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

J. Albert[a], E. Aliu[b], H. Anderhub[c], P. Antoranz[d], A. Armada[b], C. Baixeras[e], J. A. Barrio[d], H. Bartko[f], D. Bastieri[g], J. K. Becker[h], W. Bednarek[i], K. Berger[a], C. Bigongiari[g], A. Biland[c], R. K. Bock[f,g], P. Bordas[j], V. Bosch-Ramon[j], T. Bretz[a], I. Britvitch[c], M. Camara[d], E. Carmona[f], A. Chilingarian[k], J. A. Coarasa[f], S. Commichau[c], J. L. Contreras[d], J. Cortina[b], M.T. Costado[m,v], V. Curtef[h], V. Danielyan[k], F. Dazzi[g], A. De Angelis[n], C. Delgado[m], R. de los Reyes[d], B. De Lotto[n], E. Domingo-Santamaría[b], D. Dorner[a], M. Doro[g], M. Errando[b], M. Fagiolini[o], D. Ferenc[p], E. Fernández[b], R. Firpo[b], J. Flix[b], M. V. Fonseca[d], L. Font[e], M. Fuchs[f], N. Galante[f], R.J. García-López[m,v], M. Garczarczyk[f], M. Gaug[m], M. Giller[i], F. Goebel[f], D. Hakobyan[k], M. Hayashida[f], T. Hengstebeck[q], A. Herrero[m,v], D. Höhne[a], J. Hose[f], C. C. Hsu[f], P. Jacon[i], T. Jogler[f], R. Kosyra[f], D. Kranich[c], R. Kritzer[a], A. Laille[p], E. Lindfors[l,*], S. Lombardi[g], F. Longo[n], J. López[b], M. López[d], E. Lorenz[c,f], P. Majumdar[f], G. Maneva[r], K. Mannheim[a], O. Mansutti[n], M. Mariotti[g], M. Martínez[b], D. Mazin[b,*], C. Merck[f], M. Meucci[o], M. Meyer[a], J. M. Miranda[d], R. Mirzoyan[f], S. Mizobuchi[f], A. Moralejo[b], D. Nieto[d], K. Nilsson[l], J. Ninkovic[f], E. Oña-Wilhelmi[b], N. Otte[f,q], I. Oya[d], D. Paneque[f], M. Panniello[m,x], R. Paoletti[o], J. M. Paredes[j], M. Pasanen[l], D. Pascoli[g], F. Pauss[c], R. Pegna[o], E. Perlman[y], M. Persic[n,s], L. Peruzzo[g], A. Piccioli[o], E. Prandini[g], N. Puchades[b], A. Raymers[k], W. Rhode[h], M. Ribó[j], J. Rico[b], M. Rissi[c], A. Robert[e], S. Rügamer[a], A. Saggion[g], T. Saito[f], A. Sánchez[e], P. Sartori[g], V. Scalzotto[g], V. Scapin[n], R. Schmitt[a], T. Schweizer[f], M. Shayduk[q,f], K. Shinozaki[f], S. N. Shore[t], N. Sidro[b], A. Sillanpää[l], D. Sobczynska[i], A. Stamerra[o], L. S. Stark[c], L. Takalo[l], F. Tavecchio[z], P. Temnikov[r], D. Tescaro[b], M. Teshima[f], D. F. Torres[u], N. Turini[o], H. Vankov[r], V. Vitale[n], R. M. Wagner[f], T. Wibig[i], W. Wittek[f], F. Zandanel[g], R. Zanin[b], J. Zapatero[e]

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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 March 2007 and the source was observed with the MAGIC telescope from March to May 2007. Observing for 18.7 hours we find an excess of $6.2\,\sigma$ with an integrated flux above 200 GeV of $(1.58 \pm 0.32) \cdot 10^{-11}$ photons cm^{-2} s^{-1}. The VHE γ-ray flux is $> 40\%$ higher than in March–April 2006 (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 up to date.

Subject headings: gamma-rays:Observations, BL Lacs:individual:1ES 1011+496

1. INTRODUCTION

Known Very High Energy (VHE defined as > 100GeV) γ-ray emitting Active Galactic Nuclei (AGN) show variable flux in all wavebands. The relationship between the variability in different wavebands 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 March 2007. Previous observations of the source with the MAGIC telescope did not show a clear signal (Albert et al. 2007a).

1ES 1011+496 is a high frequency peaked BL Lac (HBL) object for which we now determined a redshift of $z = 0.212 \pm 0.002$ (Fig. 1). Previously, this has been uncertain since it was based on an assumed association with the cluster Abell 950 (Wisniewski et al. 1985). The redshift determined here makes 1ES 1011+496 the most distant source yet detected to emit VHE γ-rays.

The spectral energy distribution of BL Lac objects normally shows a two bump structure. The lower frequency peak originates from synchrotron radiation. Various models have been proposed for the origin of the high

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[a] Universität Würzburg, D-97074 Würzburg, Germany
[b] IFAE, Edifici Cn., E-08193 Bellaterra (Barcelona), Spain
[c] ETH Zurich, CH-8093 Switzerland
[d] Universidad Complutense, E-28040 Madrid, Spain
[e] Universitat Autònoma de Barcelona, E-08193 Bellaterra, Spain
[f] Max-Planck-Institut für Physik, D-80805 München, Germany
[g] Università di Padova and INFN, I-35131 Padova, Italy
[h] Universität Dortmund, D-44227 Dortmund, Germany
[i] University of Łódź, PL-90236 Lodz, Poland
[j] Universitat de Barcelona, E-08028 Barcelona, Spain
[k] Yerevan Physics Institute, AM-375036 Yerevan, Armenia
[l] Tuorla Observatory, Univ. of Turku, FI-21500 Piikkiö, Finland
[m] Inst. de Astrofisica de Canarias, E-38200 Tenerife, Spain
[n] Università di Udine, and INFN Trieste, I-33100 Udine, Italy
[o] Università di Siena, and INFN Pisa, I-53100 Siena, Italy
[p] University of California, Davis, CA-95616-8677, USA
[q] Humboldt-Universität zu Berlin, D-12489 Berlin, Germany
[r] Inst. for Nucl. Research and Nucl. Energy, BG-1784 Sofia, Bulgaria
[s] INAF/Osserv. Astronomico and INFN, I-34131 Trieste, Italy
[t] Università di Pisa, and INFN Pisa, I-56126 Pisa, Italy
[u] ICREA & Institut de Ciencièes de l'Espai (IEEC-CSIC), E-08193 Bellaterra, Spain
[v] Depto. de Astrofsica, Universidad, E-38206 Tenerife, Spain
[y] Department of Physics and Space Sciences, Florida Insitute of Technology, Melbourne, USA
[z] INAF/Osservatorio Astronomico di Brera, Milano, Italy
[x] deceased
[*] Send offprint requests to: E. Lindfors elilin@utu.fi; D. Mazin mazin@ifae.es

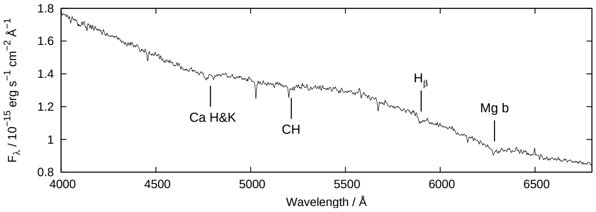

FIG. 1.— Optical spectrum of 1ES 1011+496 obtained with the Multi Mirror Telescope, using the Blue Channel Spectrograph with the 300 line/mm grating, a 1.5" slit, and Loral 3kx1k CCD. Integration time was 30 minutes. Absorption lines of the host galaxy (Ca H&K, CH G, H_β and Mg b) are clearly visible and indicate a redshift of $z = 0.212 \pm 0.002$.

frequency peak, the most popular invoke inverse Compton scattering off ambient soft photons. There have been several suggestions for the origin of the low frequency seed photons which are up-scattered into γ-rays: 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 (Mannheim et al. 1991).

When the synchrotron emission peak is located in the sub-millimeter to optical band, the objects are called low frequency peak BL Lacs. 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 M 87 (Aharonian et al. 2003, 2006a) and BL Lac (Albert et al. 2007b), all known extragalactic GeV/TeV γ-ray emitters belong to the HBL class.

2. OBSERVATIONS AND DATA ANALYSIS

The MAGIC telescope is located on the Canary Island La Palma (2200 m above sea level, 28°45′N, 17°54′W). MAGIC is currently the largest imaging atmospheric Cerenkov telescope, with a 17 m-diameter tessellated reflector dish. The 3.5° field of view camera comprises 576 photomultipliers with enhanced quantum efficiency. 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 12th (see light curve Fig. 2). The source has been monitored for more than four years in the optical with the KVA[27] and Tuorla 1m telescopes as a part of the Tuorla blazar monitoring program[28]. In March 2007 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 May 2007. The source was not detected at 37 GHz, which indicates that it was not in a high state in millimeter regime (A. Lähteenmäki, priv. comm.).

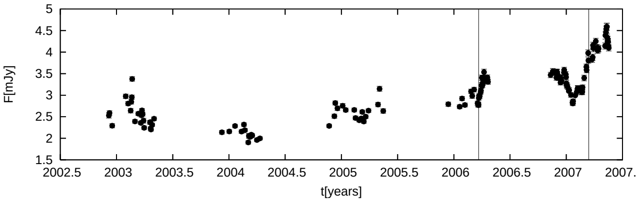

FIG. 2.— The optical R-band light curve of 1ES 1011+496 from Tuorla 1 meter and KVA 35cm telescopes. The vertical lines indicate the starting point of the MAGIC observations in 2006 and 2007.

After the alert, MAGIC observed 1ES 1011+496 in March–May 2007. The total observation time was 26.2 hours 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 hours.

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 $\theta^2 < 0.02$ deg^2 to determine the significance (Fig. 3) was optimized on nearly contemporaneous Crab data 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 those in Fig. 3 to have a higher number of γ-ray candidates. 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. Finally, the spectrum was unfolded to correct for the effects of limited energy resolution of the detector (Anykeyev et al. 1991). 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 Fig. 3. The signal of 297 events over 1591 normalized background events corresponds to an excess with significance of 6.2σ 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 in order to reduce systematic effects arising from a fast decreasing collection area

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[27] http://tur3.tur.iac.es

[28] http://users.utu.fi/∼kani/1m/

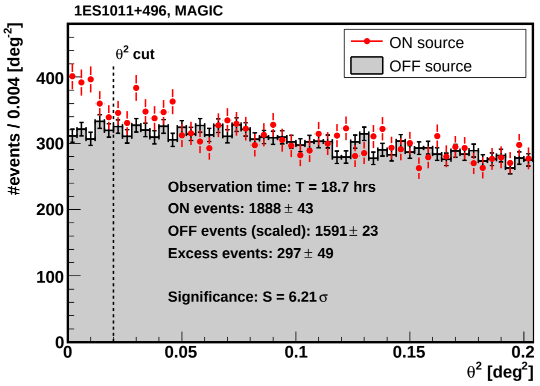

FIG. 3.— Distribution of θ^2 for ON-region data and normalized OFF-region data. The signal region is marked by the dashed line.

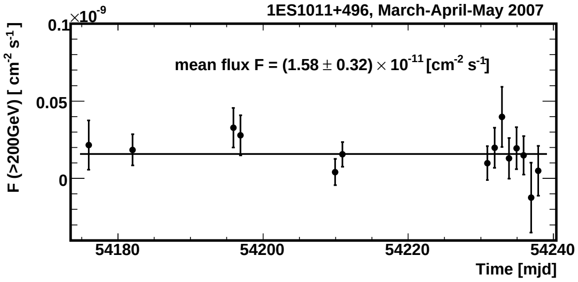

FIG. 4.— The night-by-night light curve of 1ES 1011+496 from 2007 March 17 (MJD 54176) to 2007 May 18 (MJD 54238).

for γ-rays for energies below. The flux is statistically constant at an emission level of F(>200 GeV)=$(1.58\pm0.32)\cdot 10^{-11}$ photons cm^{-2}s^{-1}.

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

$$\frac{\mathrm{d}N}{\mathrm{d}E} = (2.0 \pm 0.1)\cdot 10^{-10}\left(\frac{E}{0.2\,\mathrm{TeV}}\right)^{-4.0\pm0.5} \frac{1}{\mathrm{TeV\,cm^2\,s}}$$

The errors are statistical only. We estimate the systematic uncertainity 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 deabsorbed. 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). Even after the correction, the slope of the spectrum is $\Gamma_{\mathrm{int}} = 3.3 \pm 0.7$, (dashed brown line in Fig. 5, $\chi^2\,/\,\mathrm{NDF} = 2.55/2$) softer than observed for other HBLs.

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 up to date. The energy spectrum of 1ES 1011+496 is one of the softest measured VHE γ-ray spectrum so far. Even after the attenuation correction the spectrum remains soft with an intrinsic index of $\Gamma_{\mathrm{int}} = 3.3 \pm 0.7$. The behavior of the spectrum (soft and no significant excess above $\sim$ 800 GeV) confirms our current understanding of the evolving EBL (Kneiske et al. 2002; Primack et al. 2005; Stecker et al. 2006) and is not in conflict with the recently derived EBL limits (Aharonian et al. 2006b; Mazin & Raue 2007).

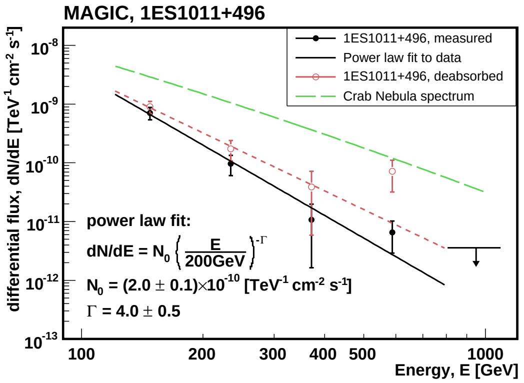

FIG. 5.— The measured spectrum (black filled circles), the power-law fit to the data (solid line), the deabsorbed spectrum (brown open circles), and the fit to the deabsorbed spectrum (dashed brown line). The last measured point is a 95% upper limit. In the deabsorbed spectrum, the last spectral point at ≈600 GeV is 1.6 σ above the fit and thus not significant. The Crab Nebula spectrum (green dashed line, Albert et al. (2007c)) is shown for comparison.

In Fig. 6 we show the spectral energy distribution (SED) of 1ES 1011+496 using historical data (open circles, from Costamante & Ghisellini (2002) and references therein) and our quasi-simultaneous optical R-band data (triangle) and the corrected MAGIC spectra (filled circles). We also report (marked with square) the EGRET flux of the source 3EG J1009+4855, possibly associated with 1ES 1011+496 (Hartman et al. (1999), but see also Sowards-Emmerd et al. (2003) whose analysis disfavor the association).

We model the SED by using a one-zone synchrotron-SSC model (see Tavecchio et al. (2001) for a description). In brief, the emission region is assumed to be spherical, with a radius R, filled with a tangled magnetic field of intensity B. The relativistic electrons follow a smoothed broken power-law energy distributions specified by the limits γ_{min} and γ_{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 time scale is available, it is possible to uniquely constrain the model parameters. Unfortunately we do not have all the required information and therefore the models reported here are not unique. In particular, we fix the synchrotron peak by requiring it will reproduce the optical flux and the historical X-ray spectrum and we assume the SSC peak to be not too far from the MAGIC threshold. With this choice we minimize the required emitted luminosity, since a lower SSC peak frequency would directly imply a larger SSC luminosity.

We present two models. The first one (solid line), assuming an electron distribution extending down to $\gamma_{\mathrm{min}} = 1$, clearly overpredicts the MeV-GeV flux measured by EGRET. In the second model (dashed line),

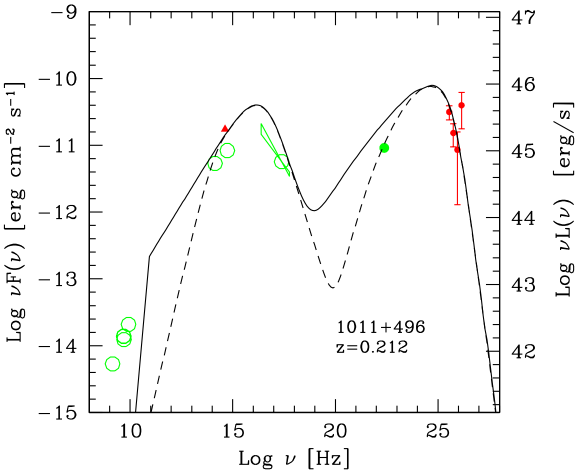

FIG. 6.— Spectral energy distribution of 1ES 1011+496. The two different fits are done by varying the minimum electron energy $\gamma_{\rm min}$ (see text). The other fit parameters are: R(radius of sphere)=10^{16} cm, δ(Doppler factor)=20, B(magnetic field) = 0.15 G, $\gamma_{\rm max}$(maximum electron Lorentz factor)= $2\cdot 10^7$ $\gamma_{\rm b}$(break electron Lorenz factor)= $5\cdot 10^4$ the slopes of the electron distribution $n_1 = 2$ and $n_2 = 5$ before and after the break energy, respectively, as well as $n_{\rm e}$(normalization of the electron energy distribution) = $2\cdot 10^4$ cm^{-3}. The model is not intended for describing the radio data, which is assumed to origin from a larger emitting volume to avoid an intrinsic absorption.

which fixes the low energy limit at $\gamma_{\rm min} = 3\cdot 10^3$ (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 could provide important constraints on the model parameters.

In both cases, the energy output of the SSC component (reaching $L \sim 10^{46}$ erg/s) 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 non-detection 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 required Doppler factor can be considerably reduced in models where the jet has a velocity structure (e.g. models by Georganopoulos & Kazanas (2003); Ghisellini et al. (2005)). However, the fitted parameters have values similar to those derived for other TeV BL Lacs.

1ES 1011+496 was previously observed with the HEGRA telescope array, resulting in an upper limit of F(E>1 TeV)≤ $1.8\cdot 10^{-12}$ photons cm^{-2}s^{-1} (Aharonian et al. 2004), that 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 March–April 2006. Being in a lower optical state (the core flux was $\sim$ 50% lower than that in March–May 2007), the observations showed a marginal signal with 3.5σ significance corresponding to an integral flux of F(>180 GeV)=$(1.26\pm 0.4)\cdot 10^{-11}$ photons cm^{-2}s^{-1}, i.e. $\sim$ 40% (Albert et al. 2007a) lower than the detected flux in March–May 2007. 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 study this follow-up observations of the detected objects as well as further observations of other AGN during high optical states are required.

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