Discovery of VHE gamma-rays from the distant BL Lacertae 1ES 0347-121


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LETTER TO THE EDITOR

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ABSTRACT

Aims. Our aim is to study the production mechanism for very-high-energy (VHE; >100 GeV) γ-rays in distant active galactic nuclei (AGN) and use the observed VHE spectrum to derive limits on the Extragalactic Background Light (EBL). We also want to determine physical quantities through the modeling of the object’s broad-band spectral energy distribution (SED).

Methods. VHE observations (~25 h live time) of the BL Lac 1ES 0347-121 (redshift z = 0.188) were conducted with the High Energy Stereoscopic System (HESS) between August and December 2006. contemporaneous X-ray and UV/ optical observations from the SWIFT satellite are used to interpret the SED of the source in terms of a synchrotron self Compton (SSC) model.

Results. An excess of 327 events, corresponding to a statistical significance of 10.1 standard deviations, is detected from 1ES 0347-121 VHE observations (~25 h live time) of the BL Lac 1ES 0347-121 (redshift z = 0.188) were conducted with the High Energy Stereoscopic System (HESS) between August and December 2006. Contemporaneous X-ray and UV/ optical observations from the SWIFT satellite are used to interpret the SED of the source in terms of a synchrotron self Compton (SSC) model. The photon index of the source redshift z = 0.188 is well described by a power law with a photon index of ~3.1 ± 0.3 TeV = 0.10 cm−2 s−1 (0.56 Crab) has been reported by the HEGRA collaboration (Aharonian et al. 2004), considerably higher than the above-mentioned prediction. The strong EBL limits confirm earlier findings, that the EBL density in the near-infrared is close to the lower limits from source counts. This implies that the universe is more transparent to VHE γ-rays than previously believed. An upper limit on the integral flux above an energy threshold of 1.46 TeV of 5 ± 0.14 × 10−12 cm−2 s−1 (0.14 ± 0.02% of the flux of the Crab Nebula above the same threshold. No VHE flux variability is detected within the data set.

Conclusions. Constraints on the EBL density at optical to near-infrared wavelengths derived from the photon spectrum of 1ES 0347-121 are close to the strongest limits derived previously. The strong EBL limits confirm earlier findings, that the EBL density in the near-infrared is close to the lower limits from source counts. This implies that the universe is more transparent to VHE γ-rays than previously believed. An SSC model provides a reasonable description of the contemporaneous SED.

Key words. galaxies: BL Lacertae objects: individual: 1ES0347-121 – gamma rays: observations – cosmology: diffuse radiation – galaxies: BL Lacertae objects: general – galaxies: active

1. Introduction

1ES 0347-121 was discovered in the Einstein Slew Survey (Elvis et al. 1992) and later classified as a BL Lac object (Schuchter et al. 1993). Located at a redshift of z = 0.188 (Woo et al. 2005) it harbors a super-massive black hole of mass log (M BH/M Sun) = 8.02 ± 0.11 (Woo et al. 2005). The host is classified as an elliptical galaxy with luminosity L r = 23.2

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2. HESS observation and results

The HESS array of four imaging atmospheric-Cherenkov telescopes (Hinton 2004) is used to search for VHE \(\gamma\)-ray emission from objects such as BL Lacs. The HESS observations of 1ES0347-121 were performed between August and December 2006. A total of 25.4 h live time of good-quality data was recorded at zenith angles ranging from 12° to 40°. The mean zenith angle is \(\sim 19^\circ\), for which the energy threshold of this analysis is \(\sim 250\) GeV. These data are analyzed with a standard Hillas-type analysis (Aharonian et al. 2006b). The data were recorded with a pointing offset of 0.5° relative to the nominal source position to allow a simultaneous estimation of the background using events from the same field of view (reflected background from Aharonian et al. 2006b).

An excess of 327 \(\gamma\)-ray candidates is measured (1167 signal events, 9241 background events, background normalization: 0.0909) corresponding to a statistical significance of 10.1 standard deviations (following Eq. (17) of Li & Ma 1983). Figure 1 shows that the extension of the excess is compatible with that expected from a point-source. The fit position of the excess \((\sigma_{12000} = 3^{\prime\prime}49\pm23.0^\prime\prime \pm 1.4^{\prime\prime}_{\text{stat}} \pm 1.3^{\prime\prime}_{\text{syst}}, \delta_{12000} = -11.58\pm38.9^\prime\prime \pm 33^{\prime\prime}_{\text{stat}} \pm 20^{\prime\prime}_{\text{syst}})\) coincides with the location of 1ES0347-121 \((\sigma_{12000} = 3^{\prime\prime}49\pm23.2^\prime\prime, \delta_{12000} = -11.59\pm27.0^\prime\prime;\) Schachter et al. 1993). The angular distance between the fit position of the VHE excess and the source position is \(47^\circ\). The differential photon spectrum of the source is shown in Fig. 2. A fit of a power-law function \(dN/dE = \Phi_0(E/1\,\text{TeV})^{-\Gamma}\) to these data results in a statistically good description \((\chi^2/\nu = 3.5/5)\) with normalization \(\Phi_0 = (4.52 \pm 0.85^{\text{stat}} \pm 0.70^{\text{syst}}) \times 10^{-11}\) cm\(^{-2}\) s\(^{-1}\) TeV\(^{-1}\) and photon index \(\Gamma = 3.10 \pm 0.23^{\text{stat}} \pm 0.10^{\text{syst}}\). The integral flux above 250 GeV taken from the spectral fit is \(\Phi(E > 250\,\text{GeV}) = (3.9 \pm 1.1^{\text{stat}} \pm 0.5^{\text{syst}}) \times 10^{-12}\) cm\(^{-2}\) s\(^{-1}\), which corresponds to \(\sim 2\%\) of the flux of the Crab Nebula above the same threshold (Aharonian et al. 2006b). As can be seen from Fig. 3, no significant variability is detected on time-scales of days or months.

3. SWIFT and ATOM observations and results

SWIFT (Gehrels et al. 2004) observations of 1ES0347-121 were performed on October 3, 2006. A total of 3.2 ks of screened data in photon-counting mode are analyzed. For the analysis of SWIFT XRT and UVOT data the HEASOFT 6.2 package with Xspec11 and the latest calibration (XRT: 2007-03-30, UVOT: 2006-11-16) was used. The XRT data has been reprocessed with SWIFT (Gehrels et al. 2004) observations of 1ES 0347-121 were performed between August and December 2006. A total of 25.4 h live time of good-quality data was recorded at zenith angles ranging from 12° to 40°. The mean zenith angle is \(\sim 19^\circ\), for which the energy threshold of this analysis is \(\sim 250\) GeV. These data are analyzed with a standard Hillas-type analysis (Aharonian et al. 2006b). The data were recorded with a pointing offset of 0.5° relative to the nominal source position to allow a simultaneous estimation of the background using events from the same field of view (reflected background from Aharonian et al. 2006b).

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with an inner radius of 5 pixels and an outer radius of 30 pixels (1 pixel = 2.36″). The background spectrum was accumulated in a wider annulus (inner radius of 45 pixels, outer radius of 90 pixels). The auxiliary response file was created with the standard tool xrtmkarf including the point-spread-function correction. A power-law model fit to the data (response matrix swxpct01012_200010101v008.rmf; photoelectric absorption fixed to the Galactic value of $n_H = 3.6 \times 10^{20} \text{cm}^{-2}$) between 0.3 and 8 keV yields a good $\chi^2$/d.o.f. = 105.3/105 = 1.00 with $\Gamma = 1.99 \pm 0.06$ (error at 90% c.l.). The unabsorbed integrated energy flux between 2 and 10 keV from the model is $f_{2-10\text{keV}} = (2.800 \pm 0.003) \times 10^{-11} \text{erg cm}^{-2} \text{s}^{-1}$.

The UltraViolet/Optical Telescope (UVOT) observations were made using 6 filter settings. Since none of the light curves from the different measurements indicate variability, the data sets for the individual filter wheel settings were added together. The aperture was chosen to be of 12 pixels radius for the optical filters while it is increased to 24 pixels for the UV filters (1 pixel = 0.48″). For the UV filter images, a 6-pixel radius region centered on a faint stellar source 12 north of 1ES 0347-121 falling into the wider-24 pixel aperture was excluded. The aperture photometry includes a pile-up correction and the flux has been calculated from the count rates by using the zero point values quoted in the calibration notes of the SWIFT UVOT team. Finally, the observed flux was corrected for galactic absorption using a reddening of $E(B-V) = 0.047$ which was then scaled to obtain $A_I$ for the SWIFT filters following the recipe given by Giovannetti et al. (2006).

The Automatic Telescope for Optical Monitoring (ATOM; Hauser et al. 2004) on the HESS site monitored 1ES 0347-121 during the HESS observing period in November 2006. The mean $B$-band flux measured is $3.8 \times 10^{-13} \text{erg cm}^{-2} \text{s}^{-1}$ and the mean $R$-band flux is $3.7 \times 10^{-12} \text{erg cm}^{-2} \text{s}^{-1}$ (aperture radius: 4″). Both fluxes are constant, as all measurements are within 10% and 4%, respectively, of the mean values.

The resulting SWIFT X-ray and ultraviolet-to-optical (UV/O) and ATOM data are shown in Fig. 4. The X-ray and UV/optical fluxes observed are the highest measured from this source today, indicating a period of enhanced activity during the HESS measurements.

To correct for the contribution from the host galaxy in the UV/optical-bands the method presented in Aharonian et al. (2007) is followed. The host galaxy flux in the $R$-band of $m_r = 17.26$ and the half-light radius $r_e = 1.25''$ are taken from Urry et al. (2000). Using a de Vaucouleurs profile, the flux from the host galaxy falling in the signal aperture is estimated to be $\sim 80\%$ for ATOM and $\sim 90\%$ for UVOT. The host galaxy flux in the $V$, $B$ and $U$-band are estimated using the elliptical galaxy spectral template at $z = 0.2$ from Fukugita et al. (1995). For the UVOT data host galaxy contributions of $\sim 35\%$ (V-band), $\sim 11\%$ (B-band) and $\sim 4\%$ (U-band) are derived. For the ATOM data the host galaxy contributions are $\sim 34\%$ (R-band) and $\sim 8\%$ (B-band). The UV/optical measurements corrected for the contribution from the host galaxy are shown as open black markers in Fig. 4.

4. Discussion

The diffuse extragalactic photon field in the ultraviolet to far-infrared wavelength region (EBL) consists of the photons emitted by stars and absorbed and re-emitted by dust redshifted and integrated over time (see, e.g., Hauser & Dwek 2001 and Kashlinsky 2005 for recent reviews). Its spectrum carries cosmological information about galaxy and star formation history.

Distant sources of VHE $\gamma$-rays can probe the EBL density (Stecker et al. 1992). VHE photons passing through the EBL are attenuated via pair production: $\gamma_{\text{VHE}} + \gamma_{\text{EBL}} \rightarrow e^+ e^- \gamma$ (Gould & Schréder 1967). Since this process is energy dependent, the VHE $\gamma$-ray spectra measured on Earth carry an attenuation imprint from the EBL. With reasonable assumptions about the emission physics of the source, limits on the EBL density can be derived.

Using the relatively hard energy spectra measured from the recently discovered VHE BL Lac 1ES 1101-232 ($z = 0.186$) and H 2356-309 ($z = 0.165$), strong constraints on the EBL density in the optical to near-infrared ($\sim 0.8-4\mu m$) were derived (Aha06). Following the exact same methodology as described in Aha06 (scaling of a reference EBL shape until the intrinsic spectrum reaches a maximum hardness) a limit on the EBL density is derived from the observed VHE spectrum of 1ES 0347-121. For
a scaling factor of 0.51 (i.e. a P0.51 shape), the fit of a power-law function to the intrinsic spectrum results in a photon index of \( \Gamma = 1.5 \), the minimum allowed value. Taking into account evolution of the EBL, again using the same arguments as Aha06, a limiting shape of P0.61 is derived. The limit is shown in Fig. 5 in comparison to the limit derived by Aha06 for 1ES 1101-232 (P0.55). The limit derived here is only slightly less constraining, which is a result of the softer observed spectrum and the smaller energy range towards low energies. The claimed excess of the EBL in the near-infrared above the value derived from source counts (Matsumoto et al. 2005), often attributed to a possible contribution of the first stars to the EBL, is again excluded.

Given the large distance of the source, the measured VHE spectrum is severely altered by the EBL attenuation. Therefore, the VHE spectrum has to be corrected for this attenuation prior to any modeling of the intrinsic SED. Since the exact shape of the EBL is not known, the intrinsic spectrum is calculated for two different EBL models: the model from Primack et al. (2005) (PRIM), which has a low EBL density, and the upper limit shape P0.45 from Aha06 (AH). The intrinsic VHE spectra (inlay in Fig. 4) are each well fit by power-law functions, which are shown in Fig. 4 above the measured VHE photon spectrum. The photon indices of the power-law functions are \( \Gamma = 2.10 \pm 0.21 \) for the PRIM and \( \Gamma = 1.69 \pm 0.22 \) for the AH shape.

A simple homogeneous one-zone synchrotron self Compton (SSC) model from Krawczynski et al. (2004) is used to describe the SED from the contemporaneous UVOT, X-ray and VHE data. For the modeling, the data are not strongly constraining. Parameter sets describing the overall spectral shape with a standard shock-accelerated particle distribution can be found with a good statistical compatibility between the host-galaxy-subtracted UVOT data, the X-ray data, both intrinsic VHE spectra and the model. In Fig. 4 an SSC model, fit to the host-galaxy-subtracted UVOT, X-ray, and the intrinsic VHE data resulting from the AH EBL shape, is shown (\( \chi^2_{\text{red}} \approx 1.2; P(\chi^2) \sim 0.25 \)). The archival radio measurements are assumed to be produced by a different particle population and are not included in the fit. The model parameters, although not strongly constrained, are similar to the parameters used previously to model other BL Lacs (e.g. Aharonian et al. 2007).
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