# Redshift measurement of Fermi Blazars for the Cherenkov Telescope Array

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**Abstract.** Blazars are active galactic nuclei, and the most numerous High Energy (HE) and Very High Energy (VHE) $\gamma$-ray emitters. Their optical emission is often dominated by non-thermal, and, in the case of BL Lacs, featureless continuum radiation. This makes the determination of their redshift extremely difficult. Indeed, as of today only about 50% of $\gamma$-ray blazars have a measured spectroscopic redshift. The knowledge of redshift is fundamental because it allows the precise modeling of the VHE emission and also of its interaction with the extragalactic background light (EBL). The beginning of the Cherenkov Telescope Array (CTA) operations in the near future will allow the detection of several hundreds of new blazars. Using the Fermi catalogue of sources above 50 GeV (2FHL), we performed simulations which indicate that a significant fraction of the 2FHL blazars detectable by CTA will not have a measured redshift. As a matter of fact, the organization of observing campaigns to measure the redshift of these blazars has been recognized as a necessary support for the AGN Key Science Project of CTA. We are planning such an observing campaign. In order to optimize our chances of success, we will perform preliminary deep imaging observations aimed at detecting or setting upper limits to the host galaxy. We will then take spectra of the candidates with the brightest host galaxies. Taking advantage of the recent success of an X-shooter GTO observing campaign, these observations will be different with respect to previous ones due to the use of higher resolution spectrographs and of 8 meter class telescopes. We are starting to submit proposals for these observations. In this paper we briefly describe how candidates are selected and the corresponding observation program.

## 1 INTRODUCTION

Blazars are a type of active galactic nuclei whose relativistic plasma jets are emitted in the direction of the observer. The majority of the energy emitted comes from the radiation of particles accelerated in the jets, which is also Doppler boosted along the line of sight. The featureless radiation of the jet hides the spectral signature of the host galaxy and makes, especially for BL Lacs objects, the determination of the redshift difficult (see Fig. 1, lower panel, for an example of a featureless optical spectrum of a BL Lac). In spite of several observing campaigns, about 50% of $\gamma$-ray BL Lacs have no measured redshift. The lack of redshift measurement on the one hand prevents the determination of the luminosity of the source and thus population studies, while on the other hand hinders the modeling of the line-of-sight absorption due to the optical Extragalactic Background Light (EBL). The absorption of the TeV photons is due to annihilation of the TeV and EBL photons to create an electron-positron pair. The resulting $\gamma$-ray opacity is strongly dependent on the distance to the source and substantially softens the TeV spectra at energies higher than 1 TeV and redshift >0.2. The lack of redshift for a high fraction of BL Lacs is therefore a serious problem which will worsen in the CTA era due to the anticipated discovery of several hundreds of VHE BL Lacs. Recently, Pita *et al.* [1]

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performed a successful observing campaign with X-shooter at the ESO's Very Large Telescope (VLT) which had a higher success rate than previous efforts. On the basis of this result, we conceived an observing campaign to measure the redshift of Fermi $\gamma$-ray BL Lacs likely to be detected with CTA.

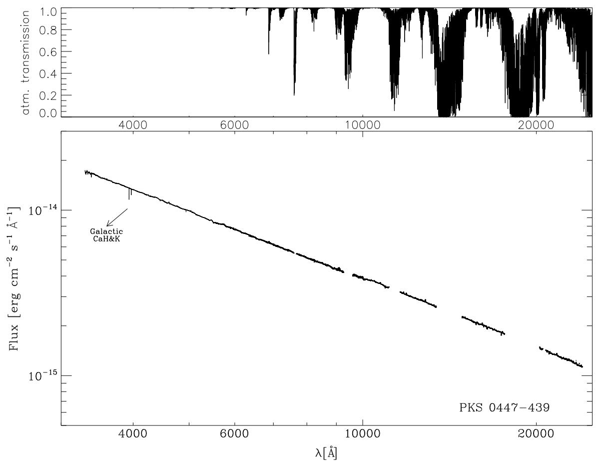


**FIGURE 1.** Bottom panel: X-shooter UV to NIR spectrum of PKS 0447-439. Top Panel: Earth atmospheric transmission for Paranal. From Pita *et al.* [1]

## 2 Previous spectroscopic observations

Pita *et al.* [1] observed eight HE BL Lacs with unknown or uncertain redshift determining the redshift of five of them and constraining the redshift of two others through the detection of intervening absorbing systems. This comparatively high success rate is due mainly to the high spectral resolution (R=$\lambda/\Delta\lambda$=10000), the sensitivity and wavelength range of the instrument and the good observing conditions. In particular the spectral resolution is very effective for the detection of narrow spectral features such as the ones due to intervening absorption systems. The resolution is also very efficient in the identification of spectral features produced by the Earth's atmosphere (see upper box in Fig. 1). The average signal-to-noise ratio (S/N) per pixel reached in these observations was about 100 in the UVB arm, about 80 in the VIS arm and about 40 in the NIR arm, the trend of lower S/N with wavelength being mainly due to the spectral shape (see Fig. 1). The high S/N combined with the unprecedented wavelength range was the key factor which allowed finding enough features to firmly determine the redshift.

## 3 Sample Selection

### 3.1 Blazars in the 2FHL catalog

We selected the most promising candidates for an early detection by CTA using the recently published 2FHL catalog [2], which lists the 360 Fermi-LAT hard sources detected at energies higher than 50 GeV in 80 months of data. The catalog is dominated by extragalactic sources (274, 75%). Out of these sources, 193 are BL Lacs and 60 blazar candidates of uncertain type (bcu), a significant fraction of which could be BL Lacs. More than 50% of these sources (143/253) have no redshift. We focus below on these sources.

### 3.2 Most promising CTA candidates with unknown redshift

To find the most promising blazar candidates for CTA, we first selected among the 143 sources cited above those which are visible from the South (Paranal) or the North (La Palma) CTA sites with zenith angles lower than 30 degrees. This filter, which ensures good sensitivity around a few hundreds of GeV, extracts 114 sources from the initial 143. We then extrapolated the 2FHL spectrum of each source into the CTA energy range. As their redshifts are unknown,

**TABLE 1.** Number of blazars with **no** spectroscopic redshift which should be detected by CTA with a significance $>5\sigma$ and an excess >200 counts in different 10-hour bins of CTA exposure. A redshift z=0.3 is assumed for the EBL attenuation. bll refers to BL Lacs and bcu to blazars of uncertain type. The second colomn indicates the declination of the source, and the corresponding CTA instrument (North or South) considered in the Monte-Carlo.

| type | Azimuth | <10h | 10-20h | 20-30h | ≥30h |
|---|---|---|---|---|---|
| bll | North | 9 | 7 | 3 | 25 |
| bll | South | 15 | 3 | 1 | 10 |
| bcu | North | 1 | 4 | 1 | 11 |
| bcu | South | 10 | 5 | 2 | 7 |

**TABLE 2.** Number of blazars with spectroscopic redshift which should be detected by CTA with a significance $>5\sigma$ and an excess >200 counts in different 10-hour bins of CTA exposure. Columns are the same as in Table 1.

| type | Azimuth | <10h | 10-20h | 20-30h | ≥30h |
|---|---|---|---|---|---|
| bll | North | 20 | 6 | 6 | 20 |
| bll | South | 18 | 6 | 3 | 7 |

we used a value of z=0.3 to convolute these spectra with the EBL absorption, which is close to the average redshift z=0.33 found in the survey of Shaw *et al.* [3]. The EBL absorption model was taken from Franceschini, Rodighiero, and Vaccari [4]. For all the sources we simulated the CTA detection using the public CTA response functions for the South and North instruments from https://portal.cta-observatory.org/Pages/CTA-Performance.aspx (corresponding to the so called 'Production 2' simulations for a zenith angle 20°). The best candidates were then selected on the basis of the exposure time needed to achieve a detection level larger than 5 sigmas and a $\gamma$-ray excess larger than 200 events. Results are summarized in Table 1.

From this work it appears that, considering a tentative redshift of z=0.3, about 54/114 2FHL blazars with unknown redshift should be detected by CTA with rather short observations (<20 hours). This number is comparable to the expected number (~50, including sources already detected by $\gamma$-ray Cherenkov telescopes) of 2FHL BL Lacs with known redshift which should be detected by CTA in the same exposure times, see Table 2.

### 3.3 Caveats

The exposure time determined in this way is only a rough estimation. This is due, in particular, to the assumption made on the redshift of the source and on the preliminary nature of the CTA instrument functions used to determine the excess (instrument functions made for a single zenith angle of 20°, corresponding to preliminary configurations of the telescopes arrays and obtained with simple - so non-optimal, see Bernlöhr *et al.* [5] - analysis methods). Nevertheless, this approach allows identifying blazars with unknown spectroscopic redshift which are among the best candidates to be studied by CTA.

## 4 Observing campaigns: imaging and spectroscopy

As spectroscopic observations with world class instruments (at VLT, Keck, etc.) are difficult to obtain (high proposal pressure), we plan to optimize the feasability of our program by selecting for spectroscopy only sources with a reliable optical or NIR counterpart which is classified as extended (i.e. the host galaxy is detected, see an example in Fig. 2). Indeed, the detection of the host galaxy in optical/NIR imaging is a very good clue for the measurability of the spectroscopic redshift. This appears clearly if we consider the sample of 100 RGB BL Lacs observed at NOT by Nilsson *et al.* [6] (with observing times between 30 minutes and one hour): of the 62 BL Lacs for which they detected the host galaxy, 56 have now a spectroscopic redshift; in comparison only 5 of the 38 remaining have a spectroscopic redshift.

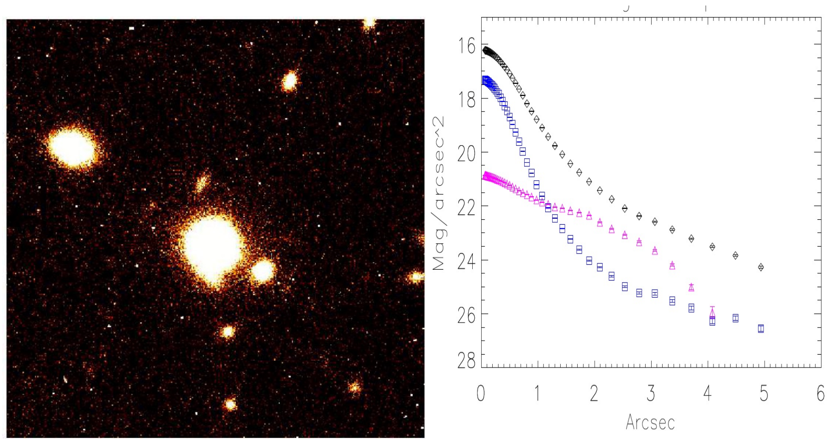


**FIGURE 2.** Example of detection of the host galaxy of a BL Lac object. Left Panel: NTT/SUSI image of the field of PKS 0301-24 (in the center the BL Lac PKS 0301-24, on the left a nearby, extended, elliptical galaxy). Right panel: The blue radial profile has been computed for a star and is representative of the PSF of the instrument, the magenta curve is the profile of the elliptical galaxy in the left panel. Finally the black profile is the one of PKS 0301-24, the profile of the central 1-2 arcsec region is compatible with the profile of the star while starting from 2 arcsec an extended wing is clearly present. From data presented in Falomo and Ulrich [7].

A first search in archival and published results allowed us to identify eight of our candidates as having an extended optical counterpart. We plan to directly submit observing proposals at VLT and/or at Keck for spectroscopic observations for those objects. For the remaining objects, the available archival images (2MASS, DSS, SDSS) are in general shallower than the ones presented in the Nilsson et al. paper. Therefore a deeper search is needed to investigate the possible presence of an extension.

We have submitted an observing proposal to the NOT telescope (PI Lindfors, accepted) with the ALFOSC instrument. The proposal has been accepted and will allow to observe in imaging for about one hour the seven $\gamma$-ray brightest and optically non-extended sources of our sample visible from the Northern Hemisphere. We plan to continue this imaging effort with suitable telescopes and instruments in both Hemispheres. In parallel, as new extended counterparts are discovered, we will submit proposals to observe them in spectroscopy.

Our redshift determination collaboration is open to further members who are experienced in this kind of research and have access to other world class telescopes and instruments similar to the ones previously mentioned.

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