The ICRANet Science Data Center, Blazars studies and Open Universe Activities within ICRANet

1 Topics

- Consolidation of the technical infrastructure for the ICRANet Science Data Center in Pescara, currently implemented at http://vo.bsdc.icranet.org/
- Development of the second version of high-transparency data analysis software: the VOU-Blazars tool V2.0, Swift_deepsky and Swift_xrtproc pipelines, including the corresponding Docker versions.
- Contribution to the project "Open Universe for blazars" currently hosted at this temporary site https://sites.google.com/view/ou4blazars
- Implementation of VO + Web interfaces to catalogs of astronomical sources published as part of ICRANet research.
- Collaboration with ICRANet-Armenia for the installation of software suitable for the generation of Fermi adaptive bin γ-ray light curves and Swift UVOT data analysis and construction of a database of blazar UV, X-ray and γ-ray light curves to be interfaced to Open Universe systems.
- Implementation, adaptation and testing of software for cross-correlation analysis of time series and light curves.
- Search for possible spatial and temporal correlations between IBL and HBL blazars and astrophysical neutrinos
- Modelling of the variable SED of blazars using large multi-frequency/multi-temporal data sets
- Generation of high level multi-frequency data products of blazars (e.g. Fermi adaptive bin light curves, Swift-XRT spectra and X-ray light curves, Swift-UVOT photometric data and lightcurves)

2 Participants

2.1 ICRANet participants

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2.2 Ongoing collaborations

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2.3 Previous collaborations

- CESUP

2.4 Postdocs

- Yu-Ling Chang
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- Bernardo Machado Fraga

3 Brief description

The activity includes three main topics:

- The consolidation of an ICRANet distributed science data center based in Pescara, Yerevan, and other sites.
- a scientific part, based on the data coming from the ICRANet data center, dedicated to the identification of samples of high energy emitting blazars (1 WHSP, 2 WHSP and 3HSP) and to the theoretical interpretation of the electromagnetic (radio to γ-ray) and high-energy neutrino emission of selected bright blazars.
- an active contribution to the United Nations (UNOOSA) Open Universe initiative consisting in the development of high-transparency scientific data analysis tools based on Vitrual Observatory infrastructure and protocols, using new software technologies such as Linux containers, and in particular Docker.

3.1 Implementation of the ICRANet Science Data Center

Following the preparatory work carried out in the past years, the establishment of the ICRANet Science Data Center on the premises of ICRANet-Pescara has reached the level of an initial implementation phase. The ICRANet data center currently hosts a copy of some of the public astronomical catalogs, several catalogs and databases developed as part of the Open Universe initiative (e.g. OUSX1, OUSPECV1, 2BIGB, etc). as well as the Swift_deepsky and Swift_xrtproc data reduction and analysis software.

In parallel, the novel Yerevan component of the collaboration is focussing on the production of Fermi high level data products, such as adaptive-binning γ-ray light curves, as well as the analysis of ultraviolet data from Swift-UVOT, of selected bright blazars. The ICRANet Science Data Center also collaborates with the ASI Space Data Center (SSDC) and contributes to the development of the United Nations Open Universe initiative.

3.2 High energy emitting blazars

3.2.1 The VHE 1WHSP, 2WHSP and 3HSP blazar catalogs

Blazars are a class of radio-loud active galactic nuclei (AGN) hosting a jet oriented at a small angle with respect to the line of sight (Blandford and Rees, 1978; Antonucci, 1993; Urry and Padovani, 1995; Padovani et al. , 2017). The emission of these objects is non-thermal over most or the entire electromagnetic spectrum, from radio frequencies to hard γ-rays. HSP blazars, those where the first SED peak is located at high energy ($\nu_{peak} > 10^{15}$ Hz), play a crucial role in very high energy (VHE) astronomy. Observations have shown that HSPs are bright and variable sources of high energy γ-ray photons (TeVCat)[1] and that they are likely the dominant component of the extragalactic VHE background (Padovani et al., 1993; Giommi et al., 2006; Di Mauro et al., 2014; Giommi and Padovani, 2015; Ajello et al., 2015). In fact, most of the extragalactic objects detected so far above a few GeV are HSPs (Giommi et al., 2009; Padovani and Giommi, 2015; Arsioli et al., 2015; Ackermann et al., 2016, see also TeVCat). However, only a few hundred HSP blazars are above the sensitivity limits of currently available γ-ray surveys. Significantly enlarging the number of high energy blazars is crucial to better understand their role within the AGN phenomenon, and shed light on their cosmological evolution, which is still a matter of debate.

Arsioli et al. (2015) built a catalog of HSP blazars named 1WHSP, based on WISE color-color diagram with the sources inside the Sedentary WISE color region(SWCD), extended from WISE blazar strip (Massaro et al., 2011; D'Abrusco et al., 2012; Massaro et al., 2012) to include all the sources from the Sedentary survey blazars (Giommi et al., 1999, 2005; Piranomonte et al., 2007).

They cross-matched the AllWISE sources (Cutri et al., 2013) in SWCD with different radio and X-ray catalogs using TOPCAT[2], applied spectrum slope criteria, and selected the source with Synchrotron peak $\nu_{peak} > 10^{15}$ Hz (Padovani and Giommi, 1995; Abdo et al., 2010) and Galactic latitude $b > |20°|$. Note

[1] http://tevcat.uchicago.edu
[2] http://www.star.bris.ac.uk/ mbt/topcat/

that there are three slope criteria in Arsioli et al. (2015) , which are radio to IR slope, IR to X-ray slope, and the AllWISE W1 to W3 slope; the criteria are obtained from normalized and rescaled the SEDs of three well-known HSP blazars.

About one year ago, Chang et al. (2017) assembled what is still the most complete and largest HSP catalog, 2WHSP, an extension of 1WHSP catalog to $b > |20°|$. Similarly to Arsioli et al. (2015), the 2WHSP catalog was built starting from cross-matching three radio catalogs (NVSS, FIRST, and SUMSS: Condon et al., 1998; White et al., 1997; Manch et al., 2003) with AllWISE IR catalog and then with various X-ray catalogs (RASS BSC and FSC, 1SWXRT and deep XRT GRB, 3XMM, XMM slew, Einstein IPC, IPC slew, WGACAT, Chandra, and BMW: Voges et al., 1999, 2000; D'Elia et al., 2013; Puccetti et al., 2011; Rosen et al., 2016; Saxton et al., 2008; Harris et al., 1993; Elvis et al., 1992; White et al., 2000; Evans et al., 2010; Panzera et al., 2003). However, 2WHSP is not subjected to WISE color-color diagram and the AllWISE W1-W3 slope criterion when selecting the sources. Therefore, the 2WHSP sample does not miss a number of good (host galaxy dominated) HSPs. We used ASDC SED tool[3] to examine and fit the Synchrotron component with a third degree polynomial to get the Synchrotron peak position (ν_{peak}) and Synchrotron peak flux ($\nu_{peak} f_{\nu_{peak}}$) for each WHSP pre-selection candidate.

The 2WHSP catalog totally includes 1,691 sources with 540 known HSPs, 288 new HSPs, and 814 HSP candidates. The name "WHSP" stands for WISE high Synchrotron peaked blazars since except for one source, 2WHSP J135340.2−663958.0, all the other sources in 2WHSP have WISE counterparts. For each 2WHSP source, we adopted as best coordinates those taken from the WISE catalog. The average ν_{peak} for our catalog is $\langle \log \nu_{peak} \rangle = 16.22 \pm 0.02$ Hz and the average redshift is $\langle z \rangle = 0.331 \pm 0.008$. We have shown that the SWCD region needs to be extended to include HSPs in which the host galaxy is dominant. The 2WHSP radio logN-logS shows that the number of HSP blazars over the whole sky is $> 2,000$ and that HBL make up $\sim 10\%$ of all BL Lacs.

A new, more complete version of the 2WHSP catalog, called 3HSP, has been prepared and is now available on-line at the following web page

http://www.ssdc.asi.it/3hsp.

It includes 2,011 objects whose blazar nature has been verified and charac-

[3]http://tools.asdc.asi.it/SED

terised on the basis of a large amount of multi-frequency information also using the data and tools available within the Open Universe portal at openuniverse.asi.it. The paper presenting this sample has been submitted to Astronomy & Astrophysics and is currently undergoing the refereeing process. Publication is foreseen in the next few weeks. This new sample does not rely on Wise infrared data and therefore is not subject to limitations due to the presence of the host galaxy. In addition the 3HSP list includes several new sources discovered at low Galactic latitudes, and provides more accurate estimates of the SED parameters, based on all the available multi-frequency archival data and new software tools developed in the framework of the United Nations "Open Universe" initiative. One of the important and unique feature of the 3HSP catalog is that it provides redshift estimation for our 88% of the sources, a much larger percentage than any other previous catalogs of High Energy peaked blazars, thanks to the availability of new spectral data a especially novel method of photometric estimation based on optical and IR data.

The 3HSP sample is by far the largest set of high-energy blazars and it nearly triples the number of known HSP blazars compared to the 5BZCAT list. A study of the Cosmological and statistical properties of blazars of this type, which are expected to be detected in large numbers in upcoming surveys of the very high energy γ-ray sky (e.g. CTA), is nearly complete and a paper will be submitted in the first months of 2019.

3.2.2 The 2BIGB catalog

The 2WHSP sources has been used as seeds of HE and VHE searches to discover new VHE detections or to find the counterparts of VHE catalogs. So far, 439 of 2WHSP sources have counterparts within the error circles from the 3FGL catalog; there is still a large number of 2WHSP HSPs which does not have γ-ray detections yet. Therefore, Arsioli and Chang (2016) analyzed bright 2WHSP sources using archival Fermi-LAT data integrated over 7.2 years observations, Pass 8 data release. By using the position of 2WHSP sources as seeds for the likelihood analysis, we found 150 previously unreported γ-ray detections.

The 150 new γ-ray sources are named with the acronym 1BIGB (first version of the Brazil ICRANet Gamma-ray Blazar catalog). Clearly, the subsample of 2WHSP blazars that have not yet been detected by Fermi-LAT is a key representative population of faint γ-ray emitters, and we show how the new detections down to TS > 10 level can probe the faint-end of the flux-distribution.

The new detections also unveil a fraction of the γ-ray sky. Our current work enabled us to associate a relevant fraction of the IGRB to a population of faint γ-ray emitters that had been previously unresolved. Moreover, we show the increasing relevance of faint-HSPs for the IGRB composition with respect to energy, specially for E > 10 GeV, reaching 6-8% in the $100 - 200$ GeV band.

Motivated by this first assessment, we plan to perform a complete γ-ray analysis of the 2WHSP sample, down to the lowest fluxes, and probably extend the search to other blazar families with potential to improve the γ-ray description of lower-significance γ-ray blazars, also helping to constrain the origins of the extragalactic diffuse γ-ray background.

3.2.3 Correlation between blazars and astrophysical neutrinos

Padovani et al. (2016) cross-matched the 2WHSP with IceCube neutrino events. Their results suggest that, among the blazar family, HSPs blazars are the most likely counterparts of astrophysical neutrinos. Resconi et al. (2017) have recently presented new evidence for a direct connection between 2FHL HBLs, very high energy neutrinos, and ultra high energy cosmic rays (UHECRs) when cross-matching 2FHL HBL subsample with UHECRs from the Pierre Auger Observatory and the Telescope Array. In a nutshell, HSPs catalogs are important and timely for HE and VHE astronomy.

The most convincing association of an astrophysical neutrino with an extragalactic object reported so far is that connected with the event occurred on September 22, 2017 (Kopper & Blaufuss, 2017), where a the very bright ($\approx$ 1Jy in the radio band) IBL/HBL BL Lac known with the name of TXS0506+056, was found within the small ($\sim$ 0.1 sqdeg) uncertainty region of the IceCube track neutrino IC170922. Our collaboration is actively participating to this research which resulted in the publication of three major papers in 2018 (Padovani et al. 2018, IceCube collaboration 2018,).

The association of the high-energy neutrino IC170922 with the blazar TXS0506+056 has been listed among the ten stories of 2018 by Science : https://www.sciencenews.org/article/top-science-stories-2018-yir

3.2.4 Temporal study of the spectral energy distribution of blazars

Many of the studies on blazars are focused on their spectral energy distribution (SED). These provide a photographic view of the source state, which in turn gives an overview of the emission energy balance. Despite we can get some limits on models, the approach not able to satisfactorily explain the dynamics of the physical emission processes, because they evolve in time in a complex way, as can be seen by the emission's variability and multi-band correlations. In particular, there is evidence for the existence of delays between emissions at different frequencies, a feature not accounted for in traditional SSC models of the SED. To try and get around these problems, other models have been proposed, such as those with contribution from radiation fields external to the jets for the inverse-Compton emission, or models where an emission zone is not homogeneous and multiple emitting blobs are considered to build up simultaneously the SED. However promising, these studies remain incipient and require further analysis. Key to the success of more in-depth studies is the availability of a large amount of multi-band data, for a detailed and combined view of the spectral properties and temporal evolution of the sources.

Usually, when dealing with the temporal evolution of blazar emission, the most commonly used method is to consider strictly simultaneous observations in multi-wavelength campaigns, and try to impose limits on different models. However, as previously mentioned, the emission at different frequencies may be correlated. Correlations between different bands are useful for determining the emission mechanism and constrain emitting region. In addition, if a correlation is discovered between two frequencies, it can be used to predict the emission of sources not yet detected. Some studies have found correlations in flare emission between, for example, radio and gamma rays and between optical and gamma rays. These multi-band correlations, if real, imply a delay in the variation of the emission at different frequencies. It is then clear, in these cases, that strictly simultaneous observations are not exploiting the same state of a source, since the lags are not taken into account. In order to analyze the time evolution of the emission, it is necessary to first analyse the multi-band correlations and to determine the lags between them, and then to collect the data of simultaneous observations, that is, separated by a period of time similar to the lag. This allows for a more rigorous study of emission models and the imposition of limits on their parameters. Although there are codes to calculate correlations and lags, a tool that would automate the whole process, from data selection and lag calculation to the construction of simultaneous SEDs, would be of immense value to the scientific community and could be integrated to the ASDC, making it available in a fast, easy and effective way for everyone. This is one of the technical goals and legacies of this work.

At first we intend to use a specific source, Mkn421, as a prototype for our study. We plan to publish a paper about the analysis of the temporal evolution of this source and its modelling by the end of the first year of research. At the same time, we have a preliminary version of the lags calculation tool and light curve construction already ready to be tested for a greater number of sources and deployment in ASDC.

With this study, we hope to be able to shed some light on the cause of variable emission in blazars. The lags estimation will allow us to determine how the emission at different frequencies are related and which physical mechanisms may be responsible for such a relationship. The construction of simultaneous SEDs will serve to discriminate between the different emission models already proposed, as well as to find out whether or not there is periodicity in a range of time scales. Today we have a large amount of data at hand, making it possible to create large catalogs of blazars (such as BZCAT and 1WHSP), making statistical studies more rigorous and precise. In order to work with a large number of sources it is necessary that the selection of simultaneous data be, to a great extent, automated. ASDC, being a great integrated platform for data analysis and visualisation, is a perfect option to implement this procedure, making the determination of correlations, lags and the subsequent construction of simultaneous SEDs easier, faster and more accessible to the community at large. The beginning of the implementation of the Brazilian Science Data Center (BSDC) in CBPF, an integrated data platform analogous to ASDC, focusing on collecting data from missions to which Brazil is a partner, will be another opportunity for the implementation of the automated analysis of the time evolution of blazars.

3.2.5 The VOU-Blazars tool and the Swift_deepsky software pipeline

To actively support the scientific activities where ICRANet is involved our collaboration contributed to the development of innovative scientific software based on Virtual Observatory protocols and on new technology such as Docker containers.

3.2.6 VOU-Blazars

VOU-Blazars is a tool developed within Open Universe, an initiative under the auspices of the United Nations with the objective of largely improving the availability and the use of space science and astronomy data. *VOU-Blazars* is designed to find blazars by mining the information extracted from a large number of multi-wavelength astronomical catalogs and spectral databases using Virtual Observatory services.

VOU-Blazars is available as source code, as a tool encapsulated in a Docker container, and as a web-based service within the Open Universe portal at openuniverse.asi.it VOU-Blazars implements a heuristic approach based on the well known spectral energy distributions that differentiate blazars from other astronomical sources. The tool surveys multi-wavelength catalogs using Virtual Observatory services, dynamically correlates the sources in different energy bands to locate blazars candidates, and builds individual spectral energy distributions to verify the blazar nature and assign a blazar sub-class to each candidate. The final word though is given by the user: *VOU-Blazars* outputs are calibrated flux tables, sky plots and spectral energy distributions for further analysis by the users.

The *VOU-Blazars* tool has been successfully applied to study the association of TXS0506+056 with the IceCube IC170922 neutrino and to search for blazar counterpars of Fermi 3FHL, Fermi 4FGL-DR2, AGILE γ-ray sources. Some of the newly discovered high synchrotron peaked blazars reported in the 3HSP catalog have been found by means of VOU-Blazars.

3.2.7 The Swift_deepsky data analysis pipeline

The Swift_deepsky data analysis pipeline encapsulates the complex HEASoft software and calibration files that are necessary for the analysis if Swift-XRT X-ray images into a Docker container that can be easily run by anyone on MacOS, Linux and Windows10 operating systems.

The Swift_deepsky pipeline can be considered a "high-transparency" X-ray data analysis software tool because a) it can be downloaded and installed in a few clicks, b) it removes platform dependencies and the need to download the data and calibration files from the archive, and c) it lowers the barrier to X-ray data analysis enabling users, with or without experience in Swift-XRT data analysis, to run data reduction software that generates science ready products usable by everyone.

We have run the Swift_deepsky on all the Swift observation that include a blazar in the field of view of the XRT telescope, resulting in over 8,000 X-ray detection of more 2,200 blazars. The products resulting from this uniform analysis of XRT imaging data, which include images, fluxes and spectral information suitable to build blazars SEDs, constitute the first contribution to a program called **Open Universe for blazars**, designed to provide high-transparency data (that is results and data products that can immediately be used for scientific or other general purposes by anyone) of blazar obtained with a number of satellites operating in the X-ray and γ-ray bands.

Two papers presenting these results based on Swift_deepsky have been recently published (Giommi et al. 2019, A&A 631, 116, Giommi et al. 2020, A&A642, 141), others are in preparation

3.2.8 The Swift_xrtproc pipeline

Swift_xrtproc is a software tool developed in the framework of the Open Universe initiative that carries out a complete processing, form raw data to calibrated data products, followed by spectral and imaging analysis of observations done with the Swift-XRT telescope. The most important steps that are executed for each Swift-XRT observation are:

1. Download of raw data and calibration files from one of the Swift archives.

2. Exposure maps and calibrated data products generation, for each snapshot and for the entire Swift observation, using the XRTPIPELINE task and adopting standard parameters and filtering criteria.

3. Source and background spectral files generation. The source counts are estimated in a circle of 20 pixels radius when no pile-up is present. For the case of PC mode, the background is extracted in an annular region centred around the source with radius sufficiently large to avoid contamination from source photons. For the WT mode the spectrum of the background was estimated from an archive deep observation.

4. Pile-up correction. A verification of the source count-rate is carried out to determine whether the data is affected by pile-up. In case pile-up is present the spectral data is extracted again excluding the central parts of the Point Spread Function, by taking counts in an annular region with inner radius chosen depending on the measured count-rate.

5. Spectral fitting using the XSPEC package assuming a power-law and a log-parabola model.

6. Conversion of best fit spectral data to nufnu units for SED plotting.

7. Photometric analysis using XIMAGE to estimate count-rates, or upper limits, in four energy bands: 0.3-1.0, 1.0-2.0, 2-10, and 0.3-10 keV, for data taken in PC readout mode.

8. Count-rate to X-ray flux conversion in the four energy bands and in nufnu units at the energy of 0.5, 1.5 and 4.5 keV.

9. Flux or upper limit estimation in nufnu units at 1 keV either from the best fit spectrum or from the photometric data (in case the source is too weak for spectral fitting) suitable for light-curve generation and time domain analysis.

The Swift_xrtproc pipeline has been run on all the Swift X-ray observations of blazars that have been pointeed by the Swift observatory at least 50 times. The results, presented in a paper that has been submitted in early 2021, will be available from the ICRANet data center via Virtual Observatory tools and in particular VOU_Blazars

4 Publications

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