Looking for blazars in a sample of unidentified high-energy emitting Fermi sources

E. J. Marchesini1,2,3,4,5, N. Masetti5,6, V. Chavushyan7, S. A. Cellone1,2, I. Andruchow1,2, L. Bassani5, A. Bazzano8, E. Jiménez-Bailón9, R. Landi5, A. Malizia5, E. Palazzi5, V. Patiño-Álvarez7, G. A. Rodríguez-Castillo10, J. B. Stephen5, and P. Ubertini8

1. Introduction

The most important objective of the Fermi mission is to study the whole sky at γ-ray energies; this is achievable with the use of the Large Area Telescope (LAT) thanks to its large collecting area and field of view (Atwood et al. 2009). The location accuracy of the telescope, which detects γ-ray objects emitting at GeV energies, is between 0.5 to 10 arcmin, depending on the source detection significance.

There are more than 3000 sources listed in the latest release of the Fermi catalogue (Acero et al. 2015). Of these, only 238 are considered firm identifications by the LAT team, based on spatial morphology, correlated variability, and/or periodic lightcurve properties. Another ~1800 sources have high confidence associations, based on cross-correlations with multwavelength catalogues. The majority of these identified and associated sources belong to one of the following categories: extragalactic objects such as blazars (flat spectrum radio quasars or BL Lacs), or Galactic sources (mainly pulsars, pulsar wind nebulae, and supernova remnants). However, there is still an important number of sources (about 30%) without proper identification, i.e. lacking association with any known class of γ-ray emitting objects, which constitute the class of unidentified/unassociated gamma-ray sources (UGSs).

A similar but less critical situation is found when considering the First Fermi Catalog of detected sources above 10 GeV (1FHL; Ackermann et al. 2013): from a total of 514 listed sources, 65 (~13%) are UGSs. These are also the numbers resulting from analysing the Second Fermi Catalog of detected sources above 50 GeV (Ackermann et al. 2016, 2FHL): it lists 360 sources, of which 48 (14%) are UGSs.

The search for counterparts of these new high-energy sources is hindered by the relatively large (in comparison with longer...
wavelengths) \textit{Fermi} positional error ellipses. This uncertainty in their location means that positional correlations with known objects is often not enough to identify a \textit{Fermi} source; thus, a multiwavelength approach is needed in order to understand their nature, using X-ray, optical and radio data of likely counterparts. X-ray data analyses are particularly useful in finding a positionally correlated object with broadband spectral parameters that might be expected in a γ-ray emitting source. Soft X-ray surveys (i.e. with energies below 10 keV) are convenient for this task because they offer 3 great advantages: they cover the whole \textit{Fermi} error ellipse, their positional accuracy is of the order of arcseconds, and they provide information in an energy band close to that at which the \textit{Fermi}-LAT operates. Since most of the 1FHL sources are BL Lacs and in particular high-energy cutoff BL Lacs (HBL), and as they show the peak of the SED synchrotron component in the X-rays, cross-matching the \textit{Fermi} catalogue with X-ray surveys should prove useful as a tool to select them. This allows the positional uncertainty of the objects detected with \textit{Fermi} to be restricted, thus facilitating the identification process.

To this end, following Stephen et al. (2010), Landi et al. (2015a,b,c) performed a crossmatch between the positions in the 1FHL catalogue, the ROSAT All-Sky Survey Bright Source Catalogue of sources detected between 0.1–2.4 keV (Voges et al. 1999), the 1SXPS Catalogue of X-ray sources detected with Swift/XRT in the 0.3–10 keV band (Evans et al. 2014), and pointed XRT observations available at the ASI Science Data Center archive. They found correlations with a strong level of confidence (∼90%), leading to evidence for the potential association of a number of UGSs with X-ray counterparts, improving the positional error in all correlated objects, and thus opening the possibility for optical follow-up.

In particular, 36 secure 1FHL/X-ray potential associations were obtained which allowed the selection of a likely low-energy (optical and below) counterpart for all of them. An investigation of the nature of these sources on the basis of their archival multiwavelength properties indicates that all potential associations are either recently identified blazars (Landi et al. 2015c; Landoni et al. 2015; Massaro et al. 2015b; Ricci et al. 2015) or blazar candidates (Landi et al. 2015b,a). The majority of blazars are expected to show γ-ray emission in the GeV range (e.g. Acero et al. 2015). Nevertheless, 24 of the potential 36 associations are still lacking an optical spectroscopic confirmation of their nature.

According to Stephen et al. (2010) and Landi et al. (2015b), 1FHL sources like these can be responsible for the emission of very high energy γ-rays, up to the teraelectronvolt (TeV) range (Padovani & Giommi 1995; Fossati et al. 1998). The interest in extreme TeV blazars arises from the possibility of obtaining information on both the acceleration processes of charged particles in relativistic flows (e.g. Ghisellini et al. 2010) and the intensity of the extragalactic background light (e.g. Georganopoulos et al. 2010), which reflects the time-integrated history of light production and re-processing in the Universe, and hence its measurement can provide information on the history of cosmological star formation (Mankuzhiyil et al. 2010). This is important when considering that in the 1FHL catalogue, only 22 (<6%) objects of the AGN type are considered to be firmly identified out of a total of 393 cases (Ackermann et al. 2013). This is why the confirmation of the nature of even a small subset of the unidentified objects of the 1FHL sample would significantly increase the statistics of the GeV/TeV emitting blazars class, which in turn is only achievable after finding the proper association. This would also be relevant for a future search of TeV blazars that can be performed with the Cherenkov Telescope Array (Massaro et al. 2013b).

Furthermore, as the number of detected sources in the high-energy surveys is growing at an ever-increasing speed, it is necessary to establish well-defined methods to correctly identify and classify as many objects as possible while strictly reducing their positional uncertainties. Therefore, the aim of this work is to spectroscopically analyse 14 optical targets with near-positional coincidence with the X-ray sources out of those 24 without classification. Following the treatment of Stephen et al. (2010), we expect no more than only one spurious correlation out of the selected sample of 14 objects.

In the following sections, we describe our optical follow-up work on a subsample of 14 of the aforementioned potentially associated objects from the 1FHL catalogue. From these, only 1FHL J1549.9-0658 appears in the 2FHL catalogue (named 2FHL J1549.8-0659), although there is also a detection positionally consistent (2FHL J0639.9-1252, at a distance of ∼3 arcmin) with 1FHL J0639.6-1244. The reason why only one of the 1FHL objects from our sample can be found in the 2FHL catalogue is the energy threshold: the 2FHL catalogue includes only those sources detected at 50 GeV or more, while the 1FHL catalogue has a threshold of 10 GeV.

We note that 1FHL J1410.4+7408 shows two different X-ray objects (Landi et al. 2015b) within its γ-ray positional error box, each with a single corresponding optical source. We define 1FHL J1410.4+7408 A as the one marked as #1 in Landi et al. (2015b), and 1FHL J1410.4+7408 B as the one marked as #2. In Sect. 2 we briefly discuss the selection of the sample, in Sect. 3 we describe the observations, in Sect. 4 we analyse our results, and in Sect. 5 we summarise our conclusions.

2. Sample selection

Our sample of 1FHL fields is a subset of those presented in Landi et al. (2015a,b).

They found only one X-ray counterpart for each \textit{Fermi} source, with the exception of 1FHL J1410.4+7408. However, despite the better positional accuracy achieved, it is important to note that X-ray error circles are still large enough (i.e. ∼6 arcsec) to find more than one optical source tentatively associated with each single X-ray counterpart. Thus, a supplementary investigation is needed to single out the actual counterpart of the γ-ray/X-ray emitter. For this reason, we set up an international campaign to obtain spectroscopic observations of candidate optical counterparts in 13 fields, which are the subject of this paper. Details on the observations can be found in Table 1.

3. Observations

The optical spectroscopic observations were carried out at four different observatories for a total of 18 nights:

- Three nights (from 10 Mar. 2015 to 12 Mar. 2015) at the 1.52 m \textit{Cassini} Telescope of the Bologna Observatory in Loiano (LOI), Italy, with the BFOSC spectrograph and a 2.0 arcsec slit (0.40 nm/px dispersion). The data covered a range from 350 to 800 nm.
- Three nights (19 May 2015, 21 Jun. 2015, and 09 Jul. 2015) at the 3.58 m \textit{Telescopio Nazionale Galileo} (TNG) in La Palma, Canary Islands, Spain, with the DOLORES (LRS)
Astronomy (AURA) under a cooperative agreement with the National Optical Astronomy Observatory, in Col. 5 the observatory, in Col. 6 the date of observation, in Col. 7 the UT time at mid exposure, and in Col. 8 the total exposure time in seconds.

Notes. We report the name in the USNO and X-rays catalogues in Col. 2, in Cols. 3 and 4 coordinates referring to J2000.0 for each optical target, in Table 2, where we report in Col. 1 the USNO source name along with the name of the proposed 1FHL counterpart and the distance between them, in Col. 2 the emission and absorption lines found (if any), in Cols. 3 and 4 their measured equivalent widths and fluxes, in Col. 5 the derived redshift (if any), and in Col. 6 the UT time at mid exposure, and in Col. 7 the total exposure time in seconds for each of the optical pointings.

| Number | USNO designator | RA(J2000) | Dec(J2000) | Observatory | UT date [mm/dd/yy] | Time [mid. exp.] | Total exp. [s] |
|--------|----------------|-----------|------------|-------------|-------------------|----------------|---------------|
| 1      | U0750-00173701  | 00°43′54″66′′ | −11°16′07″2′′ | NOT         | 10/13/2015 02 : 46 : 41 | 1200           |
| 2      | U0975-00792795  | 03°38′29″24′′ | +13°02′15″2′′ | NOT         | 10/13/2015 04 : 59 : 08 | 1200           |
| 3      | U0675-01653184  | 04°39′49″54′′ | −19°01′02″5′′ | NOT         | 10/13/2015 05 : 35 : 13 | 1200           |
| 4      | U0750-02519189  | 06°40′07″31′′ | −12°53′18″6′′ | NOT         | 10/13/2015 06 : 08 : 22 | 1200           |
| 5      | U0875-0218538   | 07°46′27″14′′ | −02°25′50″7′′ | NOT         | 10/14/2015 04 : 53 : 16 | 1200           |
| 6      | U0825-05946383  | 08°04′57″74′′ | −06°24′26″3′′ | LOI         | 03/10/2015 21 : 21 : 16 | 3600           |
| 7      | U0825-05946383  | 11°15′15″58′′ | −07°01′25″6′′ | SPM         | 01/14/2016 12 : 31 : 40 | 1800           |
| 8      | U0750-08080787  | 13°15′52″98′′ | −07°33′02″0′′ | LOI         | 03/13/2015 00 : 57 : 54 | 3600           |
| 9      | U1575-03416792  | 14°10′45″83′′ | +74°05′11″1′′ | TNG         | 08/26/2015 22 : 36 : 36 | 2400           |
| 10     | U1575-03416943  | 14°10′52″03′′ | +74°04′15″1′′ | TNG         | 08/26/2015 23 : 40 : 59 | 1200           |
| 11     | U0600-17715078  | 15°12′12″76′′ | −22°55′08″4′′ | TNG         | 08/27/2015 22 : 41 : 45 | 2000           |
| 12     | U0825-08948904  | 15°49′52″17′′ | −06°59′08″3′′ | TNG         | 08/27/2015 23 : 30 : 37 | 2400           |
| 13     | U1125-10089754  | 18°41′21′′12′′ | +29°09′41″2′′ | TNG         | 08/27/2015 00 : 24 : 02 | 1600           |
| 14     | U1530-0317394   | 20°02′45″36′′ | +63°02′33″6′′ | TNG         | 08/29/2015 00 : 03 : 54 | 3600           |

Notes. We report the name in the USNO and X-rays catalogues in Col. 2, in Cols. 3 and 4 coordinates referring to J2000.0 for each optical target, in Col. 5 the observatory, in Col. 6 the date of observation, in Col. 7 the UT time at mid exposure, and in Col. 8 the total exposure time in seconds for each of the optical pointings.

The data covered a range from 370 to 500 nm.

- Two nights (13 Oct. 2015 and 14 Oct. 2015) at the 2.5 m Nordic Optical Telescope (NOT), in La Palma, Canary Islands, Spain, with the ALFOSC spectrograph and a 1.0 arcsec slit (0.30 nm/pixel dispersion). The data covered the 350 to 900 nm range.
- Eight nights (from 06 Nov. 2015 to 09 Nov. 2015 and from 14 Jan. 2016 to 17 Jan. 2016) at the 2.12 m telescope in San Pedro Mártir (SPM), Mexico, with the Boller & Chivens spectrograph and a 2.5 arcsec slit (0.23 nm/pixel dispersion). The data covered a range from 350 to 800 nm.

The data were cleaned from cosmic rays, bias corrected, flat-fielded, and both wavelength and flux calibrated using IRAF standard packages, wavelength calibration lamps, and spectrophotometric standard stars. In each case, the estimated wavelength calibration error is less than 0.4 nm.

2 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation.

4. Results

In Fig. 1, we present the optical spectra for each analysed object in the upper panels, while in the lower panels we show the continuum-normalised spectra in order to highlight the presence of spectral features (if any).

In 12 out of 14 cases, the spectra resulted in non-thermal continua. Moreover, no intrinsic features were present in 10 out of 14 objects. Both are typical characteristics of blazar spectra. In all cases in which some features are found, a redshift (or at least a lower limit to it) was derived, in addition to obtaining equivalent widths and fluxes for all lines, in order to determine the nature of each source. Results from our analysis can be found in Table 2, where we report in Col. 1 the USNO source name along with the name of the proposed 1FHL counterpart and the distance between them, in Col. 2 the emission and/or absorption lines found (if any), in Cols. 3 and 4 their measured equivalent widths and fluxes, in Col. 5 the derived redshift (if any), and in Col. 6 the classification of the source. Further details are shown in the next sections.

It is worth mentioning that, in the cases of 1FHL J1115.0-0701 and 1FHL J0043-1115, the correlation with X-ray data in the next sections.
Fig. 1. Optical spectra obtained for the whole sample presented in this paper. Upper panels show the observed spectra, while lower panels show the spectra with normalised flux. Absorption lines or bands present at 686.9 nm, 718.6 nm, and 760.5 nm are telluric. Absorption lines present at 589.0 nm and 589.6 nm correspond to the NaI doublet from the interstellar medium, although in the case of 1FHL J0639.6-1244 it could possibly be superimposed on the MgI line at z = 0.135. Lines marked “DIB” correspond to diffuse interstellar bands, while those marked with a question mark are hard to identify because they are on the edge of detection and because of the lack of other lines to obtain a redshift value. Sources are given with their USNO designator, while the proposed 1FHL counterpart is given in parenthesis.
while in optical wavelengths (as seen in the USNO plates, with a limiting magnitude of $V \approx 21$ mag) two objects could be found within the X-ray error circle. In both cases, the other object was also analysed and ruled out because of its star-like spectrum, i.e. showing a thermal continuum, no emission lines, and a variety of absorption lines potentially associated with stellar processes (for instance, the Balmer series) at redshift zero. A different case is that of fields 1FHL J1410.4+7408 A and B, which are potentially associated with the same source in the 1FHL catalogue but for which two X-ray objects were found within the γ-ray error ellipse (Landi et al. 2015b) and, consequently, two putative optical counterparts could be potentially associated with this γ-ray source. This case will be discussed in Sect. 5.2.

Once confirmed as potential counterparts (i.e. after discarding all the sources from which no high-energy emission is expected, as for example stars), we improved their equatorial coordinates by searching for detected objects in the 2MASS (Skrutskie et al. 2006) catalogue, which provides positions with uncertainties of less than 0.1 arcsec. Only four of them were not found in this catalogue: the optical sources potentially associated with 1FHL J1410.4+7408 A, B, and 1FHL J1549.9+0658, and 1FHL J1841.1+2914. Nevertheless, the first three were found in the USNO-A2.0 catalogue (Monet 1998), and the last one in the USNO-B1.0 catalogue (Monet et al. 2003), which provide an accuracy of 0.2 arcsec.

Source details are given in the following subsections.
Table 2. Nature of each of the observed optical counterpart candidates for 1FHL sources.

| USNO designator | Features | EW [Å] | Flux | Redshift | Class |
|-----------------|----------|--------|------|----------|-------|
| 1FHL association (Distance) | (1) | (2) | (3) | (4) | (5) | (6) |
| U0750-00173701 | – | – | – | – | BL Lac |
| 1FHL J0044.0-1111 (5.7) | – | – | – | – | |
| U0975-00792795 | – | – | – | – | BL Lac |
| 1FHL J0338.4+1304 (2.5) | – | – | – | – | |
| U0675-01653184 | – | – | – | – | BL Lac |
| 1FHL J0439.9-1858 (2.9) | – | – | – | – | |
| U0750-02519189 | G | 1.0 ± 0.6 | –8 ± –4 | 0.135 ± 0.001 | BL Lac |
| 1FHL J0639.6-1244 (10.7) | Na | 2.3 ± 1 | –21 ± –10 | | |
| U0875-0218538 | – | – | – | – | BL Lac |
| 1FHL J0746.3-0225 (1.7) | – | – | – | – | |
| U0825-05946383 | – | – | – | – | BL Lac |
| 1FHL J0804.8-0626 (2.1) | – | – | – | – | |
| U0825-05946383 | Lyα | 312 ± 28 | 95 ± 10 | 2.929 ± 0.003 | QSO |
| 1FHL J1115.0-0701 (3.2) | NV | 262 ± 49 | 76 ± 12 | | |
| SiV/OIV | 79 ± 14 | 21 ± 3 | | | |
| CIV | 264 ± 31 | 82 ± 6 | | | |
| U0750-08080787 | – | – | – | – | BL Lac |
| 1FHL J1315.7-0730 (3.3) | – | – | – | – | |
| U1575-03416792 | MgII | 17 ± 6 | 15 ± 4 | 0.429 ± 0.001 | NLS1 |
| 1FHL J1410.4+7408 A (4.4) | Hγ | 18 ± 9 | 9 ± 4 | | |
| 1FHL J1410.4+7408 B (3.3) | Hβ | 35 ± 14 | 14 ± 5 | | |
| [OIII] | – | – | | | |
| U1575-03416943 | – | – | – | – | BL Lac |
| 1FHL J1410.4+7408 B (3.3) | – | – | – | – | |
| U0600-17715078 | – | – | – | – | BL Lac |
| 1FHL J1512.1-2255 (1.0) | – | – | – | – | |
| U0825-08948904 | – | – | – | – | BL Lac |
| 1FHL J1549.9-0658 (1.4) | – | – | – | – | |
| U1125-10087954 | – | – | – | – | BL Lac |
| 1FHL J1841.1+2914 (5.6) | – | – | – | – | |
| U1530-0317394 | FeII | 11 ± 7 | –1.5 ± –0.9 | ≥0.9 | BL Lac |
| 1FHL J2002.6+6303 (1.1) | MgIIa | 10 ± 3 | –1.6 ± –0.6 | | |
| 1FHL J2002.6+6303 (1.1) | MgIIb | 7 ± 2 | –1.1 ± –0.4 | | |

Notes. The units for all the reported flux densities are $1 \times 10^{-16} \text{erg cm}^{-2} \text{s}^{-1} \text{Å}^{-1}$. The equivalent width (EW) is given in the observer’s frame. Emission lines are given as positive flux values, and absorption lines as negative flux values. The distance between the USNO source and the 1FHL centroid is given in arcseconds.

4.1. BL Lacs

Out of the 14 optical sources observed, we were able to classify 12 as blazars of BL Lac class. These are our associations with Fermi sources 1FHL J0044.0-1111, 1FHL J0338.4+1304, 1FHL J0439.9-1858, 1FHL J0639.6-1244, 1FHL J0746.3-0225, 1FHL J0804.8-0626, 1FHL J1315.7-0730, 1FHL J1410.4+7408 B, 1FHL J1512.1-2255, 1FHL J1549.9-0658, 1FHL J1841.1+2914, and 1FHL J2002.6+6303. Indeed, all the sources show a non-thermal, power-law, intrinsically blue continuum, and no apparent intrinsic emissions or absorptions, with the exception of U0750-02519189 (associated with 1FHL J0639.6-1244), in which its host galaxy contribution is visible (meaning it is a blazar of the BZG type, as described by the Roma-BZCAT catalogue in Massaro et al. (2015a)), showing Na and G-band absorptions at a redshift $z = 0.135 ± 0.001$. This, alongside a lower limit for the redshift of our association for 1FHL J2002.6+6303, U1530-0317394 ($z \geq 0.9$), obtained from the detection of intervening FeII and MgII absorptions, is the only value for $z$ we were able to derive from the spectra of this BL Lac subsample.

In the case of the optical association of 1FHL J0804.8-0626, there are two optical sources inside the X-ray error box, according to the USNO plates. Both of them were observed and analysed. The faintest one (at optical position 80°04′58″48″, −6°24′21″51″) showed a normal G-type star spectrum, thus discarding any possibility of potential association with the high-energy emitting source. The coordinates published in Table 1 are thus those of the BL Lac conclusively associated through optical spectroscopy, which is the WISE source suggested by Landi et al. (2015a) and which we associate with the γ-ray source.

4.2. U1575-03416943

This source potentially associated with 1FHL J1410.4+7408 A shows clear emission lines (MgII, Hδ, Hγ, Hβ, and [OIII]) at a common redshift $z = 0.429 ± 0.001$. Given that the velocities
associated with the emission of the Hβ line are around 1450 km s^{-1}, and that the ratio between the fluxes of emission lines \([\text{[OIII]}] \) and \([\text{Hβ}] \) is \(\leq 0.5\), we conclude that this object is a narrow line Seyfert 1 galaxy (NLS1, Osterbrock & Pogge 1985; Goodrich 1989).

4.3. U0825-05946383

The field associated with 1FHL J1115.0-0701 presented two optical sources within the X-ray positional uncertainty box, according to the USNO plates. In this case, again, both spectra were analysed, and we could discard one of them on the basis of typical stellar features (in particular, we classified it as a K-type star, at position 11°15′15″, -07°01′26″/9″).

The spectrum of the other optical source shows strong, luminous emission lines for Lyα, NV, SIV, and CIV, at the high redshift value of \(z = 2.929 \pm 0.003\); these characteristics are typical of a high-redshift quasar. However, its potential association with the 1FHL source is not ironclad (see Sect. 5.3).

5. Discussion

In this section we analyse in detail the spectral characteristics of the results obtained for the 14 objects we spectroscopically associated in this work. In particular, we discuss general properties in subsets divided by class of object: BL Lacs (12 objects), NLS1 (1 object), and quasars (1 object).

5.1. BL Lacs

In order to analyse the emission processes involved, we built a plot of spectral indices as shown in Abdo et al. (2010), which is useful to easily spot the synchrotron peak for each object. To this end, and following Masetti et al. (2013), we searched for the X-ray fluxes of the sources in our sample as measured with XRT or ROSAT, corrected from Galactic absorption with PIMMS (Mukai 1993) using the Galactic \(N_H\) values given by Landi et al. (2015b), when available, or those given by Kalberla et al. (2005). We also retrieved their \(R\) magnitudes from the USNO catalogues, from which we derived absorption-corrected fluxes using the absorption maps from Schlegel et al. (1998), the reddening law of Cardelli et al. (1989), and the total-to-selective extinction ratio of Rieke & Lebofsky (1985); with the conversion factor of Fukugita et al. (1995) we then rescaled the flux values to 500 nm using the same procedure given by Masetti et al. (2013). Furthermore, we obtained their radio flux density at 1.4 GHz, when available, from the NVSS catalogue (Condon et al. 1998) and rescaled them to 5 GHz assuming a radio flat spectral shape (Begelman et al. 1980) in order to use the same relationship given in Abdo et al. (2010).

With the radio, optical, and X-ray absorption-corrected fluxes we were able to obtain spectral indices \(\alpha_{\text{ro}}\) from X-ray to optical and \(\alpha_{\text{ro}}\) from optical to radio frequencies. In Fig. 2, we included all the sources from this sample, numbered in order of right ascension (see Table 1), in a \(\alpha_{\text{ro}} - \alpha_{\text{ro}}\) plot (Padovani & Giommi 1995; Abdo et al. 2010). In dashed lines, we indicate the location of synchrotron peaks at low (10^{14} Hz), intermediate (10^{15} Hz), and high (10^{16} Hz) frequencies. Eight BL Lacs in our sample have their synchrotron peaks at a frequency higher than 10^{15} Hz, which are likely candidates to be detected at TeV energies (Massaro et al. 2008). It is important to highlight that the BL Lac associated with 1FHL 1410.4+7408 B did not show any radio emission, which is why we used the detection threshold from the NVSS survey (2.5 mJy) as upper limit to its radio flux density. The resulting lower limit to \(\alpha_{\text{ro}}\) is indicated in the plot with an arrow.

For completeness, we also included the recently studied optical objects associated with 1FHL J1129.2-7759, 1FHL J1328.5-4728, and 1FHL 2257.9-3644 which were confirmed as BL Lacs by Massaro et al. (2015b) (for which we found an intermediate synchrotron peak, marked with an M in Fig. 2), Ricci et al. (2015) (which shows a low synchrotron peak, marked with an R) and Landi et al. (2015) (intermediate synchrotron peak, marked with an L), respectively. These objects are also part of the sample selected by Landi et al. (2015a) and Landi et al. (2015b). In addition, we added the two non-BL Lac objects from our sample, the potential associations with 1FHL J1414.0+7408 A (the NLS1 presented in Sect. 4.2) and 1FHL J1115.0-0701 (the quasar) just to present the whole sample in one plot, although it is not possible to compare these sources with BL Lacs given that this kind of objects generally present a thermal emission component which cannot be easily separated from the non-thermal one. Neither one presents radio emission, as seen in Fig. 2, so also in this case we used the NVSS threshold value to determine a lower limit for \(\alpha_{\text{ro}}\).

5.2. The case of 1FHL J1414.0+7408

As 1FHL J1414.0+7408 is potentially associated with two different X-ray emitting and optically peculiar objects according to Landi et al. (2015b), it is not clear which of them is responsible for the detected y-ray emission.

Given that the spectral index of the y-ray source, according to the 1FHL catalogue, is \(\alpha_y = 2.65\), its counterpart is more likely a flat spectrum radio quasar (FSRQ) than a BL Lac (Ackermann et al. 2015). We were not able to find any radio counterpart association in public surveys for the NLS1 potentially associated with 1FHL J1414.0+7408 A. Although NLS1 have been indicated as responsible for y-ray as well as X-ray
emission (e.g. Abdo et al. 2009b; Foschini et al. 2015, and references therein), the fact that it is not detected at radio bands brings up the possibility that this association is the product of a contamination of the sample due to the relative width of the Fermi positional error boxes. Only radio loud NLS1 have been detected in high energies.

Likewise, the BL Lac object probably associated with 1FHL J1140.4+7408 B also does not show radio emission. It is important to note that, if confirmed, the BL Lac object 1FHL J1140.4+7408 B would be one of the very few radio quiet γ-ray emitting BL Lac objects identified to date. Similar recent cases can be found in Paggi et al. (2014) and in Ricci et al. (2015).

To be conservative, it is thus safe to say that it is still not clear which of the two sources is the actual γ-ray emitter, or that the two objects are possibly contributing to the total γ-ray flux detected with Fermi. However, given the above considerations, it is more likely that the counterpart to this 1FHL γ-ray source is the BL Lac object associated with 1FHL J1141.0+7408 B.

Regarding the NLS1 object associated with 1FHL J1140.4+7408 A, a central black hole mass value can be estimated through measuring the FWHM and flux of the Hγ line (Kaspi et al. 2000; Wu et al. 2004) corrected for foreground galactic absorption. This allows us to infer a mass of $\sim 5 \times 10^6 M_\odot$ for the black hole.

5.3. The case of 1FHL J1115.0-0701

We classified the optical counterpart of the X-ray source found within the 1FHL J1115.0-0701 positional uncertainty ellipse as a high-redshift quasar, with $z = 2.929 \pm 0.003$. This value, in turn, allows us to estimate a luminosity distance of $\sim 247$ Gpc, assuming $H_0 = 70.0$, $\Omega_m = 0.3$ and $\Omega_{\Lambda} = 0.7$. Following Park et al. (2013), we measured the flux and width of the CIV emission line together with the flux level of the continuum at 135 nm (rest-frame), both corrected for foreground galactic absorption, to obtain an estimate for the mass of its central black hole. This resulted in $4.6 \times 10^9 M_\odot$, which is within the range of expected black hole masses for this kind of AGN (Vestergaard & Peterson 2006). Moreover, the above distance estimate implies an X-ray luminosity of $L_X = 7.9 \times 10^{45}$ erg/s in the 2–10 keV band, whereas the black hole mass corresponds to an Eddington luminosity $L_{\text{Edd}} = 5.5 \times 10^{45}$ erg/s. Adopting a correction factor $C_X = 15.8$ to obtain the X-ray bolometric luminosity (Ho 2009), we find an Eddington ratio of $L_X / L_{\text{Edd}} = 0.2$. Assuming this quasar is the real counterpart for the 1FHL source, its γ-ray luminosity results in $L_\gamma = 3.2 \times 10^{45}$ erg/s. This value, although rarely reached, is within the range expected for γ-ray emitting FSRQs (Cavaliere & D’Elia 2002).

However, Petrov et al. (2013), Massaro et al. (2013a), and Schinzel et al. (2015) proposed a potential association of this Fermi source with a radio object (NVSS J111511–070238) located at a distance ~90 arcsec from the X-ray source found by Landi et al. (2015b). The radio source NVSS J111511–070238 is located at a distance of ~2.5 arcmin from the 1FHL source, while the X-ray source lies at a distance of ~3.2 arcmin from the latter. These two objects are not positionally consistent with each other. Therefore, this suggests that there may be two AGN within the Fermi error ellipse, a radio emitting one and an X-ray emitting one, which is the one we classify as a quasar.

In an attempt to discard one of the two proposed counterparts, we searched for archival multiwavelength data for both sources. We found no radio emission at the position of the X-ray quasar, suggesting that the object is possibly radio quiet and/or too cosmologically distant to be detected in the NVSS. However, this non-detection does not completely rule out the quasar as the real counterpart. Figure 14 of Abdo et al. (2009a) suggests a connection between radio luminosities and the γ-ray spectral indices obtained with the whole energy band at which Fermi/LAT works (i.e. 20 MeV to 300 GeV). If this object falls on the faint side of the connection ($\sim 1 \times 10^{42}$ erg/s), shallow radio surveys are not able to detect any emission: indeed, at a redshift $z = 2.929$ that luminosity would correspond to a flux density of ~1 mJy, which is well below the detection threshold of the NVSS (2.5 mJy).

Moreover, given that the spectral index across the whole Fermi/LAT energy range ($\alpha_\gamma = 2.11$) is too low for typical FSRQs, but rather normal for BL Lac objects (Ackermann et al. 2013).

In conclusion, although no other high-energy emitting source was found within the 1FHL positional uncertainty ellipse, we cannot rule out the possibility that this quasar is a background object and that the potential association is actually spurious. To conclusively pinpoint the true association it is necessary to obtain a spectrum of the optical counterpart of the above mentioned radio source, which shows a magnitude $R$ of ~19.5 in the USNO-B1.0 catalogue.

6. Conclusions

We obtained optical spectra for 14 potential associations with γ-ray sources from the 1FHL catalogue, which were selected on the basis of their X-ray emission. These are our findings:

1. From these spectra, it is clear that 12 of these objects correspond to blazars belonging to the BL Lac class, with non-thermal continua and no spectral features. There are two exceptions: U0750-02519189, associated with 1FHL J0639.6-1244, whose host galaxy’s spectroscopic signature is visible and allowed us to place it at a redshift of $z = 0.135 \pm 0.001$; and U1530-0317394, associated with 1FHL J2002.6+6303, which presents absorption from an intervening medium, placing it at a minimum redshift $z \geq 0.9$. The other 10 BL Lac sources remain without a value for their redshifts.

2. At least 8 out of the 12 BL Lacs present spectral indices in agreement with a synchrotron peak at a frequency higher than 10$^{13}$ Hz, meaning they are likely candidates to be detected at TeV energies.

3. The X-ray counterpart within the field of 1FHL J1115.0-0701 presents strong, broad optical emission lines at a redshift of $z = 2.929 \pm 0.003$, indicating that it is an AGN of the quasar class. By measuring the flux and width of the CIV emission line, we could estimate the mass of the central black hole as $4.6 \times 10^9 M_\odot$. Assuming this is the real counterpart for 1FHL J1115.0-0701, its luminosity would be $L_\gamma = 3.2 \times 10^{45}$ erg/s and $L_X = 7.9 \times 10^{45}$ erg/s. However, from multiwavelength considerations, we cannot rule out the possibility that this quasar is a background object and that its potential association with the γ-ray source is the product of statistical contamination. Further analysis is needed, in particular concerning the other object proposed as the real counterpart, radio source NVSS J111511–070238.

4. U1575–03416943, potentially associated with 1FHL J1410.4+7408 A, shows relatively narrow but strong emission lines at a redshift of $z = 0.429 \pm 0.001$. Given its optical
spectral characteristics, we classified it as a NLS1. For this object we infer a central black hole mass of $\sim 5 \times 10^6 M_\odot$.

5. Given that the source 1FHL J1410.4+7408 was potentially associated with objects A (a NLS1) and B (a BL Lac), we suggest -to be conservative- that it is still not clear which of the two sources is the actual $\gamma$-ray emitter, or if both of them are contributing to the total $\gamma$-ray emission. However, it is more likely the BL Lac object associated with 1FHL J1410.4+7408 B.

6. Our optical spectroscopy confirmed all the counterpart candidates of the X-ray sources potentially associated with 1FHL objects selected for this paper, with 1FHL J1115.0–0701 as the only possible exception. We were able to classify all of them as extragalactic high-energy active nuclei. This strengthens the utility of the proposed approach – cross-matching $\gamma$-ray positions to soft X-ray ones, improving accuracy, then completing the identification process with optical follow-up work and multiwavelength archival data.

Acknowledgements. E. J. Marchesini would like to thank Francesco Massaro and Paola Grandi for the useful discussions on this work, and Gianluca Israel for coordinating the NOT observations and for useful comments. N. Masetti thanks the Facultad de Ciencias Astronómicas y Geofísicas de La Plata for the warm hospitality during the preparation of this paper. We thank Roberto Gualandi for his work is funded under the co-tutoring agreement between University of Turin and University of La Plata.

References

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2009a, ApJ, 700, 597
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2009b, ApJ, 707, L142
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010, ApJ, 715, 429
Acero, F., Ackermann, M., Ajello, M., et al. 2015, ApJS, 218, 23
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
Atwood, W. B., Abdo, A. A., Ackermann, M., et al. 2009, ApJ, 697, 1071
Begelman, M. C., Blandford, R. D., & Rees, M. J. 1980, Nature, 287, 307
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Cavaliere, A., & D’Elia, V. 2002, ApJ, 571, 226
Condon, J. J., Cotton, W. D., Greisen, E. W., et al. 1998, AJ, 115, 1693
Evans, P. A., Osborne, J. P., Beardmore, A. P., et al. 2014, ApJS, 210, 8
Foschini, L., Berton, M., Caccianiga, A., et al. 2015, A&A, 575, A13
Fossati, G., Maraschi, L., Celotti, A., Comastri, A., & Ghisellini, G. 1998, MNRAS, 299, 433
Fukugita, M., Shimasaku, K., & Ichikawa, T. 1995, PASP, 107, 945
Georganopoulos, M., Finke, J. D., & Reyes, L. C. 2010, ApJ, 714, L15
Ghisellini, G., Tavecchio, F., Foschini, L., et al. 2010, MNRAS, 402, 497
Goodrich, R. W. 1989, ApJ, 342, 626
Ho, L. C. 2009, ApJ, 699, 651
Kalberla, P. M. W., Burton, W. B., Hartmann, D., et al. 2005, A&A, 440, 775
Kaspi, S., Smith, S. P., Netzer, H., et al. 2000, ApJ, 533, 631
Landi, R., Bassani, L., Stephen, J. B., et al. 2015a, IASF Bologna Internal Report, 651
Landi, R., Bassani, L., Stephen, J. B., et al. 2015b, A&A, 581, A57
Landi, R., Bassani, L., Stephen, J. B., et al. 2015c, Proc. Swift: 10 Years of Discovery [arXiv:1506.07006]
Landoni, M., Massaro, F., Paggi, A., et al. 2015, AJ, 149, 163
Mankuzhiyil, N., Persic, M., & Tavecchio, F. 2010, ApJ, 715, L16
Masetti, N., Sharufatti, B., Parisi, P., et al. 2013, A&A, 559, A58
Massaro, F., Tramacere, A., Cavaliere, A., Perri, M., & Giommi, P. 2008, A&A, 478, 395
Massaro, F., D’Abrusco, R., Paggi, A., et al. 2013a, ApJS, 209, 10
Massaro, F., Paggi, A., Errando, M., et al. 2013b, ApJS, 207, 16
Massaro, E., Maselli, A., Leto, C., et al. 2015a, Ap&SS, 357, 75
Massaro, F., Landoni, M., D’Abrusco, R., et al. 2015b, A&A, 575, A124
Monet, D. G. 1998, in BAAS, AAS Meet. Abstr., 30, 651
Monet, D. G., Levine, S. E., Canzian, B., et al. 2003, AJ, 125, 984
Mukai, K. 1993, Legacy, 3, 21
Osterbrock, D. E., & Pogge, R. W. 1985, ApJ, 297, 166
Padovani, P., & Giommi, P. 1995, ApJ, 444, 567
Paggi, A., Milisavljevic, D., Masetti, N., et al. 2014, AJ, 147, 112
Park, D., Woo, J.-H., Denney, K. D., & Shin, J. 2013, ApJ, 770, 87
Petrov, L., Mahony, E. K., Edwards, P. G., et al. 2013, MNRAS, 432, 1294
Ricci, F., Massaro, F., Landoni, M., et al. 2015, AJ, 149, 160
Rieke, G. H., & Lebofsky, M. J. 1985, ApJ, 288, 618
Schnitzel, F. K., Petrov, L., Mahony, E. K., et al. 2014, ApJS, 217, 4
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, AJ, 131, 1163
Stephen, J. B., Bassani, L., Landi, R., et al. 2010, MNRAS, 408, 422
Vestergaard, M., & Peterson, B. M. 2006, ApJ, 641, 689
Voges, W., Aschenbach, B., Boller, T., et al. 1999, A&A, 349, 389
Wu, X.-B., Wang, R., Kong, M. Z., Liu, F. K., & Han, J. L. 2004, A&A, 424, 793