Publication Year	2016
Acceptance in OA	2020-04-29T16:07:58Z
Title	Looking for blazars in a sample of unidentified high-energy emitting Fermi sources
Authors	Marchesini, E. J., MASETTI, NICOLA, Chavushyan, V., Cellone, S. A., Andruchow, I., BASSANI, LOREDANA, BAZZANO, ANGELA, Jiménez-Bailón, E., Landi, R., MALIZIA, ANGELA, PALAZZI, ELIANA, Patiño-Álvarez, V., RODRIGUEZ CASTILLO, Guillermo Andres, STEPHEN, JOHN BUCHAN, Ubertini, P.
Publisher's version (DOI)	10.1051/0004-6361/201629028
Handle	http://hdl.handle.net/20.500.12386/24345
Journal	ASTRONOMY & ASTROPHYSICS
Volume	596

A&A 596, A10 (2016)
DOI: 10.1051/0004-6361/201629028

Astronomy & Astrophysics

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

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Received 31 May 2016 / Accepted 30 July 2016

ABSTRACT

Context. Based on their overwhelming dominance among associated *Fermi* γ-ray catalogue sources, it is expected that a large fraction of the unidentified *Fermi* objects are blazars. Through crossmatching between the positions of unidentified γ-ray sources from the First *Fermi* Catalog of γ-ray sources emitting above 10 GeV (1FHL) and the ROSAT and *Swift*/XRT catalogues of X-ray objects and between pointed XRT observations, a sample of 36 potential associations was found in previous works with less than 15 arcsec of positional offset. One-third of them have recently been classified; the remainder, though believed to belong to the blazar class, still lack spectroscopic classifications.

Aims. We study the optical spectrum of the putative counterparts of these unidentified gamma-ray sources in order to find their redshifts and to determine their nature and main spectral characteristics.

Methods. An observational campaign was carried out on the putative counterparts of 13 1FHL sources using medium-resolution optical spectroscopy from the Osservatorio Astronomico di Bologna in Loiano, Italy; the Telescopio Nazionale *Galileo* and the Nordic Optical Telescope, both in the Canary Islands, Spain; and the Observatorio Astronómico Nacional San Pedro Mártir in Baja California, Mexico.

Results. We were able to classify 14 new objects based on their continuum shapes and spectral features.

Conclusions. Twelve new blazars were found, along with one new quasar and one new narrow line Seyfert 1 (NLS1) to be potentially associated with the 1FHL sources of our sample. Redshifts or lower limits were obtained when possible alongside central black hole mass and luminosity estimates for the NLS1 and the quasar.

Key words. gamma rays: general – X-rays: general – galaxies: active – BL Lacertae objects: general

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 multiwavelength 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) *Fermi* positional error ellipses. This uncertainty in their location means that positional correlations with known objects is often not enough to identify a *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 *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 *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, crossmatching the *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 *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[1] 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 *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 *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 Telescopio Nazionale *Galileo* (TNG) in La Palma, Canary Islands, Spain, with the DOLORES (LRS)

[1] http://www.asdc.asi.it/

Table 1. Observed sample of unidentified sources from the 1FHL catalogue.

Number (1)	USNO designator X-ray association (2)	RA(J2000) (3)	Dec(J2000) (4)	Observatory (5)	UT date [mm/dd/yy] (6)	Time [mid. exp.] (7)	Total exp. [s] (8)
1	U0750-00173701 1RXS J004349.3-111612	$00^{h}43^{m}48^{s}.66$	−11°16′07″.2	NOT	10/13/2015	02 : 46 : 41	1200
2	U0975-00792795 1SXPS J033829.0+130213	$03^{h}38^{m}29^{s}.24$	+13°02′15″.2	NOT	10/13/2015	04 : 59 : 08	1200
3	U0675-01653184 1SXPS J043949.5-190102	$04^{h}39^{m}49^{s}.54^{s}$	−19°01′02″.5	NOT	10/13/2015	05 : 35 : 13	1200
4	U0750-02519189 1SXPS J064007.1-125313	$06^{h}40^{m}07^{s}.31^{s}$	−12°53′18″.6	NOT	10/13/2015	06 : 08 : 22	1200
5	U0875-0218538 1SXPS J074627.1-022550	$07^{h}46^{m}27^{s}.14^{s}$	−02°25′50″.7	NOT	10/14/2015	04 : 53 : 16	1200
6	U0825-05946383 1RXS J080458.3-062432	$08^{h}04^{m}57^{s}.74^{s}$	−06°24′26″.3	LOI	03/10/2015	21 : 21 : 16	3600
7	U0825-05946383 SWXRT J111515.3-070126	$11^{h}15^{m}15^{s}.58^{s}$	−07°01′25″.6	SPM	01/14/2016	12 : 31 : 40	1800
8	U0750-08080787 1SXPS J131553.0-073301	$13^{h}15^{m}52^{s}.98^{s}$	−07°33′02″.0	LOI	03/13/2015	00 : 57 : 54	3600
9	U1575-03416792 1SXPS J141045.3+740508	$14^{h}10^{m}45^{s}.83^{s}$	+74°05′11″.1	TNG	08/26/2015	22 : 36 : 36	2400
10	U1575-03416943 1SXPS J141051.3+740410	$14^{h}10^{m}52^{s}.03^{s}$	+74°04′15″.1	TNG	08/26/2015	23 : 40 : 59	1200
11	U0600-17715078 1RXS J151213.1-225515	$15^{h}12^{m}12^{s}.76^{s}$	−22°55′08″.4	TNG	08/27/2015	22 : 41 : 45	2000
12	U0825-08948904 1SXPS J154952.1-065908	$15^{h}49^{m}52^{s}.17^{s}$	−06°59′08″.3	TNG	08/27/2015	23 : 30 : 37	2400
13	U1125-10089754 1RXS J184121.8+290932	$18^{h}41^{m}21^{s}.72^{s}$	+29°09′41″.2	TNG	08/27/2015	00 : 24 : 02	1600
14	U1530-0317394 1RXS J200245.4+630226	$20^{h}02^{m}45^{s}.36^{s}$	+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.

spectrograph and a 1.5 arcsec slit (0.25 nm/px dispersion). The data covered a range from 370 to 800 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/px 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/px 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[2] 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 J0804.8-0626, the correlation with X-ray data showed only one source inside the γ-ray positional error area,

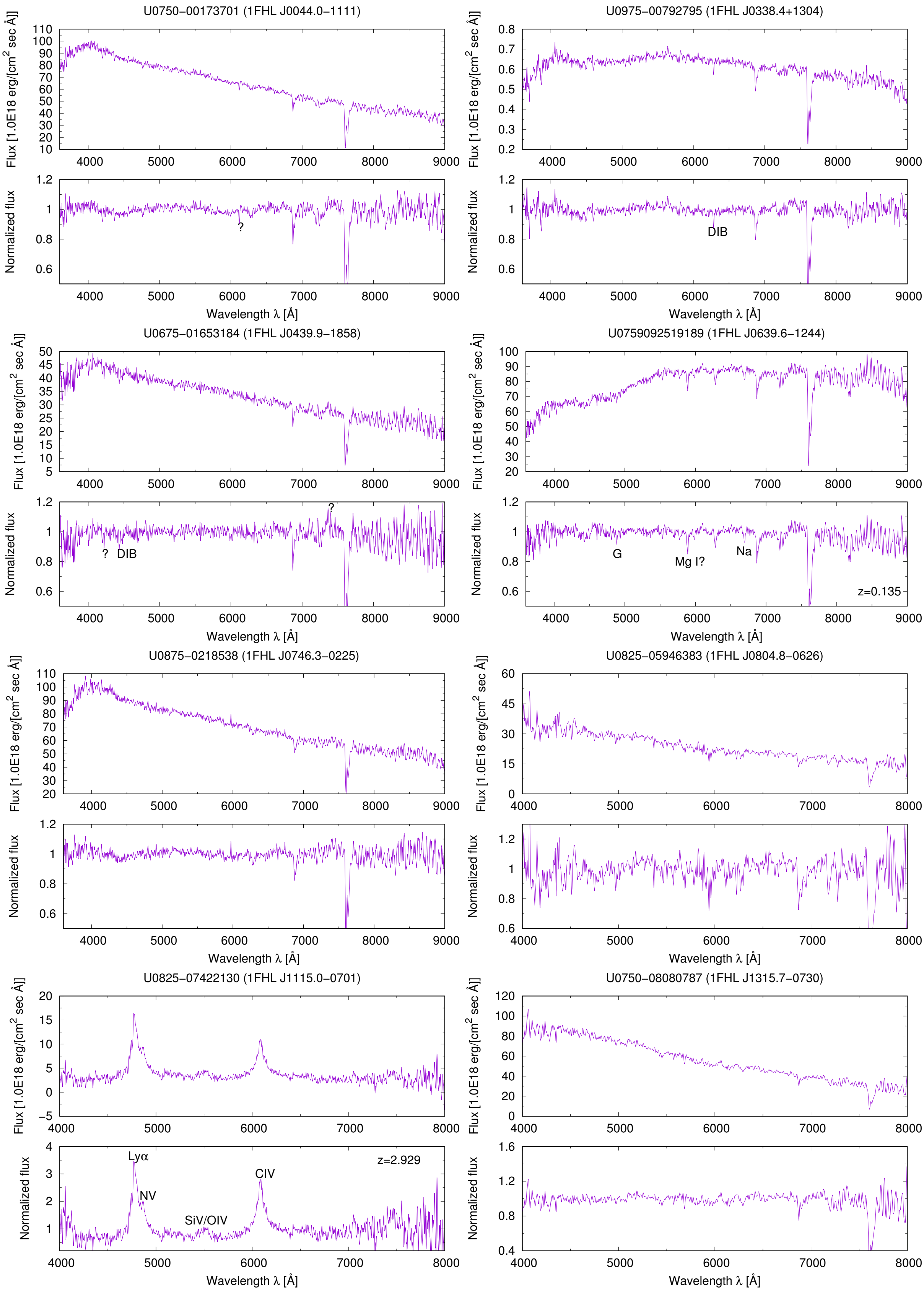

Fig. 1. Optical spectra obtained for the whole sample presented in this paper. *Upper panels* show the observed spectra, while *lower panels* show the spectra with normalised flux. Absorption lines or bands present at 686.9 nm, ~718.6 nm, and 760.5 nm are telluric. Absorption lines present at 589.0 nm 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.

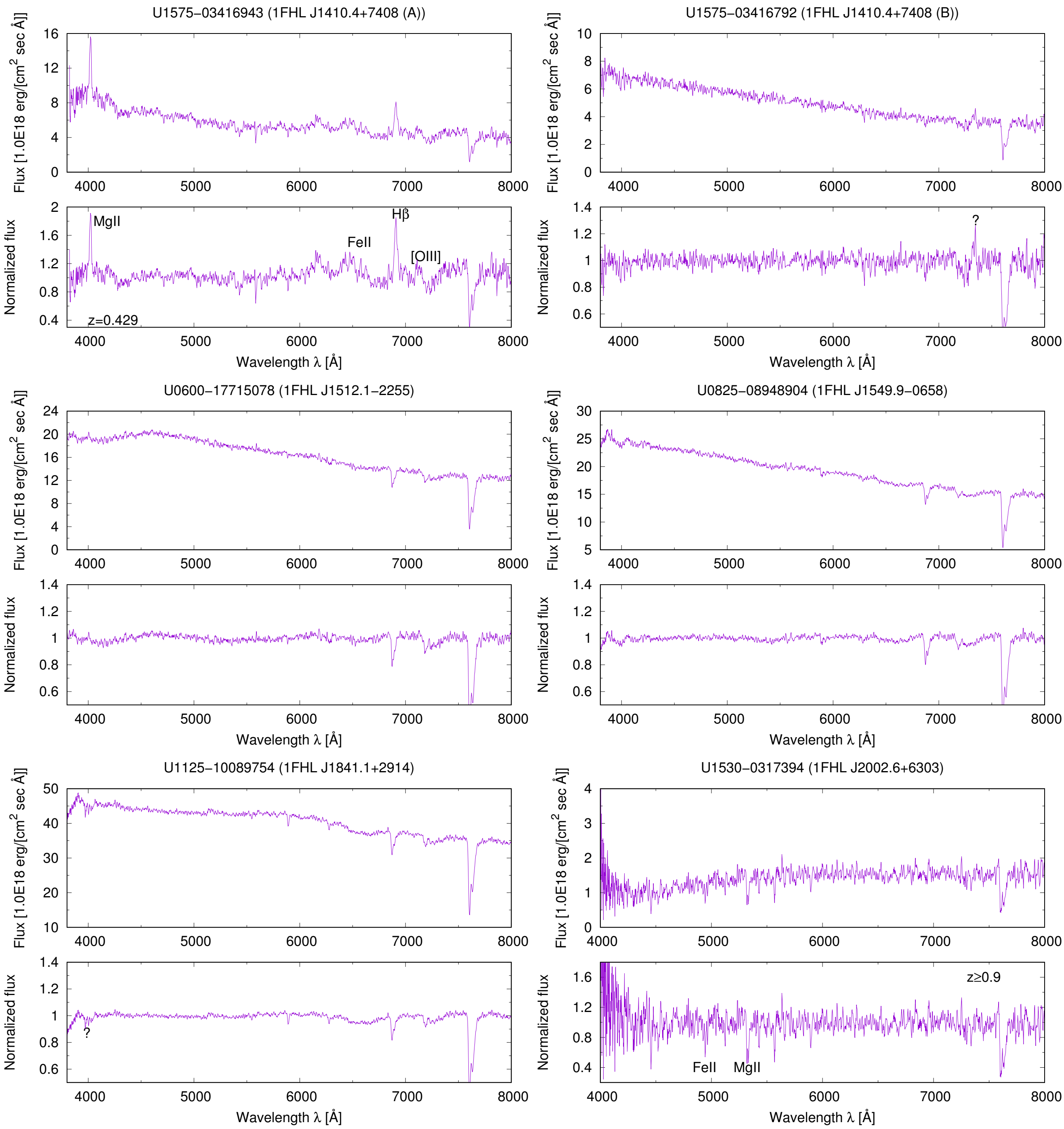

Fig. 1. continued.

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+7408A, 1FHL J1410.4+7408B, 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 1FHL association (Distance) (1)	Features (2)	*EW* [Å] (3)	Flux (4)	Redshift (5)	Class (6)
U0750-00173701 1FHL J0044.0-1111 (5.7)	– –	– –	– –	– –	BL Lac
U0975-00792795 1FHL J0338.4+1304 (2.5)	– –	– –	– –	– –	BL Lac
U0675-01653184 1FHL J0439.9-1858 (2.9)	– –	– –	– –	– –	BL Lac
U0750-02519189 1FHL J0639.6-1244 (10.7)	G Na	1.0 ± 0.6 2.3 ± 1	−8 ± −4 −21 ± −10	0.135 ± 0.001	BL Lac
U0875-0218538 1FHL J0746.3-0225 (1.7)	– –	– –	– –	– –	BL Lac
U0825-05946383 1FHL J0804.8-0626 (2.1)	– –	– –	– –	– –	BL Lac
U0825-05946383 1FHL J1115.0-0701 (3.2)	Lyα NV SiV/OIV CIV	312 ± 28 262 ± 49 79 ± 14 264 ± 31	95 ± 10 76 ± 12 21 ± 3 82 ± 6	2.929 ± 0.003	QSO
U0750-08080787 1FHL J1315.7-0730 (3.3)	– –	– –	– –	– –	BL Lac
U1575-03416792 1FHL J1410.4+7408 A (4.4)	MgII Hγ Hβ [OIII]	17 ± 6 18 ± 9 35 ± 14 –	15 ± 4 9 ± 4 14 ± 5 –	0.429 ± 0.001	NLS1
U1575-03416943 1FHL J1410.4+7408 B (3.3)	– –	– –	– –	– –	BL Lac
U0600-17715078 1FHL J1512.1-2255 (1.0)	– –	– –	– –	– –	BL Lac
U0825-08948904 1FHL J1549.9-0658 (1.4)	– –	– –	– –	– –	BL Lac
U1125-10089754 1FHL J1841.1+2914 (5.6)	– –	– –	– –	– –	BL Lac
U1530-0317394 1FHL J2002.6+6303 (1.1)	FeII MgIIa MgIIb	11 ± 7 10 ± 3 7 ± 2	−1.5 ± −0.9 −1.6 ± −0.6 −1.1 ± −0.4	≥0.9	BL Lac

Notes. The units for all the reported flux densities are 1×10^{-16} erg cm^{-2} s^{-1} 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 $z = 0.135 \pm 0.001$. 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 $8^h04^m58\overset{s}{.}48^s$, $-6°24'21\overset{''}{.}1$) 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 $z = 0.429 \pm 0.001$. Given that the velocities associated with the emission of the Hβ line are around 1450 $\mathrm{km\,s^{1}}$, and that the ratio between the fluxes of emission lines [OIII] and 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 $11^{h}15^{m}15.^{s}3^{s}$, $-07^{\circ}01'26.''9$).

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 $N_{\rm H}$ 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 densities at 1.4GHz, 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 $\alpha_{\rm ox}$ from X-ray to optical and $\alpha_{\rm ro}$ 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 $\alpha_{\rm ox} - \alpha_{\rm ro}$ 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 $\alpha_{\rm ro}$ is indicated in the plot with an arrow.

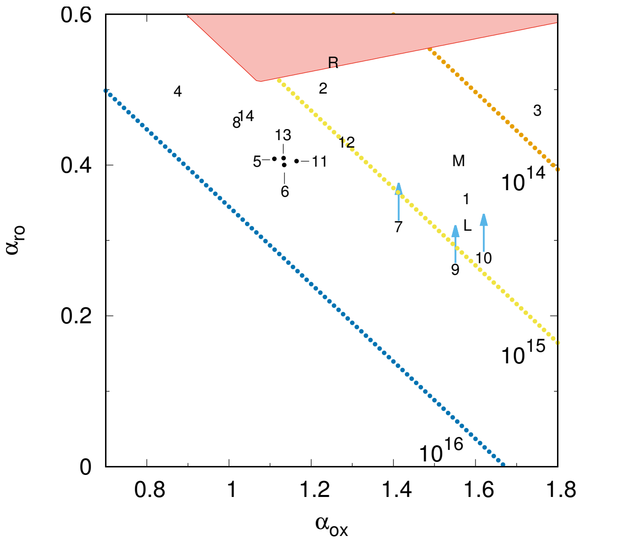

Fig. 2. Analysed sources in the spectral indices $\alpha_{\rm ox} - \alpha_{\rm ro}$ plane. Lower limits are indicated with an arrow. Numbers refer to the values presented in Table 1, while letters L, M, and R refer to the objects in Landi et al. (2015b,a) associated by Landoni et al. (2015), Massaro et al. (2015b), and Ricci et al. (2015), respectively. Sources 5, 6, 11 and 13 are shown as points for the sake of clarity. The red shaded area indicates the region where the relationship describing synchrotron peak values changes its functional form, as explained in Abdo et al. (2010).

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 Landoni 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 J1410.4+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 $\alpha_{\rm ro}$.

5.2. The case of 1FHL J1410.4+7408

As 1FHL J1410.4+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 γ-ray emission.

Given that the spectral index of the γ-ray source, according to the 1FHL catalogue, is $\alpha_{\gamma} = 2.65$, 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 J1410.4+7408 A. Although NLS1 have been indicated as responsible for γ-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 J1410.4+7408 B also does not show radio emission. It is important to note that, if confirmed, the BL Lac object 1FHL J1410.4+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 J1410.4+7408 B.

Regarding the NLS1 object associated with 1FHL J1410.4+7408 A, a central black hole mass value can be estimated through measuring the FWHM and flux of the H_β 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$24.7 Gpc, assuming H_0 = 70.0, Ω_m = 0.3 and Ω_Λ = 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 4.6×10^9 $M_\odot$, 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 value $L_{Edd} = 5.5 \times 10^{47}$ 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 $L_X/L_{Edd} = 0.2$. Assuming this quasar is the real counterpart for the 1FHL source, its γ-ray luminosity results in $L_\gamma = 3.2 \times 10^{47}$ 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 $\sim$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 $\sim$2.5 arcmin from the 1FHL source, while the X-ray source lies at a distance of $\sim$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 $\sim$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 ($\alpha_\gamma = 2.11$, Acero et al. 2015) for this γ-ray source is an intermediate value between those of each kind, we cannot determine whether it is a BL Lac or a FSRQ.

On the other hand, its γ-ray spectral index above 10 GeV ($\alpha_\gamma = 1.88$) 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 $\sim$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 Lacs 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^{15}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 4.6×10^9 $M_\odot$. Assuming this is the real counterpart for 1FHL J1115.0-0701, its luminosity would be $L_\gamma = 3.2 \times 10^{47}$ 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 γ-ray emitter, or if both of them are contributing to the total γ-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 γ-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 night assistance at the Loiano telescope, and Gloria Andreuzzi for coordinating our service mode observation at the TNG. We also acknowledge the Italian Space Agency financial support (ASI/INAF agreement No. 2013-025.R.0). This work is funded under the co-tutoring agreement between University of Turin and University of La Plata.

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