PROCEEDINGS OF SCIENCE

Deciphering the physical properties of the engines of neutrino-emitter blazars

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High-energy neutrinos detected by the IceCube Observatory provide an exclusive opportunity to study the origin of cosmic rays and the nature of the sources producing them. Blazars are among the proposed birthplaces for the astrophysical high-energy neutrinos. Our studies [13–15] put forward a small set of blazars as likely counterparts to IceCube neutrinos.

In this contribution, we focus on this well-defined sample of objects in order to characterize the nature of the sources and the peculiarities of their central engine. Thanks to archival and proprietary data, we provide new insights into the intrinsic properties of this sub-population of neutrino-emitter blazars. We carry out a comprehensive investigation of the observational and physical properties that govern the physics of these blazars, among which redshifts, black hole masses, accretion regimes, radiation fields, etc. Such properties can provide us with crucial clues to decipher what may make this set of objects capable of accelerating cosmic rays. We will discuss our findings, and place our results in the general context of the properties displayed by the overall blazar population.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

ICRC2023
38th International Cosmic Ray Conference
The Astroparticle Physics Conference

[*] Speaker

PoS(ICRC2023)1537

1. Introduction

The origin of the diffuse flux of high-energy neutrinos in the $\gtrsim$ 100 TeV to $\sim$ 10 PeV range detected by the IceCube Neutrino Observatory is still a matter of debate. Among the putative candidates for being the astrophysical birthplaces of these elusive particles, blazar jets have gained growing attention in recent years. Beginning with the coincidence of the blazar TXS 0506+056 with the extremely high-energy IceCube event IC 170922A in 2017 [1, 2], several recent observations led to increased evidence of a connection between blazars and neutrinos. Blazars are a subclass of active galactic nuclei (AGN), powerful astrophysical objects which harbor an actively accreting supermassive black hole (SMBH) in the center and show the presence of relativistic jets pointed towards the line of sight of the observer. The variable, non-thermal emitted radiation from the jets is strongly boosted, and spans the whole electromagnetic spectrum, from the radio to the very-high-energy $\gamma-$ray band. Inspecting the behavior at different frequencies allows us to probe various sides of the underlying physics.

The central black hole is usually surrounded by an optically thick (but geometrically thin) accretion disc. The emission from the disc can be obscured by a surrounding torus of molecular dust (a "dust torus", DT) and/or reprocessed in the so-called narrow- and broad-line regions (NLR and BLR) which are clouds of gas and dust at greater and smaller distance from the central black hole, respectively. Blazars are traditionally subdivided into the two classes of BL Lacertae (BL Lacs) and flat spectrum radio quasar (FSRQ) objects. According to the observed properties of the optical spectrum, we see that BL Lacs show extremely weak or absent emission lines (absorption lines are detected in some cases, and they can trace the surrounding medium as well as the host galaxy), with EW $<$ 5 Å, while broad and strong emission profiles appear in FSRQs. This is a purely empirical distinction, and a more physical taxonomy points to the accretion properties of the system. In this scenario, the leading parameter is the accretion rate defined as the luminosity of the BLR in Eddington units; radiatively efficient blazars are characterized by $L_{\rm BLR}/L_{\rm Edd} \gtrsim 5 \times 10^{-4}$, instead inefficient accretors have values below the threshold [32]. This is consistent with the alternative distinction in high- and low-excitation galaxy (HEGs and LEGs, respectively, see [16, 26]). HEGs efficiently accrete cold gas via an optically thick accretion disc at high rates, have high radio power and show strong high-excitation optical lines. On the other side, LEGs exhibit low Eddington rates, the accretion occurs through hot gas from the surrounding interstellar medium piling up on the massive core and the optical spectrum appears featureless. For the second class of objects, the traditional picture with the disc is replaced by an optically thin (and geometrically thick) accretion flow through which the energy is not radiated, but advected (i.e. advection dominated inner accretion flow, ADAF). Some sources seem to show intermediate behavior between the two classes ("masquerading BL Lacs" and "blue flat spectrum radio quasar", [23, 27]) or even variations over time ("changing-look blazars", [31]). Two examples are TXS 056+056 and PKS 1424+240, which have a featureless optical spectrum but are intrinsically FSRQ with broad lines overwhelmed by the non-thermal emission from the jet. Blazars have been put forward as favorable sites for the production of neutrinos because several processes of particle acceleration can take place in their jets [17, 19]. In this study, we focus on a small set of blazars that have been recently put forward as likely counterparts of IceCube neutrinos, with the intention of understanding which physical processes and features could favor the production of neutrinos. Our study is based on the investigation of the physical properties of these selected objects, using a multi-wavelength (MWL) approach on proprietary and archival data. We present the intrinsic features shown by these sources at optical, radio and γ−ray wavelengths.

2. The sample

We carried out our study on 52 blazars, i.e. "PeVatron blazars" selected through the statistical cross-correlation analysis between IceCube data and blazars of the fifth data release of the Roma BZCat catalog (5BZCat, [3]) of [13–15]. The 5BZCat includes 3561 sources with identified or highly probable blazar nature, that have been individually inspected without any specific selection in wavelength band or survey strategy. Among the sources of our interest, 10 are hosted in the Southern celestial hemisphere ($-85° < \delta < -5°$) and 42 in the Northern ($-3° \leq \delta \leq 81°$). For these targets, we gathered information from the literature and public archives to decipher their behavior at optical, radio and γ−ray energies. The next Section describes the collection of data in more detail.

3. The dataset

3.1 Optical spectroscopy

The investigation of PeVatron blazars through optical spectroscopy was the main part of our work. We observed 5 objects for which no public spectrum was available in the archives, nor information in the literature. Specifically, for two of them we acquired spectra with the European Southern Observatory (ESO) Very Large Telescope at Paranal Observatory (VLT) X-Shooter spectrograph [34] in the ESO-VLT-U3 telescope in the three arms (NIR, VIS and UVB) of the instrument. Also, we observed 3 targets using the R150 grism of the Gemini Multi-Object Spectrographs of Gemini South (GMOS-S, [6, 7]). The reduction was performed, in both cases, with the standard procedure of bias and dark current subtraction, flat field correction, cosmic ray removal, wavelength calibration using the arc lamp exposures, sky subtraction to remove the background contribution from the science spectra and, finally, flux calibration after the reduction and comparison with the spectra of the correspondent standard star and estimation of the sensitivity curve. This was done using the `EsoReflex` version `2.11.5` pipeline [9] for X-Shooter and the Gemini `IRAF` package version `2.16`[1] and `DRAGONS` data reduction software v`3.1.0` [8] for GMOS-S. Thereafter, for the X-Shooter dataset, the `Molecfit` version `4.2.3` [10] software tool was used to correct the science spectra for atmospheric contamination features, in particular the contribution of telluric absorption lines. For the remaining blazars in the sample, we employed spectra that were publicly available in several archives or published information taken from the literature.
Optical spectroscopy is a powerful tool to gain insight into the intrinsic radiative luminosity and power of the central engine, investigate the region surrounding the central supermassive black hole (SMBH), and typify blazars according to the efficiency of the involved accretion processes. For the most part, optical light is emitted by the accretion disc, and then it is reprocessed through photoionization of the gas of the BLR and NLR. In particular, when present, the emission line profiles can be used to determine the distance of the observed target (through the redshift measurement),

[1]Please visit `https://noirlab.edu/science/programs/csdc/usngo/gmos-cookbook/`

estimates the luminosity of the broad line region and the mass of the central black hole and, consequently, the mass accretion rate in Eddington units.

3.2 Fermi Large Area Telescope properties

The $\gamma-$ray luminosity can be used as a proxy for the power of the jet. The information for the sources in our sample was collected from the Data Release 3 of the Fourth Fermi Large Area Telescope (LAT) AGN Catalog (4LAC−DR3, [4]). Among the PeVatron blazars, 5 Southern and 21 Northern sources have a Fermi detection. We estimated the luminosity L_γ using the spectral index and the photon flux as in [21].

$$L_\gamma = 4\pi d_{\rm L}^2 \cdot \frac{S_\gamma\,(\nu_1,\nu_2)}{(1+{\rm z})^{1-\alpha_\gamma}} \tag{1}$$

where $d_{\rm L}$ is the luminosity distance estimated from the redshift with Astropy[2], $\alpha_\gamma = \Gamma_\gamma - 1$ is evaluated from the photon spectral index Γ_γ in the Fermi energy band, and $S_\gamma\,(\nu_1,\nu_2)$ is the $\gamma-$ray energy flux between the frequencies ν_1 and ν_2, calculated from the photon flux $F_\gamma\,({\rm E} > 50{\rm MeV})\,\left[{\rm ph}\cdot{\rm cm}^{-2}\cdot{\rm s}^{-1}\right]$ as,

$$S_\gamma\,(\nu_1,\nu_2) = \begin{cases} \frac{\alpha_\gamma h\nu_1\cdot F_\gamma}{1-\alpha_\gamma}\cdot\left[\left(\frac{\nu_2}{\nu_1}\right)^{1-\alpha_\gamma} - 1\right] & \text{for } \alpha_\gamma \neq 1\,, \\ h\nu_1 F_\gamma \ln\left(\frac{\nu_2}{\nu_1}\right) & \text{for } \alpha_\gamma = 1\,. \end{cases} \tag{2}$$

In our case, $\nu_1 = 1.207\times10^{22}$ Hz (50 MeV) and $\nu_2 = 2.413\times10^{27}$ Hz (1000 GeV) to cover the full energy band of the 4LAC-DR3 catalog. For the remaining 26 blazars with no Fermi detection, we placed an upper limit on the luminosity using the sensitivity of the instrument and $F_\gamma = 5\times10^{-10}\,{\rm ph}\cdot{\rm cm}^{-2}\cdot{\rm s}^{-1}$, $\Gamma_\gamma = 3.5$.

3.3 Radio properties

The 5BZCat catalog is built so that each blazar has detection in radio. We are especially interested in the observed flux at 1.4 GHz as a proxy for the intrinsic power of the relativistic jet. For this reason, we collected the NRAO VLA Sky Survey (NVSS, [5]) values to explore the non-thermal physical processes and related energies that come into play and classify blazars in radio-loud/radio-quiet or high-excitation/low-excitation objects, as in [16]. Also, the radio power traces the evolution of AGN, with low-value ($P_{1.4\,{\rm GHz}} \lesssim 10^{26}\,{\rm W}\cdot{\rm Hz}^{-1}$) sources evolving less than high-power ones [26, and references therein].

4. Method

To perform the analysis, we extracted and visually inspected the optical spectra of our interest in order to identify detected emission line profiles. We were especially interested in the hydrogen lines of the Lyman or Balmer series Lyα, Hα and Hβ and the ionized species of Mg II, C IV lines which are produced in the BLR, along with [O II] and [O III], which are instead emitted in the NLR. Once identified, the lines are first used to check the measure of the redshift. Then, the Image

[2]More details at https://docs.astropy.org/en/stable/cosmology/index.html

Reduction and Analysis Facility (IRAF, [11]) software was used to fit the features with either one or multiple Gaussian functions according to the morphological shape of the profile. The results from the fit[3] have been extracted, compared to independent fits performed with scipy[4] and used for further analysis. The flux, equivalent width (EW) and full width at half maximum (FWHM) were used to estimate the central engine properties of the blazars in our sample ([18, 22, 27–29, 33]).

Our list of sources includes blazars classified as both FSRQs and BL Lacs, hence some of the collected spectra appear featureless by definition. To get a hint on their properties, we estimated upper limits on the luminosity of the non-detected emission lines [32]. Thereafter, the luminosity (or the upper limit) of the emission lines was employed to estimate the total luminosity of the broad line region and of the accretion disc,

$$L_{\rm BLR} \simeq 10\%\, L_{\rm disc} = L_{\rm line} \cdot \frac{\langle L_{\rm BLR} \rangle}{L_{\rm rel.\,frac.}} \tag{3}$$

with $L_{\rm rel.\,frac.} = 77, 22, 34, 63$ for Hα, Hβ, Mg II and C IV being the contribution of each line to the total BLR luminosity as estimated on the basis of the composite spectrum of [20], assuming a relative flux of 100 for Lyα. When more than one emission line appears in the spectrum, we took the average of the BLR luminosity measured for each profile.

The relation between the luminosity of the broad line region and the accretion disc holds, as broad emission lines are produced by clouds that are photoionized by the radiation coming from the disc. It directly links the accretion disc luminosity with the observed broad emission lines, it makes the estimation independent of the viewing angle since the lines are assumed to be isotropically emitted, and it avoids contamination from the non-thermal continuum. The expected average uncertainty on the resulting value is a factor of 2. The luminosity and FWHM of the line were employed in the estimation of the virial mass of the central black hole through the empirical scaling laws of [33]. Indeed, we assume that the BLR is gravitationally bounded to the central BH potential, in such a way that we can estimate the mass of the central object by evaluating the orbital radius and Doppler velocity of the region through an inspection of the emitted lines. The evaluation is made through the following equation,

$$\log\left(\frac{M_{\rm BH}}{M_\odot}\right) = a + b \cdot \log\left(\frac{L_{\rm line}}{10^{44}\ {\rm erg\cdot s^{-1}}}\right) + c \cdot \log\left(\frac{\rm FWHM}{\rm km\cdot s^{-1}}\right) \tag{4}$$

where the coefficients are [33]:

$$({\rm a, b, c}) = \begin{cases} (0.379, 0.43, 2.1) & \text{for H}\alpha\,, \\ (0.672, 0.61, 2.0) & \text{for H}\beta\,, \\ (0.740, 0.62, 2.0) & \text{for Mg II}\,, \\ (0.660, 0.53, 2.0) & \text{for C IV}\,, \end{cases} \tag{5}$$

From the black hole mass, we can estimate the Eddington luminosity of the sources as $L_{\rm Edd} = 3 \times 10^4 \left(\frac{M}{M_\odot}\right) L_\odot$. The resulting value only depends on the mass of the central accreting object.

[3]splot function for profile deblending and Gaussian fitting available at https://astro.uni-bonn.de/~sysstw/lfa_html/iraf/noao.onedspec.splot.html

[4]More details at https://docs.scipy.org/doc/scipy/reference/generated/scipy.optimize.curve_fit.html

Also, by definition, it sets an upper limit on the accretion luminosity of the central compact core. Therefore, the disc luminosity in Eddington units traces the normalized accretion rate [24, 33] $M \equiv \frac{\dot{M}_{\rm acc}}{\dot{M}_{\rm Edd}} = \frac{L_{\rm disc}}{\eta \cdot L_{\rm Edd}}$, where η is the radiative efficiency of accretion, and for geometrically thin accretion discs depends on the location of the innermost stable orbit of the disc and, thus, the spin of the central black hole. For rapidly rotating black holes, $\eta = 0.3$ is a good assumption [24].
The non-thermal emission of the jet is assumed to come from a spherical region, which is embedded in a homogeneous but tangled magnetic field. In this model, the radiation component takes into account the contributions of the emission disc, the broad line region, the dusty torus surrounding the disc, and the part of the radiation that is intercepted in the infrared and re-emitted. This structure allows us to estimate the distance of the broad line region and the dusty torus from the luminosity of the disc. Following the works of [22, 24, 25], we measure the radius of the BLR and the torus as $r_{\rm BLR} = 10^{17} \cdot \left(L_{\rm disc}/10^{45}\,{\rm erg \cdot s^{-1}}\right)^{1/2}$ cm and $r_{\rm DT} = 2 \times 10^{18} \cdot \left(L_{\rm disc}/10^{45}\,{\rm erg \cdot s^{-1}}\right)^{1/2}$ cm, respectively.

5. Discussion and conclusions

In this work, we were able to study a selected sample of highly likely neutrino-emitter blazars. The multi-wavelength study of optical, radio and γ-ray properties of the objects led us to inspect the accretion regime of the central engine and the energy content of the relativistic jet. Our sample includes sources classified as both FSRQs and BL Lacs according to the traditional empirical method, while we made a tentative classification on the basis of the accretion regime and radio power. To do so, we adopted the approach of [28, 29, 32] of identifying blazars with $L_{\rm BLR}/L_{\rm Edd} \gtrsim 5 \times 10^{-4}$, $L_{\gamma}/L_{\rm Edd} \gtrsim 0.1$ as radiatively efficient. For the radio power, instead, we investigated the trend using $P_{1.4\,{\rm GHz}} \sim 10^{26}\,{\rm W \cdot Hz^{-1}}$ as dividing line between HEGs and LEGs [16, 30]. A comparison with the overall population of blazars allowed us to identify common trends in the behavior of the sources, that will be shown in a follow-up work [12].

Acknowledgments

This work was supported by the European Research Council, ERC Starting grant *MessMapp*, S.B. Principal Investigator, under contract no. 949555.

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