the evolving EBL provided by the best-fit model of Kneiske et al. (2002). Within given model uncertainties, the model is in good agreement with alternative models (Primack et al. 2005; Stecker et al. 2006) and EBL upper limits (Aharonian et al. 2006c; Mazin & Raue 2007). Even after the correction, the slope of the spectrum is $\Gamma_{\text{int}} = 3.3 \pm 0.7$ (short-dashed line in Fig. 5; $\chi^2/\text{NDF} = 2.55/2$), softer than observed for other HBLs in TeV energies and thus not providing new constraints on the EBL density.

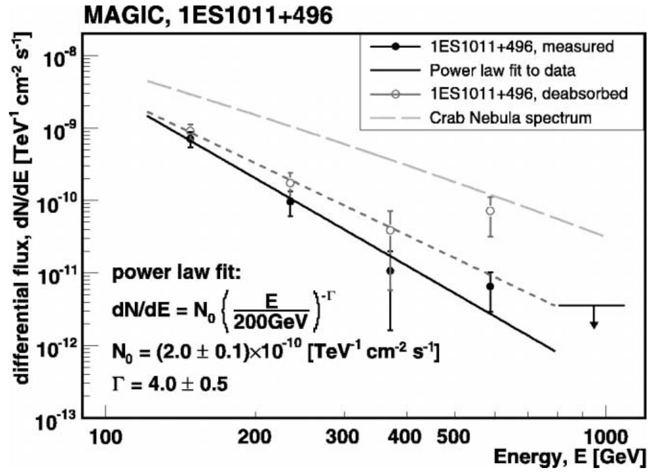

FIG. 5.—Measured spectrum (*filled circles*), power-law fit to the data (*solid line*), deabsorbed spectrum (*open circles*), and fit to the deabsorbed spectrum (*short-dashed line*). The last measured point is a 95% upper limit. In the deabsorbed spectrum, the last spectral point at ≈600 GeV is 1.6 σ above the fit and thus not significant. The Crab Nebula spectrum (*long-dashed line*; Albert et al. 2007c) is shown for comparison. [*See the electronic edition of the Journal for a color version of this figure.*]

4. DISCUSSION

We report the discovery of VHE γ-ray emission from BL Lac object 1ES 1011+496. With the redshift of $z = 0.212$, it is the most distant source detected to emit VHE γ-rays to date. The observed spectral properties (soft and no significant excess above ∼800 GeV) are consistent with the state-of-the-art EBL models (Kneiske et al. 2002; Primack et al. 2005; Stecker et al. 2006) and confirm recently derived EBL limits (Aharonian et al. 2006c; Mazin & Raue 2007).

In Figure 6 we show the SED of 1ES 1011+496 using

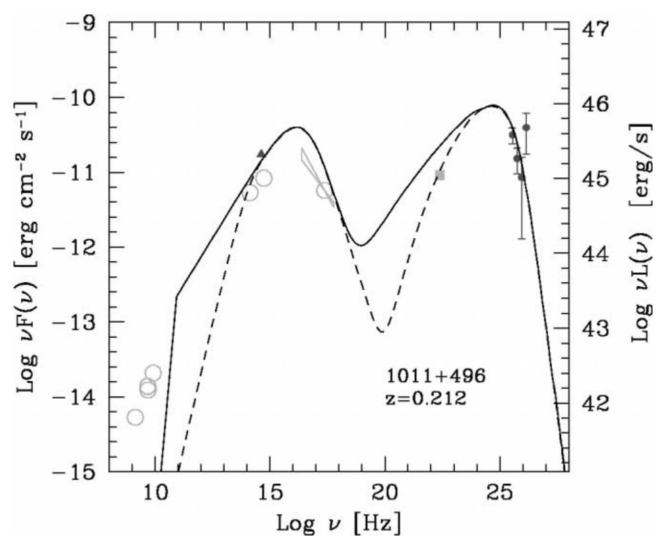

FIG. 6.—SED of 1ES 1011+496. The two different fits are done by varying the minimum electron energy γ_{min} (see text). The other fit parameters are R (radius of sphere) $= 10^{16}$ cm; δ (Doppler factor) $= 20$; B (magnetic field) $=$ 0.15 G; γ_{max} (maximum electron Lorentz factor) $= 2 \times 10^7$; γ_b (break electron Lorenz factor) $= 5 \times 10^4$; slopes of the electron distribution $n_1 = 2$ and $n_2 = 5$ before and after the break energy, respectively; and n_e (normalization of the electron energy distribution) $= 2 \times 10^4\ \text{cm}^{-3}$. The model is not intended for describing the radio data, which is assumed to originate from a larger emitting volume to avoid an intrinsic absorption. [*See the electronic edition of the Journal for a color version of this figure.*]

historical data (*open circles*; Costamante & Ghisellini 2002 and references therein) and our nearly simultaneous optical *R*-band data (*triangle*), together with the MAGIC spectrum corrected for attenuation (*filled circles*). We also display (*square*) the EGRET flux of the source 3EG J1009+4855, which has been suggested to be associated with 1ES 1011+496 (Hartman et al. 1999; but see also Sowards-Emmerd et al. 2003, whose analysis disfavors the association).

We model the SED by using a one-zone synchrotron-SSC model (see Tavecchio et al. 2001 for a description). In brief, a spherical emission region is assumed with radius R, filled with a tangled magnetic field of mean intensity B. The relativistic electrons follow a broken-power-law energy distributions specified by the limits $\gamma_{\rm min}$ and $\gamma_{\rm max}$ and the break at γ_b. Relativistic effects are taken into account by the Doppler factor δ.

As discussed in Tavecchio et al. (1998), if the position and the luminosity of the synchrotron and SSC peaks are known and an estimate of the minimum variability timescale is available, it is possible to uniquely constrain the model parameters. Unfortunately, we do not have all the required information to accomplish this. In particular, we have fixed the synchrotron peak by requiring that it reproduce the optical flux and the historical X-ray spectrum and we assume the SSC peak to be close to the MAGIC threshold. These choices minimize the required emitted luminosity, since a lower SSC peak frequency would require a higher SSC luminosity.

We present two models. The first (*solid line*), assuming an electron distribution extending down to $\gamma_{\rm min} = 1$, clearly overpredicts the MeV–GeV flux measured by EGRET. In the second case (*dashed line*), which fixes the low energy limit at $\gamma_{\rm min} = 3 \times 10^3$ (leading to a "narrowing" of both the synchrotron and SSC bump; see Katarzynski et al. 2006), the model is compatible with the reported EGRET flux. It is evident that simultaneous *GLAST*-MAGIC observations of this source will provide important constraints on the model parameters.

In both cases, the energy output of the SSC component (reaching observed values of $L \sim 10^{46}$ ergs s^{-1}) dominates over the synchrotron luminosity, implying a relatively low magnetic field, $B = 0.15$ G. In that case the source would be strongly electron dominated, since the magnetic energy density would be several orders of magnitude below that of the relativistic electrons. A larger synchrotron flux (limited by the nondetection by BAT and ASM) could alleviate the problem. Simultaneous X-ray and VHE observations are mandatory to further investigate this issue. We also note the fit Doppler factor ($\delta = 20$) is rather high and should be verified by very long baseline interferometric observations. The fitted parameters are similar to those derived for other TeV-emitting BL Lacs. We note, however, that adopting models where the jet has a velocity structure (e.g., models by Georganopoulos & Kazanas 2003; Ghisellini et al. 2005) would considerably reduce the required Doppler factors.

1ES 1011+496 was previously observed with the HEGRA telescope array, resulting in an upper limit of $F(E > 1\ {\rm TeV}) \leq 1.8 \times 10^{-12}$ photons cm^{-2} s^{-1} (Aharonian et al. 2004), which is well above the detected flux we found. The source was also observed by MAGIC, as part of a systematic scan of X-ray-bright HBLs, in 2006 March–April. Being in a lower optical state (the core flux was ~50% lower than that in 2007 March–May), the observations showed a marginal signal with 3.5 σ significance corresponding to an integral flux of $F(>180\ {\rm GeV}) = (1.26 \pm 0.4) \times 10^{-11}$ photons cm^{-2} s^{-1}, i.e., ~40% (Albert et al. 2007d) lower than the detected flux in 2007 March–May (see also the inset in Fig. 4). A similar trend was also found for BL Lac (Albert et al. 2007b), where the observations during a lower optical state failed to detect VHE γ-rays. This seems to indicate that there is a connection between the optical high state and the higher flux of VHE γ-ray emission, at least in some sources. To further investigate this possibility, follow-up observations of the detected objects, as well as further observations of other AGNs during high optical states, are required.

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