New High-z BL Lacs Using the Photometric Method with Swift and SARA

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Abstract

BL Lacertae (BL Lac) objects are prominent members of the third Fermi Large Area Telescope catalog of γ-ray sources. Half of the members of the BL Lac population (~300) lack redshift measurements, which is due to the absence of lines in their optical spectra, thereby making it difficult to utilize spectroscopic methods. Our photometric dropout technique can be used to establish the redshift for a fraction of these sources. This work employed six filters mounted on the Swift-UVOT and four optical filters on two telescopes, the 0.65 m SARA-CTIO in Chile and 1.0 m SARA-ORM in the Canary Islands, Spain. A sample of 15 sources was extracted from the Swift archival data for which six filter UVOT observations were conducted. By complementing the Swift observations with the SARA ones, we were able to discover two high-redshift sources: 3FGL J1155.4–3417 and 3FGL J1156.7–2250 at $z = 1.83^{+0.10}_{-0.13}$ and $z = 1.73^{+0.11}_{-0.15}$, respectively, resulting from the dropouts in the power-law template fits to these data. The discoveries add to the important (26 total) sample of high-redshift BL Lacs. While the sample of high-z BL Lacs is still rather small, these objects do not seem to fit well within known schemes of the blazar population and represent the best probes of the extragalactic background light.

Key words: BL Lacertae objects: general

1. Introduction

Active galactic nuclei (AGNs) possessing jets aligned with our lines of sight are known as blazars (Blandford & Rees 1978). The spectral energy distribution (SED) of these sources displays two broad bumps attributed to synchrotron emission at low energies (IR to X-ray) and the inverse Compton scattering at high energies (X-ray to γ-rays Abdo et al. 2011a, 2011b). Abdo et al. (2010) introduced a classification criteria for blazars based on their peak synchrotron frequencies, $\nu_{pk}^\gamma$. These authors divided blazars into three classes: high-synchrotron-peak (HSP, $\nu_{pk}^\gamma > 10^{15}$ Hz), intermediate-synchrotron-peak, (ISP, $10^{14} < \nu_{pk}^\gamma < 10^{15}$ Hz), and low-synchrotron-peak (LSP, $\nu_{pk}^\gamma < 10^{14}$ Hz) objects. Another classification scheme for blazars divides them into two classes due to the differences in their optical spectrum properties: BL Lacertae objects and flat spectrum radio quasars (FSRQs). The former exhibit no or very weak (<5 Å equivalent width) emission lines (Urry & Padovani 1995), whereas the latter show broad emission lines. The absence of lines in BL Lacs implies that either their spectrum is dominated by the synchrotron emission from the jet (Marcha & Browne 1996) or that the emission from the disk and broad line region is very weak due to, likely, inefficient (or low) accretion, jet dilution, or a combination of both scenarios (Giommi et al. 2011). Most of the FSRQs are identified as LSPs, whereas BL Lacs can belong to all three classes (LSP, ISP, and HSP) with most BL Lacs exhibiting ISP and HSP characteristics, i.e., substantial emission at $>10$ GeV (Ackermann et al. 2015). This property makes BL Lacs bright γ-ray emitters and hence excellent probes of the extragalactic background light (EBL Domínguez and Ajello 2015), which consists of all the emission from the stars and accreting objects in the observable universe since galaxy formation.

The direct measurement of EBL is challenging due to the bright zodiacal light and emission from our Galaxy (Hauser & Dwek 2001). An indirect method to study the EBL intensity is by using γ-ray emitters. The underlying principle for this method utilizes the interaction of the γ-ray photons with the EBL photons to produce electron–positron pairs. This leads to a characteristic attenuation in the γ-ray spectra (Stecker et al. 1992; Ackermann et al. 2012). This imprint can be used to study the EBL and its evolution with redshift (Aharonian et al. 2006). Moreover, sources at higher redshifts are more strongly attenuated, thereby leading to better EBL constraints. High-redshift BL Lacs, because of their prominent emission at $>10$ GeV are thus the best probes of the EBL, but they are rare. So far, only 24 BL Lacs, among the 700 Fermi-LAT 3LAC sources (Ackermann et al. 2015), have $z > 1.3$. Several authors utilized various facilities to obtain the redshifts for these objects using the spectroscopic method, but only telescopes greater than the 8 m class yieldredshift measurements. Otherwise, lower limits were placed due to the faint absorption lines from the galaxies along our line of sight (e.g., Landt 2012; Shaw et al. 2013a, 2013b; Massaro et al. 2015; Crespo et al. 2016).

The photometric method for calculating redshifts for BL Lacs was first introduced by Rau et al. (2012), which used quasi-simultaneous observations with UVOT (Ultraviolet and Optical Telescope; Roming et al. 2005) mounted on the Neil Gehrels Swift Observatory (Gehrels et al. 2004) and GROND (Greiner et al. 2008), a multicolor imager at the 2.2 m MPG telescope, mounted at the ESO La Silla Observatory, Chile. This inexpensive and time efficient method is based on the following principle: the UV photons from BL Lacs are absorbed by the neutral hydrogen along our line of sight, thereby attenuating the flux bluewards of the Lyman limit. This dropout in the SED of a BL Lac can be modeled to obtain a (photometric) redshift. These authors found 9 (6 new) high-redshift BL Lacs (out of 103), increasing the total sample of high-z BL Lacs by 50% utilizing ~1 ks Swift-UVOT exposure time per source for all filters combined and 4–5 minutes with GROND. Upper limits (typically $z < 1.2$–1.3) were established for the rest of the sources in that work. Kaur et al. (2017)
continued this work and found 5 more high-$z$ BL Lacs from a sample of 40 objects.

The work presented here is the continuation of this successful program. In this new analysis, we rely for the first time on archival Swift-UVOT data and two ground-based facilities, as explained in the next section. This paper is organized as follows: Section 2 introduces the facilities, data collection, and the observing strategy. Section 3 explains the data analysis steps used for the completion of this work. Section 4 illustrates the SED fitting, followed by the results in Section 5. The paper is concluded in Section 6 with a brief discussion of our findings. It should be noted that a flat $\Lambda$CDM cosmological model with $H_0 = 0.73 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.27$, $\Omega_{\Lambda} = 0.73$ was adopted for all the calculations in this work.

### 2. Sample Selection

First, the HEASARC archive was explored to search for BL Lacs in the 3FGL catalog (Acero et al. 2015). Sources observed in all six ($uvw2$, $uvw2$, $uvw1$, $u$, $b$, $v$) filters of UVOT mounted on the Neil Gehrels Swift observatory were selected and not included in Rau et al. (2012) or Kaur et al. (2017). These BL Lacs were then observed using two ground facilities: the Southeastern Association for Research in Astronomy consortium’s 0.65 m and 1.0 m telescopes at Cerro Tololo, Chile (SARA-CT) and Roque de los Muchachos Observatory, Canary Islands (SARA-ORM), respectively. The data were obtained in four SDSS filters ($g'$, $r'$, $i'$, $z'$) mounted on these two telescopes. See Keel et al. (2016) for further details on these two ground facilities.

A sample of 15 BL Lacs was selected from the Swift archive based on the abovementioned criteria. These objects were then observed with the two ground-based facilities, with exposures times ranging from 20 to 60 minutes per filter.

The details of observations for all the facilities are presented in Table 1. The combined data from the Swift satellite and SARA telescopes resulted in 10 filter flux measurements for each object.

### 3. Method

#### 3.1. Swift-UVOT

The standard UVOT pipeline procedure (Poole et al. 2007) was followed to extract the final products, which were flat fielded and corrected for the system response. The magnitudes were derived using the UVOT task, UVOTMAGHIST from HEASoft v.6.214 using a circular aperture of variable radius for each object to maximize the signal-to-noise ratio. The background subtraction was performed by selecting an annular region with inner and outer radii $10''$ and $25''$ for each source. A careful analysis was performed to select the background aperture to avoid any contamination from the nearby objects in the field. These extracted magnitudes were corrected for the Galactic foreground extinction using Table 2 presented in Kataoka et al. (2008) and then converted to the AB system, reported in Table 2.

#### 3.2. SARA-ORM and SARA-CT

The data from the two ground facilities were analyzed using the standard aperture photometry technique employing IRAF (v.2.16; Tody 1986; Kolb 2002). Photometric calibrations were performed for each object using one to two standard stars observed each night. The Sloan filters ($g$, $r$, $i$, $z$) mounted on the two telescopes were employed for the measurements. The foreground galactic extinction was applied using the calculations from Schlafly & Finkbeiner (2011). The final magnitudes in the AB system are shown in Table 2.

#### 3.3. Variability Correction

In our previous work, Rau et al. (2012) and Kaur et al. (2017), a special measure was taken to observe each source in all the filters simultaneously from the ground-based facility and within 1–10 days from the Swift observations. In this work, we are utilizing archival Swift-UVOT data for the BL Lacs and the observations using ground telescopes were performed within the last year. In order to account for the uncertainties due to the

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Note.

4 The observation dates for for Swift and SARA correspond to the beginning of the exposures.

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### Table 1

**Swift-UVOT and SARA Observations**

| Name     | Swift    | R.A. J2000 (hh:mm:ss) | Decl. J2000 ($^\circ; \; '$; '') | Swift Date* (UT) | SARA Date* (UT) | $A_V$ (mag) |
|----------|----------|-----------------------|---------------------------------|------------------|------------------|------------|
| PKS 0302–16 | 03:05:15.04 | −16:08:16.3 | 2011 Jan 07.96 | 2016 Dec 04.2 | 0.12 |
| NVSS J070312–391418 | 07:03:12.66 | −39:14:18.9 | 2011 Dec 06.64 | 2016 Dec 01.1 | 0.35 |
| 3C 209 | 08:55:58.31 | −07:26:36.9 | 2011 Oct 26.93 | 2016 Dec 01.2 | 0.09 |
| 1RXS J094709.2–254506 | 09:47:09.50 | −25:41:00.0 | 2013 Oct 06.80 | 2016 Dec 04.3 | 0.20 |
| 2FHL J1155.5–3417 | 11:55:20.47 | −34:17:19.9 | 2016 Jul 26.80 | 2017 Feb 18.1 | 0.22 |
| 1WHSP J115633.2–225004 | 11:56:33.20 | −22:50:04.5 | 2016 Nov 24.15 | 2017 Feb 18.2 | 0.13 |
| PMN J1219–4826 | 12:19:02.270 | −48:26:28.1 | 2013 Jun 26.88 | 2017 Jan 25.2 | 0.33 |
| TXS 1515–273 | 15:18:3.59 | −27:31:30.6 | 2014 Sep 307 | 2017 Mar 21.2 | 0.22 |
| TAN 1716–771 | 17:23:50.81 | −77:33:50.5 | 2011 May 13.81 | 2017 Mar 21.2 | 0.70 |
| PMN J1758–4820 | 17:58:58.45 | −48:21:12.4 | 2013 Aug 17.70 | 2017 Mar 21.3 | 0.55 |
| 2WHSP J184121.7+290940 | 18:41:21.70 | −29:09:41.0 | 2015 Dec 10.86 | 2017 Jul 14.0 | 0.64 |
| PMN J1911–1908 | 19:11:29.73 | −19:08:24.5 | 2014 Jul 30.45 | 2017 Jun 09.2 | 0.43 |
| 1RXS J195500.6–160328 | 19:55:00.58 | −16:03:37.9 | 2014 Aug 06.98 | 2017 Jun 09.3 | 0.56 |
| RX J2030.8+1935 | 20:30:57.13 | +19:36:1 | 2014 Jun 01.54 | 2017 Jul 14.1 | 0.25 |
| PMN J2336–7620 | 23:36:27.59 | −76:20:37.8 | 2014 Jul 19.39 | 2017 Jul 10.4 | 0.19 |

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4 https://heasarc.nasa.gov/lheasoft/
Table 2

Swift-UVOT and SARA Photometry

| 3FGL Name   | $g'$       | $r'$       | $i'$       | $i''$      | $uvw2$     | $uvw2$     | $uvw1$     | $u$        | $b$        | $v$        |
|-------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|
| J0305.2−1607| >20.89     | 18.96 ± 0.06| 18.40 ± 0.06| 18.68 ± 0.17| 22.24 ± 0.12| 21.99 ± 0.14| 21.98 ± 0.16| 21.61 ± 0.19| 21.29 ± 0.26| >20.84     |
| J0703.4−3914| 18.71 ± 0.03| 17.54 ± 0.01| 15.76 ± 0.02| 16.38 ± 0.03| 20.42 ± 0.12| 20.46 ± 0.18| 20.16 ± 0.17| 19.31 ± 0.12| 18.93 ± 0.14| 18.61 ± 0.19|
| J0855.2−0718| 19.87 ± 0.12| 18.93 ± 0.05| 18.34 ± 0.08| 18.86 ± 0.28| 22.09 ± 0.22| 21.37 ± 0.24| 20.86 ± 0.17| 20.40 ± 0.19| 20.04 ± 0.25| >19.61     |
| J0947.1−2542| 16.74 ± 0.02| 16.50 ± 0.01| 17.41 ± 0.01| 16.49 ± 0.03| 17.73 ± 0.06| 17.75 ± 0.08| 17.45 ± 0.07| 17.09 ± 0.06| 16.77 ± 0.07| 16.78 ± 0.12|
| J1155.4−3417| 18.19 ± 0.02| 17.95 ± 0.01| 17.84 ± 0.02| 17.72 ± 0.04| 19.80 ± 0.14| 19.64 ± 0.15| 19.36 ± 0.17| 18.91 ± 0.18| 18.22 ± 0.17| 18.03 ± 0.24|
| J1156.7−2250| 19.17 ± 0.04| 18.91 ± 0.02| 18.76 ± 0.03| 18.73 ± 0.07| 20.77 ± 0.16| 20.37 ± 0.17| 20.30 ± 0.20| 19.64 ± 0.19| 19.20 ± 0.36| >18.91     |
| J1218.8−4827| 17.24 ± 0.04| 16.46 ± 0.02| 16.44 ± 0.02| 16.10 ± 0.04| 18.58 ± 0.09| 18.56 ± 0.18| 18.17 ± 0.10| 18.01 ± 0.12| 17.38 ± 0.11| 17.39 ± 0.18|
| J1518.0−2732| 17.44 ± 0.12| 16.51 ± 0.03| 16.20 ± 0.04| 15.97 ± 0.07| 18.67 ± 0.09| 18.75 ± 0.11| 18.46 ± 0.12| 17.81 ± 0.10| 17.60 ± 0.14| 16.97 ± 0.14|
| J1723.7−7713| 18.42 ± 0.05| 17.99 ± 0.02| 17.92 ± 0.03| 17.53 ± 0.06| 19.35 ± 0.22| >19.79     | 19.34 ± 0.28| >19.33     | 18.49 ± 0.29| >17.86     |
| J1759.1−4822| 15.57 ± 0.04| 13.03 ± 0.02| 15.24 ± 0.03| 15.26 ± 0.06| >17.87     | >17.52     | >17.33     | >16.97     | 16.17 ± 0.31| >15.65     |
| J1841.2+2910| 16.83 ± 0.01| 17.09 ± 0.01| 17.10 ± 0.01| 16.90 ± 0.03| 18.14 ± 0.18| >18.57     | 17.57 ± 0.18| 17.37 ± 0.20| 16.77 ± 0.19| >16.90     |
| J1911.4−1908| 18.24 ± 0.03| 17.62 ± 0.01| 17.30 ± 0.01| 16.97 ± 0.02| 19.83 ± 0.27| 19.73 ± 0.26| >19.46     | 18.69 ± 0.27| 18.34 ± 0.29| 17.66 ± 0.36|
| J1955.0−1605| 17.72 ± 0.05| 17.35 ± 0.02| 17.04 ± 0.02| 16.69 ± 0.03| 19.02 ± 0.20| >19.22     | 18.35 ± 0.26| 18.17 ± 0.20| 17.77 ± 0.24| >17.58     |
| J2031.0+1937| 17.52 ± 0.01| 17.93 ± 0.01| 17.75 ± 0.01| 17.57 ± 0.04| 18.33 ± 0.13| 18.45 ± 0.24| 18.17 ± 0.19| 17.50 ± 0.17| 17.45 ± 0.30| >16.95     |
| J2336.5−7620| 18.06 ± 0.05| 16.53 ± 0.02| 17.34 ± 0.03| 17.24 ± 0.08| 19.74 ± 0.16| 19.43 ± 0.22| 19.12 ± 0.17| 18.82 ± 0.18| 18.35 ± 0.20| 18.18 ± 0.32|
variable nature of blazars, we applied an additional systematic uncertainty of $\Delta m = 0.1$ mag for each UVOT filter, which was established by Rau et al. (2012).

Moreover, our previous works utilized the overlap between the $g'$ and $b'$ filters in GROND (Greiner et al. 2008) and Swift-UVOT for the intercalibration between the two instruments (see Krühler et al. 2011). Since the GROND and SDSS filters yield the same measurements in $g'$, $r'$, $i'$, $z'$ filters, we employ the same relationship as shown in Equation (1) to calibrate Swift-UVOT data with respect to the SARA observations. The offsets calculated from this equation in the $b$ band were applied to the all the UVOT filters. The resulting AB magnitudes from both instruments are provided in Table 2

$$b - g' = 0.15(g' - r') + 0.03(g' - r')^2. \quad (1)$$

4. SED Fitting

Under the assumption that the SED does not change with flux changes from the UV–Opt–near-IR regime for the BL Lacs and that it is dominated by the non-thermal synchrotron emission, the 10 filter data obtained in this work could be assumed to follow a power-law spectrum (typical of BL Lacs). The fitting program, LePhare v.2.2 (Arnouts et al. 1999; Illbert et al. 2006), was utilized to determine the photometric redshifts. This program is based on the $\chi^2$ statistics for evaluating the difference between the observational and theoretical models. It should be noted that this program includes the response curves for all the filters. Therefore, the red leaks for UVW1 and UVW2 are taken into account during the fitting procedure. In the context of this work, we employed three different libraries to fit our data. The first library consisted of 60 power-law templates of the form $F_\lambda \propto \lambda^{-\beta}$. The value of $\beta$ was chosen to be in the range 0–3, since the typical indices for BL Lacs in this wavelength range are in the abovementioned range. The dropout from the typical power-law fitting was employed to estimate the redshifts. The second and third libraries comprised of galaxy and stellar templates, respectively, were also fit to check any false associations. The galaxy templates were derived from Salvato et al. (2009, 2011) and the stellar templates were obtained from Pickles (1998), Bohlin et al. (1995), and Chabrier et al. (2000). Rau et al. (2012) performed Monte Carlo simulations for 27,000 test SEDs with $\beta$ between 0.5 and 2.0 and redshifts from 0 to 4, in order to test the reliability of this fitting procedure to determine the photometric redshifts. These simulations yielded that the sources with redshifts greater than 1.2 reproduced the results within an accuracy of $|\Delta z (1 + z_{\text{phot}})| < 0.15$. Moreover, upper limits for four sources were obtained as BL Lac c sources. The redshift estimates provided by the latter fits suggest $z = 1.5$ for each source. The details of the fitting method and the inference of these results are described in Sections 4 and 5, respectively.

![Figure 1. Swift-UVOT + SARA spectral energy distribution of the two high-z sources. The (solid line) power-law templates are fitted for each source with a clearly seen dropout toward the shorter wavelengths. In addition, the (dashed line) galaxy template fits to these objects are presented. The redshift estimates provided by the latter fits suggest $z = 1.5$ for each source. The details of the fitting method and the inference of these results are described in Sections 4 and 5, respectively.](image)

are shown in Figure 1. The redshifts for these two BL Lac sources were found to be $z = 1.83^{+0.10}_{-0.11}$ and $z = 1.73^{+0.11}_{-0.09}$, respectively, using the power-law template fits. In addition, galaxy templates were fit to these data, which yielded redshifts estimates, $z = 1.50^{+0.02}_{-0.03}$ and $z = 1.50^{+0.10}_{-0.07}$ assuming hybrid QSO templates from Salvato et al. (2011). Both the sources, 3FGL J1155.5-3417 and 3FGL J1156.6–2250 are identified as BL Lac (D’Abrusco et al. 2014) and HSP BCU II (Ackermann et al. 2015; associated with the BL Lac class), respectively; therefore, the redshift estimates provided by the QSO templates with prominent broad emission lines are rather unlikely. Moreover, the QSO templates yield redshift estimates without including any fit to the optical emission lines (See Figure 1), we therefore assume the redshift estimated provided by the power-law fits to be more precise. Therefore, the rest of the analysis will be based on the redshift estimates derived from power-law fits. Moreover, upper limits for four sources were established. All these results are presented in Table 3. None of the sources in our sample were consistent with the stellar templates used for the SED fitting; therefore, those results are not displayed in Table 3.

The outcome of the combined analysis of BL Lac observations taken at different epochs can be affected by spectral variability. To verify our findings of two new high-z sources, we obtained new observations for these two sources using Swift and SARA simultaneously on 2017 December 28 and 27, respectively. The results of this analysis yielded $z = 1.73^{+0.11}_{-0.15}$ and $z = 1.83^{+0.12}_{-0.15}$ for 3FGL J1155.5+3417 and 3FGL J1156.6–2247, respectively, which are consistent with our archival data analysis, within the uncertainties.
6. Discussion and Conclusions

The two newly discovered high-z BL Lacs are also part of the recent third catalog of high-energy sources (3FHL, Ajello et al. 2017, 3FGL J1155.5+3417 is also present in the 2FHL Ackermann et al. 2016 catalog). Therefore, we utilized the 3FGL and 3FHL catalogs to construct the SEDs of these two sources. These were fitted with a power law with an EBL absorption of the form, $e^{-\tau(E, \gamma)}$ using the Domínguez et al. (2011) model as illustrated in Figures 2 and 3. These fits indicate that the observed flux at high energies from these two sources was reduced by a factor of $\sim 10$, due to the EBL absorption, in both cases. We also reproduced the cosmic gamma-ray horizon plot (i.e., the redshift at which, for a given energy, the universe becomes opaque to $\gamma$ rays, see Domínguez et al. 2013) using all the sources in the

![Spectral energy distribution of 3FGL J1155.4-3417 using the 3FGL and 3FHL catalogs. The black line is a power-law fit to the 3FHL data, which is absorbed by the EBL, utilizing Domínguez et al. (2011).](image)

**Table 3**

| SED Fitting |
|-------------|
| **3FGL Name** | **$z_{\text{phot, best}}$** | **Power-law Template** | **Galaxy Template** |
| | | $\chi^2$ | $P_{\nu}$ | $\beta$ | $\chi^2_{\text{phot}}$ | $P_{\nu}$ | Model |
| J1155.4−3417 | 1.83$^{+0.10}_{-0.13}$ | 20.0 | 99.9 | 0.65 | 1.50$^{+0.02}_{-0.05}$ | 28.8 | 100.0 | pl_QSOH_template_norm.sed |
| J1156.7−2250 | 1.73$^{+0.11}_{-0.19}$ | 9.2 | 98.5 | 0.70 | 1.50$^{+0.02}_{-0.07}$ | 7.1 | 99.9 | pl_QSOH_template_norm.sed |

**Sources with Photometric Redshift Upper Limits**

| J0305.2−1607 | ... | 0.85$^{+0.01}_{-0.18}$ | 565.2 | 45.8 | 0.80 | 1.22$^{+0.02}_{-0.02}$ | 297.3 | 93.6 | S0_template_norm.sed |
| J0703.4−3914 | ... | 4.00$^{+0.00}_{-0.01}$ | 267.6 | 100.0 | 0.45 | 0.61$^{+0.04}_{-0.04}$ | 25.4 | 89.5 | Sey2_template_norm.sed |
| J0855.2−0718 | ... | 3.86$^{+0.00}_{-0.00}$ | 128.0 | 82.3 | 1.10 | 0.45$^{+0.02}_{-0.02}$ | 39.3 | 99.9 | M82_template_norm.sed |
| J0947.1−2542 | ... | 1.63$^{+0.10}_{-0.08}$ | 70.6 | 99.9 | 0.45 | 1.33$^{+0.08}_{-0.04}$ | 24.9 | 63.6 | pl_TQS01_template_norm.sed |
| J1218.8−4827 | ... | 1.23$^{+0.27}_{-0.08}$ | 181.7 | 50.9 | 1.40 | 0.26$^{+0.01}_{-0.01}$ | 28.8 | 100.0 | pl_QSOH_template_norm.sed |
| J1518.0−2732 | <1.1 | 0.05$^{+0.03}_{-0.05}$ | 22.9 | 16.8 | 1.85 | 0.19$^{+0.06}_{-0.06}$ | 11.07 | 98.0 | Mrk231_template_norm.sed |
| J1723.7−7713 | ... | 2.74$^{+0.21}_{-0.04}$ | 44.3 | 99.5 | 0.80 | 0.01$^{+0.01}_{-0.01}$ | 19.8 | 99.8 | Spi4_template_norm.sed |
| J1759.1−4822 | ... | 3.86$^{+0.00}_{-0.00}$ | ... | ... | ... | ... | ... | ... | ... |
| J1841.2+2910 | ... | 2.06$^{+0.04}_{-0.10}$ | 176.7 | 100.0 | 0.45 | 0.45$^{+0.03}_{-0.03}$ | 244.9 | 100.0 | S0_80_QSO2_20.sed |
| J1911.4−1908 | <1.6 | 1.33$^{+0.28}_{-0.13}$ | 21.2 | 41.0 | 1.60 | 0.06$^{+0.02}_{-0.02}$ | 7.1 | 100.0 | Mrk231_template_norm.sed |
| J1955.0−1605 | <1.2 | 0.03$^{+0.05}_{-0.03}$ | 25.7 | 13.6 | 1.65 | 1.26$^{+0.05}_{-0.05}$ | 36.2 | 100.0 | J22491.90_TQS01_10.sed |
| J2031.0+1937 | ... | 2.03$^{+0.10}_{-0.04}$ | 247.8 | 100.0 | 0.05 | 1.93$^{+0.02}_{-0.05}$ | 255.9 | 100.0 | J22491.70_TQS01_20.sed |
| J2336.5−7620 | <1.5 | 1.33$^{+0.22}_{-0.11}$ | 9.5 | 60.8 | 1.35 | 0.08$^{+0.04}_{-0.04}$ | 8.9 | 100.0 | Spi4_template_norm.sed |

**Notes.**

a Best photometric redshift.
b Photometric redshifts with $2\sigma$ confidence level.
c Redshift probability density at $z_{\text{phot}} \pm 0.1 (1 + z_{\text{phot}})$.
d Spectral slope for the power-law model of the form $F_{\nu} \propto \lambda^{-\beta}$. 



3FHL catalog and including the two new sources found here. This is displayed in Figure 4, which shows that the photometric method is able to find γ-ray sources that can constrain the cosmic γ-ray horizon (CGRH), which is defined by the energy at which the optical depth τ is one, as a function of redshift, at redshifts where data are scarce. Interestingly, the highest energy photon from J1155.4-3417 lies above the CGRH with τ ≈ 2.8. The objects discovered with our photometric technique (the two reported here and also those in Rau et al. 2012 and Kaur et al. 2017) allow us to probe a region of the cosmic γ-ray horizon where measurements are scarce and as such they allow us to better constrain the EBL. Indeed, the detection of many high-energy photons above the horizon may imply that the EBL model used may be too opaque to characterize the real level of the EBL in the universe. In the case of Figure 4, the model of Gilmore et al. (2012) is less favored (because it is more opaque) than that of Domínguez et al. (2011). To understand how these high-γ BL Lacs fit within the larger blazar population (Maraschi et al. 1995; Sambruna et al. 1996; Fossati et al. 1998), we calculated various parameters like the synchrotron peak frequency ν_{ps}, the luminosity at the synchrotron peak (L_{ps}), and the Compton Dominance (CD, the ratio between the luminosities of the inverse Compton and synchrotron peaks). Fossati et al. (1998) observed some correlations between the abovementioned parameters using the available blazar data. This
Figure 5. Peak synchrotron frequency in the rest frame ($\nu_{\text{pk}}^{\text{sy}}$) vs. the peak synchrotron luminosity ($L_{\text{pk}}^{\text{sy}}$). The magenta stars represent the two new sources found in the present work. These are consistent with the other high-z BL Lacs using the photometric method, which displays the high luminosity and high-synchrotron peak behavior. We show six new BL Lacs from Rau et al. (2012, cyan diamonds), five BL Lacs from Kaur et al. (2017, yellow squares), and all the FSRQs and BL Lacs from the 3LAC catalog with known redshifts (red and blue circles, respectively). The separation of the LSP, ISP, and HSP regions are also plotted (dotted lines).

Figure 6. Relationship between the Compton dominance and $n_{\text{pk}}^{\text{sy}}$. The color scheme for data symbols follows from Figure 5. All of the upper limits, including the ones from this work are represented by green filled triangles. The black horizontal lines represent the range of $\nu_{\text{pk}}^{\text{sy}}$ for redshifts from zero to the upper limits, provided in our sample.
sequence indicates that the more luminous blazars possess lower synchrotron frequencies, but substantial γ-ray emission (FSRQs in general), whereas BL Lacs are less luminous, but achieve larger synchrotron peak frequencies. We test these correlations by plotting all the blazars in the 3LAC catalog, together with the high-z BL Lacs discovered in all of our photometric campaigns. Figure 5 suggests the presence of large luminosity, high-frequency synchrotron peak blazars, which do not fit very well with the known blazar sequence scheme. Although, in order to draw a more robust conclusion in this scenario, a larger sample of such sources is required. Figure 6 displays peak synchrotron frequency versus compton dominance and shows that all of our BL Lacs display CD ≤ 1, which is consistent with the typical SED of this subclass of blazars, suggesting a more dominant synchrotron emission.

Including the results of this work, our continuing photometric method has discovered 13 BL Lacs. Overall, 26 (including the 2 found here) BL Lacs are known in the literature with z > 1.3, of which 50% were provided by us. Moreover, the accuracy of this method was shown in Figure 2 in Kaur et al. (2017) by successfully matching the spectroscopic and photometric redshift estimates for the BL Lacs.

In the present 3LAC catalog (Ackermann et al. 2013), about 300 BL Lacs lack redshift measurements. The primary objective of our photometric program is to provide the redshifts or at least the upper limits for the 3LAC catalog for all the BL Lacs. Based on the previous results, this work has yielded a total of 16 sources (9–6 new—from Rau et al. 2012, 5 from Kaur et al. 2017, and 2 from this work) with high redshifts from sample sizes of 103, 40, and 15, respectively. Based on the probability of finding 10%–15% of BL Lacs at the high redshifts from our samples, we estimate that we will obtain 30–35 more high-z BL Lacs from the 3LAC catalog, which has ~300 BL Lacs with no redshifts measurements. This will provide a total number of ~50 high-z BL Lacs, leading to the completion of this work and more importantly, will provide a large enough sample of BL Lacs at high redshifts for EBL studies.

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