**Fermi** LARGE AREA TELESCOPE DETECTION OF TWO VERY-HIGH-ENERGY \((E > 100 \text{ GeV})\) \(\gamma\)-RAY PHOTONS FROM THE \(z = 1.1\) BLAZAR PKS 0426–380

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Received 2013 August 2; accepted 2013 September 26; published 2013 October 18

**ABSTRACT**

We report the *Fermi* Large Area Telescope (LAT) detection of two very-high-energy (VHE, \(E > 100 \text{ GeV}\)) \(\gamma\)-ray photons from the directional vicinity of the distant (redshift, \(z = 1.1\)) blazar PKS 0426–380. The null hypothesis that both the 134 and 122 GeV photons originate from unrelated sources can be rejected at the 5.5\(\sigma\) confidence level. We therefore claim that at least one of the two VHE photons is securely associated with PKS 0426–380, making it the most distant VHE emitter known to date. The results are in agreement with recent *Fermi*-LAT constraints on the extragalactic background light (EBL) intensity, which imply a \(z \sim 1\) horizon for \(\lesssim 100 \text{ GeV}\) photons. The LAT detection of the two VHE \(\gamma\)-rays coincided roughly with flaring states of the source, although we did not find an exact correspondence between the VHE photon arrival times and the flux maxima at lower \(\gamma\)-ray energies. Modeling the \(\gamma\)-ray continuum of PKS 0426–380 with daily bins revealed a significant spectral hardening around the time of the first VHE event detection (LAT photon index \(\Gamma \approx 1.4\)) but on the other hand no pronounced spectral changes near the detection time of the second one. This combination implies a rather complex variability pattern of the source in \(\gamma\)-rays during the flaring epochs. An additional flat component is possibly present above several tens of GeV in the EBL-corrected *Fermi*-LAT spectrum accumulated over the \(\sim 8\) month high state.

**Key words:** acceleration of particles – galaxies: active – galaxies: jets – gamma rays: galaxies – quasars: individual (PKS 0426–380) – radiation mechanisms: non-thermal

**Online-only material:** color figures

1. INTRODUCTION

Blazars are radio-loud active galactic nuclei with relativistic jets viewed at small angles to the Earth’s line of sight. Their broad-band spectral energy distributions (SEDs) are typically dominated by two non-thermal emission components widely believed to be due to synchrotron and inverse-Compton emission from a single population of ultra-relativistic electrons accelerated within the innermost parts of the jets (e.g., Urry & Padovani 1995). The exact particle acceleration processes at work, as well as the location and structure of the dominant energy dissipation zone in blazar sources (hereafter “the blazar zone”), are still under debate. Blazars are typically sub-divided into flat-spectrum radio quasars (FSRQs) and BL Lacertae objects (BL Lacs) based on the equivalent widths of the emission lines in their optical spectra (e.g., Urry & Padovani 1995). BL Lacs are characterized by much weaker emission lines than FSRQs, or even featureless optical continua, that can be understood in terms of distinct accretion rates in an otherwise homogeneous population of sources (e.g., Ghisellini et al. 2011).

Since the launch of the *Fermi* satellite in 2008, high-redshift blazars have been established as very-high-energy (VHE; \(> 100 \text{ GeV}\)) emitters (Neronov et al. 2011, 2012), with the highest-redshift case reported being a 126 GeV photon from B2 0912+29, a \(z = 1.521\) BL Lac, though the redshift is still uncertain (see Neronov et al. 2012). Although collectively detected, individually these associations are based on single photons and the chance coincidence probabilities for the VHE events to be detected around the sources are not low enough to claim discovery of a single source. Detection of sub-TeV VHE photons from \(z \sim 1\) blazars is in principle reconcilable with most of the recently refined extragalactic background light (EBL) models ( Franceschini et al. 2008; Domínguez et al. 2011; Stecker et al. 2012; Inoue et al. 2013).

Here, we report the discovery of VHE \(\gamma\)-ray emission from the blazar PKS 0426–380, classified early on as a BL Lac (e.g., Sbarufatti et al. 2005), and only recently recognized as a FSRQ based on a new classification scheme advocated by Ghisellini et al. (2011) and Sbarrato et al. (2012). These authors proposed that the dividing line between the two types of blazars corresponds to the critical broad-line region (BLR) luminosity in the Eddington units, \(L_{\text{BLR}}/L_{\text{Edd}} \approx 5 \times 10^{-4}\). In the case of PKS 0426–380, the precise characterization of the optical spectrum by Very Large Telescope (VLT) observations revealed a broad [Mg ii] line with an equivalent width of 5.7 Å and a relatively high luminosity of \(7.2 \times 10^{42} \text{ erg s}^{-1}\) (Sbarufatti et al. 2005). This leads to \(L_{\text{BLR}}/L_{\text{Edd}} \approx 10^{-5}\) for a black hole.
mass $M_{\text{BH}} \approx 10^9 M_\odot$ (see Section 4), and therefore the FSRQ classification according to the proposed scheme (Ghisellini et al. 2011).

The VLT detection of the broad [Mg ii] $\lambda 2798$ emission line mentioned above by Sbarufatti et al. (2005), together with C[iv] and [O ii] $\lambda 3727$, enabled the determination of a redshift, $z = 1.105$, for the source ($d_L \approx 7.52$ Gpc, assuming standard cosmology with $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.27$, and $\Omega_{\Lambda} = 0.73$). Independently, Heidt et al. (2004) also derived $z = 1.111$ based on the single [Mg ii] $\lambda 2798$ emission line; the non-detection of a host galaxy in the Hubble Space Telescope image (Urry et al. 2000) is consistent with the high redshift. Given all these findings, we conclude that the redshift determination for PKS 0426$-$380 is robust.

The Fermi Large Area Telescope (LAT) detection of a VHE event from near the direction of PKS 0426$-$380 in 2010 January was previously reported (Ackermann et al. 2011; Neronov et al. 2012). However, the probability that the VHE event originated from other sources (including background/foreground diffuse emissions) was relatively large, and the significance did not reach $5\sigma$. In this Letter, we report the Fermi-LAT detection of a second VHE event from the directional vicinity of PKS 0426$-$380 in 2013 January, and claim convincingly that it is now the most distant VHE emitter currently detected.

2. DATA REDUCTION

The Fermi-LAT Pass7 event and spacecraft data (ft1 and ft2 files, respectively) were downloaded from the LAT Data Server\textsuperscript{13} at the Fermi Science Support Center Web page. We took the ft1 photon event data file spanning Mission Elapsed Time (MET, measured in seconds from 2001 January 1) 239557417 (2008 August 4 15:43:36 UT) to 389039485 (2013 April 30 18:31:23 UT) and chose a $10^\circ$ radius for the region of interest (ROI) centered at the radio position of PKS 0426$-$380. The event selection and data analysis were performed in a standard manner using version v9r27p1 of the Fermi Science Tools. Only the CLEAN class events from 100 MeV to 300 GeV were selected. The maximum zenith angle was set to $100^\circ$ to avoid contamination from Earth limb $\gamma$-rays. The good time interval was generated by applying a recommended filter expression of $(\text{DATA\_QUAL}==1) && (\text{LAT\_CONFIG}==1) && \text{ABS(ROCK\_ANGLE)}<52$ and ROI-based zenith angle cut (roiCut=yen). We used the P7CLEAN V6 instrument response functions (IRFs).

We first performed unbinned maximum likelihood (gtlike) analysis for the 4.7 yr LAT data by using an XML source model\textsuperscript{14} in which the spectral parameters of all the sources included in the second Fermi-LAT catalog (2FGL; Nolan et al. 2012) within $10^\circ$ radius were set free, while those within an annulus from $10^\circ$ to $15^\circ$ were fixed to their 2FGL values. For PKS 0426$-$380 we assumed a log-parabola spectral shape, as measured in the 2FGL catalog. The template files gaL_2yearp7v6_v0.fits and iso_p7v6clean.txt were used to represent the Galactic and isotropic diffuse emission components, respectively.\textsuperscript{15} To allow for potential small errors in the flux and spectrum of the Galactic diffuse emission model we multiplied it by a power law in energy whose normalization and index were free during the fit. Using the output XML file obtained after running gtlike, we ran the gtsrcprob tool to calculate a probability that each detected VHE event originates from the direction of PKS 0426$-$380. For the same output XML file, we freed only the normalizations of the surrounding 2FGL sources and the Galactic and extragalactic diffuse emission components and modeled PKS 0426$-$380 with a single power law with both the normalization and the photon index allowed to vary. Then, we ran gtlike and generated a weekly (7 day binned) light curve for PKS 0426$-$380. Finally, when calculating daily fluxes and power-law indices for PKS 0426$-$380, only the source normalization and power-law slope were left free, along with the normalizations of the two diffuse emission components, while all the other parameters were fixed to the values obtained with gtlike for the entire 4.7 yr data set to avoid unreasonably large errors.

To construct the $\gamma$-ray spectrum of the source, we first selected energy intervals chosen as 11 octaves ranging from 0.1 to 204.8 GeV (namely, 0.1$-$0.2, 0.2$-$0.4, ... , 102.4$-$204.8 GeV). In the XML source model, the normalizations of the surrounding sources within $10^\circ$ of and of the Galactic and extragalactic diffuse emission components were set free, while all the other spectral parameters were fixed to the values derived for the LAT data accumulated for the selected period. PKS 0426$-$380 was modeled using a broken power-law model with the photon indices and break energy fixed to the values that we derived for the entire data set, but with the normalization set free. Using this XML file, we ran gtlike for each energy bin and generated the spectrum of the source.

3. RESULTS

In Figure 1 we present the LAT count map of ULTRACLEAN events (a subset of the CLEAN class with the highest probability of being $\gamma$-rays) with 5$-$300 GeV energies around PKS 0426$-$380. One can clearly see that the two VHE photons, with energies 134 GeV and 122 GeV, coincide with the position of the blazar (angular separations from the blazar of $<0\circ021$) and are well inside the point-spread function (PSF) of Fermi-LAT. A detailed summary of the VHE events, including their precise localizations and arrival times, is given in Table 1. Based on the gtsrcprob results (see Table 1), we calculated the null hypothesis probability that both events originate from foreground/background (Galactic/extragalactic) diffuse emission components, or other surrounding 2FGL sources rather than PKS 0426$-$380, using Fisher's method and obtained $1.47 \times 10^{-8}$. We can therefore reject the null hypothesis at the $5.5\sigma$ confidence level (CL), and claim robustly that at least one of the two detected VHE $\gamma$ rays originates from PKS 0426$-$380, making it the most distant VHE emitter known to date.

Although the two VHE events are classified as ULTRACLEAN ones, we further visually inspected the tracks in the LAT tracker subsystem after the point of pair conversion. The first event converted at the top layer of a tower and the long straight paths of the converted electron–positron pairs were nicely tracked. The second event converted at the third layer of the tracker and similarly showed no unusual signatures. The showers in the calorimeters for both events were also well-behaved. In conclusion, we did not find any problematic features in the case of the analyzed VHE detections.

Figure 2 presents the weekly (7 day binned) Fermi-LAT light curve of PKS 0426$-$380 within the energy range 0.1$-$300 GeV, along with the arrival times of $\gamma$-rays with energies above 50 GeV. It is clear that the two VHE events were detected during high states of the source. Interestingly however, the VHE
Figure 1. Fermi-LAT count map of 5–300 GeV ULTRACLEAN events (scale = 0.05 pixel$^{-1}$) centered on the radio position of PKS 0426–380 (red diamond). The magenta and yellow crosses indicate the positions of the two VHE and five 50–100 GeV events, respectively. The dashed circle indicates the 68% containment radius (0.12) of Fermi-LAT PSF for front-converting events above 100 GeV (Ackermann et al. 2012a). (A color version of this figure is available in the online journal.)

Table 1

| Energy (GeV) | MET (UT) | R.A. (J2000) (deg) | Decl. (J2000) (deg) | Angular Separation (deg) | gtsrcprob Probability |
|--------------|----------|--------------------|---------------------|--------------------------|------------------------|
| 134          | 285043901.724 | 67.182             | -37.930             | 0.013                    | 0.9999763              |
|              | (2010 Jan 13 02:51:39.724) |                    |                     |                          |                        |
| 122          | 380539944.325  | 67.194             | -37.943             | 0.021                    | 0.9999720               |
|              | (2013 Jan 22 09:32:21.325) |                    |                     |                          |                        |

Notes. Both of the events are ULTRACLEAN class and FRONT converting.

a The energy resolution is of the order of 10% (Ackermann et al. 2012a).
b Angular separation is calculated from the radio position of PKS 0426–380, R.A. = 67.1684342$^\circ$ and decl. = -37.987719$^\circ$ (J2000; Johnston et al. 1995).
c The probability that the event belongs to PKS 0426–380, which is calculated by using gtsrcprob.

detections did not coincide with the flux maxima of the flaring epochs. Complex structures of the source light curve, with multiple peaks within each flaring state, preclude us however from speculating if the VHE photons preceded or followed the flux maxima at lower photon energies. To further investigate the temporal and spectral variations within ±10 days of the two VHE events, in Figure 3 we show the daily changes of the flux and power-law index for the source. In neither case did the 0.1–300 GeV flux dramatically increase on the day of the VHE detection. On the other hand, a significant spectral hardening can be noticed on the day of the first VHE detection, but not on the day of the second one.

Figure 4 shows the $\gamma$-ray spectrum of PKS 0426–380 during the most energetic flare, derived from the accumulated Fermi-LAT data between MET 280000000 and 302000000 (see Figure 2). No high-energy cutoff expected from the EBL-related attenuation of the $\gamma$-ray continuum seems to be present up to several tens of GeV, although the highest energy (102.4–204.8 GeV) datapoint is a 95% CL upper limit due to the limited photon statistics (corresponding to a single net photon). We found that a broken power-law model of $\Gamma_{\text{low}} = 1.91 \pm 0.04$, $\Gamma_{\text{high}} = 2.72 \pm 0.17$, and $E_{\text{break}} = 8.0 \pm 0.9$ GeV maximized the likelihood, and this is also drawn in Figure 4. We emphasize that the presented spectrum was derived from the Fermi-LAT data accumulated over ~8 months. Hence, keeping in mind the large-amplitude variability of the source in $\gamma$-rays, one has to be very careful in interpreting spectral features apparent in the figure, like for example the discontinuity around 10 GeV (see Abdo et al. 2010, for other examples). Based on the observed SED, we generated the EBL-corrected spectra of the source (Figure 4) using two different EBL models (Franceschini et al. 2008; Inoue et al. 2013). The de-absorbed spectra seem to reveal an additional high-energy flat-spectrum component above several tens of GeV (see also Şentürk et al. 2013). However, the significance of this feature is marginal and, more importantly, model dependent. Nonetheless, the results obtained do suggest that PKS 0426–380 is a very promising target for future follow-up studies with Imaging Atmospheric Cherenkov Telescopes.
Figure 2. Top panel: arrival times (MJD) and energies of the seven most energetic $E > 50$ GeV ULTRACLEAN events detected from the vicinity of the direction of PKS 0426$-$380 (see Figure 1). Bottom panel: Fermi-LAT weekly binned light curve of PKS 0426$-$380 (0.1–300 GeV energy range). Black triangles denote the 95% CL flux upper limits (when test statistic $< 10$). The two vertical dashed lines denote the VHE detection times (MJD 55209.11920977 and 56314.39746904; see Table 1). Also shown by a black horizontal line is the accumulation period for which the Fermi-LAT spectrum was constructed (see Figure 4). (A color version of this figure is available in the online journal.)

Figure 3. Fermi-LAT daily binned light curve and power-law indices (0.1–300 GeV energy range) derived for PKS 0426$-$380 around the times ($\pm 10$ days) of the VHE detections as denoted in the figure by blue vertical dashed lines (MJD 55209,11920977 and 56314.39746904). Triangles without vertical error bars denote the 95% CL flux upper limits when test statistic $< 10$. Note the 4.7 yr average 0.1–300 GeV photon flux was $1.8 \pm 0.1 \times 10^{-7}$ photons cm$^{-2}$ s$^{-1}$. (A color version of this figure is available in the online journal.)

(IACTs) such as H.E.S.S. II and Cherenkov Telescope Array (CTA) (Actis et al. 2011).

4. DISCUSSION

Three blazars classified as FSRQs have previously been detected in the VHE range by IACTs, 3C 279 ($z = 0.536$; Albert et al. 2008), PKS 1510$-$089 ($z = 0.361$; Abramowski et al. 2013), and 4C +21.35 ($z = 0.432$; Aleksic et al. 2011). VHE emissions from more distant objects such as KUV 00311$-$1938 at $z = 0.61$ (Becherini et al. 2012, though the redshift is still tentative) and PKS 1424+240 at $z \geq 0.6035$ (Furniss et al. 2013) have been recently detected. The observational results presented in this Letter therefore establish PKS 0426$-$380, which is located at $z = 1.1$, as the most distant VHE emitter observed to date. We note that the redshift of PKS 0426$-$380 is just around the horizon for $\approx 100$ GeV $\gamma$-rays (namely, EBL-related optical depth of the Universe $\tau_{100\text{GeV}} \sim 1$) as recently determined by Fermi-LAT (Ackermann et al. 2012b,
As mentioned previously, the observed luminosity of the broad [Mg II] line in the optical spectrum of PKS 0426–380 is \( L_{\text{Mg II}} \approx 7.2 \times 10^{42} \) erg s\(^{-1}\) (Sbarufatti et al. 2005), implying a BLR luminosity \( L_{\text{BLR}} \approx 1.2 \times 10^{44} \) erg s\(^{-1}\) using the scaling relation \( L_{\text{BLR}} \approx 1.6 \times 10^{44} \) erg s\(^{-1}\) (Wang et al. 2004). Spectral modeling of the accretion-related continuum in the source (Ghisellini et al. 2011; Sbarufatti et al. 2012) yields \( M_{\text{BH}} \approx 4 \times 10^{5} \) \( M_{\odot}\). Based on the [Mg II] line FWHM of 4700 km s\(^{-1}\), and the observed V-band magnitude of 18.6 (assuming negligible starlight contamination), we derived a slightly larger value of \( M_{\text{BH}} \approx (0.9-1.3) \times 10^{5} \) \( M_{\odot}\), using the scaling relations from Wang et al. (2009) and Vestergaard & Osmer (2009). This corresponds to the Eddington luminosity \( L_{\text{Edd}} \approx 10^{44} \) erg s\(^{-1}\), the ratio \( L_{\text{BLR}}/L_{\text{Edd}} \approx 10^{-2}\), and the accretion rate at the level of \( \dot{M}_{\text{acc}} = L_{\text{disk}}/L_{\text{Edd}} \approx 30\%\) (assuming the standard bolometric correction factor \( L_{\text{disk}} \approx 10 \times L_{\text{B}} \) for the B-band source luminosity \( L_{\text{B}} \approx 4.5 \times 10^{44} \) erg s\(^{-1}\)). The derived high accretion rate is consistent with PKS 0426–380 being a FSRQ.

The intense \( \gamma\)-ray emission of FSRQs is widely thought to arise due to inverse-Compton up-scattering of low-energy photons generated outside of a jet by ultra-relativistic electrons accelerated within the innermost parts of the relativistic outflows (Sikora et al. 2009; Ghisellini & Tavecchio 2009). If this blazar emission zone is located at sub-parsec distances from the central black hole, as is often anticipated in the literature, then the abundant circum-nuclear photon fields provided by the BLR and/or hot dust are expected to attenuate the VHE blazar emission substantially due to the photon–photon pair production, leading to the formation of breaks and cutoffs in the \( \gamma\)-ray spectrum of FSRQs (see in this context the discussion in Poutanen & Stern 2010; Tanaka et al. 2011). The observed sharp break (\( \Gamma_{\text{high}} - \Gamma_{\text{low}} \approx 0.8\)) at \( \approx 8 \) GeV would be understood by a scenario with the blazar emission zone deep within the BLR. However, we note again that the \( \gamma\)-ray spectrum when corrected for the cosmological absorption showed a flattened shape at energies above 10 GeV. This flat component, if connected to the sub-TeV range, should come from another emission region outside the BLR to avoid \( \gamma\gamma\) attenuation.

Care must be taken not to over-interpret such high-energy features (flattening) in unfolded blazar spectra constructed using Fermi-LAT data accumulated over longer periods of time, since those may simply arise due to averaging over different activity states characterized by different spectral properties (see the related discussion and analysis in Abdollahpour et al. 2011, concerning the well-known BL Lac object Mrk 501). Still, the results presented here for PKS 0426–380 are in principle consistent with the emergence of an additional VHE flat-spectrum component during the flaring states of the source. One possibility for the production of such a component could be electron pile-up at the highest energies due to the efficient and continuous acceleration processes limited only by the radiative losses (Stawarz & Petrošian 2008; Lefa et al. 2011). Another possibility could be an additional hadronic emission component dominating occasionally the source spectrum in the VHE range (e.g., Böttcher et al. 2009; Dermer et al. 2012). In particular, assuming that PKS 0426–380 generates cosmic rays with energies above 10 EeV, or \( \gamma\) rays above 30 TeV, the induced intergalactic cascade emission may provide a non-negligible contribution within the VHE range of the source spectrum (Essey & Kusenko 2010; Murase et al. 2012; Takami et al. 2013). The time scale of the expected delay between the production of the primary ultra-high energy cosmic rays/\( \gamma\)-ray photons and the observed re-processed VHE signal is \( \sim (3/100 \text{ GeV})^{-1} (B/10^{-18} \text{ G}) (\lambda_{\gamma\gamma}/100 \text{ Mpc}) \) days and \( \sim (3/100 \text{ GeV})^{-2} (B/10^{-18} \text{ G}) (\lambda_{\gamma\gamma}/1 \text{ Gpc}) \) days for the photon and the cosmic-ray induced cascade emission at \( z = 1\), respectively, where \( B \) is the intergalactic magnetic field strength, \( \lambda_{\gamma\gamma} \) is the mean free path of the pair creation, and \( \lambda_{\gamma\gamma} \) is the mean free path of the Bethe–Heitler process (Murase 2012).

Rather speculative, if there are axion-like particles, photon and axion mixing in the intergalactic medium may in addition enhance the EBL-absorbed photon flux (e.g., Sánchez-Conde et al. 2009). Lorentz invariance violation, on the other hand, could inhibit pair production (e.g., Protheroe & Meyer 2000).

In summary, with Fermi-LAT we have detected two VHE \( \gamma\) rays from close to the direction of a high-redshift FSRQ, PKS 0426–380 at \( z = 1\). Both of the events were detected during high \( \gamma\)-ray states of the source, although the specific VHE arrival times did not coincide with any particularly large 0.1–300 GeV source flux. Only in the first case was the observed LAT spectrum harder than usual. The very complex \( \gamma\)-ray variability patterns revealed by the Fermi-LAT data for PKS 0426–380 calls for sensitive follow-up studies with simultaneous VHE coverage provided by IACTs such as H.E.S.S II or futurecta.

We appreciate the referee’s critical reading and valuable comments. Y.T.S. is supported by Kakenhi 24840031. Work by C.C.C. at NRL is supported in part by NASA DPR S-15633-Y. Ł. S. was supported by Polish NCS grant DEC-2012/04/A/ST9/00083.

The Fermi-LAT Collaboration acknowledges support from a number of agencies and institutes for both development and the operation of the LAT as well as scientific data analysis. These include NASA and DOE in the United States, CEA/IRFU and IN2P3/CNRS in France, ASI and INFN in Italy, MEXT, KEK, and JAXA in Japan, and the K.A. Wallenberg Foundation, the Swedish Research Council and the National Space Board in Sweden. Additional support from INAF in Italy and CNES in France for science analysis during the operations phase is also gratefully acknowledged.

Facility: Fermi (LAT)

REFERENCES

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010, ApJL, 710, 1271
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2011, ApJL, 727, 129
Abramowski, A., Acero, F., Aharonian, F., et al. 2013, A&A, 554, A107
Ackermann, M., Ajello, M., Albert, E., et al. 2012a, ApJL, 753, L4
Ackermann, M., Ajello, M., Allafort, A., et al. 2011, ApJL, 743, L171
Ackermann, M., Ajello, M., Allafort, A., et al. 2012b, Sci, 338, 1190
Acìtis, M., Agnetta, G., Aharonian, F., et al. 2011, ExA, 32, 193
Albert, J., Aliu, E., Anderhub, H., et al. 2008, Sci, 320, 1752
Aleksić, J., Antolini, L. A., Antoranz, P., et al. 2011, ApJL, 730, L8
Becherini, Y., Boisson, C., Cerruti, M., & H. E. S. Collaboration, 2012, in AIP Conf. Proc., 1505, High Energy Gamma-Ray Astronomy, ed. F. A. Aharonian, W. Hofmann, & F. M. Rieger (Melville, NY: AIP), 490
Böttcher, M., Reimer, A., & Marscher, A. P. 2009, ApJ, 703, 1168
Dermer, C. D., Muraue, K., & Takami, H. 2012, ApJL, 755, 147
Dominguez, A., Primack, J. R., Rosario, D. J., et al. 2011, MNRS, 410, 2556
Essey, W., & Kusenko, A. 2010, ApJs, 33, 81
Franciosini, A., Rodighiero, G., & Vaccari, M. 2008, A&A, 487, 837
Furniss, A., Williams, D. A., Danforth, C., et al. 2013, ApJL, 768, L31
Ghisellini, G., & Tavecchio, F. 2009, MNRS, 397, 985
Ghisellini, G., Tavecchio, F., Foschini, L., & Ghirlanda, G. 2011, MNRS, 414, 2674
Heidt, J., Töller, M., Nilsson, K., et al. 2004, A&A, 418, 813
Insue, Y., Inoue, S., Kobayashi, M. A. R., et al. 2013, ApJL, 768, 197
Johnston, K. J., Fey, A. L., Zacharias, N., et al. 1995, AJ, 110, 880
Lefa, E., Rieger, F. M., & Aharonian, F. 2011, ApJL, 740, 64
Murase, K. 2012, ApJL, 745, L16
Murase, K., Dermer, C. D., Takami, H., & Migliori, G. 2012, ApJ, 749, 63
Neronov, A., Semikoz, D., & Vovk, I. 2011, A&A, 529, A59
Neronov, A., Semikoz, D. V., Taylor, A. M., & Vovk, I. 2012, arXiv:1207.1962
Nolan, P. L., Abdo, A. A., Ackermann, M., et al. 2012, ApJS, 199, 31
Poutanen, J., & Stern, B. 2010, ApJL, 717, L118
Protheroe, R. J., & Meyer, H. 2000, PhLB, 493, 1
Sanchez-Conde, M. A., Paneque, D., Bloom, E., Prada, F., & Dominguez, A. 2009, PhRvD, 79, 123511
Sbarufatti, B., Treves, A., Falomo, R., et al. 2005, AJ, 129, 559

Şentürk, G. D., Errando, M., Böttcher, M., & Mukherjee, R. 2013, ApJ, 764, 119
Sikora, M., Stawarz, L., Moderski, R., Nalewajko, K., & Madejski, G. M. 2009, ApJ, 704, 38
Stawarz, L., & Petrosian, V. 2008, ApJ, 681, 1725
Stecker, F. W., Malkan, M. A., & Scully, S. T. 2012, ApJ, 761, 128
Takami, H., Murase, K., & Dermer, C. D. 2013, ApJL, 771, L32
Tanaka, Y. T., Stawarz, L., Thompson, D. J., et al. 2011, ApJ, 733, 19
Urry, C. M., & Padovani, P. 1995, PASP, 107, 803
Urry, C. M., Scarpa, R., O’Dowd, M., et al. 2000, ApJ, 532, 816
Vestergaard, M., & Osmer, P. S. 2009, ApJ, 699, 800
Wang, J.-G., Dong, X.-B., Wang, T.-G., et al. 2009, ApJ, 707, 1334
Wang, J.-M., Luo, B., & Ho, L. C. 2004, ApJL, 615, L9