ABSTRACT

Determining redshifts for BL Lacertae (BL Lac) objects using the traditional spectroscopic method is challenging due to the absence of strong emission lines in their optical spectra. We employ the photometric dropout technique to determine redshifts for this class of blazars using the combined 13 broadband filters from Swift-UVOT and the multi-channel imager GROND at the MPG 2.2 m telescope at ESO’s La Silla Observatory. The wavelength range covered by these 13 filters extends from far-ultraviolet to the near-infrared. We report results on 40 new Fermi-detected BL Lacs with the photometric redshift determinations for five sources, with 3FGL J1918.2–1110 being the most distant in our sample at z = 2.16. Reliable upper limits are provided for 20 sources in this sample. Using the highest energy photons for these Fermi-LAT sources, we evaluate the consistency with the gamma-ray horizon due to the extragalactic background light.

Key words: BL Lacertae objects; general – galaxies: active – gamma rays: diffuse background

1. INTRODUCTION

Blazars represent a class of active galactic nuclei (AGNs) with relativistic jets pointing along our line of sight (Blandford & Rees 1978). Their spectral energy distribution (SED) exhibits two characteristic broad bumps, which are attributed to synchrotron emission at the lower energies (Infrared to X-ray) and synchrotron self Compton at the higher energies (X-ray to γ-rays, e.g., Maraschi et al. 1994). On the basis of their optical spectroscopic characteristics, blazars can be further classified into two types: flat spectrum radio quasars (FSRQs), characterized by broad emission lines and BL Lacertae objects (BL Lacs), with no or at best weak emission lines (equivalent width <5 Å, Urry & Padovani 1995). Furthermore, another classification scheme for blazars was introduced by Abdo et al. (2010) based on the location of their synchrotron peak frequency, ν_{pk}. The authors subdivided these objects into three classes: high-synchrotron peaked blazars (HSP) for ν_{pk} > 10^{15} Hz, intermediate-synchrotron-peak (ISP) for 10^{14} Hz < ν_{pk} < 10^{15} Hz, and low-synchrotron-peak (LSP) for ν_{pk} < 10^{14} Hz. Most of the FSRQs fall in the LSP category, but half the population of BL Lacs display peak synchrotron frequencies >10^{15} Hz (Ackermann et al. 2015). These high values of ν_{pk} imply the presence of relativistic multi-TeV electrons, therefore, making BL Lacs very bright γ-ray sources with substantial emission above 10 GeV (Ackermann et al. 2013).

Blazars play an important role in the study of the extragalactic background light (EBL), which represents the integrated light from all the stars and other compact objects since the re-ionization epoch. The photons from blazars are attenuated by EBL photons through production of electron–positron pairs, which imprint a characteristic signature in the spectra of these γ-ray sources (Stecker et al. 1992). This feature in blazar spectra enables us to constrain the EBL and its evolution with cosmic time (Aharonian et al. 2006; Ackermann et al. 2012; Domínguez et al. 2013). In the case of FSRQs, the presence of broad emission lines implies the presence of a disk, whose UV radiation field could attenuate γ-ray photons, thereby making it a challenging task to differentiate the attenuation signal from the EBL photons from the circum-nuclear one. On the other hand, absence of broad emission lines in BL Lacs in addition to the abundance of photons above 10 GeV render them the perfect class of blazars to explore the EBL (Domínguez & Ajello 2015). To enable such studies, redshift measurements for these sources are essential. In particular, high-redshift BL Lacs are critical for probing the EBL, since the strength of the attenuation increases with redshift. Moreover, high-z blazars are crucial for testing the EBL evolution, which at present is poorly constrained. Estimating redshifts of BL Lacs in the traditional spectroscopic way is yet another challenge, because of the weakness, or even absence of lines (e.g., Shaw et al. 2013; Massaro et al. 2015; Álvarez-Crespo et al. 2016). Rau et al. (2012) initiated a program to determine redshifts for BL Lac sources via a photometric technique. The underlying principle for this photometric redshift (photo-z) determination is based on the absorption of UV photons by neutral hydrogen along the line of sight, which absorbs photons bluewards of the Lyman limit. This leads to a dropout in the flux at the Lyman limit whose position in the SED can be used to determine the photo-z. This approach was applied by Rau et al. (2012) for a sample of 103 blazars.

The immediate aim of this study is to determine photo-zs of high-z (z > 1.3, which is the lower limit measurable with this method) BL Lacs to increase the sample in the important high-redshift regime. Only 19 BL Lacs with z > 1.3 are known, of which 13 are reported in the third catalog of Fermi-detected AGNs (3LAC, Ackermann et al. 2015). A total of 9 BL Lacs were reported in Rau et al. (2012), of which 3 sources are provided among the 13 in the 3LAC catalog. Therefore, Rau et al. (2012) provided six new high-z BL Lacs with the photometric technique. The outline of this paper is as follows. Section 2 explains the details of observations. The data analysis procedure is explained in Section 3. The resulting high-z BL Lac parameters are reported in Section 4 and the interpretation of our results is presented in Section 5. A flat ΛCDM cosmological model with H_{0} = 71 km s^{-1} Mpc^{-1}, Ω_m = 0.27, and Ω_{Λ} = 0.73 was adopted for all the calculations.
2. OBSERVATIONS

2.1. Sample Selection

Our sample was selected from sources classified as BL Lacs in the third catalog of Fermi-detected sources (3FGL, Acero et al. 2015) without a measured redshift. The selection procedure was based on two main criteria, one being that only sources with decl. <25° were chosen in order to accommodate the visibility from the ground-based telescope, situated in Chile. The second selection criterion was the minimization of the Galactic foreground reddening, ensured by selecting objects away from the Galactic plane (|b| > 10°). Here we report on the 40 sources observed so far whose basic properties are presented in Table 1.

2.2. Facilities

The Swift satellite (Gehrels et al. 2004) and MPG 2.2 m telescope at ESO La Silla, Chile were employed for conducting the observations. All sources were observed in 13 filters; (uvw2, uvw1, u, b, v) of Swift-UVOT (The Ultraviolet and Optical Telescope, Roming et al. 2005) and 7 optical-IR filters (g′, r′, i′, z′, J, H, Ks) of GROND (Gamma-Ray Optical/Near-infrared Detector, Greiner et al. 2008). The resulting 13-filter SED covers a wavelength range of 1600–20000 Å. The main advantage of using the overlap of two filters: g′ from GROND and b from UVOT is to cross-calibrate the two instruments for the combined data analysis.

2.3. Observing Strategy

GROND observations were performed as close to the Swift observations as possible. While truly simultaneous observations...
were rarely feasible due to ground visibility constraints, both instruments often observed within one to two days of each other. *Swift*-UVOT observed in each of its six filters in sequence, while GROND conducted observations in all the seven filters, simultaneously, which is very crucial for blazars, due to their variable nature. The typical integration times for *Swift* were 100 s in *u*, *b*, and *v* and 200, 240, and 400 s in *uvw1*, *uvm2*, and *uvw2*, respectively; though, the exposure times changed based on the brightness of each object. A typical GROND observation had an integration time of approximately two minutes in *g*, *r*, *i*, *z* and ∼4.0 minutes in *J*, *H*, *K*

3. DATA ANALYSIS

3.1. *Swift*-UVOT

*Swift* data were processed through the standard UVOT pipeline procedure (Poole et al. 2007) in order to remove the bad pixels, to flat-field and to correct for the system response. The magnitude extraction per filter was performed with the UVOT task, UVOTMAGHIST. A circular region was selected for the aperture extraction with variable radius in order to maximize the signal-to-noise ratio. The resulting magnitudes in each filter were corrected for Galactic extinction, utilizing Table 5 presented in Kataoka et al. (2008). The final magnitudes were converted to the AB system and the results are presented in Table 2.

3.2. GROND

The data reduction procedure for GROND is described in detail in Krühler et al. (2008), and here it is only mentioned briefly. The point-spread function (PSF) photometric technique was used for *g*, *r*, *i*, *z* filters, whereas, due to the undersampled PSF in the near-infrared, the standard aperture extraction technique was applied for *J*, *H*, *K* filters. The four optical filters were calibrated with the stars in the SDSS Data Release 8 (Aihara et al. 2011), which provides the final magnitudes in the AB system. 2MASS stars (Skrutskie et al. 2006) were employed for calibration of the near-IR filters. The correction for the Galactic foreground extinction was performed with measurements in Schlafly & Finkbeiner (2011). The resulting data were converted to the AB system (Table 3).

3.3. Variability Correction

Blazars, in general, exhibit emission that varies on timescales of a few minutes to years. This variability can have a significant impact on the redshift determination via the photometric technique. GROND data are not affected by intrinsic variability because the observations are performed in all seven filters simultaneously. However, since *Swift*-UVOT cycles through every filter, in addition to the non-simultaneous GROND-*Swift* observations, these variations in the emission could add to the existing uncertainties. Rau et al. (2012) established that the inherent blazar variability introduces a systematic uncertainty of Δm = 0.1 mag for each UVOT filter. The other important factor to consider is that the total SED is obtained by combining the UVOT and GROND data, which are two different instruments, which thus need to be calibrated against each other. Krühler et al. (2011) performed this task by combining *Swift*-UVOT and GROND filter curves, utilizing their spectral overlap and established the following calibration relationship:

\[ b - g' = 0.15 (g' - r') + 0.03 (g' - r')^2. \]  

This equation is based on the assumption that a BL Lac SED is represented by a power law and that its slope does not change over the UV–IR regime. This relation, which is valid for \(-1 \leq (g' - r') \leq 2\), was applied to all the UVOT filters before SED fitting. The UV-Opt-IR SED of BL Lacs is thought to be dominated by non-thermal synchrotron emission. It can be modeled over the wavelength interval used here as a power-law spectrum. Our 13 band photometry covers this energy regime of the SED of a BL Lac, and moreover the absence of any broad lines makes this approximation valid, in particular, for these kind of blazars. In addition, stellar templates were fitted to these sources to check for non-power-law behavior as explained in the next section.

3.4. SED fitting

The LePhare v.2.2 program\(^5\) (Arnouts et al. 1999; Ilbert et al. 2006) was employed to determine the photometric redshifts for these objects. This program evaluates the difference between the observational and theoretical data based on the \(\chi^2\) statistic. We selected three separate template libraries to fit the data, independently. Our first library is comprised of 60 power-law SED templates of the form \(F_\lambda \propto \lambda^{-\beta}\), such that \(\beta\) ranged from 0 to 3 in steps of 0.05, under the assumption that the UV-Optical-Near-Infrared regime for BL Lacs can be fit with a single power-law template. In addition, a library of galaxies and galaxy/AGN hybrids (Salvato et al. 2009, 2011) as well as a stellar library using templates from Pickles (1998), Bohlin et al. (1995), and Chabrier et al. (2000) were used. The results from the first two libraries are presented in Table 4. None of our SEDs required a contribution from the stellar libraries.

4. RESULTS

The results of SED fitting for 40 sources are presented in Table 4. The reliability of our photometric results was determined by Monte Carlo simulations performed in Rau et al. (2012), where 27,000 test SEDs were simulated with \(\beta\) ranging from 0.5 to 2.0 and redshifts of 0 to 4. These SEDs were supplied to LePhare to calculate the redshifts and were then compared to the input values. The authors concluded that for sources with simulated redshifts, \(z_{\text{sim}} > 1.2\), the photometric redshift reproduced the input value within an accuracy of \(|\Delta z (1 + z_{\text{sim}})| < 0.15\). In addition, a more quantitative selection procedure was applied, which was based on a quantity, \(P_z = \int f(z)dz \text{ at } \Delta z \pm 0.1 (1 + z_{\text{sim}})\), the integral of the probability distribution function. This quantity describes the probability that the redshift of a source is within a factor of 0.1(1 + z) of the best-fit value. Measurements with \(P_z > 90\%\) were considered reliable photometric redshifts. We apply both selection criteria defined above to our SED fitting, which resulted in determining photometric redshifts for 5 sources and establishing upper limits for 20 of them, which is presented in Table 4. The *Swift*-UVOT and GROND spectral energy distributions for the new five high-\(z\) sources, i.e., 3FGL J0525.6–6013, 3FGL J1339.0+1153, 3FGL J1520.8–0348,

\(^5\) http://www.cfht.hawaii.edu/~arnouts/lephare.html
Notes.

3FGL J1918.2–4110, and 3FGL J2146.6–1344 are shown in Figure 1.

5. DISCUSSION

Ackermann et al. (2015) reported 604 BL Lacs out of which 326 sources have redshift measurements of which only 13 with high-$z$ ($z > 1.3$). Three of these sources were reported among the 9 high-$z$ BL Lacs by Rau et al. (2012) utilizing the photometric redshift technique. Our study is a continuation of Rau et al. (2012), who calculate the redshifts for BL Lacs with the photometric technique, which increases the sample size by ~30% by finding 5 BL Lacs at $z > 1.3$ from our sample of 40 sources. ~50% of the total number of 24 known high-$z$ BL Lacs (5 from this work and 6 from Rau et al.’s 2012 work) are determined by the photo-$z$ method. A comparison between the spectroscopic and photometric redshift determinations for $z > 1.3$ BL Lacs is presented in Figure 2. As seen in this figure, both approaches are consistent with each other. The spectroscopic redshift for the source, 3FGL J1312.5–2155, has been determined by using the absorption features, i.e., C IV and Mg II (Ryabinkov et al. 2003), which could possibly imply a lower limit. This demonstration shows that our photometric
campaign is an efficient way to uncover rare high-redshift BL Lacs.

5.1. Blazar Sequence

The “Blazar Sequence” is a scheme that suggests the existence of a unified model to represent all classes of blazars. Several authors, e.g., Maraschi et al. (1995), Sambruna et al. (1996), and Fossati et al. (1998) proposed this unification idea through observed SEDs for blazars. These authors concluded that the blazar phenomenon is primarily governed by the total luminosity, which is the best indicator for determining the physical properties as well as the radiation mechanisms in these sources. Fossati et al. (1998) noticed several anti-correlations, e.g., $\nu_{\gamma V}^{pk}$ and luminosity at this peak ($L_{\gamma V}^{pk}$), $\nu_{\gamma V}^{pk}$ and the Compton Dominance (CD), and the $\gamma$-ray photon index ($\Gamma_\gamma$). These results indicate that the blazar family lined up on a sequence where more luminous blazars had lower synchrotron peak frequencies, but dominant $\gamma$-ray emission (i.e., $CD > 1$), which is generally the case for powerful FSRQs. On the other hand, the less luminous, high-peaked sources (typically BL Lac objects) have $CD \lesssim 1$. In other words, the blazar sequence predicts the non-existence of high-frequency peaked, highly luminous BL Lac objects. A theoretical justification of these correlations is discussed in Ghisellini et al. (1998).
Table 4
SED Fitting

| Name                        | $z_{\text{ph}}$ | $z_{\text{spec}}$ | $\chi^2$ | $\beta$ | $R^2$ | Model                  |
|-----------------------------|----------------|-------------------|----------|---------|-------|------------------------|
| SUMSS J052542–601341        | 1.78 $^{+0.16}_{-0.13}$ | ... | 10.4     | 98.9    | 1.25  | ...                   |
| FRBA J1338+1153             | 1.49 $^{+0.15}_{-0.14}$ | >1.587 | ... | 3.7     | 98.8  | 1.05 | ... | 0.02 $^{+0.03}_{-0.02}$ | 54.7 | 99.9 | ... | Spi4_template_norm.sed |
| IFGL J1521.0–0530           | 1.46 $^{+0.12}_{-0.11}$ | >0.867 | ... | 7.6     | 99.7  | 0.90 | ... | 0.19 $^{+0.08}_{-0.07}$ | 27.0 | 81.8 | ... | I22491_40_TQSO1_60.sed |
| CRATES J1918–4111           | 2.16 $^{+0.01}_{-0.01}$ | >1.591 | ... | 5.6     | 100.0 | 1.20 | ... | 0.00 $^{+0.00}_{-0.00}$ | 128.0 | 100.0 | ... | S0_90_QSO2_10.sed |
| IFGL J2146.6–1345           | 1.34 $^{+0.01}_{-0.00}$ | <1.005 | ... | 15.1    | 93.5  | 0.75 | ... | 1.45 $^{+0.03}_{-0.03}$ | 39.2 | 100.0 | ... | pl_I22491_20_TQSO1_80.sed |

Notes.

a Best photometric redshift.

b Spectroscopic redshift, if known.

c Photometric redshifts with 2σ confidence level.

d Redshift probability density at $z_{\text{ph}}$ ± 0.11 + $z_{\text{ph}}$.

e Spectral slope for power-law model of the form $F_{\nu} \propto \nu^{-\beta}$.

The concept of a Blazar sequence is an interesting but still debated idea (e.g., Ghisellini et al. 2012; Padovani et al. 2012). The motivation here is to test how the new high-redshift BL Lacs presented in this study fit in the proposed blazar sequence. We utilize the 3LC (Ackermann et al. 2015) catalog to extract relevant SED parameters, e.g., $P_{\text{50}}^{\text{pk}}$, ($\nu P_{\text{50}}^{\text{pk}}$)_{50}, CD, and $\gamma$-ray photon index, for all the blazars present in 3LC data. 

...
which CD values were not provided, we calculated them with an online SED fitting tool.\(^6\) We calculate luminosities at the peak synchrotron frequencies as they would appear in their rest frame. The obtained parameters are presented in Figures 3–5. It should be noted that only blazars with known redshifts are plotted in these figures. As can be seen in Figure 3, the five high-redshift BL Lac objects (shown with yellow squares) tend to occupy the high \(L_{\text{syn pk}}\) and a relatively high \(\nu_{\text{syn pk}}\) region among the known blazar population. We find that all of our high-\(z\) BL Lacs are consistent with the known anti-correlation of CD and

\(^6\) http://tools.asdc.asi.it/SED/
erg s\(^{-1}\) as a function of
\[
\log(\nu_{\text{pk}}^{\text{rest}} \text{ Hz})
\]

Figure 5. Correlation between the \(\gamma\)-ray photon index and the redshift corrected peak synchrotron frequency for all the blazars. The black horizontal bars represent the \(\nu_{\text{pk}}^{\text{rest}}\) with redshift range from zero to the upper limit provided in this work. The color scheme for different data sets follows from Figure 3. Please note that the \(\gamma\)-ray photon indices have not been corrected for the EBL absorption.

\(\nu_{\text{sy}}^{pk}\) (see Figure 4) with CD \(< 1\) for all the five high-\(z\) BL Lacs, as generally seen in this class of blazars. These findings are in agreement with the theoretical model of Finke (2013), which suggests the existence of sources with high \(\nu_{\text{sy}}^{pk}\) and high \(L_{\text{sy}}^{pk}\) but having a CD value less than unity. Furthermore, these objects are hard \(\gamma\)-ray spectrum sources and we do not find any exception when placed in the \(\gamma\)-ray photon index versus the \(\nu_{\text{sy}}\) diagram (Figure 5).

5.2. Fermi Blazar Divide

Ghisellini et al. (2009) utilized \(\sim 100\) blazars from the first three-month survey of \textit{Fermi}-LAT data (Abdo et al. 2009) and noticed a division between FSRQs and BL Lacs by comparing their \(\gamma\)-ray spectral indices (\(\Gamma_{\gamma}\)) to the \(\gamma\)-ray luminosities (\(L_{\gamma}\)). These observations revealed that BL Lacs exhibited harder spectra (\(\Gamma_{\gamma} \approx 2.2\)) and were less luminous (\(L_{\gamma} \approx 10^{47}\) erg s\(^{-1}\)) than FSRQs. It was suggested that this “Fermi Blazar Divide” could be interpreted primarily based on the different mass accretion rates with FSRQs having high accretion rates. Moreover, this division between two groups of blazars on the \(\Gamma_{\gamma} - L_{\gamma}\) plane has been discussed by various authors, e.g., Padovani et al. (2012) and Ghisellini et al. (2012). The former authors noticed high \(\Gamma_{\gamma}\) and hard \(\Gamma_{\gamma}\) for some of the BL Lacs from Rau et al. (2012), which was argued against by the latter suggesting that, although these BL Lacs fall into the higher end of \(\Gamma_{\gamma} - L_{\gamma}\) plane, they are consistent with the separation of two populations. In particular, Ghisellini et al. (2012) proposed that the emission region in these sources may lie outside the broad line region (BLR) and therefore the resultant SEDs are similar to BL Lacs. In other words, such objects are “blue” FSRQs with the broad emission lines in their optical spectra are swamped by a high level of synchrotron emission. In Figure 6, we show the variation of \(L_{\gamma}\) as a function of \(\Gamma_{\gamma}\) for 3LAC blazars. In this diagram, we also show high-\(z\) BL Lacs obtained in this work and by Rau et al. (2012). The \(L_{\gamma}\) for all of these sources were calculated using Equation (1) in Ghisellini et al. (2009). Interestingly, as can be seen in Figure 6, all five high-\(z\) BL Lacs have high \(\Gamma_{\gamma}\) but having a CD value less than unity. Furthermore, these objects are hard \(\gamma\)-ray spectrum sources and we do not find any exception when placed in the \(\gamma\)-ray photon index versus the \(\nu_{\text{sy}}\) diagram (Figure 5).

\[
L_{\text{BLR}} \sim 4L_{\gamma}^{0.93}
\]

where \(L_{\text{BLR}}\) is the BLR luminosity. This indicates that for \(L_{\gamma} \sim 1 \times 10^{47}\) erg s\(^{-1}\), we have \(L_{\text{BLR}} \sim 2 \times 10^{44}\) erg s\(^{-1}\). Assuming a fraction of 10\% of the disk luminosity is reprocessed by the BLR, the disk luminosity is \(\sim 2 \times 10^{45}\) erg s\(^{-1}\). Since there is no estimate of the central black hole mass available in the literature for the five high-\(z\) BL Lacs, we assume an average value of \(5 \times 10^{8}\) \(M_{\odot}\) (e.g., Sbarrato et al. 2012). This assumption implies \(L_{\text{disk}}/L_{\text{edd}} \sim 0.03\), which makes their accretion disk radiatively efficient, similar to what is typically observed in powerful FSRQs. However, these quantities should be considered with some caution due to underlying assumptions (e.g., Ghisellini et al. 2012; Sbarrato et al. 2012) and we defer to a future multi-wavelength study for a more detailed discussion. Furthermore, although the \(L_{\gamma}\) of these BL Lac objects appear to be similar to FSRQs, they are consistent with a separation in the \(\gamma\)-ray photon index alone, a property that has been established and known since EGRET and it is more robust against the redshifts completeness of the redshift population (e.g., Hartman et al. 1999; Venter & Pavlidou 2007).

5.3. The Extragalactic Background Light

Increasing the sample size of high-\(z\) BL Lacs is particularly important for probing the EBL, and to better understand the cosmic evolution of the blazar population (Ajello et al. 2012). Photons from sources at \(z > 1.3\) and energy above 50 GeV have a probability \(\geq 25\%\) of interacting with the photons of the UV-optical component of the EBL that leads to the generation of an electron–positron pair. For this reason, we looked into which source of the entire photo-\(z\) sample (five sources from this paper
and six from Rau et al. (2012) was also reported in the 2FHL catalog of Fermi-LAT sources detected above 50 GeV (Ackermann et al. 2016). We found three: 1FGL J2146.6−134, CRATES J0630−2406, and SUMSS J052542−601341. Their highest energy photons at 81 GeV, 83 GeV, and 71 GeV, respectively (reported in Ackermann et al. 2016) allow us to probe the cosmic γ-ray horizon (i.e., the distance at which $\tau_{\gamma\gamma} = 1$, e.g., Domínguez et al. 2013). Figure 8 shows that those photons are consistent with the γ-ray horizon in the EBL model developed by Domínguez et al. (2011). It is important to realize that these high-z sources provide a valuable constraint on the γ-ray horizon in a region where the sources are scarce.

Figure 7 shows the γ-ray SED of 1FGL J2146.6−134, CRATES J0630−2406, and SUMSS J052542−601341 obtained combining 3FGL, 1FHL, and 2FHL data (Ackermann et al. 2013, 2016; Acero et al. 2015). For each source, we fitted a power law to the 3FGL data and applied to it EBL absorption (in the form $e^{-\tau_{\gamma\gamma}(E,z)}$) adopting the Domínguez et al. (2011) model and taking the redshift uncertainty into account. All of these sources exhibit hard spectra with photon spectral indices of $\Gamma \approx 1.8$, similar to the one of Mrk 421, but belonging to objects that are much farther away. The redshift uncertainty produces a negligible effect in the expected source flux at $z \gtrsim 1.5$. As such, one may use BL Lacs with photo-z estimates to constrain the EBL in the same way as BL Lacs with spectroscopic redshift have been used in Ackermann et al. (2012).

Figures 7 and 8 show that the γ-ray horizon for $z \gtrsim 1.5$ is at energy $\lesssim 100$ GeV: i.e., well in the Fermi-LAT band and well constrained by the first energy bin of the 2FHL.

Figure 7. Spectral energy distributions of SUMSS J052542−601341, CRATES J0630−2406, and 1FGL J2146.6−134 obtained combining data reported in the 3FGL, 1FHL, and 2FHL catalogs (Ackermann et al. 2013, 2016; Acero et al. 2015). The black line is a fit to the 3FGL data with a power law that is absorbed by the EBL using the model of Domínguez et al. (2011). The gray area at high energy denotes the uncertainty in the source attenuation (and correspondingly in the source flux) due to the uncertain redshift.

Figure 8. Plot of the highest energy of photons from sources (with $E > 50$ GeV) vs. their redshift. The colors of different sources imply their corresponding optical depth ($\tau$) values (see colorbar). Various estimates of the cosmic γ-ray horizon, obtained from the EBL models by Finke (2010; dotted orange line), Domínguez et al. (2011; solid black line, with its uncertainties as a shaded band), and Gilmore et al. (2011; dashed red line) are plotted for comparison. The highest energy photons from three of the high-z sources from our sample are consistent with the cosmic γ-ray horizon (blue filled stars) as estimated by Domínguez et al. (2011).
catalog. For two out of three sources the flux is reduced by a factor of \( \geq 5 \) with respect to the unabsorbed flux.

6. CONCLUSIONS

This work is a continuation of the photometric redshift determination program utilizing the simultaneous GROND+\( -\)UVOT data described in Rau et al. (2012), which provided photo-z estimates/limits for hundreds of Fermi. We present 40 sources from the 3FGL catalog, for which redshifts (or upper limits) were determined by the photometric technique. Five of these sources are high-redshift BL Lacs \( (z > 1.3) \). The Fermi 3LAC catalog is comprised of 13 high-\( z \) BL Lacs, in addition to the 6 provided by Rau et al. (2012). By including the 5 BL Lacs in this work, the total number of \( z > 1.3 \) sources increases to 24, of which 13 are provided by the spectroscopic method and the other 11 by the photometric technique. Therefore, this work increases the sample size of known high-\( z \) BL Lacs by \( \sim 30\% \). It should be noted that \( \sim 50\% \) of the known high-\( z \) BL Lacs have been found using the photometric redshift method. The latter method is efficient since obtaining data requires a considerably shorter integration time than the spectroscopic method as described in Section 2. Moreover, the properties of these objects are in agreement with the blazar sequence and were examined using the various parameters as illustrated in Figures 3–5. All five new sources are classified as LSPs or HSPs exhibiting \( L_{\gamma}^{pk} \simeq 10^{46–48} \text{erg s}^{-1} \). The \( \gamma \)-ray luminosities associated with these objects are \( L_{\gamma} \gtrsim 10^{47} \text{erg s}^{-1} \), which are higher than the suggested values in the “Fermi Blazar Divide” introduced by Ghisellini et al. (2009) who divided the FSRQs and BL Lacs on the \( \Gamma_{\gamma} – L_{\gamma} \) plane, such that the BL Lacs show hard spectra \( (\Gamma_{\gamma} < 2.2) \) with low \( \gamma \)-ray luminosity \( (L_{\gamma} \lesssim 10^{47} \text{erg s}^{-1}) \). Three of these new objects were reported in the 2FHL catalog, from which the highest energy photons \( (E > 50 \text{GeV}) \) coupled with the redshift measurements were utilized to test the consistency with the currently known EBL models, e.g., Finke (2010), Domínguez et al. (2011), and Gilmore et al. (2011). Detecting high-\( z \) BL Lacs with a substantial amount of \( \gamma \)-ray emission allowed us to constrain the EBL in a region where there are not, as yet, measurements of the optical depth. The ones derived here show consistency with the prediction of the EBL model of Domínguez et al. (2011), which is in agreement with the galaxy counts.

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REFERENCES

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2009, ApJ, 700, 597
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010, ApJ, 723, 1082
Acero, F., Ackermann, M., Ajello, M., et al. 2015, ApJS, 218, 23
Ackermann, M., Ajello, M., Allafort, A., et al. 2012, Sci, 338, 1190
Ackermann, M., Ajello, M., Allafort, A., et al. 2013, ApJS, 209, 34
Ackermann, M., Ajello, M., Atwood, W. B., et al. 2015, ApJ, 810, 14
Ackermann, M., Ajello, M., Atwood, W. B., et al. 2016, ApJS, 222, 5
Aharonian, F., Akhperjanian, A. G., Bazer-Bachi, A. R., et al. 2006, Natur, 440, 1018
Aihara, H., Allenle Prieto, C., An, D., et al. 2011, ApJS, 193, 29
Ajello, M., Shaw, M. S., Romani, R. W., et al. 2012, ApJ, 751, 108
Arnouts, S., Cristiani, S., Moscardini, L., et al. 1999, MNRAS, 310, 540
Álvarez-Crespo, N., Massaro, F., Milisavljevic, D., et al. 2016, AJ, 151, 95
Blandford, R. D., & Rees, M. J. 1978, Phys, 17, 265
Bolhin, R. C., Colina, L., & Finley, D. S. 1995, AJ, 110, 1316
Chabrier, G., Baraffe, I., Allard, F., & Hauschildt, P. 2000, ApJ, 542, 464
Domínguez, A., & Ajello, M. 2015, ApJ, 813, L34
Domínguez, A., Finke, J. D., Prada, F., et al. 2013, ApJ, 770, 77
Domínguez, A., Primack, J. R., Rosario, D. J., et al. 2011, MNRAS, 410, 2556
Finke, J. D. 2013, ApJ, 763, 134
Finke, J. D., Razzano, S., & Dermer, C. D. 2010, ApJ, 712, 238
Fossati, G., Maraschi, L., Celotti, A., Comastri, A., & Ghisellini, G. 1998, MNRAS, 299, 433
Gehrels, N., Chincarini, G., Giommi, P., et al. 2004, ApJ, 611, 1005
Ghisellini, G., Celotti, A., Fossati, G., Maraschi, L., & Comastri, A. 1998, MNRAS, 301, 451
Ghisellini, G., Maraschi, L., & Tavecchio, F. 2009, MNRAS Lett. Letters, 396, L105
Ghisellini, G., Tavecchio, F., Foschini, L., et al. 2012, MNRAS, 425, 1371
Gilmore, R. C., Somerville, R. S., Primack, J. R., & Domínguez, A. 2011, MNRAS, 422, 3189
Greiner, J., Bornemann, W., Clemens, C., et al. 2008, PASP, 120, 405
Hartman, R. C., Bertsch, D. L., Bloom, S. D., et al. 1999, ApJS, 123, 79
Ilbert, O., Arnouts, S., McCracken, H. J., et al. 2006, A&A, 457, 841
Kataoka, J., Madejski, G., Sikora, M., et al. 2008, ApJ, 672, 787
Krühler, T., KüpcüYoldas, A., Greiner, J., et al. 2008, ApJ, 685, 376
Krühler, T., Schady, P., Greiner, J., et al. 2011, A&A, 526, A153
Maraschi, L., Fossati, G., Tagliaferri, G., & Treves, A. 1995, ApJ, 443, 578
Maraschi, L., Ghisellini, G., & Celotti, A. 1994, in IAU Symp. 159, Multi-Wavelength Continuum Emission of AGN, ed. T. Courvoisier & A. Blecha (Dordrecht: Kluwer), 221
Massaro, F., Iandoni, M., D'Abrusco, R., et al. 2015, A&A, 575, 124
Padovani, P., Giommi, P., & Rau, A. 2012, MNRAS Letters, 422, L48
Pickles, A. 1998, PASP, 110, 863
Poole, T. S., Breeveld, A. A., Page, M. J., et al. 2007, MNRAS, 383, 627
Rau, A., Schady, P., Greiner, J., et al. 2012, A&A, 538, A26
Roming, P. W. A., Kennedy, T. E., Mason, K. O., et al. 2005, SSRv, 120, 95
Ryabinkov, A. I., Kaminker, A. D., & Varshalovich, D. A. 2003, A&A, 412, 707
Salvato, M., Hasinger, G., Ilbert, O., et al. 2009, ApJ, 690, 1250
Salvato, M., Ilbert, O., Hasinger, G., et al. 2011, ApJ, 742, 61
Sambruna, R. M., Maraschi, L., & Urry, C. M. 1996, ApJ, 463, 444
Sbarrato, T., Ghisellini, G., Maraschi, L., & Colpi, M. 2012, MNRAS, 421, 1764
Slafsky, E. F., & Finkbeiner, D. P. 2011, ApJ, 737, 103
Shaw, M. S., Romani, R. W., Cotter, G., et al. 2013, ApJ, 764, 135
Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, AJ, 131, 1163
Stecker, F. W., de Jager, O. C., & Salamon, M. H. 1992, ApJL, 390, L49
Urry, C. M., & Padovani, P. 1995, PASP, 107, 803
Venters, T. M., & Pavlidou, V. 2007, ApJ, 666, 128