The Open Universe VOU-Blazars tool

Yu-Ling Chang\textsuperscript{1,2}, Carlos H. Brandt\textsuperscript{2,3}, Paolo Giommi\textsuperscript{4,5,2}

Abstract

Context: Blazars are a remarkable type of Active Galactic Nuclei (AGN) that are playing an important and rapidly growing role in today’s multi-frequency and multi-messenger astrophysics. In the past several years, blazars have been discovered in relatively large numbers in radio, microwave, X-ray and $\gamma$-ray surveys, and more recently have been associated to high-energy astrophysical neutrinos and possibly to ultra-high energy cosmic rays. Blazars are expected to dominate the high-energy extragalactic sky that will soon be surveyed by the new generation of very high-energy $\gamma$-ray observatories such as CTA. In parallel to the discovery of many blazars at all frequencies, the technological evolution, together with the increasing adoption of open data policies, is causing an exponential growth of astronomical data that is freely available through the network of Virtual Observatories (VO) and the web in general, providing an unprecedented potential for multi-wavelength and multi-messenger data analysis.

Product: We present VOU-Blazars, a tool developed within the Open Universe initiative that has been designed to facilitate the discovery of blazars and build their spectral energy distributions (SED) using public multi-wavelength photometric and spectral data that are accessible through VO services. The tool is available as source code, as a Docker container, and as a web-based service accessible within the Open Universe portal\textsuperscript{*}.

Methods: VOU-Blazars implements a heuristic approach based on the well known SED that differentiate blazars from other astronomical sources. The VOU-Blazars outputs are flux tables, bibliographic references, sky plots and SEDs.

Results: This paper describes the working mechanism of the tool, gives details of the catalogues and on-line services that are used to produce the output, and gives some examples of usage. VOU-Blazars has been extensively tested during the selection of new high-energy peaked (HSP) blazars recently published in the 3HSP catalog, and has been used to search for blazar counterparts of Fermi 3FHL, Fermi 4FGL, AGILE $\gamma$-ray sources, and of IceCube astrophysical neutrinos.

Keywords: Software and its engineering: Real-time systems software ; Applied computing: Astronomy ; BL Lacertae objects: general

\textsuperscript{*}Email address: ylchang@sjtu.edu.cn (Yu-Ling Chang) \textsuperscript{*}Tsung-Dao Lee Institute, Shanghai Jiao Tong University, 800 Dongchuan RD. Minhang District, Shanghai, China \textsuperscript{2}ICRANet, Piazza della Repubblica 10, Pescara, Italy \textsuperscript{3}Agenzia Spaziale Italiana, Via del Politecnico s.n.c., Rome, Italy \textsuperscript{4}Institute for Advanced Study, TUM, Lichtenberg strasse, Garch-
1. Introduction

We present a software tool developed in the context of the Open Universe Initiative (Giommi et al., 2018) that has been designed to facilitate the identification and the broad-band spectral study of blazars and other astrophysical sources, based on public multi-frequency data retrieved from the Virtual Observatories\textsuperscript{6} network.

Blazars are a special type of Active Galactic Nuclei (AGN) distinguished by the emission of strong non-thermal radiation across the entire electromagnetic spectrum (Padovani et al., 2017), a unique characteristics among extragalactic objects that gives them a central role in contemporary $\gamma$-ray and multi-frequency astronomy, and likely in the emerging field of multi-messenger astrophysics. Developing efficient tools useful for the detailed study of these sources is therefore important and timely to support a rapidly evolving research in this field.

From a physical viewpoint the non-thermal continuum seen in the spectral energy distribution (SED) of blazars is due to the radiation emitted by energetic particles moving in a relativistic jet emerging from the central super-massive black hole(Padovani et al., 2017).

From the observational viewpoint, the multi-waveband SED plot (Fig. 1) of any blazar well covered from radio to high-energy (to x-ray, $\gamma$-ray) typically presents two distinct features: high variability and two large bumps. The first bump is generally attributed to synchrotron emission, while the second one may be due to inverse Compton scattering or to radiation originating in a hadronic or lepto-hadronic scenarios (Reimer, 2012; Cerruti et al., 2011; Petropoulou et al., 2015, 2016; Gokus et al., 2018).

The position where the first bump peaks has been used to further classify blazars into low synchrotron peaked (LSP) and high synchrotron peaked (HSP) objects(Padovani and Giommi, 1995; Abdo et al., 2010). LSP blazars will present an associated peak energy below $Hz < 10^{14}$, while HSP blazars’ peak at $Hz > 10^{15}$. Objects peaking at intermediate energies are called ISP blazars.

Observations have shown that HSP blazars are bright and variable sources of high-energy $\gamma$-rays (TeVCat)\textsuperscript{7} and that they are likely the dominant component of the extragalactic very high-energy (VHE, $E > 100 \text{ GeV}$) background (Padovani et al., 1993; Giommi et al., 2006; Di Mauro et al., 2014; Giommi and Padovani, 2015; Ajello et al., 2015). Very high-energy emitters are rare and still poorly understood astrophysical sources. So far only a few hundred of them have been detected in the VHE band. The identification of VHE sources is receiving increasing attention, especially in relation with the likely connection with high-energy neutrinos and ultra high-energy cosmic-rays. A non negligible fraction of the cataloged $\gamma$-ray or VHE sources, or neutrino events, are not associated to lower energy sources yet.

\textsuperscript{6}http://www.ivoa.net/

\textsuperscript{7}http://tevcat.uchicago.edu
The recent association between the astrophysical high-energy neutrino IceCube-170922 with the bright blazar TXS0506+056 (The IceCube Collaboration et al., 2018; The IceCube Collaboration, 2018; Padovani et al., 2018) represents a strong mark, and possibly a smoking gun, in the search for the sources of ultra high-energy (UHE) particles, opening up the new era of blazar studies. Motivated by such evidences and in view of the increasing sensitivity of the next generation of VHE and multi-messenger observatories, we developed a tool, VOU-Blazars, to mine the existing and constantly increasing multi-wavelength databases to support the search of new blazars and study their broadband spectral properties and their temporal behavior.

The name, VOU, is the combination of VO (virtual observatory) and OU (open universe) as VOU-Blazars has been developed in the framework of Open Universe and is based on VO protocols. Open Universe is an initiative conceived to make astronomical data more openly available and usable by the widest possible community. Initially proposed by Italy to the United Nations Committee on the Peaceful Uses of Outer Space (COP-UOS) in 2016, Open Universe is now being actively developed by a number of countries in coordination with the UN Office for Outer Space Affairs (UNOOSA).

The VOU-Blazar software is available as source code, as a tool encapsulated in a Docker container, and as a web service that can be activated from the Open Universe portal. The databases used in the tool are all publicly available within the VO network.

2. Workflow

It is well known since the early days of multi-frequency astronomy that blazars can be discovered through the analysis of radio, optical/IR and X-ray data (see e.g. Padovani and Giommi (1995); Perlman et al. (1998); Giommi et al. (1999); Chang et al. (2017); Arsioli et al. (2015)). The VOU-Blazars software exploits this property as shown in scheme of Fig. 2, which illustrates the two-phase working mechanism of the tool. The first phase locates blazars candidates in the requested area, which can be relatively large, while the second phase deals with only one candidate at a time, generating and plotting the SED and the corresponding error circle map. The error circle map is a plot where all the nearby detections, as well as their position error circle, are visualized.

The main purpose of the first phase is to identify blazar candidates within a given searching area, whose size that can be as small as one arcminute or less to several degrees. Given that the majority of the blazars are detected in both the radio and X-ray band, VOU-Blazars begins with searching for sources in all available lists of radio or X-ray emitters within the specified searching region. In this phase the tool retrieves data from several catalogs providing photometric data through VO conesearch pipeline, and estimates the possible presence of blazar candidates.

The tool also interrogates type-specific catalogs of known sources (blazars, γ-ray burst (GRB), pulsars, γ-ray sources, and clusters of galaxies) to further help the user on possible ambiguities. In the first phase, currently a total of 34-catalog searches are made through the conesearch pipeline, and estimates the possible presence of blazar candidates.

The catalog used in this phase are listed in Table 1, while Table 2 gives the frequencies
of the X-ray data from each catalog.

It is well known that the radio to X-ray flux ratios are very different in HSP and LSP blazars (e.g. Padovani and Giommi, 1995; Padovani et al., 2003, 2007). VOU-Blazars uses the spectral slope between radio and X-ray, \( \alpha_{\nu_1-\nu_2} \), to classify every radio-X-ray matching sources in the first phase. Some of the cataloged blazars and pulsars (see table 1 for catalog’s references) might not have both radio and X-ray detections. We list them among the selected sources during the first phase as well. Table 3 shows the details of classification of the radio-X-ray matching candidates. All the blazar candidates as well as the cataloged sources (5BZCat, 3HSP, CRATES) are available in the second phase for a thorough examination.

Several LSP blazars are not detected in the X-ray band, as the X-ray emission of this type of objects is weak and their flux may easily be below the sensitivity of currently available observations. For similar reasons, HSPs with relatively high \( \nu_{\text{peak}} \) values might not be de-
Table 1: Catalogs applied in the first phase

| Radio/Fermi Catalogs                                           | X-ray Catalogs                          |
|---------------------------------------------------------------|-----------------------------------------|
| NVSS (Condon et al., 1998)                                    | XMMSS Dr2 Clean (Saxton et al., 2008)  |
| FIRST (White et al., 1997; Helfand et al., 2015)              | 3XMM Dr8 (Watson et al., 2009)          |
| SUMSS V2.1 (Manch et al., 2003)                               | RASS 2RXS (Boller et al., 2016)         |
| CRATES (Healey et al., 2007)                                  | WGACAT2 (White et al., 2000)            |
| Fermi 4FGL (The Fermi-LAT collaboration, 2019)                | Swift 1SXPS (Evans et al., 2014)        |
| Fermi 3FHL (The Fermi-LAT collaboration, 2017)                | 3XMM Dr8 (Watson et al., 2009)          |
| Fermi 3GFL (Acero et al., 2015)                               | RASS 2RXS (Boller et al., 2016)         |
| 1BIGB SED (Arsioli et al., 2018)                              | WGACAT2 (White et al., 2000)            |
| MST-9Y (Campana et al., 2018)                                 | Swift 1SXPS (Evans et al., 2014)        |
| FermiMeV (Principe et al., 2018)                              | 3XMM Dr8 (Watson et al., 2009)          |
| 2AGILE (Bulgarelli et al., 2019)                              | RASS 2RXS (Boller et al., 2016)         |

| Blazar/Pulsar/GRB/Quasar Catalogs                            | Cluster of galaxies Catalogs            |
|--------------------------------------------------------------|-----------------------------------------|
| 5BZCat (Massaro et al., 2015)                                | ZW CLUSTERS (Zwicky et al., 1968)       |
| 3HSP (Chang et al., 2019)                                    | PLANCK SZ2 (Planck Collaboration, 2016) |
| ATNF PULSAR (Manchester et al., 2005)                        | ABELL (Abell et al., 1989)              |
| Fermi 2PSR (The Fermi-LAT Collaboration, 2013)               | MCXC (Piffaretti et al., 2011)          |
| Fermi GRB (Ajello et al., 2019)                              | SDSS WHL (Wen et al., 2009)             |
| Million Quasar (Flesch, 2015)                                | SW XCS (Liu et al., 2015)               |

In the second phase, the user can complete the data analysis of one or more of the candidates found in the first phase building a complete SED using data from additional 34 catalogs, covering the high-frequency radio, microwave, far IR, IR, optical, UV, hard X-ray, γ-ray, and TeV bands. The list of catalogs used in the second phase is given in Table 1.

As blazars are extragalactic sources data from IR, optical, and UV catalogs need to be corrected for Galactic extinction. To take into account of this we follow the extinction rule in Fitzpatrick (1999). Effective wavelengths and zero-magnitude fluxes applied for every bands are listed in Table 5.

3. Examples of the use of VOU-Blazars and some results

In this section, we illustrate two examples of the use of VOU-Blazars and describe the output.

The simplest way to use the VOU-Blazars tool is to input three parameters: R.A., Dec., and radius, to define the position in the sky and the radius of a circular area detected in radio surveys. Here we call radio sources without X-ray detections ”single radio sources”, and vice versa. If the requested searching area is small, a process called intermediate phase is “triggered” to search for additional blazar candidates among single radio or X-ray sources. If no sources without radio-X-ray matching is present inside the error area, the intermediate phase will not be called.

The intermediate phase makes use of the GALEX, PMN, and GB6 catalogs (see table 4 for catalog’s references) to search for possible UV emission and to estimate the radio spectral index. The searching radius for VO conesearch in this step is set to same as the input radius, same as in the first phase. The GALEX data then are converted to monochromatic fluxes and de-reddened using Fitzpatrick (1999) extinction rule.

In the second phase, the user can complete the data analysis of one or more of the candidates found in the first phase building a complete SED using data from additional 34 catalogs, covering the high-frequency radio, microwave, far IR, IR, optical, UV, hard X-ray, γ-ray, and TeV bands. The list of catalogs used in the second phase is given in Table 1.

As blazars are extragalactic sources data from IR, optical, and UV catalogs need to be corrected for Galactic extinction. To take into account of this we follow the extinction rule in Fitzpatrick (1999). Effective wavelengths and zero-magnitude fluxes applied for every bands are listed in Table 5.
| X-ray catalogue          | Energy band          | Energy of nufnu flux for SED plotting (keV) |
|-------------------------|----------------------|--------------------------------------------|
| XMMSL Dr2 Clean         | b8 (0.2 - 12 keV)    | 1.0                                        |
|                         | b6 (0.2 - 2 keV)     | 1.1                                        |
|                         | b7 (2 - 12 keV)      | 7.0                                        |
| 3XMM Dr8                | EP8 (0.2 - 12 keV)   | 1.0                                        |
|                         | EP1 (0.2 - 0.5 keV)  | 0.35                                       |
|                         | EP2 (0.5 - 1 keV)    | 0.75                                       |
|                         | EP3 (1 - 2 keV)      | 1.5                                        |
|                         | EP4 (2 - 4.5 keV)    | 3.25                                       |
|                         | EP5 (4.5 - 12 keV)   | 8.25                                       |
| RASS 2RXS               | 0.1 - 2.4 keV        | 1.0                                        |
| WGACAT2                 | 0.24 - 2 keV         | 1.0                                        |
| Swift 1SXPS             | Total 0.3 - 10 keV   | 1                                          |
|                         | Soft 0.3 - 1 keV     | 0.65                                       |
|                         | Medium 1 - 2 keV     | 1.5                                        |
|                         | Hard 2 - 10 keV      | 6                                          |
| XRT DeepSky / SDS82     | Total 0.3 - 10 keV   | 3.0                                        |
|                         | Soft 0.3 - 1 keV     | 0.5                                        |
|                         | Medium 1 - 2 keV     | 1.5                                        |
|                         | Hard 2 - 10 keV      | 4.5                                        |
| Einstein IPC / IPC slew survey | 0.2 - 3.5 keV   | 1.0                                        |
| BMW-HRI                 | 0.1 - 2.4 keV        | 1.0                                        |
| Chandra                 | Full band 0.5 - 7 keV| 1.0                                        |
|                         | Ultra Soft 0.2 - 0.5 keV | 0.35                         |
|                         | Soft 0.5 - 1.2 keV   | 0.85                                       |
|                         | Medium 1.2 - 2 keV   | 1.6                                        |
|                         | Hard 2 - 7 keV       | 4.5                                        |
| Swift OUSXB / OUSXG     | Full band 0.3 - 10.0 keV | 3                                        |
|                         | Soft 0.3 - 1.0 keV   | 0.5                                        |
|                         | Medium 1.0 - 2.0 keV | 1.5                                        |
|                         | Hard 2.0 - 10.0 keV  | 4.5                                        |
|                         | Interpolation 0.5 and 1.5 keV | 1.0                              |

Table 2: List of X-ray catalogues, energy bands and SED energies

Table 3: Classification of the candidates

| Condition                                           | Description |
|-----------------------------------------------------|-------------|
| $0.43 < \alpha_{\text{rx}} < 0.78$, $\log \nu_{\text{peak}} > 15.5$ | HSP candidate |
| $0.43 < \alpha_{\text{rx}} < 0.78$, $\log \nu_{\text{peak}} < 15.5$ | ISP candidate |
| $0.78 < \alpha_{\text{rx}} < 0.95$                  | LSP candidate |
| $\alpha_{\text{rx}} < 0.43$                         | non-jetted AGN candidate |
| $0.95 > \alpha_{\text{rx}}$                        | Unknown     |

where to search for blazars. The RA and Dec are in the unit of degrees (epoch J2000.0), and the searching radius is in the unit of arc-minutes, as in the following example.
Figure 3: Top: Map showing all blazars candidates found in the area of interest. Orange symbols: HBL/HSP blazars, Cyan: IBL/ISP, Blue: LBL/LSP, the red circle with open square represent a flat radio source (from the CRATES catalog) with no associated X-ray detection. Bottom: Map showing all radio (red filled circles) and X-ray (blue open circles) sources in the field of interest. Both maps refer to case 1. See text for details.

$\text{VOU-Blazars 77.43 5.72 80}$

Additional parameters, such as the value of NH (Hydrogen Column density in the Galaxy at the requested position, in units of cm$^{-2}$), and the parameters to define up to two circular (or elliptical) search areas can also be specified:

$\text{VOU_Blazars 77.43 5.72 80 3.e21 50 60 25 45}$

The value of NH is used to de-absorb the (near-IR, optical or X-ray) flux values retrieved from the catalogs to take into account of absorption in our galaxy. If no NH value is provided, VOU-BLazars uses the NH value obtained from the NH tool within HEASOFT$^{16}$.

The first case considered above refers to a search in a circular region centered at the position R.A. = 77.43 and Dec. = 5.72 degrees with a radius of 80 arc-minutes. In the second example the input further specifies the nH value (3.e21 cm$^{-2}$), one circular region (with radius 50 arcmin), and one elliptical area (major and minor axis of 60 and 25 arcmins and position angle (45 degrees). See the GitHub page for more information on input parameters (see Sect.5).

At the end of the first phase, the tool produces two figures, one candidate map and one Radio-X-ray source map, that are shown in the top and bottom parts of Fig. 3. The meaning of the symbols in the source map is explained in Table 6. The circular area of radius 50 arcmin is where sources are searched, while the elliptical area is plotted in light blue color, which in this example approximates the uncertainty in the arrival direction of the neutrino IC170922.

Six known or candidate blazars are found within the searching region. Source number 4, the closest to the center, is the bright blazars TXS 0506+056 that has

$^{16}$https://heasarc.gsfc.nasa.gov/docs/software/heasoft/
been associated to the neutrino (The IceCube Collaboration et al., 2018; Padovani et al., 2018). It is an ISP blazar and therefore it is represented with a light blue circle. Two HBL candidate blazars (orange circles) are also found around the neutrino detection, source number 2, inside the 90% error ellipse, is a 3HSP source (3HSP J050833.3+053109) and it is also marked with golden star; source number 3, outside the error ellipse, is an uncatalogued HSP candidate. Source number 1, an LSP object (dark blue circles) is a known source listed in 5BZCat (5BZQ J0505+0459), and source number 5 is an ISP candidate close to cluster of galaxies (ZW 4472), and for this reason it appears as a light blue symbol with a question mark. In addition, there are two γ-ray detections (3FHL J0505.4+0458 and 4FGL J0505.3+0459), represented by purple triangles. Source number 6, the flat-spectrum radio source CRATESJ051256+060835, is without an X-ray counterpart and is shown as the red filled circle (radio source) with a blue open square (CRATES sources) on it. Source numbers 1 and 4 are also in million quasar catalog with small dark green circle on it. Note that for candidate numbers 1, 4, and 5, the size of the X-ray counterpart on the candidate map is smaller than that of the radio counterpart, causing the open circle to be covered by the filled circle. In these situations, the X-ray counterparts are shown with a magenta color.

In the example illustrated by Fig. 4 the VOU-Blazars tool was run on the position of the Fermi γ-ray source 4FGL J0439.4-3202. The elliptical shape represents the uncertainty on the arrival direction of the γ-ray source, while the larger area is a circle with radius of 5 arcminutes, approximately half the size of the total searching radius. The candidate map shows two known blazars: the HSP 3HSP J043932.2-320052 and the LSP 5BZU J0439-3210, which is also in CRATES (J043929-320956). The 3HSP source, candidate number 1, is inside the error region of the Fermi source and is very likely the counterpart of the γ-ray source. Sources numbered 3 and 4 are also plotted in the candidate map and listed as possible blazars, following the comparison of their positions and fluxes with 4.8GHz and UV catalogues data in the intermediate phase.
After the second phase, the VOU-Blazars plots the SED of the requested candidate(s) and the associated error circle map(s). Fig. 5, 6, and 7 are examples of these plots. The meaning of the color of each error circle is given in Table 7.

3.1. The VOU-Blazars SED mode

The VOU-Blazar tool can also be used to directly produce SEDs of objects with known position. This is called the “SED mode” and can be activated from the command line, as in the following example

$ $VOU-Blazars RA DEC r s$

where “r” is the radius of a circular area, typically 1 arcminute, where to plot the error uncertainties of the data retrieved, and “s” is a flag specifying that the tool should run in SED mode. The same mode can also be activated from the Open Universe portal by clicking on
The SED mode of VOU-Blazars is designed to build the SED of a source with known precise coordinates. The tool finds all the counterparts from every catalogs of the first and second phase without interruption. Comparing with the usual Find Candidate mode, the SED mode only returns flux and error circle along with the SED and error circle map for all the matched counterparts rather than returning a list and a map of potential candidates. Cross-matched radius in SED mode is the position error of each searching catalogs. Fig. 8 shows an example of the SED generated by VOU-blazars compared to the one produced by Italian Space Agency (ASI) Space Science Data Center (SSDC) SED Builder tool\textsuperscript{17}. The corresponding file containing flux values and references is illustrated in Fig. 9. The data on SED obtained from the VOU-Blazars are very similar to that of the SSDC tool. Moreover, the VOU-Blazars SED contains a number of measurements that the SSDC tool did not retrieve. On the other hand the SSDC SED tool shows many other points in different colors, some of which were retrieved from sites not reachable via VO protocols and uploaded manually. The two tools are therefore complementary.

\textsuperscript{17}https://tools.ssdci.asi.it/SED/

Figure 7: Same as Fig.5 for candidate number 1, an HSP, in case 2

the icon indicated by the blue dashed arrow in Fig. 10.
4. Previous applications of the tool

A preliminary version of VOU-Blazars has already been used in some scientific papers. In particular, the tool was extensively used by some of us to find new HSP blazars to be included in the 3HSP catalog (Chang et al., 2019). Padovani et al. (2018) used the tool to study in detail all the possible counterparts of the neutrino event IceCube-170922A (The IceCube Collaboration, 2018). The tool has been implemented as one of the options available within the Open Universe portal, where it can be used also to identify sources with large positional uncertainty. Figure 10 shows the case of the source 4FGL J1211.6+3901.

Figure 3 is the candidate map which lists all the possible counterparts for IceCube-170922A. The larger error elliptical is 90% of the neutrino position, and the smaller error circle is set to 15 arc-minutes for testing. Source number 4, and ISP, TXS 0506+056, also cataloged in 5BZCat (5BZBJ0509+0541) and CRATES (J050926+054143) with the blue square and golden diamond on the figure. This source is the closet and most possible counterpart for the neutrino event. (The IceCube Collaboration et al., 2018; Padovani et al., 2018) The ISP is also detected by Fermi and in 3FHL catalog (3FHL J0509.4+0542), with purple triangles nearby.

Apart from identifying possible counterpart for VHE/neutrino detections, there were many good HSPs found by running the tool. Specifically, around 30 new
Figure 9: The file containing the $\nu f(\nu)$ flux, the corresponding uncertainties, observation date (when available) and the bibliographic references used by VOU-Blazars to build the SED of CTA102 shown in Fig.8. For reasons of brevity only one entry per catalog or database and per representative frequency are reported. The real file includes over 1600 lines.

5. Availability of the tool

In compliance with the Open Universe principles of transparency and easiness of use, the VOU-Blazars tool is openly available in various forms, as described below.

5.1. Source code on GitHub

The VOU-Blazars source code can be downloaded from GitHub at https://github.com/ecylchang/VOU_Blazars. To install the VOU-Blazars code and run the tool on your own computer, please follow the instructions available at the GitHub page.

5.2. Implementation as a Docker container

A version of the VOU-Blazars tool encapsulated in a Docker container is available at the following address https://hub.docker.com/r/chbrandt/voublazars, which allows the user to run VOU-Blazars in a simple way.

Because Docker command-lines may be complex depending on the user’s familiarity to such environment we developed a small Python tool that simplifies the use of Docker for VOU-Blazars. The tool is called dockeri and is available at https://github.com/chbrandt/dockeri. Dockeri works with any version of Python. Once Docker18 and dockeri19 are installed,

---
18https://docs.docker.com/install/
19https://github.com/chbrandt/dockeri
VOU-Blazars is run with a command-line like:

```
$ dockeri -w output_dir \\
    chbrandt/voublazars
```

which will run the latest version of VOU-Blazars. If no positional arguments are given – like the above example –, VOU-Blazars will ask for them interactively. The user can also directly give the input parameters:

```
$ dockeri -w output_dir \\
    chbrandt/voublazars \\
    77.43 5.72 1 s
```

which runs VOU-Blazars in SED mode (see section 3.1). After the processing is complete, the results will be found in directory output_dir.

5.3. Implementation within the Open Universe portal

VOU-Blazars has been integrated with the Open Universe web portal. To use this on-line version of the tool simply enter the desired sky coordinates (or the name of an astronomical object) in the input area located on the top right side of the portal, highlighted by a red box in Fig. 10, then click on the VOU-Blazar button indicated by the red arrow. The figure gives the example of the region around a Fermi 4FGL γ-ray source. For sources from catalogues of objects that have non negligible positional uncertainty the Open Universe portal retrieves both the best coordinates of the source and the parameters of the uncertainty region.

6. Conclusion and future developments

We have developed VOU-Blazars, a new software tool that makes use of multi-frequency data-sets retrieved using VO protocols, to find blazars anywhere in the sky, and particularly in moderately large areas (up to a few degrees), that are typical of the positional uncertainty of γ-ray sources, high-energy astrophysical neutrinos, UHECRs, etc.

During the development and testing phase the VOU-Blazars tool has been used to find potential IceCube neutrinos counterparts (Padovani et al., 2018), and to discover several new HSP blazars during the preparation of the 3HSP catalog(Chang et al., 2019). The consolidated version of VOU-Blazars presented in this paper will be useful to discover new blazars and for the identification of the counterparts of the many high-energy extragalactic sources discovered by the current and by the next generations of γ-ray and neutrino observatories.

In the near future, we plan to make a number of improvements to the tool, including

- enhanced identification methods based on more multi-frequency and multi-temporal information;
- the use of machine learning techniques;
- increase the number of catalogs providing more spectral and timing information

All of the above will keep the tool up to date with new catalogs as they come on-line, will make it more precise in the identification process (reducing the number of uncertain candidates that may generate confusion in large searching area), and will enable spectral and timing analysis.

13
Figure 10: The implementation of VOU-Blazars within the Open Universe portal. This example shows the case of the Fermi γ-ray source 4FGLJ1211.6+3901, whose position and elliptical uncertainty region parameters have been retrieved by the system. The candidate blazars map (bottom left) showing the blazar 3HSP J121134.2+390053 in orange color to be the only likely counterpart in the 95% error ellipse, and the radio/X-ray sources map (bottom right) has been produced by VOU-Blazars by clicking on the icon pointed by the red arrow.

Acknowledgment

YLC is supported by the Government of the Republic of China (Taiwan). Most of this work was carried out at Agenzia Spaziale Italiana, as part of the Open Universe initiative, and at the University La Sapienza of Rome, Department of Physics. We make use of archival data and bibliographic information obtained from the NASA/IPAC Extragalactic Database (NED), data and software facilities from the ASDC managed by the Italian Space Agency (ASI).

CHB acknowledges the support of ICRANet and the Brazilian government, funded by the CAPES Foundation, Ministry of Education of Brazil under the project BEX 15113-13-2.

PG acknowledges the support of the Technische Universität München - Institute for Advanced Study, funded by the German Excellence Initiative (and the European Union Seventh Framework Programme under grant agreement no. 291763)

We thank Sara Turriziani and Theo Glauch for helpful suggestions.
References

Abdo, A. A., Ackermann, M., Aguilo, I., Ajello, M., Aller, H. D., Aller, M. F., Angelakis, E., Arkharov, A. A., Axelsson, M., Bach, U., et al., 2010. ApJ 716 (1), 30–70.

Abell, G. O., Corwin, H. G. J., Olowin, R. P., 1989. ApJS (70), 1–138.

Abolfathi, B., Aguado, D. S., Aguilar, G., Prieto, C. A., Almeida, A., Ananna, T. T., Anders, F., Anderson, S. F., Andrews, B. H., Anguiano, B., et al., 2018. ApJS 235, 42.

Acero, F., Ackermann, M., Ajello, M., Albert, A., Atwood, W. B., Axelsson, M., Baldini, L., Ballet, J., Barbiellini, G., Bastieri, D., et al., 2015. ApJS 218 (2).

Ackermann, M., Ajello, M., Atwood, W. B., et al., 2015. ApJS 218 (2).

Ajello, M., Arimoto, M., Axelsson, M., Baldini, L., Ballet, J., Barbiellini, G., Bastieri, D., et al., 2019. ApJ 878, 52.

Ajello, M., Gasparrini, D., Sanchez-Conde, M., Zaharijas, G., Gustafsson, S., Cohen-Tanugi, J., Dermer, C. D., Inoue, Y., Hartmann, D., Ackermann, M., Bechtol, K., et al., 2015. ApJ 800 (2), L27.

Arsioli, B., Barres de Almeida, U., Prandini, E., Fraga, B., Foffano, L., 2018. MNRAS 480, 2165.

Arsioli, B., Fraga, B., Giommi, P., Padovani, P., Marrese, P. M., 2015. A&A 579, A34.

Baumgartner, W. H., Tueller, J., Markwardt, C. B., Skinner, G. K., Barthelmy, S., Mushotzky, R. F., Evans, P. A., Gehrels, N., 2013. ApJS 207 (2).

Bessell, M. S., 1979. PASP 91 (October), 589.

Bianchi, L., de la Vega, A., Shiao, B., Bohlin, R., 2018. Ap&SS 363 (3), 56.

Blanton, M. R., Bershady, A. M., Abolfathi, B., Albareti, F. D., Prieto, C. A., Almeida, A., Alonso-García, J., Anders, F., Anderson, S. F., Andrews, B. H., et al., 2017. AJ 154 (2).

Boyer, T., Freyberg, M. J., Trumper, J., Haberl, F., Voges, W., Nandra, K., 2016. A&A 103, 1–26.

Bonato, M., Liuzzo, E., Herranz, D., González-Nuevo, J., Bonavera, L., Tucci, M., Massardi, M., De Zotti, G., Negrello, M., Zwaan, M. A., 2019. MNRAS 485 (1), 1188–1195.

Brandt, C. H., Giommi, P., 2019 in preparation.

Bulgarelli, A., Fioretti, V., Parmigiani, N., Verrecchia, F., Pittori, C., Lucarelli, F., Tavani, M., Abudan, A., Cardillo, M., Giuliani, A., Cattaneo, P. W., Chen, A. W., Piano, G., Rappoldi, A., Baroncelli, L., Argan, A., Antonelli, L. A., Donnarumma, I., Gianotti, F., Giommi, P., Giusti, M., Longo, F., Pellizzoni, A., Pilia, M., Trifoglio, M., Trois, A., Vercellone, S., Zoli, A., 2019. A&A 627, A13.

Campana, R., Massaro, E., Bernieri, E., 2018. A&A 619, A23.

Cerruti, M., Zech, A., Bosscon, C., Inoue, S., Dec 2011, Lepton-hadronic modelling of blazar emission. In: Alecian, G., Belkacem, K., Samadi, R., Valls-Gabaud, D. (Eds.), SP2A-2011: Proceedings of the Annual meeting of the French Society of Astronomy and Astrophysics. pp. 555–558.

Chambers, K. C., Magnier, E. A., Metcalfe, N., Flewelling, H. A., Huber, M. E., Waters, C. Z., Denneau, L., Draper, P. W., Farrow, D., Finkbeiner, D. P., et al., 2016. ArXiv e-prints 1612.05560.

Chang, Y.-L., Arsioi, B., Giommi, P., Padovani, P., 2017. A&A 598, A17.

Chang, Y.-L., Arsioi, B., Giommi, P., Padovani, P., Brandt, C., 2019. A&A submitted.

Conden, J. J., Cotton, W. D., Greisen, E. W., Yin, Q. F., Perley, R. A., Taylor, G. B., Broderick, J. J., 1998. AJ 115 (5), 1693–1716.

Cutri, R. M., Wright, E. L., Conrow, T., Fowler, J. W., Eisenhardt, P. R. M., Grillmair, C., Kirkpatrick, J. D., Masci, F., McCaill, H. L., Wheelock, S. L., et al., 2013. Explanatory Supplement to the AllWISE Data Release Products. Tech. rep.

De Breuck, C., Tang, Y., de Bruyn, A. G., Röttgering, H., van Breugel, W., 2002. A&A 394 (1), 59–69.

Di Mauro, M., Donato, F., Lamanna, G., Sanchez, D. A., Serpico, P. D., 2014. ApJ 786 (2), 129.

Doi, M., Tanaka, M., Fukugita, M., Gunn, J. E., Yasuda, N., Ivezic, Z., Brinkmann, J., de Haars, E., Kleinman, S. J., Krzesinski, J., Leger, R. F., 2010. AJ 139 (4), 1628–1648.

Evans, I. N., Primini, F. A., Glotfelty, K. J., Anderson, C. S., Bonaventura, N. R., Chen, J. C., Davis, J. E., Doe, S. M., Evans, J. D., Fabbiano, G., et al., 2010. ApJS 189 (1), 37–82.

Evans, P. A., Osborne, J. P., Beardmore, A. P., Page, K. L., Willingale, R., Mountford, C. J., Pagani, C., Burrows, D. N., Kennea, J. A., Perri, M., Tagliaferri, G., Gehrels, N., 2014. ApJS 210 (1), 8.

Fitzpatrick, E. L., 1999. PASP 111, 63–75.

Flesch, E. W., Mar 2015. PASA 32, e010.

Gaia Collaboration, 2016. A&A 595, A1.

Gaia Collaboration, Brown, A. G. A., Vallenari, A., Prusti, T., de Bruijne, J., Mignard, F., Drimmel, R., Co-authors, 2016 595, A2.

Giommi, P., Sep. 2015. JHEAp 7, 173–179.

Giommi, P., Ariggo, G., Barres De Almeida, U., De Angelis, M., Del Rio Vera, J., Di Ciacco, S., Di Pippo, S., Iacovoni, S., Pollock, A. M. T., 2018. arXiv e-prints, arXiv:1805.08505.

Giommi, P., Brandt, C. H., Barres De Almeida, U., Pollock, A. M. T., Arneodo, F., Chang, Y. L., Civitarese, O., De Angelis, M., D’Elia, Trifoglio, M., Trois, A., Vercellone, S., Zoli, A., 2019. A&A 627, A13.
Reimer, A., Mar. 2012. On the Physics of Hadronic Blazar Emission Models. In: Journal of Physics Conference Series. Vol. 355 of Journal of Physics Conference Series. p. 012011.

Saxton, R. D., Read, A. M., Esquej, P., Freyberg, M. J., Altieri, B., Bermejo, D., 2008. A&A 480, 611–622.

Schulz, B., Valtchanov, I., María, A., 2017. ArXiv e-prints.

Skrutskie, M. F., Cutri, R. M., Stiening, R., Weinberg, M. D., Schneider, S., Carpenter, J. M., Beichman, C., Capps, R., Chester, T., Elias, J., et al., 2006. AJ 131 (2), 1163–1183.

The Fermi-LAT Collaboration, 2013 ApJS 208, 17.

The Fermi-LAT collaboration, 2017. ApJS.

The Fermi-LAT collaboration, 2019. Fermi Large Area Telescope Fourth Source Catalog. arXiv e-prints, arXiv:1902.10045.

The IceCube Collaboration, 2018. Science 361 (6398), 147–151.

The IceCube Collaboration, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, Swift/NuSTAR, VERITAS, VLA/17B-403 teams, 2018. Science 361 (6398), eaat1378.

Tonry, J. L., Stubbs, C. W., Lykke, K. R., Doherty, P., Shivvers, I. S., Burgett, W. S., Chambers, K. C., Hodapp, K. W., Kaiser, N., Kudritzki, R. P., Magnier, E. A., Morgan, J. S., Price, P. A., Wainscoat, R. J., 2012. ApJ 750 (2).

Watson, M. G., Schröder, A. C., Fyfe, D., Page, C. G., Lamer, G., Mateos, S., Pye, J., Sakano, M., Rosen, S., Ballet, J., Barcons, X., et al., 2009. A&A 493 (1), 339–373.

Wen, Z. L., Han, J. L., Liu, F. S., 2009. ApJS 183 (2), 197–213.

White, N., Giommi, P., Angelini, L., 2000. VizieR Online Data Catalog.

White, R. L., Becker, R. H., 1992. ApJS 79, 331–467.

White, R. L., Becker, R. H., Helfand, D. J., Gregg, M. D., 1997. ApJ 475 (2), 479–493.

Wright, A. E., Griffith, M. R., Burke, B. F., Ekers, R. D., 1994. ApJS 91, 111.

Wright, A. E., Griffith, M. R., Hunt, A. J., Troup, E., Burke, B. F., Ekers, R. D., 1996. ApJS 103, 145.

Yershov, V. N., 2014. Ap&SS 354 (1), 97–101.

Zwicky, F., Herzog, E., Wild, P., Karpowicz, M., Kowal, C. T., 1968. Catalogue of galaxies and of clusters of galaxies.
| Catalogs applied in the second phase | Search Radius |
|-------------------------------------|---------------|
| **4.8/8.6 GHz catalogs**            |               |
| GB6 (Gregory et al., 1996)          | 30 arc-seconds |
| GB87 (Gregory and Condon, 1992)     | 30             |
| PMN (Griffith et al., 1994, 1995; Wright et al., 1994; Griffith and Wright, 1993; Wright et al., 1996) | 30 |
| ATPMN (McConnell et al., 2012)      | 15             |
| AT20G (Murphy et al., 2010)         | 15             |
| NORTH20CM (White and Becker, 1992) | 120            |
| CRATES (Healey et al., 2007)        | 15             |
| **Microwave/mm catalogs**           |               |
| WISH 352 MHz (De Breuck et al., 2002) | 0.25 arc-minutes |
| PCNT (Planck Collaboration et al., 2018) | 3             |
| ALMA (Bonato et al., 2019)          | 0.25           |
| **Far IR/IR catalogs**              |               |
| SPIRE250 (Schulz et al., 2017)      | 15             |
| SPIRE350 (Schulz et al., 2017)      | 15             |
| SPIRE500 (Schulz et al., 2017)      | 15             |
| 2MASS (Skrutskie et al., 2006)      | 10             |
| AllWISE (Cutri et al., 2013)        | 10             |
| **Optical catalogs**                |               |
| SDSS Dr14 (Blanton et al., 2017; Abolfathi et al., 2018) | 10 |
| HST GSC2.3.2 (Lasker et al., 2008)  | 10             |
| Pan-STARRS Dr1 (Chambers et al., 2016) | 10             |
| Gaia Dr1 (Gaia Collaboration et al., 2016; Gaia Collaboration, 2016) | 10 |
| **UV/X-ray catalogs**               |               |
| UVOT SSC 1.1 (Page et al., 2014; Yershov, 2014) | 15 |
| GALEX (Morrissey et al., 2007; Bianchi et al., 2018) | 15 |
| XMMOMSUSS 3 (Page et al., 2012)     | 15             |
| XRT spectral data (Giommi, 2015)    | 15             |
| OUSpectrum (Giommi et al., 2019 in preparation) | 15 |
| BAT 105 Months (Baumgartner et al., 2013) | 10 arc-minutes |
| **γ-ray catalogs**                  |               |
| Fermi 3FGL (Acero et al., 2015)     | 20             |
| Fermi 2FHL (Ackermann et al., 2015) | 20             |
| Fermi 3FHL (The Fermi-LAT collaboration, 2017) | 20 |
| Fermi 4FGL (The Fermi-LAT collaboration, 2019) | 20 |
| 1BIGB SED (Arsioli et al., 2018)    | 10             |
| 2AGILE (Bulgarelli et al., 2019)    | 50             |
| Fermi MeV (Principe et al., 2018)   | 30             |
| **TeV/IACTs catalogs**              |               |
| MAGIC                                | 10             |
| VERITAS                              | 10             |

Table 4: Catalogs applied in the second phase
| Catalog  | Band | Zero-magnitude flux | Effective wavelength | Reference                      |
|----------|------|---------------------|----------------------|--------------------------------|
| 2MASS    | J    | 1594                | 12350                | Skrutskie et al. (2006)        |
|          | H    | 1024                | 16620                |                                 |
|          | K    | 666.7               | 21590                |                                 |
| AllWISE  | W1   | 309.540             | 34000                | Cutri et al. (2013)            |
|          | W2   | 171.787             | 46000                |                                 |
|          | W3   | 31.674              | 120000               |                                 |
|          | W4   | 8.363               | 220000               |                                 |
| USNO     | B    | 4260                | 4400                 | Bessell (1979)                 |
|          | R    | 3080                | 6400                 |                                 |
| SDSS     | u    | 3631                | 3568                 | Doi et al. (2010)              |
|          | g    | 3631                | 4653                 |                                 |
|          | r    | 3631                | 6148                 |                                 |
|          | i    | 3631                | 7468                 |                                 |
|          | z    | 3631                | 8863                 |                                 |
| GSC      | U    | 1810                | 3600                 | Bessell (1979)                 |
|          | B    | 4260                | 4400                 |                                 |
|          | V    | 5500                | 3640                 |                                 |
|          | R    | 3080                | 6400                 |                                 |
|          | I    | 2550                | 7900                 |                                 |
| PanSTARRs| g    | 3631                | 4810                 | Tonry et al. (2012)            |
|          | r    | 3631                | 6170                 |                                 |
|          | i    | 3631                | 7520                 |                                 |
|          | z    | 3631                | 8660                 |                                 |
|          | y    | 3631                | 9620                 |                                 |
| GAIA     | G    | 2918                | 6730                 | Jordi et al. (2010)            |
| UVOT     | u    | 3631                | 3501                 | Poole et al. (2008)            |
|          | b    | 3631                | 4329                 |                                 |
|          | v    | 3631                | 5402                 |                                 |
|          | w1   | 3631                | 2634                 |                                 |
|          | m2   | 3631                | 2231                 |                                 |
|          | w2   | 3631                | 2030                 |                                 |
| GALEX    | FUV  | 3631                | 1538.6               | Morrissey et al. (2007)        |
|          | NUV  | 3631                | 2315.7               |                                 |
| XMMOM    | u    | 3631                | 3440                 | Page et al. (2012)             |
|          | b    | 3631                | 4500                 |                                 |
|          | v    | 3631                | 5430                 |                                 |
|          | w1   | 3631                | 2910                 |                                 |
|          | m2   | 3631                | 2310                 |                                 |
|          | w2   | 3631                | 2120                 |                                 |

* The G band magnitude is measured in Vega system, it depends on the flux densities of A0V star, and the zero magnitude flux here is obtained from A0V star template from STSDAS calibrated database system at [http://www.stsci.edu/hst/observatory/crds/calspec.html](http://www.stsci.edu/hst/observatory/crds/calspec.html).

Table 5: Magnitude reduction details for catalogs used in the second phase.

19
| Color   | Meaning                | Symbol          | Meaning             |
|---------|------------------------|-----------------|---------------------|
| Orange  | HBL candidate          | Open circle     | X-ray component     |
| Cyan    | IBL candidate          | Filled circle   | Radio component     |
| Dark Blue | LBL candidate        |                 |                     |
| Green   | Non-jetted AGN candidate |               |                     |
| Black   | Unknown type radio + X-ray source |       |                     |

| Symbol and Color          | Meaning               | Symbol and Color   | Meaning          |
|---------------------------|-----------------------|--------------------|------------------|
| Gold Star                 | 3HSP source           | Red filled Circle  | radio source     |
| Gold Diamond              | 5BZCat source         | Blue open circle   | X-ray source     |
| Question Mark             | Cluster of galaxies   | Purple open triangle | γ-ray sources |
| Blue open square           | Crates source         | Purple filled pentagon | Pulsar         |
| Dark green circle          | Quasars               | Green concave open quadrilateral | GRB         |

Table 6: Symbol meaning of the candidate map and Radio-X-ray map

| Color | Waveband   |
|-------|------------|
| Red   | Radio      |
| Orange | Infrared   |
| Gold  | Optical    |
| Green | Ultraviolet|
| Blue  | X-ray      |
| Purple | γ-ray      |

Table 7: Color used in the error circle maps