Title: A Unique Window into the Universe: the underlying messages of Blazars

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Abstract. Blazars are a peculiar subclass of active galactic nuclei (AGN) with relativistic jets aligned closely to the observer's line of sight. These extreme cosmic accelerators emit across the entire electromagnetic spectrum, from radio waves to high-energy gamma rays. They could be considered laboratories for the study of relativistic flux, cosmic ray acceleration, and the extragalactic background light. This study explores the physical mechanisms underlying blazar emission, focusing on particle acceleration and multi-wavelength observations. We analyse recent data from Fermi-LAT, IceCube, and other instruments, highlighting the case of TXS 0506+056, one of the first blazar linked to a high-energy neutrino detection. The research focuses on the analysis of spectral energy distribution (SED), to classify the blazar type, and on the light curve, to understand its emission mechanisms over time. Our results strengthen the role of blazars as potential sources of astrophysical neutrinos and ultra-high-energy cosmic rays. These findings have implications for multi-messenger astrophysics, contributing to a better understanding of cosmic accelerators and their role in high-energy astrophysics.

1.Introduction

Understanding the emission mechanisms of blazars is the key to high-energy astrophysics and multi-messenger astronomy. The INFN (National Institute of Nuclear Physics)-OCRA (Outreach Cosmic Ray Activities) collaboration has significantly contributed to cosmic ray research outreach. In 2017, multi-messenger observations from IceCube and Fermi LAT confirmed the link between blazars and high-energy neutrinos, with TXS 0506+056 as the first identified source [1]. These findings highlight the need for continued observational efforts and interdisciplinary collaborations.

1.1 Students breakthrough in the World of Research

The research journey began on October 19th at the Science Centre of Città della Scienza in Naples, where students were introduced to the work of INFN researchers involved in the CTAO (Cherenkov Telescope Array Observatory) project, which focuses on constructing the largest ground-based observatory for high-energy cosmic rays. Official research activities started on International Cosmic Day (November 26th), organized by DESY (Dark Energy Spectroscopic Instrument) and supported by OCRA and INFN-Naples. The event included an introductory lecture on cosmic ray physics and multi-messenger astronomy, preparing students for muon studies and cosmic ray acceleration. The experiment involved measuring muon flux at different trajectory inclinations using the Cosmic Ray Cube, and an online meeting in which international teams shared findings through slides presentations. This paper marks the project's conclusion in order to inspire students in scientific research and publication. (To know more: https://www.iistelesia.edu.it/2024/12/04/a-caccia-di-muoni/)

2. Research methods

Observations of blazars are conducted using both ground-based and space-based technologies capable of measuring different wavelengths, including gamma-ray, X-ray, and radio frequencies. These telescopes collect data that are systematically recorded in databases for further study. In this work, we utilize data from IceCube (IceCube Neutrino Observatory), an observatory in Antarctica, and Fermi LAT (Fermi Large Area Telescope), a space-based gamma-ray telescope. Additionally, we refer to the catalogs TeVCAT and Firmamento, as primary sources for our blazar analysis. The aim of this study is to analyse the spectral energy distribution (SED) to classify the blazar type and investigate its emission mechanisms over time. Observational measurements are compared with theoretical models of synchrotron and inverse Compton scattering processes. TeVCAT is a comprehensive database of blazar properties that provides detailed observational data, including redshift, synchrotron peak frequency, and other relevant parameters. This database allows researchers to compare different blazar populations and the study of their evolution over cosmic time. Through the use of TeVCAT [2], users can access scientific articles and reports related to specific blazars. After selecting an object (in this case with the name TXS 0506+056), a page dedicated to sourcing details provides essential information such as alternative object names (e.g., in the Firmamento catalog, the blazar is listed as 4FGL J0509.4+0542), position data (right ascension and declination), and redshift values (e.g., 0.3365 ± 0.001). Redshift is an important concept to understand why we are so interested in the study of extragalactic astronomy: it is the way we measure the distance of the source by considering the stretch of the electromagnetic waves due to the doppler effect. Indeed the expansion of the universe causes a constant distancing of source and receiver, the particles of the sources emit a specific radiation that appears shifted to lower frequencies compared with the theoretical one measured in labs from specific lamps. Examining the "Citations" section, it is possible to trace the discovery history of a blazar. For instance, the blazar analysed in this study was first identified in 2017 following the detection of a high-energy neutrino by IceCube. This event was among the first pieces of evidence supporting the hypothesis that blazars emit relativistic particles. Firmamento [3] is another crucial platform that specializes in interactive visualizations of cosmic ray events. This catalog aggregates data from various instruments, providing insights into event properties, origins, and correlations with high-energy astrophysical phenomena. To analyse a blazar through Firmamento, users navigate to the "High-energy catalogs" section and select "Fermi 4FGL-DR4." Ensuring the correct catalog designation (e.g., 4FGL J0509.4+0542) and using the "pick" function for both the entire catalog and the candidate results list, the platform generates a frequency-energy chart and retrieves the corresponding SED data, which can be downloaded in CSV format. The downloaded data are processed using Google Colab. The energy and frequency values are structured into charts and converted to a logarithmic scale for enhanced visualization and comparison with reference models. Using Colab, we reconstruct the SED from the original dataset extracted from Firmamento. This initial analysis allows the classification of the blazar; however, a comprehensive understanding requires not only the consideration of particle flux at different frequencies, but also its temporal variations. Blazars are highly dynamic and variable objects, often associated with extreme astrophysical events. Their variability can be observed in their light curves. To analyse the light curve, we extract data from a specific Firmamento catalog [4]. By entering the object's name in the "keywords" field, then selecting the desired observation period and the option "Energy Flux", in the "source ID" section, the relevant data can be downloaded. Using Colab, it is possible to generate light curve visualizations, with a process similar to that used for SED analysis. This methodology allowed us to investigate the physical properties and temporal evolution of blazars and contributed to a deeper understanding of their nature and emission mechanisms.

3. Results

The analysis of the blazar's spectral energy distribution (SED) reveals key features for its classification and the interpretation of its physical properties. Examining the graph of electromagnetic energy distribution at different frequencies, we identify two main peaks:

- The first peak, associated with synchrotron radiation, occurs at a frequency corresponding to the maximum energy of the particles charged in a magnetic field.
- The second peak, linked to inverse Compton scattering, represents the maximum energy of photons that have gained energy from relativistic particles.

Measurement biases are related to instrumental limitations and background noise and they are shown in the following chart (1).

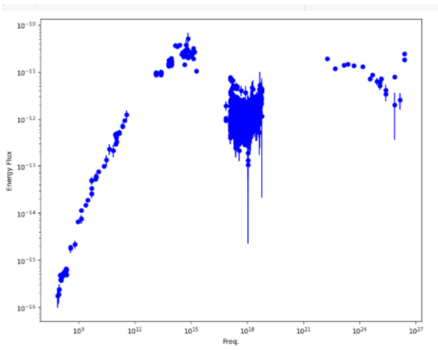

figure 1. flux-freq chart made in Colab

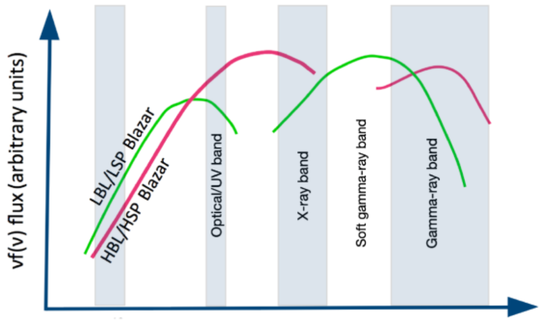

figure 2. theoretical chart from Firmamento

By comparing our results (**figure 1**) with standard blazar classification curves from "Firmamento" (**figure 2**), we confirm that the observed Blazar fits into the HBL/HSP (High Energy Blazar/High Synchrotron Peaked) category. This classification matches previous models that predict a high level of energy released by the Blazar. The peak locations correspond to theoretical expectations for HBLs, in which synchrotron emission extends to X-ray energies and inverse Compton scattering results in gamma-ray production

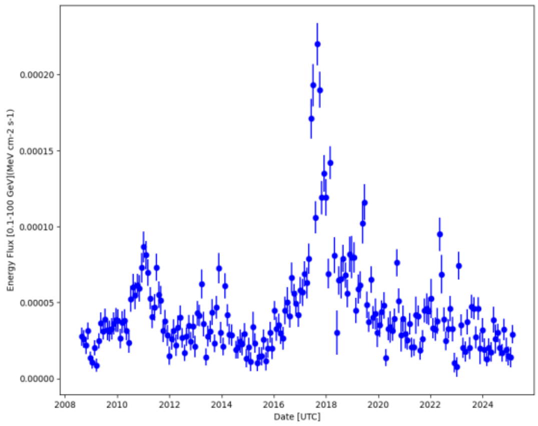

Figure 3. light curve

The light curve (**figure 3**) shows the variability of a blazar's energy flux over time (2008-2024). Several emission peaks are observed, with a significant maximum around 2017-2018, indicating a strong gamma-ray flare. After this event, the flux decreases but remains highly variable, with other increases between 2019 and 2023. The irregular variability suggests the presence of shock phenomena in the relativistic jet, magnetic reconnection, or variations in the black hole's accretion disk. Long-term observation is essential to understand the emission processes and the condition of the blazar.

The study of blazar emissions contributes significantly to multiple areas of astrophysics:

- High-Energy Astrophysics: Understanding the particle acceleration mechanisms in blazars helps to refine models of cosmic ray acceleration and jet dynamics.
- Relativity and Extreme Environments: The observation of relativistic jets provides a natural testbed for special and general relativity under extreme conditions.
- Dark Matter Studies: The interaction of high-energy gamma rays with the interstellar medium may reveal indirect signatures of dark matter.
- Cosmic Evolution: given that blazars are located at cosmological distances, studying their emissions provides insights into the history of the universe and galaxy formation.
- Multi-Messenger Astronomy: Correlations between blazar emissions and neutrino or gravitational wave signals contribute to a comprehensive understanding of high-energy astrophysical processes.

4. Conclusion and final remarks

This study highlights the importance of blazars as extreme astrophysical objects and their role in advancing multi-messenger astronomy. Analysing their spectral energy distribution and variability, we gain valuable insights into the underlying mechanisms of particle acceleration and high-energy emissions in the universe. The connection between blazars, cosmic rays, and neutrinos underscores the importance of interdisciplinary research and international collaborations.

References

[1] Can the neutrinos from TXS 0506+056 have a coronal origin? - paper published by Fiorillo, Damiano F. G. Testagrossa, Federico; Petropoulou, Maria; Winter, Walter (2017)
[2] http://tevcat2.uchicago.edu/sources/HpuBf
[3] https://firmamento.nyuad.nyu.edu/data_access
[4] https://fermi.gsfc.nasa.gov/ssc/data/access/lat/LightCurveRepository/
[5] lecture of Carla Aramo for the International Cosmic Day (october 19th 2024)
[6] lecture of Marco Iuliano and Carla Aramo (march 11th 2025)