Are many radio-selected BL Lacs radio quasars in disguise?

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ABSTRACT

We show that a blazar classification in BL Lacs and Flat Spectrum Radio Quasars may not be adequate when it relies solely on the equivalent widths (EWs) of optical lines. In fact, depending on redshift, some strong emission lines can fall in the infrared window and be missed. We selected a sample of BL Lacs with firm redshift identification and good visibility from Paranal. We targeted with the X-shooter spectrograph the five BL Lacs with $z > 0.7$, i.e., those for which the H$\alpha$ line, one of the strongest among blazars, falls outside the optical window and determined the EW of emission lines in both the infrared and optical bands. Two out of five sources show an observed H$\alpha$ EW $> 5$ Å (one has rest frame EW $> 5$ Å) and could be classified as FSRQs by one of the classification schemes used in the literature. A third object is border-line with an observed EW of $4.4 \pm 0.5$ Å. In all these cases H$\alpha$ is the strongest emission line detected. The H$\alpha$ line of the other two blazars is not detected, but in one case it falls in a region strongly contaminated by sky lines and in the other one the spectrum is featureless. We conclude that a blazar classification based on EW width only can be inaccurate and may lead to an erroneous determination of blazar evolution. This effect is more severe for the BL Lac class, since FSRQs can be misclassified as BL Lacs especially at high redshifts ($z > 0.7$), where the latter are extremely rare.

Key words: BL Lacertae objects: general - quasars: emission lines - radiation mechanisms: non-thermal - radio continuum: galaxies

1 INTRODUCTION

Blazars are active galactic nuclei (AGN) with strong jets forming a small angle w.r.t. the line of sight and emitting variable, non-thermal radiation across the entire electromagnetic spectrum (Blandford & Rees 1978; Urry & Padovani 1995). Although intrinsically rare, blazars are being detected in increasingly larger numbers by extragalactic surveys. In fact, although only 3,500 blazars are currently known (Massaro et al. 2009, 2015), their number is steadily growing thanks to, e.g., the Fermi (Abdo et al. 2010a,b, 2011), the optical Sloan Digital Sky Survey (SDSS; Plotkin et al. 2010), and the Planck (Planck Collaboration 2011) surveys. Some faint blazars are also being detected as serendipitous sources in Swift-XRT images (Turriziani 2010).

Blazars come in two main subclasses, whose major difference lies in their optical properties: 1) Flat Spectrum Radio Quasars (FSRQs), which show strong, broad emission lines in their optical spectrum, just like radio quiet QSOs; and 2) BL Lacs, which are instead characterized by an optical spectrum, which at most shows weak emission lines, sometimes displays absorption features, and in many cases can be completely featureless. Historically, the separation between BL Lacs and FSRQs has been made at the (rather arbitrary) equivalent width (EW) value of 5 Å, rest-frame by Stickel et al. (1991) and observed-frame by Stocke et al. (1991). However, the search for a possible bimodal distribution in the EW of the broad lines of radio quasars has been unsuccessful. Indeed, Scarpa & Falomo (1997) pointed out that radio-selected BL Lacs were, from the point of view of the emission line properties, very similar to FSRQs but with a stronger continuum. Most BL Lacs selected in the X-ray band, on the other hand, had very weak, if any, emission lines, and Stocke et al. (1991), when studying the properties of the X-ray selected Einstein Medium Sensitivity Survey (EMSS) sample, had to introduce another criterion to identify BL Lacs, this time to separate them from normal galaxies. This was based on the Ca H&K break, a stellar
absorption feature typically found in the spectra of elliptical galaxies at $\lambda \sim 4,000 \, \text{Å}$. Given that its value in non-active ellipticals is $\sim 50\%$, Stocke et al. (1993) chose a maximum value of 25% to ensure the presence of a substantial non-thermal continuum superposed to the host galaxy spectrum. This was later revised to 40% Marcha et al. (1996; Landt et al. 2002).

Based on all the above, it is clear that blazar classification depends then on the details of their appearance in the optical band where they emit a mix of three types of radiation: 1) a non-thermal, jet-related, component; 2) thermal radiation coming from the accretion onto the supermassive black hole and from the broad line region (at least in most radio selected sources); 3) light from the host (giant elliptical) galaxy. The strong non-thermal radiation, the only one that spans the entire electromagnetic spectrum, is composed of two broad humps, a low-energy one attributed to synchrotron radiation, and a high-energy one, usually thought to be due to inverse Compton radiation (Abdo et al. 2010).

Motivated by this observational background, Giommi et al. (2012; see also Giommi et al. 2013; Padovani & Giommi 2013) run simulations to try to explain the many selection effects that bias the FSRQ/BL Lac classification. These simulations included, amongst other ingredients, the blazar luminosity function and evolution, the thermal, non-thermal and host galaxy components, and the peak frequency of the synchrotron emission and EW distributions. Once the simulated samples had been produced, the bias effects were introduced, in order to compare the simulations with the real samples. These biases are basically the limiting fluxes, to assess whether or not a source is detected by a specific survey, and the diluted EW, which depends (apart from the intrinsic EW) on the shape and intensity of the simulated non-thermal emission and the host galaxy light, and determines whether a source gets classified as a BL Lac or an FSRQ. One of the results of this analysis was that what we call a BL Lac can either be an object with a strong non-thermal continuum (possibly due to strong Doppler factors), which heavily dilutes its lines below the (arbitrary) dividing value of EW $= 5 \, \text{Å}$, or a source with intrinsically weak emission lines. Radio surveys tend to preferentially select the first type of sources (as these are intrinsically radio powerful), while X-ray surveys select mainly sources with lower radio power, related to low-ionization radio galaxies (LERGs) and therefore optically featureless. The consequence of this scenario is that the first kind of sources are classified as BL Lacs only because they have a strong non-thermal emission, or a high Doppler boosting, which swamp their emission lines. Such objects are intrinsically FSRQs and so they should be classified. On the other hand, most X-ray selected BL Lacs are truly (or nearly) featureless and constitute the genuine BL Lac class (Giommi et al. 2012).

The aim of this work is to test these predictions through X-shooter optical and infrared spectroscopy of a sample of BL Lacs. The paper is organized as follows: in Sect. 2 we describe the criteria adopted to build our sample; in Sect. 3 we deal with the X-shooter observations and the data reduction process; in Sect. 4 we present our results; finally in Sect. 5 we discuss our findings and draw our conclusions.

2 SAMPLE SELECTION

An effective way of searching for FSRQs that have been erroneously misclassified is to observe BL Lacs at $z > 0.7$ in the infrared band. This is because at these redshifts one of the most prominent emission lines in blazars, $\text{H}_\alpha$ (rest-frame wavelength $\lambda_{\text{H}_\alpha} = 6562.8 \, \text{Å}$) moves out of the wavelength range where optical spectroscopy is normally done. In this scenario, some blazars might have been classified as BL Lacs only because one of their strongest and less contaminated emission lines falls beyond the spectroscopic range normally used to classify blazars.

To verify this possibility, we selected a small sample of BL Lacs to be observed at infrared wavelengths as follows: we started from the BZCAT catalogue (Massaro et al. 2002) and singled out all radio-selected BL Lacs with good visibility from Paranal ($\delta < 25\degr$), $z > 0.7$, and a firm redshift identification (at least two lines detected in emission. Stickel, Fried & Kühr 1993; Rector & Stocke 2001; Bharafati, Treves & Falomo 2005). We then removed the objects for which the $\text{H}_\alpha$ line was expected to fall in regions dominated by atmospheric absorption features. Since the observed redshift distribution of BL Lacs peaks at very low redshifts, our final sample includes only five objects, which are listed in Table 1. Three of these have a redshift $z \sim 0.7 - 1$, and the $\text{H}_\alpha$ line falls in the J band, while the other two have a redshift $z \sim 1.2 - 1.3$ and the $\text{H}_\alpha$ is in the H band.

3 X-SHOOTER OBSERVATIONS AND DATA REDUCTION

We observed our blazar sample with X-shooter (D’Odorico et al. 2006; Vernet et al. 2011), a single-object medium resolution ($R = \lambda/\Delta \lambda = 4000-14000$) echelle spectrograph mounted at the VLT-UT2 telescope. The observations were carried out under programme 091.B-0092. The choice of X-shooter as operating instrument stems from its capabilities to perform simultaneous optical and IR spectroscopy with a single exposure. This way we can also study the ratio between optical and IR band lines without being affected by the variability typical of blazars.

For both observations the slit width was set to 0.9" in the visual (VIS) and near-infrared (NIR) arms, and 1.0" in the ultra-violet and blue (UVB) arm. The UVB and VIS CCD detectors were rebinned to 1 x 2 pixels (binned in the spectral direction but not in the spatial one) to reduce the readout noise. With this configuration, the nominal resolution is different for the three arms: $R \sim 5100$, 8800, 5300 for the UVB, VIS, and NIR arms, respectively.

All our targets were observed during ESO period P91, i.e., between 1 April and 30 September 2013. The list of observations is reported in Table 1, together with the observing dates and the total exposure times. Sources requiring more than 1 hour of integration were observed more than once. Each observation is constituted by several exposures, taken nodding along the slit with an offset of 5" between exposures, following a standard ABBA pattern.

We processed the spectra using version 1.4.5 of the X-shooter data reduction pipeline (Goldoni et al. 2006; Modigliani et al. 2010). The pipeline carries out the follow-
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4 RESULTS

We computed the rest-frame EWs for the emission lines of our sources, which are given in Table 2. The EWs have been computed through direct line integration. Errors have been estimated resampling the spectra and take into account both the normalization uncertainties and the S/N of the spectra. We discuss the sources individually in the following subsections.

4.1 BZBJ0141−0928 (PKS 0138−097)

For this blazar we detected the MgII doublet at 2800 Å and three oxygen lines, namely, [OII] and the [OIII] doublet (see Fig. 1). A redshift of $z = 0.736 \pm 0.001$ is derived, in agreement with that reported by Rector & Stocke (2001). Despite a very high S/N ratio, we cannot detect Hydrogen emission lines, but the Hα line falls in a region strongly contaminated by sky lines. An intervening system is detected at $z = 0.5005 \pm 0.0005$, featuring absorption by the MgII λλ2796,2803, FeIIλλ2586,2600 doublets, and the FeIIλ2382 line.

4.2 BZBJ0238+1636 (AO 0235+164)

This is the blazar featuring the most prominent emission lines in our sample. We confirm the redshift of this source to be $0.942 \pm 0.001$ (Healey et al. 2008). Five lines have been detected, namely, the MgII doublet, [OII], the [OIII] doublet and Hα. The Hβ line falls in a telluric region, so only a shallow upper limit could be set. The Hα line rest-frame EW is higher than 5 Å. All the other features detected in the optical band have instead values $< 5$ Å. BZBJ0238+1636, previously classified as a BL Lac due to the EW of its optical lines, should be re-classified as an FSRQ according to its redshift.

4.3 BZBJ2031+1219 (PKS 2029+121)

This blazar is almost completely featureless. We only report a tentative detection of the MgII doublet at the redshift $z = 1.215$, consistent with that by Stickel & Kühr (1993). In addition, we detect the intervening absorber seen by Bergeron, Boissé, & Ménard (2011) at $z = 1.116$, which features the MgIIλ, λ2796, 2803 doublet and the [MgI]λ2852 line, which gives more robustness to our redshift determination. Since the main emission lines should fall in regions relatively free of sky lines, this might suggest that we have caught BZBJ2031+1218 in a high state, during which the thermal emission is overwhelmed by the synchrotron emission below the detection threshold of our spectrum. Only upper limits for [OII], the [OIII] doublet, Hβ and Hα have been set at the redshift of $z = 1.215$ (see Table 2).

4.4 BZBJ2134−0153 (4C−02.81)

This blazar shows three emission lines, namely, [OII], [OIII]λ5007 Å and Hα. We found a redshift of $z = 1.286 \pm 0.001$, consistent with that reported by Rector & Stocke (2001). For the Hβ and [OIII]λ4959 Å features we could...
Table 1. X-shooter observations

| Source        | RA (J2000, hr) | Dec (J2000, deg) | redshift | Observation date 1 | Exposure time (s) 1 | S/N 1 | airmass 1 |
|---------------|----------------|-----------------|----------|--------------------|---------------------|-------|-----------|
| BZBJ0141−0928 | 01 41 25.83    | -09 28 42.9     | 0.733    | 2013-07-24T08:39:08.945 | 2880 ~ 20 1.09  |       |           |
|               |                |                 |          | 2013-08-17T04:57:54.150 | 2880 ~ 20 1.56  |       |           |
|               |                |                 |          | 2013-08-19T04:55:01.183 | 2880 ~ 20 1.52  |       |           |
|               |                |                 |          | Total              | 8640 ~ 35          |       |           |
| BZBJ0238+1636 | 02 38 38.93    | +16 36 59.0     | 0.94(3)  | 2013-08-10T02:38:58.540 | 1800 ~ 12 1.34  |       |           |
| BZBJ2031+1219 | 20 31 54.99    | +12 19 41.0     | 1.215(2) | 2013-08-10T03:49:49.421 | 2880 ~ 8 1.30   |       |           |
|               |                |                 |          | Total              | 5760 ~ 12          |       |           |
| BZBJ2134−0153 | 21 34 10.30    | -01 53 17.0     | 1.283(1) | 2013-05-27T06:29:07.736 | 3600 ~ 15 1.54  |       |           |
| BZBJ2243−2544 | 22 43 26.40    | -25 44 30.0     | 0.774(4) | 2013-06-20T08:33:30.168 | 1800 ~ 35 1.02  |       |           |

(1) Rector & Stocke (2001); (2) Stickel & Kühr (1993); (3) Healey et al. (2008); (4) Stickel, Fried & Kühr (1993)

Table 2. Rest-frame equivalent widths for our blazar sample.

| Source        | MgIIλ2800Å | [OII]λ3728Å | Hβ | [OIII]λ4959Å | [OIII]λ5007Å | Hα |
|---------------|------------|-------------|----|-------------|-------------|----|
| BZBJ0141−0928 | 1.0 ± 0.2  | 0.3 ± 0.2   | < 0.2 | 0.3 ± 0.1 | 1.0 ± 0.2   | < 1.2 |
| BZBJ0238+1636 | 1.5 ± 0.4  | 0.5 ± 0.4   | < 0.2 | 0.6 ± 0.3 | 1.5 ± 0.4   | < 0.5 |
| BZBJ2031+1219 | Tentative  | < 0.2       | < 0.3 | < 0.3      | < 0.3      | < 0.5 |
| BZBJ2134−0153 | < 0.3      | < 0.3       | < 0.4 | < 0.4      | < 0.4      | < 0.5 |
| BZBJ2243−2544 | < 0.2      | < 0.2       | < 0.2 | < 0.2      | < 0.2      | < 0.5 |

set only upper limits. However, the [OIII] doublet falls in a region highly contaminated by sky lines. It is interesting to note that the Hβ lower limit is about eight times smaller than the Hα value, despite the ratio between the two oscillator strengths being only ~ 5. We do not detect the MgII emission line reported in Bergeron, Boissé, & Ménard (2011) nor the MgII intervening absorber at z = 1.2458. However, the reported EW of the intervening MgII system (~ 0.2Å) is below our detection threshold. The detected emission lines are displayed in Fig. 3.

4.5 BZBJ2243−2544 (PKS 2240−260)

This blazar shows four emission lines, namely [OII], the [OIII] doublet and Hα. The redshift determined for this object is z = 0.780 ± 0.002, consistent with Stickel, Fried & Kühl (1993). For the Hβ feature only an upper limit could be set. Again, we note that this lower limit is more than ten times lower than the Hα value, despite the ratio between the two oscillator strengths is just a factor of ~ 5. The detected emission lines are displayed in Fig. 4.
5 DISCUSSION AND CONCLUSIONS

We have looked for Hα emission in the IR spectra of five BL Lacs at $z > 0.7$. We have found that two sources (BZBJ0238+1636, rest-frame EW > 5 Å and BZBJ2134−0153, observed EW > 5 Å) could be classified as FSRQs by one of the classification criteria that have been used in the literature. Indeed, BZBJ0238+1636 was defined as an “intruder” BL Lac in Ghisellini et al. (2011).

This is because its high γ-ray luminosity and Eddington ratio resemble those of typical FSRQs, despite its γ-ray energy index being border-line between the two classes. Concerning BZBJ2134−0153, its classification is ambiguous, since it was considered an FSRQ in the 1LAC catalog (Abdo et al. 2010) and a BL Lac in the 2FGL one (Nolan et al. 2012). Its γ-ray luminosity of $\sim 10^{47}$ erg s$^{-1}$ and its WISE colors (Massaro et al. 2011) better place this object in the FSRQ class. In addition, given the steep NIR-to-UV slope, if the redshift of this object were $z \sim 2$, a strong Ly-α line would have been detected, definitely placing BZBJ2134−0153 in the FSRQ class. A third source in our sample shows border-line (observed) EW (BZBJ2243−2544, EW = 4.4 ± 0.5 Å). The remaining two objects show very weak lines or nearly featureless spectra.

Our sample shows that, whenever emission lines are present, Hα is always the most prominent one (the only exception being BZBJ0141−0928, for which it falls in a region strongly contaminated by sky lines). This appears to be the case even if this feature falls relatively close to the peak of the synchrotron emission in our sources, which are low synchrotron-peaked BL Lacs. In this situation the synchrotron emission, which is non-thermal, should strongly dilute the thermal processes such as the Hα emission lines. Hα turns then out to be very important if one has to rely on a classification scheme that discriminates BL Lacs from FSRQs according to the EW of their lines. In this context IR spectroscopy turns out to be vital for relatively high redshift ($z > 0.7$) sources.

The danger of source misclassification based solely on EW strength has been recently stressed also by Ruan et al. (2014). They studied multi-epoch spectra of more than 300 blazars, finding that for six of them the EW of their emission lines crossed the 5 Å dividing line in different observations. These objects have high accretion rates, strong variability both in the thermal and non-thermal continuum and a synchrotron peak frequency similar to that of FSRQs. Ruan et al. (2014) propose that these sources are likely FSRQs whose jet axis points extremely close to the line of sight. This peculiar geometry causes the emission lines to be strongly diluted by the non-thermal continuum when the latter is particularly strong. They conclude, similarly to Giommi et al. (2012), that a simple classification based on the EW strength may lead to consider these FSRQs as BL Lacs and to a wrong evaluation of the BL Lac evolution, especially at high redshifts. This effect could be even more severe when considering that blazars with redshift larger than 0.7, currently classified as BL Lacs, could be in fact FSRQs with the Hα emission line in the IR window. Thus, a new, EW-independent operational definition for "BL Lac object" is needed.

Such a picture has also strong implications on blazar classification and evolution and on the so-called “blazar sequence”, and predicts the association of “real” BL Lacs with LERGs and “fake” BL Lacs with high-ionization radio galaxies (HERGs). In particular, the evolution derived for FSRQ samples in the radio, and also γ-ray, band could be biased by the exclusion of relatively high-redshift misclassified sources. Given the role that radio emission is thought to play in galaxy evolution through the so-called “radio mode” accretion (Croton et al. 2006), this is also relevant for “AGN feedback” via the selection of relatively high-redshift HERGs.
but especially LERGs, which being intrinsically less powerful are harder to identify, already at moderately high redshifts, through blazar samples.

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