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Multi-wavelength observation of 1ES 0414+009 detected at VHE

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Abstract. 1ES 0414+009 is a blazar at $z = 0.287$, which was detected for the first time in 1978 by the HEAO 1 satellite in the energy range of 0.2 keV-10 MeV. Multi-wavelength observations of 1ES 0414+009 have been performed in the energy range from radio to very-high-energy (VHE) gamma rays, suggesting that 1ES 0414+009 is a BL Lac object. In this work a multi-wavelength modelling of the source is performed assuming a leptonic and lepto-hadronic origin for the observed spectral energy distribution.

Resumo. O blazar 1ES 0414+009, localizado a um redshift$z = 0.287$, foi detectado pela primeira vez em 1978 pelo satélite HEAO 1, na faixa de energia de 0,2 keV a 10 MeV. Observações em múltiplos comprimentos de onda foram realizadas para esta fonte, abrangendo desde o rádio até raios gama de altíssima energia (VHE), indicando que o 1ES 0414+009 é um objeto do tipo BL Lac. Neste trabalho, é realizada uma modelagem em múltiplos comprimentos de onda da fonte, considerando uma origem leptônica e lepto-hadrônica para a distribuição espectral de energia observada.

Keywords. Galaxies: active – BL Lacertae objects: individual–Radiation mechanisms: non-thermal

1. Introduction

1.1. Blazars

Most active galactic nuclei (AGNs) Zabalza (2015) exhibit energy emission from their central region that cannot be explained solely by radiation produced by stars. This energy is generated through the conversion of gravitational potential energy from matter accreted by a supermassive black hole via an accretion disk.

Blazars are a particular class of AGNs characterized by the observation of a radio galaxy from a viewing angle aligned with the relativistic jet emanating from the nucleus. These objects dominate the extragalactic sky at very high energies, accounting for 70 out of 78 extragalactic very high-energy sources identified so far Albert et al. (2019). The spectral energy distribution (SED) of blazars exhibits two distinct components. The first component typically peaks between the far-infrared and soft X-rays, corresponding to synchrotron emission, while the second one peaks in the MeV to GeV range and is attributed to the inverse Compton scattering process.

1.2. 1ES 0414+009

1ES 0414+009 is a TeV-detected BL Lacertae-type blazar with a well-measured redshift of $z = 0.287$ Halpern et al. (1991), and the central black hole mass is estimated to be 2×10^9 $M_\odot$ Falomo et al. (2003). The source is located in equatorial coordinates with a right ascension (RA) of ($04^h16^m53.0^s$)(64.2208°) and a declination (Dec) of (+01°05′20.4″)(1.0809°). In the galactic coordinate system, its position corresponds to a longitude of (191.82°) and a latitude of (−33.16°)[1]. These coordinates place the source in a region of the sky significantly offset from the Galactic plane, which facilitates high-energy observations because of the reduced interference from the Milky Way's diffuse emission.

It was first detected in X-rays in 1978 by the HEAO1 satellite (High Energy Astronomy Observatory)[2] in the energy range of 0.2 keV to 10 MeV Ulmer et al. (1980) and was initially associated with a galaxy cluster. Subsequently, based on radio, X-ray, and optical observations, it was reclassified as a luminous BL Lacertae-type object in X-rays Ulmer et al. (1983). Further X-ray observations Wolter et al. (1998) showed that 1ES 0414+009 exhibits spectral characteristics typical of BL Lacertae objects, with a synchrotron emission peak at high frequencies and a luminosity comparable to sources such as Markarian 421 and PKS 2155-304 in the 2-10 keV energy range.

VERITAS[3] also observed 1ES 0414 + 009 between January 2008 and February 2011, detecting a total of 822 excess events with a statistical significance of 6.4σ Aliu et al. (2012). The differential photon spectrum obtained from VERITAS observations was fitted to a power law, and the measured spectral parameters are consistent with those from the H.E.S.S. Observatory[4]. The integrated flux measured during the VERITAS observations was $(5.2 \pm 1.1_{\rm stat} \pm 2.6_{\rm sys}) \times 10^{-12}$ photons cm^{-2}, or 2% of the Crab Nebula flux above 200 GeV Aliu et al. (2012). The Crab Nebula is often used as a standard for comparisons of flux, luminosity, and other parameters.

Observations of the highest-energy region of the blazar emission spectrum are crucial for characterizing the temporal variability of the source Singh & Meintjes (2020). Thus, investigating the physics responsible for blazar radiation emission is essential to understand the extreme phenomena occurring in the Universe.

2. Spectral Energy Distribution Modeling

To study the SED of 1ES 0414 + 009, we adopt a single-zone radiation emission model, which assumes that non-thermal relativistic particle populations exist in a spherical emission region with radius R, permeated by a magnetic field of intensity B, in

[1] https://www.ssdc.asi.it/showEntry.php?radeg=64.220667&decdeg=1.089&lii=191.816756&bii=-33.158013

[2] https://heasarc.gsfc.nasa.gov/docs/heao1/heao1.html
[3] https://veritas.sao.arizona.edu/
[4] https://www.mpi-hd.mpg.de/HESS/

the relativistic jet. In this framework, both purely leptonic and lepto-hadronic particle models are considered. The interaction of particles with the magnetic and radiation fields, through various physical processes, generates a non-thermal radiation spectrum.

2.1. Leptonic Processes

For the explanation of low-energy and high-energy radiation, a leptonic modeling approach is sufficient to provide a comprehensive understanding of the source. The resulting emission follows a power-law energy distribution Spurio (2018):

$$\frac{dn}{dE}dE = kE^{-\alpha_e}dE \quad (1)$$

This model primarily involves two processes: synchrotron emission and inverse Compton scattering. Synchrotron radiation is emitted by a charged particle with charge Z_e, mass m, and energy $E = \gamma mc^2$, accelerated to relativistic speeds in a magnetic field of intensity B. The SSC (Synchrotron Self-Compton) process occurs when electrons, accelerated through the Fermi mechanism within the emission region, scatter synchrotron radiation photons to higher energies. This mechanism is described in Fraija et al. (2017).

$$\epsilon^{SSC}_{\gamma,(m,c,max)} \simeq \gamma^2_{e,(min,c,max)} \epsilon^{syn}_{\gamma,(m,c,max)} \quad (2)$$

2.2. Lepto-hadronic Processes

The lepto-hadronic model, in contrast, explains the production of gamma rays through the interaction of high-energy hadrons with target photons Mannheim (1993).Furthermore, the study of lepto-hadronic interactions provide opportunities to investigate neutrino emissions in addition to gamma rays through different processes, as seen in Rodrigues et al. (2019):

$$\begin{aligned}
p\gamma &\rightarrow \Delta^+ \rightarrow n\pi^+ \quad (\mathrm{BR} = 2/3)\\
n &\rightarrow pe^-\bar{\nu}_e\\
\pi^+ &\rightarrow \mu^+\nu_\mu\\
\mu^+ &\rightarrow e^+\bar{\nu}_\mu\nu_e\\
p\gamma &\rightarrow \Delta^+ \rightarrow p\pi^0 \quad (\mathrm{BR} = 1/3)\\
\pi^0 &\rightarrow \gamma\gamma
\end{aligned}$$

One of the advantages of using the lepto-hadronic model is precisely the observation of the production of these energetic neutrinos along with gamma rays. Thus, we can correlate the emissions of photons, neutrinos, and ultra-high-energy cosmic rays Rodrigues et al. (2019). The primary proton-photon interaction can also produce an electron-positron pair, which is cooled through synchrotron or inverse Compton scattering processes. This electron-positron pair is also known as a Bethe-Heitler pair.

3. Methodology

3.1. SED Builder

To model the spectral energy distribution of 1ES 0414+009 at multiple wavelengths, we use astronomical data collected by both space and ground-based observatories, covering frequencies from radio to gamma rays. For this purpose, the tools Space Science Data Center (SSDC)[5] and Firmamento[6] were used.

The SSDC was established by the Italian Space Agency (ASI, acronym for *Agenzia Spaziale Italiana* in Italian)[7] and serves as a mission for the storage and processing of data from various space and ground-based observatories.

Firmamento is a web-based tool developed through a collaboration between the Center for Astro, Particle, and Planetary Physics[8] and the Citizen Researcher initiative[9] at New York University, Abu Dhabi.

3.2. Astrophysical Multi-Messenger Modelling Softwares

For the energy spectral emission modeling of 1ES 0414+009, we used two software tools capable of processing the data collected by SSDC and Firmamento. The JetSet[10] software was responsible for the leptonic modeling, while AM3[11] handled the lepto-hadronic part.

The JetSeT software reproduces radiative and accelerative processes in relativistic jets and fits numerical models to observed data. It is an open-source C/Python code that defines a dataset and links it to tables and quantities from astropy[12]. The physical processes implemented in JetSeT include Synchrotron Self-Compton (SSC), external Compton (EC), and EC on the Cosmic Microwave Background (CMB).

AM[3] is an open-source software that efficiently solves coupled differential equations for the temporal and spectral evolution of particle densities, such as photons, electrons, positrons, protons, neutrons, pions, muons, and neutrinos. This toolset includes all relevant non-thermal processes, such as synchrotron, inverse Compton scattering, photon-photon annihilation, pion production via proton-proton and proton-photon interactions, and pair photoproduction.

4. Results and Discussion

4.1. Leptonic Modeling

The modeling performed with JetSet utilized parameters derived from Aliu et al. (2012). Figure 1 illustrates the SSC modeling considering only the presence of leptonic particles (electrons and positrons).

The spectral analysis shown in Figure 1 reveals two distinct emission regions. The synchrotron component peaks at $\sim 10^{16}$ Hz, characterizing the source as a high-peaked BL Lac (HBL). This emission region is dominated by relativistic electrons interacting with magnetic fields, as predicted by the synchrotron emission model.

In the high-energy band, the Inverse Compton (IC) component peaks at $\sim 10^{25}$ Hz, corresponding to gamma-ray energies. Both energy bands may exhibit possible contributions from additional mechanisms, such as External Compton (EC) scattering or hadronic processes at ultra-high energies. The residual plot below the graph in Figure 1 highlights the agreement between the modeled data, represented by the dashed curve, and the observational data, depicted by vertical lines.

Furthermore, JetSet enables the generation of Corner plots 2 via SSC modeling. These plots provide the distributions of each

[5] https://www.ssdc.asi.it/

[6] https://firmamento.hosting.nyu.edu/home

[7] https://www.asi.it/en/

[8] https://nyuad.nyu.edu/en/research/faculty-labs-and-projects/center-for-astrophysics-and-space-html

[9] https://citizenresearcher.hosting.nyu.edu/

[10] https://jetset.readthedocs.io/en/1.3.0/index.html

[11] https://am3.readthedocs.io/en/latest/

[12] https://www.astropy.org/

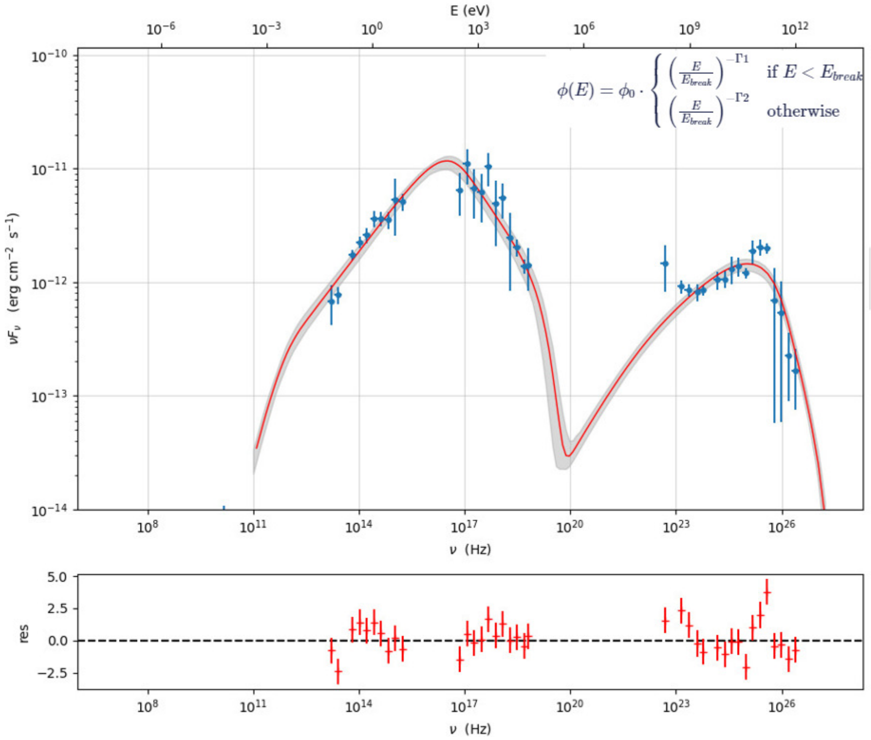

Figure 1. SSC modeling for the source 1ES 0414+009. Source: Author.

parameter along with their associated probabilities, offering a comprehensive view of the parameter space. The diagonal in the plot represents the distributions of each parameter along with their associated probabilities. The off-diagonal plots show pairwise comparisons of the parameters, where the points indicate regions with the highest probability density. The more elliptical and inclined the contours are, the stronger the correlation between the parameters.

4.2. Lepto-Hadronic Modeling

Using AM^3 it was possible to perform the lepto-hadronic modeling by using the output parameters from JetSet as input (see Figure 3). For the modelling, we assumed a proton luminosity given approximately by an increase of 10^3Rodrigues et al. (2019) over the Eddington luminosity, which corresponds to the maximum luminosity a star can achieve when there is balance between the force of radiation acting outward and the gravitational force acting inward:

$$L_p^{phys} \sim 10^3 L_{edd} \tag{3}$$

The different curves correspond to the contributions of various emission mechanisms to the blazar spectrum. The dark blue and green curves correspond to leptonic processes, while the red, yellow, and light blue curves represent hadronic processes, such as pp interactions and Bethe-Heitler $p\gamma$ interactions. These processes can produce mesons like π^0 and $\pi^\pm$, leading to particle cascades.

The data points correspond to observations from different observatories, such as Fermi-LAT and H.E.S.S. The solid pink line on the right and the dashed line indicate the maximum all flavor neutrino fluxes produced by charged particle decay, which could be observed by the IceCube Neutrino Observatory. However, no neutrinos from this source have been detected so far.

5. Conclusion

This work explored the potential of 1 ES 0414+009 as possible source of astrophysical neutrinos, gamma rays, and cosmic rays. Gamma-ray emission from leptonic and hadronic interactions was investigated, as well as the all flavor neutrino production from charged particle decay. The lower-energy peak is attributed to synchrotron radiation from electrons in the jets, while the higher-energy peak likely arises from inverse Compton scattering of photons by these electrons. Moreover, there is a contribution from Bethe-Heitler process at about 10^{11} eV.

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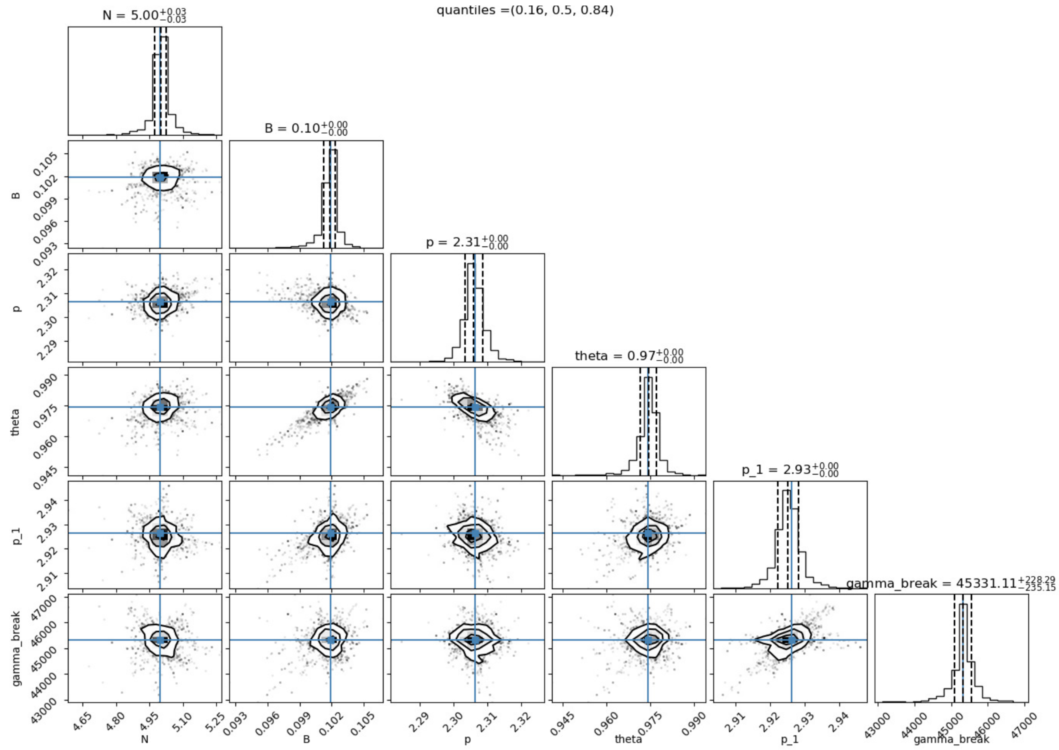

FIGURE 2. Corner plot, generated through SSC modeling, for the source 1ES 0414+009

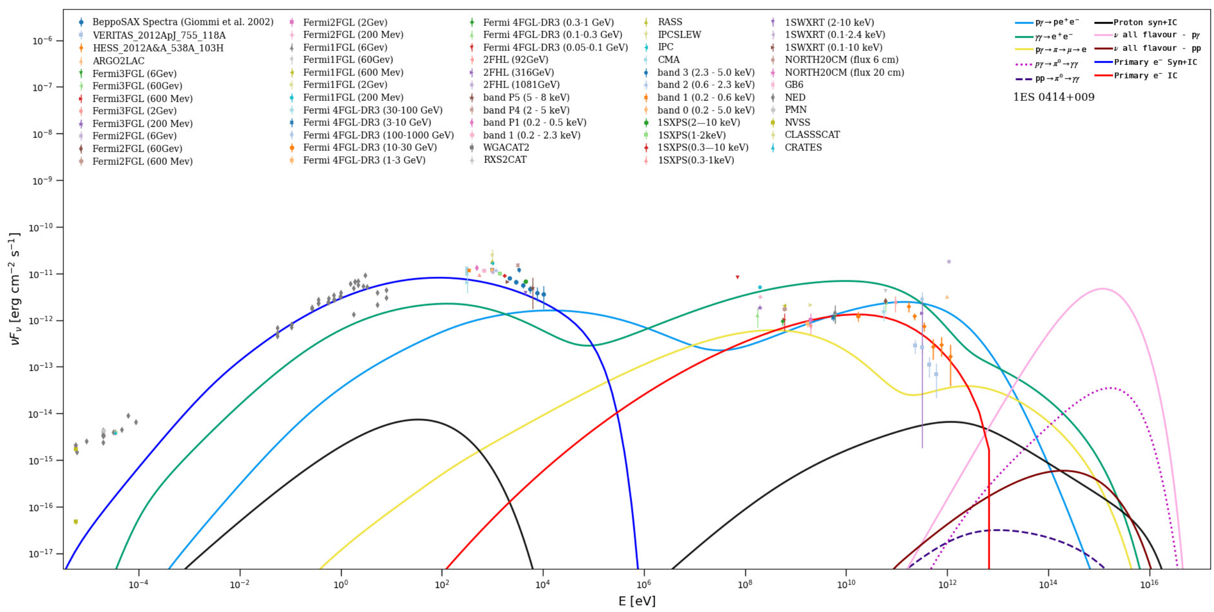

FIGURE 3. Spectral Energy Distribution (SED) and multiwavelength data of 1ES 0414+009, represented by the dark blue and red line. The markers represent the observational data from multiple instruments and catalogs, including BeppoSAX, VERITAS, Fermi-LAT, and others, spanning radio to gamma-ray frequencies. The curves illustrate contributions from various radiation processes modeled using a lepto-hadronic framework: proton-photon interaction ($p\gamma$, light blue curves) observed from 10^{-3} eV to 10^{15} eV, photon-photon interaction ($\gamma\gamma$, green curve) observed in the range 10^{-5} eV to 10^{15} eV, proton-photon interaction generating pions ($p\gamma$, yellow curve) observed from 10^{-1} eV to 10^{15} eV, neutral pion production from proton-photon interaction ($p\gamma$, pink dotted curve) observed in the range 10^{11} eV to 10^{16} eV, proton-proton interaction generating neutral pions (pp, purple dashed line) observed in the range 10^{11} eV to 10^{15} eV, proton synchrotron emission represented by the black line, and proton-photon and proton-proton interactions generating neutrinos represented by the light pink and burgundy lines, respectively, in the range 10^{11} eV to 10^{16} eV. Source: Author.