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Multi-messenger emission characteristics of blazars

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Multi-messenger observations and theories of astrophysical objects are rapidly becoming a critical research area in the astrophysics scientific community. In particular, point-like objects such as BL Lacertae (BL Lac) objects, flat-spectrum radio quasars (FSRQs), and blazar candidates of uncertain type (BCUs) are of distinct interest to researchers studying the synchrotron, Compton, neutrino, and cosmic ray emissions sourced from compact objects. Notably, there is also much interest in the correlation between multi-frequency observations of blazars and neutrino surveys on source demographics. In this review, we look at such multi-frequency and multi-physics correlations of the radio, X-ray, and γ-ray fluxes of different classes of blazars from a collection of survey catalogs. This multi-physics survey of blazars shows that there are characteristic cross-correlations in the spectra of blazars when considering their multi-frequency and multi-messenger emission. In addition, a review of cosmic ray and neutrino emissions from blazars and their characteristics is presented.

KEYWORDS

high-energy astrophysics, multi-messenger astrophysics, supermassive black holes, blazars, active galactic nuclei, γ-ray, X-ray

1 Introduction

Active galactic nuclei (AGN) are the largest, most luminous, and persistent extragalactic objects observed in the Universe. These sources feature emissions across the full gamut of electromagnetic spectra, from radio to γ-ray up to ultra-high-energy cosmic rays. AGN, in general, encompass a large population of the high-energy γ-ray sources in the known Universe, comprising nearly 61.4% of the 5,064 γ-ray sources in the most recent completed update to the *Fermi*-LAT 4FGL catalog (Abdollahi et al., 2020). Blazars and other point-like objects such as misaligned AGN or radio galaxies (Abdo et al., 2010a) and Narrow-Line Seyfert 1 galaxies (D'Ammando, 2019), which feature similar emission patterns and mechanisms, play an essential role in our understanding of the high-energy Universe, potentially revealing crucial information about the evolutionary process of itself and the host galaxy. Blazars are of particular interest as they allow for direct observations of the relativistic jet emission and the resulting luminosity amplification due to the Doppler boosting of the emission. They are characterized by their extreme variability, high polarization, radio-core dominance, and superluminal velocities (Liu, 2009; Fan et al., 2016) and vary widely in time scales ranging from minutes to hours (intra-day variability), weeks to months (short-term variability), and months to years (long-term variability) (Wagner and Witzel, 1995; Gupta et al., 2016). They are known to show two prominent broad-spectral features: the first peak is the result of synchrotron radiation, and the second bump is potentially the result of inverse-Compton emission (Gupta et al., 2016; Valverde et al., 2020) that dominates leptonic models. The corresponding hadronic models in blazar spectral energy distributions (SEDs) result from the higher-energy proton–synchrotron emission resulting from cascades of protons and pions in photo-meson productions (Böttcher, 2007; Cerruti, 2020). Blazars are categorized into two main subclasses, BL Lacertae (BL Lac) objects and flat-spectrum radio quasars (FSRQs) (Fan et al., 2016; Zhang and Fan, 2018; Kramarenko et al., 2021; Prandini and Ghisellini, 2022; Mohana A et al., 2023), along with a somewhat chameleon type of subclassification called *changing-look blazars* (Kang et al., 2024). The most notable differences between the two classes are the contrasts in emission lines. BL Lacs produce weakly peaked emission lines, while FSRQs produce very strong emission lines (Liu, 2009). The history of blazar unification has been a long-standing problem in AGN observations (Urry and Padovani, 1995; Fossati et al., 1998; Padovani et al., 2017; Rieger, 2019).

The *Fermi*-LAT collaboration (Atwood et al., 2009) has generated one of the most extensive catalogs of AGN in the high-energy regime (Ajello et al., 2020; Abdollahi et al., 2020; Ballet et al., 2023). A growing number of developing probe and mission concepts are dedicated to the multi-messenger aspects of observing these energetic objects with variable emissions. Additionally, when considering correlations of higher-energy observations with radio emissions of blazars, the joint Monitoring Of Jets in Active galactic nuclei with VLBA Experiments (MOJAVE)–FERMI (Lister et al., 2011) catalog correlates these emission regimes observed by *Fermi*-LAT and MOJAVE collaborations. Similarly, on the lower end of the frequency spectrum, the MOJAVE (Lister et al., 2009) is stated as being a long-term program that observes the brightness and polarization of radio jets in AGN. Furthermore, sources are continuously added to the joint MOJAVE-FERMI AGN catalog (Kramarenko et al., 2021). Recommendations from the Pathways to Discovery in Astronomy and Astrophysics for the 2020s (Astro2020) (National Academies of Sciences and Medicine, 2023) have generated a number of products and initiatives that prioritize science gaps for time-domain and multi-messenger (TDAMM) (ESA/ATG medialab, 2023) astrophysics. The γ-ray Transient Network Science Analysis Group (GTN SAG) (Burns et al., 2023) and various workshops and conferences solicit community synergy like that of the TDAMM workshop: The Dynamic Universe: Realizing the Science Potential of Time Domain and Multi-Messenger Astrophysics, was held following the recommendations from the National Academies of Sciences and Medicine (2023).

The remainder of this review is organized as follows: Section 2 provides a focused description of state-of-the-art physical characteristics of blazars and their emitted jets across a multi-physics regime looking at the intersecting physics of jet launching; Section 3 reviews current efforts that explore multi-spectral correlations and variability in blazars; and lastly, we end this paper with a discussion on multi-messenger science gaps, making parallels with other high-energy point-like objects that show similar emission characteristics as blazars. This section also highlights ongoing efforts and projects that attempt to reveal new areas of scientific interest in relation to a central black hole.

2 Multi-physics characteristics of blazars

2.1 Power spectrum

Relativistic jets comprise non-thermal emission within the AGN spectra, ranging from synchrotron sources of radio emission to higher-energy γ-ray and even cosmic ray emissions as can be seen in Figure 1. The power spectrum associated with synchrotron and self-synchrotron emission can be determined using Eq. 1 below

$$P(\nu) = \frac{\sqrt{3}e^3 B \sin\alpha}{m_e c^2}\left(\frac{\nu}{\nu_c}\right)\int_{\nu/\nu_c}^{\infty} K_{5/3}(\eta)\,d\eta, \tag{1}$$

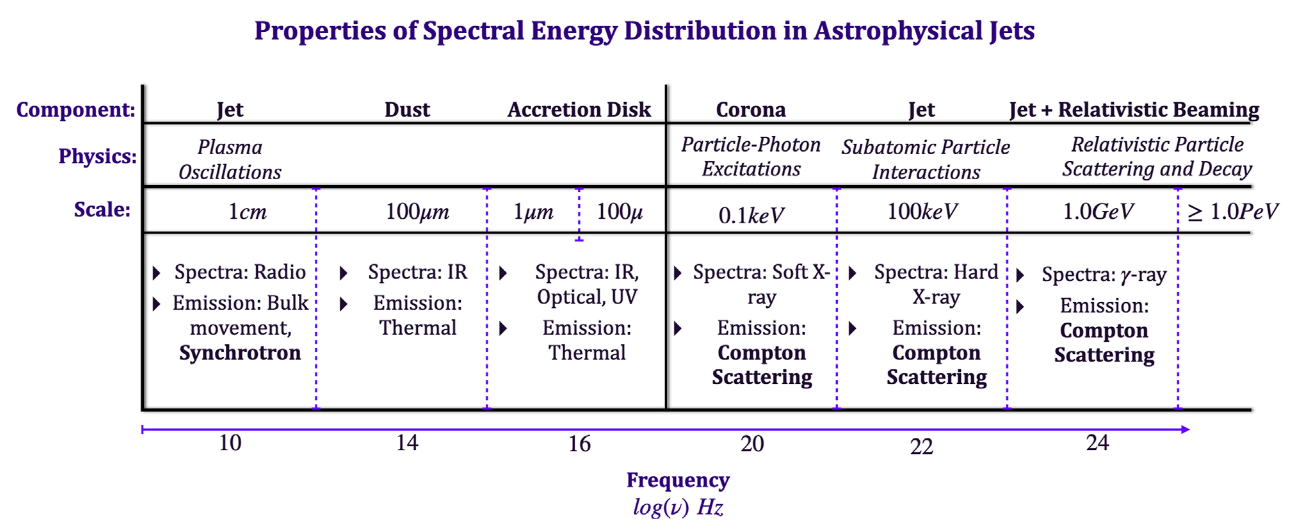

FIGURE 1
Properties of relativistic jet spectra and their corresponding radiation transfer phenomena (Gamble, 2022).

where the critical frequency, ν_c, is given by

$$\nu_c = \frac{3}{2}\gamma^2 \nu_G \sin\alpha, \tag{2}$$

with ν_G as the gyrofrequency. The parameters B, α, and ν are the magnetic field strength, pitch angle, and emission frequency, respectively. The integral in the synchrotron power function here is characterized by the modified Bessel function of the second kind $K_{5/3}(\eta)$, where η is defined as the ratio of the frequency to critical frequency ν_c. Additionally, their spectra can be determined using various observational data analysis methods and SED correlation schemes (Homan et al., 2021). Current data analyses from observational missions have shown that the SEDs of BL Lacs and FSRQs exhibit significant continuum variability in their observed frequency bands (Harris and Krawczynski, 2006; Abdollahi et al., 2020; Valverde et al., 2020; Mohana A et al., 2023). These spectral data can be connected back to the black hole–disk system to infer the local properties of the surrounding accretion disk (i.e., matter content, dust/plasma temperature, and particle accelerations/scatterings) but are limited in describing the gravitationally induced dynamics of the relativistic jet (Gamble, 2022).

2.2 Jet emission mechanisms

Currently, the mechanisms for relativistic jet emissions associated with AGN and other high-energy astrophysical objects like γ-ray bursts (GRBs) and microquasars are of interest in the astrophysics scientific community. Jet formation theory and emission is a major problem yet to be solved in high-energy astrophysics. One of the most widely argued models for describing this type of emission has been the Blandford–Znajek (BZ) process (Blandford and Znajek, 1977). This process describes the rotational energy extraction from black holes involving the torsion of magnetic field lines, resulting in Poynting flux-dominated outflows parallel to the rotation axis of the central object (Blandford and Znajek, 1977; Znajek, 1977).

$$L_{BZ} = f(\alpha_H) B_\phi^2 r_s^2 c 8\pi^{-1}, \tag{3}$$

where Eq. 3 provides the BZ luminosity. Here, we define the parameters $\alpha_H, B_\phi, and r_s$ as the spin parameter of the black hole horizon, magnetic field strength in the ϕ-direction, and the corresponding Schwarzschild radius, respectively. The nature of such highly complex energetic emission mechanisms from these systems, which feature event horizons in rotating spacetimes, has been studied extensively over the last few decades (Williams, 2004; 1995; Pei et al., 2016; Toma and Takahara, 2016; King and Pringle, 2021; Gamble, 2022). Recent numerical and observational models incorporating magnetohydrodynamic (MHD) and general relativistic magnetohydrodynamic (GRMHD) methods have shown that a major contribution to jet outflows is from the poloidal magnetic field configurations from relativistic matter accreting onto the central object (Komissarov, 2005; Nathanail and Contopoulos, 2014; Koide, 2020; Akiyama et al., 2022). Unanswered questions on the relativistic nature of these jets involve figuring out how particles that make up the jet content are accelerated to ultra-relativistic speeds, of which the Lorentz factors are $\Gamma_{Lorentz} > 10$. What is the origin of the relativistic particles that produce non-thermal radiation that we observe? Moreover, how do these jets become *matter-loaded*? Focusing on the theoretical aspects of jet formation mechanisms, fundamental questions continue to remain unresolved, one of which is the causal connection of the jet to the exterior Kerr spacetime. An application of the BZ process to alternatives or extensions of general relativity by Pei et al. (2016) has shown the versatility of the decade-old theory but, again, exhibits how the BZ process needs extensions to incorporate the sources of the magnetic fields it describes (Garofalo and Singh, 2021; King and Pringle, 2021).

As mentioned, a relativistic jet is described as a beam of light that carries linear momentum and, thus, is influenced by an appreciable amount of external angular momentum in both the non-relativistic and relativistic regimes. This angular momentum would then be dependent on the origin of an associated coordinate system, owing to the intrinsic gauge dependence of angular momentum in fundamental physics descriptions. If we then proceed to describe BL Lac and FSRQ blazars as energetic point sources, we can infer the physical characteristics of the jet emission as relativistic beams transported across galactic distances. These point sources should then inherently carry rotational symmetry corresponding to rotated field lines with respect to the host black hole (Gamble, 2022). The following equations of motion described in Eq. 4, specifically under the influence of curved spacetime near the jet-launching region, illustrate the complexities of jet launching from the supermassive black holes of blazar types. Here, the potentials parameterizing particle paths in this near-horizon region are defined, yielding a set of Hamilton–Jacobi equations for each direction. It is easy to see the expected symmetries in the particle paths for the t and ϕ directions. Here, the functions $R(r)$ and $V(\theta)$ in Eqs 6, 7 correspond to the traditional motions in the r and θ directions, respectively.

$$\Sigma \frac{dr}{d\lambda} = \pm\sqrt{R(r)}, \tag{4a}$$

$$\Sigma \frac{d\theta}{d\lambda} = \pm\sqrt{V_\theta(\theta)}, \tag{4b}$$

$$\Sigma \frac{d\phi}{d\lambda} = -\left(\alpha_H E - L/sin^2\theta\right) + \alpha_H T/\Delta, \tag{4c}$$

$$\Sigma \frac{dt}{d\lambda} = -\alpha_H\left(\alpha_H E sin^2\theta - L\right) + \left(r^2 + \alpha_H^2\right) T/\Delta, \tag{4d}$$

where the functions T, $R(r)$, and $V_\theta(\theta)$ are defined as

$$T \equiv E\left(r^2 + \alpha_H^2\right) - \alpha_H L, \tag{5}$$

$$R(r) \equiv T^2 - \Delta\left[m_0^2 r^2 + (L - \alpha_H E)^2 + Q\right], \tag{6}$$

$$V_\theta(\theta) \equiv Q - cos^2\theta\left[\alpha_H^2\left(m_0^2 - E^2\right)\frac{L^2}{sin^2\theta}\right]. \tag{7}$$

Here, E and L are the particle energy and angular momentum, respectively, m_0 is the rest mass of a test particle, and Q is identified as Carter's constant. The functions $\Sigma = r^2 + \alpha_H^2 cos^2\theta$ and $\Delta = r^2 - Mr + \alpha_H^2$ are defined from the components of the Kerr spacetime for a rotating black hole of arbitrary mass. Within the context of this discussion on blazar jet emission, it is logical to consider not only the particle distributions in jets but also the intrinsic geometry of particle paths moving at high Lorentz factors, specifically above $\Gamma_{bulk} \geq 10 - 10^2$. Additionally, there have been efforts to incorporate non-equatorial instabilities that contribute to the e^-/e^+ pair production at γ-ray energies $\geq GeV$ around high-spin $\alpha_H \geq 0.8$ black hole horizons in a description of jet launching (Williams, 1995; Williams, 2004), thus removing some of the mystery of the physical mechanisms that cause some jets to twist and carry a proportionate amount of angular momentum from the black hole. It is then intuitive to think about how one can infer the mechanisms causing such polarization in the observed spectra. Observations of blazars and radio-loud AGN have shown that polarization states exist in the spectra from these sources (Homan et al., 2021; Liodakis et al., 2021).

3 Multi-spectral variability of blazars

3.1 Variability and flaring of VLBI-selected blazars

Observing the variability of blazars can reveal the necessary information to infer the composition of the jet emissions, the mechanisms behind the jet formation, and changes in the accretion rate of the accretion disk and can allow for the localization of the innermost emitting regions (Lawrence, 2016; Valverde et al., 2020). As the central supermassive black hole (SMBH) at the cores of blazars accretes matter and forms the surrounding accretion disk, it launches relativistic jets that emit across the electromagnetic spectrum (radio to γ-rays) (Gupta et al., 2016). Figure 2 shows such a distribution in the GeV energy flux associated with γ-ray emissions *versus* the very long baseline array (VLBA) flux for these radio–gamma correlated sources. This distribution shows a differentiation between high-synchrotron peak (HSP) BL Lacs that feature peaks in the range $v > 10^{15}$Hz and low-synchrotron peaked (LSP) BL Lacs that fall in the range $v < 10^{14}$Hz (Sahakyan, 2020). Refer to Giommi and Padovani (1994) and Abdo et al. (2010b) for more detailed descriptions comparing HSP and LSP signatures for BL Lacs.

Figure 3 shows that there exists a delayed variability in the radio emission for the blazar TXS 0506 + 056 (4FGL J0509.4 + 0542) compared to its higher-energy counterpart in the light curve at $E_{ph} > 1.07$ GeV. This light curve, along with blazars in the MOJAVE-FERMI catalog, features this type of variability, where the radio and γ-ray emissions are correlated according to a respective time lag. There exists significant correspondence with the γ-ray flaring of TXS 0506 + 056 (4FGL J0509.4 + 0542) with neutrino incidence in the direction of this blazar (IceCubeFermi-LATMAGICAGILEASAS-SNHAWC et al., 2018). Analyzing the photo-meson production for HSP as stated above, such particle interactions within the jets of highly energetic sources like TXS 0506 + 056 (4FGL J0509.4 + 0542) and PKS 0735 + 178 (4FGL J0738.1 + 1742) (Prince et al., 2023) are a testament of the dynamic multi-messenger and multi-physics aspect of sources that feature extremely accelerated ejecta. The correlation between the radio and very high-energy (VHE) γ-ray emissions is a curious notion highlighting the new frontier of multi-messenger astrophysics in the modern era of astronomy. Additionally, HSP blazars with similar flaring characteristics are also likely to exhibit particle cascade mechanisms that produce cosmic rays (high-energy nucleons and charged particles). The 116 sources in the MOJAVE-*FERMI*-LAT 1FGL catalog are a prototypical example of the type of variability blazars exhibit across multiple spectral frequencies. Note that the catalog only correlates VLBI-selected 15-GHz radio-loud sources with a significant correlation to their γ-ray peaks. The catalog is sourced from the study by Kramarenko et al. (2021), a decade of joint MOJAVE-Fermi AGN monitoring: localization of the γ-ray emission region that features 331 sources with down selection to N-blazars with significantly strong radio emission (> = 80%) of the 331 catalogs of sources. Both blazar classes have been reported to present strong correlations between the radio and γ-ray emissions (Max-Moerbeck et al., 2014; Mufakharov et al., 2015; Fan et al., 2016), thus indicating that the production of these jet emissions coincides with a common mechanism. A more extensive overview of radio VLBI/γ-ray catalogs of blazars: MOJAVE-*FERMI*-LAT 1FGL, National Radio Astronomy Observatory (NRAO) catalogs, Atacama Large Millimeter/submillimeter Array (ALMA), and Event Horizon Telescope results and simulations will be provided in subsequent papers focusing on more details of the cross-correlation in blazars. Figure 4 shows such intra-week variability at 15 GHz in the time domain. This variability illustrates the need for time-domain follow-up for energetic sources. We can see that on a month-to-month time scale, the correlation strength peaks at ~5 months. This suggests that there could be a significant observing campaign for follow-up observations. From a multi-physics perspective, improved time-dependent theoretical models and GRMHD simulations are needed to decipher such physics.

4 Discussion

4.1 Blazar parallels with γ-ray bursts

Given the nature of the high-energy emission characteristics of BL Lac and FSRQ blazars, it is additionally safe to compare them to GRBs. Both types of high-energy sources are considered to be sourced by compact objects (i.e., SMBH, X-ray binaries, neutron star mergers, core-collapse supernovae, and stellar mass black holes). Both energetic phenomena exhibit similar physical characteristics when considering their respective ejecta mechanisms. It is no coincidence that GRBs and blazar jets also feature similarities in the spectral peaks, illuminating commonalities in their respective radiation physics (Nemmen et al., 2012). A more detailed description of these physical comparisons can be found in works highlighting such comparisons (Lyu et al., 2014; Srinivasaragavan et al., 2023). An even more interesting recent inclusion in the “AGN zoo” is *changing-look blazars*. These are blazars that feature changes in their accretion processes, intrinsically changing from FSRQ-type to BL Lac and vice versa (Kang et al., 2024). This suggests that further investments in TDAMM science and its technological developments are needed to further elucidate the dynamical properties of AGN with blazar types, BL Lac, FSRQs, and BCUs.

4.2 Ground-based follow-up

4.2.1 ALMA: radio

Specifically, within the radio frequency regime, the ground-based ALMA (Wootten and Thompson, 2009) is extraordinary

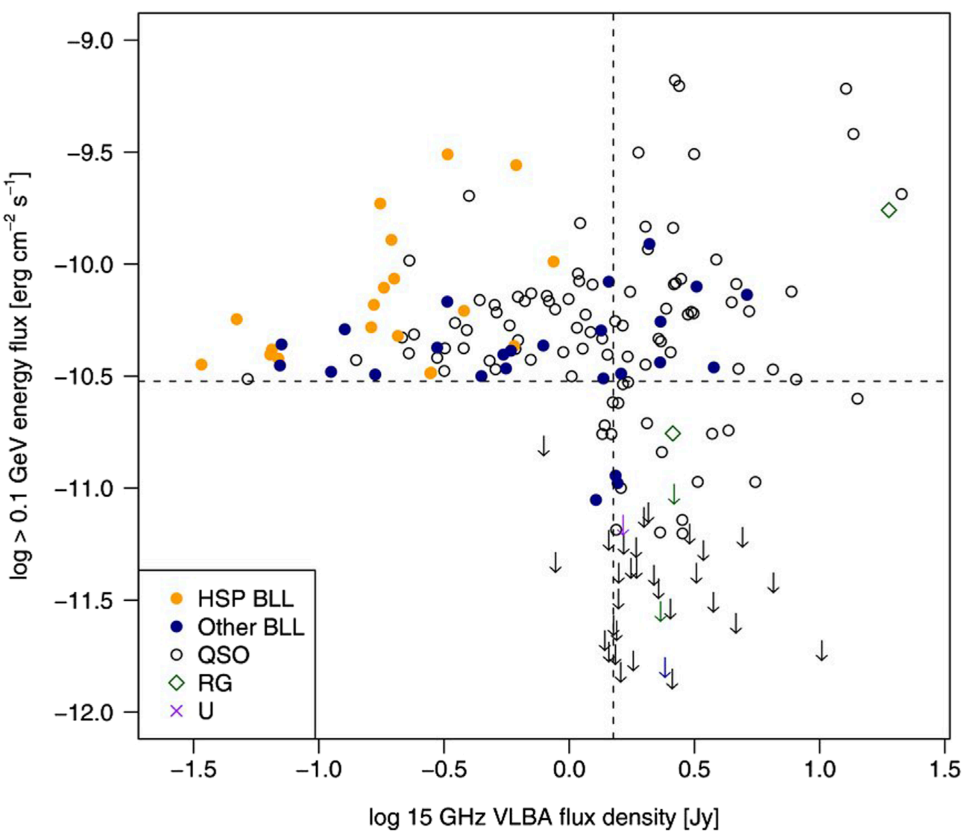

FIGURE 2
Plot of 11-month Fermi average $> 0.1 GeV$ energy flux vs 15-GHz VLBA flux density of the joint blazar samples given by Lister et al. (2011). The filled circles represent BL Lac objects, with the HSP objects in orange and others in blue. The open circles represent quasars, the green diamonds denote radio galaxies, and the purple crosses denote optically unidentified objects. Upper limits on the γ-ray fluxes are indicated by arrows. All of the BL Lac objects are detected by the LAT, with the exception of J0006-0623. The vertical dashed line indicates a sample radio limit of $1.5 Jy$, and the horizontal dashed line indicates a γ-ray limit of $3\times10^{-11} erg\ cm^{-2}\ s^{-1}$. The figure and caption are sourced from the MOJAVE-*FERMI*-LAT 1FGL catalog (Lister et al., 2011).

for observing, in general, AGN of different classifications as it provides a perspective of these high-energy objects in the radio and infrared spectrum. With its ground-breaking interferometric array of 66 high-precision antennas, its performance results in high-resolution images with the brightness sensitivity of a single-antenna array (Brown et al., 2004). LSP BL Lac objects offer a distinctive spectral climb when comparing their γ-ray peaks to their maximal synchrotron peaks (Mohana A et al., 2023), with blazars of type FSRQ almost exclusively falling under LSP (Sahakyan, 2020). Conversely, when analyzing the spectral correlation of HSP BL Lac objects with similar γ-ray energies, the correlation is not strong enough ($< 10 GeV$).

Quasar PKS 1549–79 was previously observed by Oosterloo et al. (2019) in order to analyze its radio jet, using millimeter- and very long baseline interferometry 2.3-GHz continuum observations. PKS 1549–79 is known as a radio-loud quasar, having a stronger radio emission and higher energy than the more common radio-quiet quasar (Barvainis et al., 2005). PKS 1549–79 is also the closest quasar that has been observed merging with an AGN in the first phases of its evolution. Oosterloo et al. (2019) also presented CO (1–0) and CO (3–2) observations of its molecular gas. Their results showed that the massive outflow of 650 $M_\odot\ yr^{-1}$ confined to $r < 120$ pc of the inner galaxy suggests that the AGN drives this outflow. The radio-quiet quasar SDSS J0924 + 0219 was observed by Badole et al. (2021) using 45 of ALMA antennas and very large array (VLA). It is evident that analyzing both LSP and HSP blazars contributes to a more compounded description of blazar models when looking at the entire non-thermal spectra of blazars in the AGN zoo.

4.2.2 IceCube: neutrinos and cosmic rays

The flaring and variability of the blazar spectra listed in the MOJAVE-FERMI catalog, the *Fermi*-LAT catalogs, and various others that feature high-energy γ-ray emission from blazars residing in their active phases are important aspects for identifying the neutrino production from such sources (e.g., TXS 0506 + 056 (4FGL J0509.4 + 0542) and PKS 0735 + 178 (4FGL J0738.1 + 1742)). Analyzing the particle production mechanisms, we can see that the particle phenomenology associated with the electromagnetic and cosmic-ray producing interactions overlaps with their decay mechanisms as well. The photo-meson particle production in the

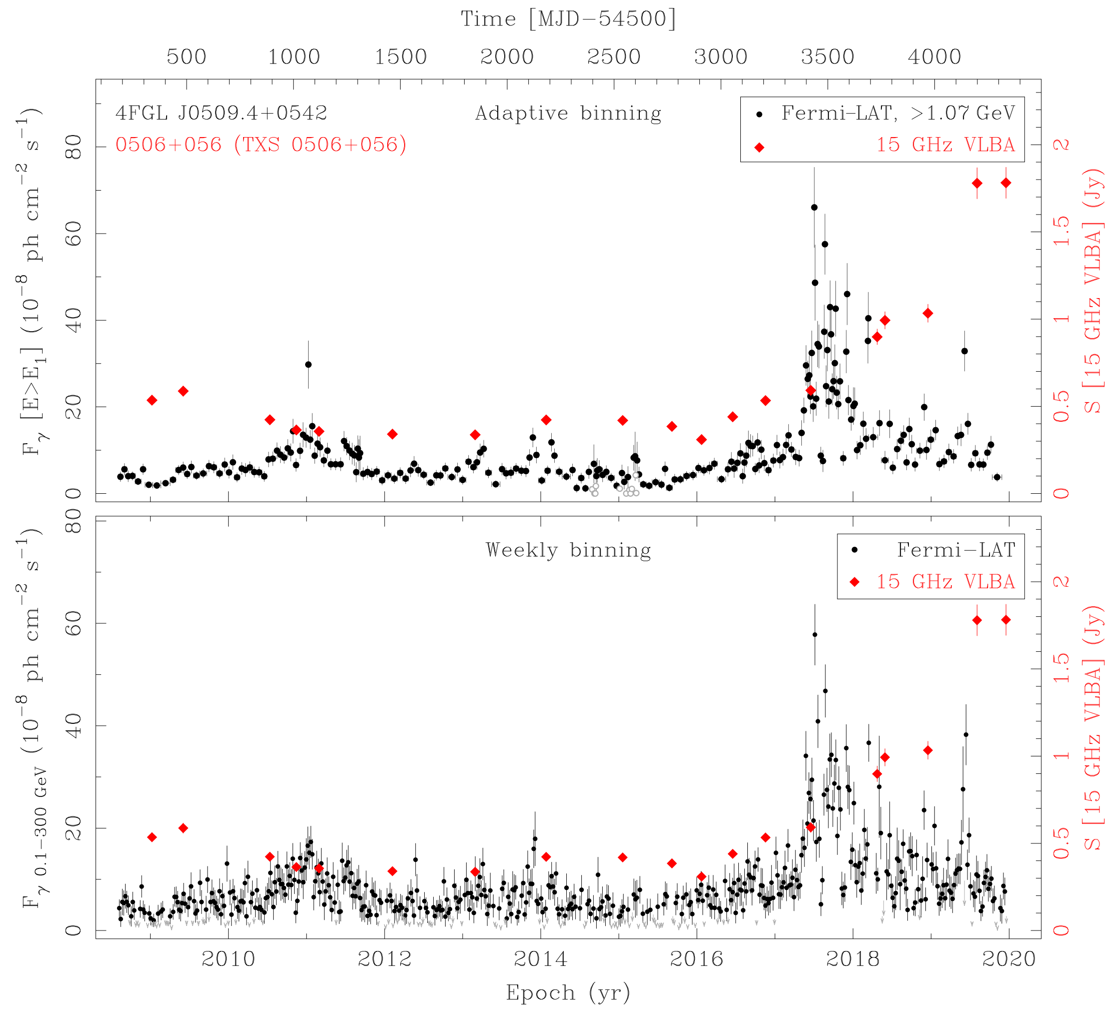

FIGURE 3
Intra-week variability overlap of the γ-ray emission at $E_{ph} > 1.07$ GeV (in black) and the VLBA radio emission at 15 GHz (in red) of the blazar TXS 0506 + 056 (4FGL J0509.4 + 0542). The two panels show the light curve with adaptive binning on the top and weekly binning on the bottom where the epoch spans 12 years. The multi-epoch light curve is sourced from the MOJAVE-*FERMI*-LAT 1FGL catalog (Lister et al., 2011).

accelerated environments of jets is shown in Eqs 8, 9, where protons scatter off photons to produce a cascade of charged and neutral pions (π^0, π^+, π^-).

$$\begin{aligned} p+\gamma &\rightarrow p' + \pi^0 \\ p+\gamma &\rightarrow n + \pi^+ \\ p+\gamma &\rightarrow p' + \pi^+ + \pi^-. \end{aligned} \tag{8}$$

This interaction of accelerated protons with γ-ray photons provides a precursor to the neutral and charge pions. The subsequent decay of (π^-, π^+) into a cascade of muons (μ^+, μ^-) and neutrinos (ν_e, ν_μ) (of e^- and μ^+ types) and their respective symmetric (antimatter) pairs introduces the weak interaction into hadronic/meson blazar jet models.

$$\begin{aligned} \pi^0 &\rightarrow 2\gamma \\ \pi^+ &\rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \overline{\nu}_\mu + \nu_\mu \\ \pi^- &\rightarrow \mu^- + \overline{\nu}_\mu \rightarrow e^- + \overline{\nu}_e + \nu_\mu + \overline{\nu}_\mu. \end{aligned} \tag{9}$$

Ultimately, the presence of these cascades detected by neutrino and Cherenkov telescopes is a prominent clue for finding relativistic protons in the jet (Muecke et al., 1999; Cerruti, 2020). The IceCube Neutrino Observatory (Aartsen et al., 2017) has made significant progress in detecting neutrinos of astrophysical origin emanating from blazars. Blazars, such as TXS 0506 + 056 (4FGL J0509.4 + 0542) and PKS 0735 + 178 (4FGL J0738.1 + 1742), have been extensively studied in recent years (Padovani et al., 2015; IceCubeFermi-LATMAGICAGILEASAS-SNHAWC et al., 2018; Prince et al., 2023). Multi-messenger observations and their follow-up have thus proven to be a powerful methodology for determining the VHE characteristics of blazars.

5 Conclusion

This focused review of blazars of type FSRQ, BL Lac, and BCU shows just how dynamic these point-like objects

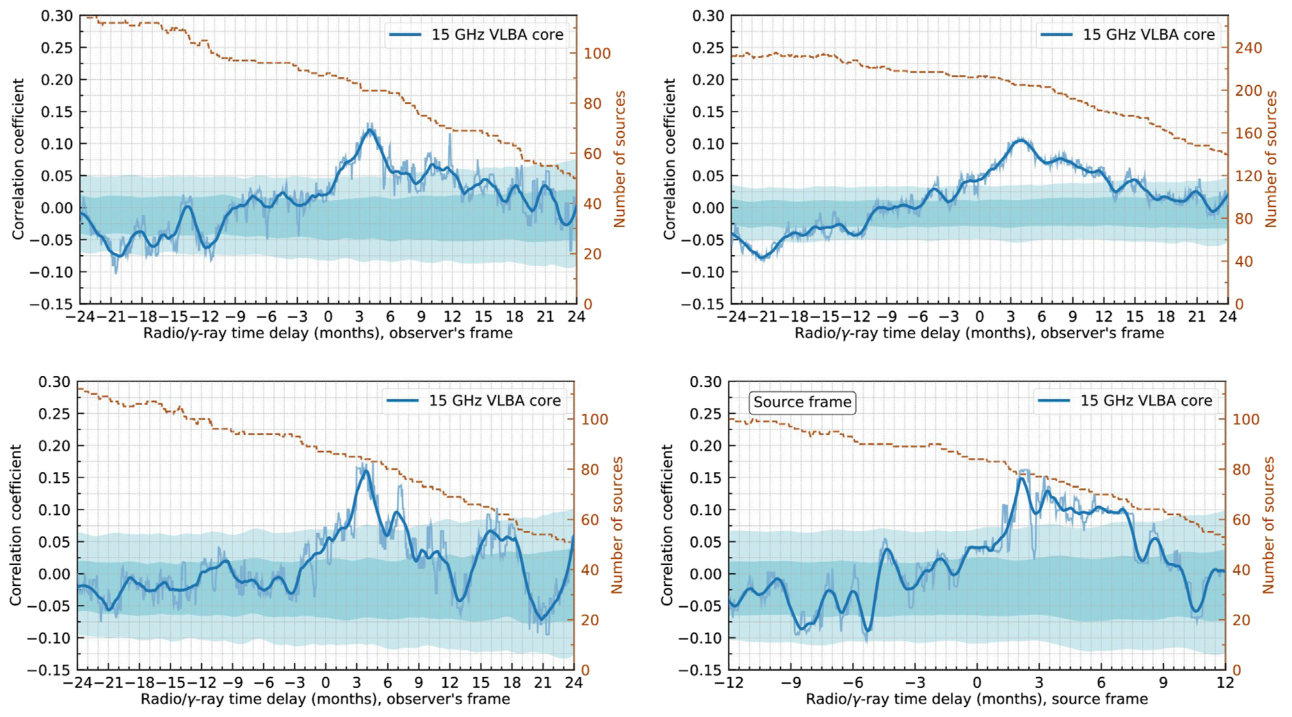

FIGURE 4
Intra-week variability cross-correlation at 15-GHz VLBA. Reproduced with permission from Kramarenko et al. (2021).

are regarding their relativistic properties. The multi-physical nature of such astronomical objects suggests significant gaps in our understanding of their multi-messenger characteristics. The recommendations from the Astro2020 decadal survey offer an initiation of thoughts surrounding TDAMM science gaps. Further investments from the broader astronomy/astrophysics community are required to elucidate and decipher the true nature of blazars, their relativistic jet emission, and future multi-spectral analyses and missions. The utilization of unconventional thoughts and methodologies would prove useful in our quest to understand the energetic Universe. The synergy between radio (ALMA and MOJAVE), X-ray (IXPE, XRISM, Chandra, and SWIFT), γ-ray (VERITAS, *Fermi*-LAT, MAGIC, and H.E.S.S.), and cosmic-ray/neutrino (IceCube) observations plays an important role in the analysis and theoretical modeling of variable energetic blazars as it allows for more detailed observations of these objects.

Author contributions

RG: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, supervision, validation, visualization, writing–original draft, and writing–review and editing. JF: conceptualization and writing–original draft. AB: conceptualization and writing–original draft. GS: conceptualization and writing–review and editing. IH: conceptualization and writing–review and editing. MJ: conceptualization and writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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