

Article

# A Multi-Wavelength View of OJ 287 Activity in 2015–2017: Implications of Spectral Changes on Central-Engine Models and MeV-GeV Emission Mechanism

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**Abstract:** A diverse range of observational results and peculiar properties across the domains of observation have made OJ 287 one of the best-explored BL Lac objects on the issues of relativistic jets and accretion physics as well as the strong theory of gravity. We here present a brief compilation of observational results from the literature and inferences/insights from the extensive studies but focus on the interpretation of its  $\sim 12$ -yr quasi-periodic optical outbursts (QPOOs) and high energy emission mechanisms. The QPOOs in one model are attributed to the disk-impact related to dynamics of the binary SMBHs while alternative models attribute it to the geometrical effect related to the precession of a single jet or double jets. We discuss implications of the new spectral features reported during the 2015–2017 multi-wavelength high activity of the source—a break in the NIR-optical spectrum and hardening of the MeV-GeV emission accompanied by a shift in the location of its peak, in the context of the two. The reported NIR-optical break nicely fits the description of a standard accretion disk emission from an SMBH of mass  $\sim 10^{10} M_{\odot}$  while the time of its first appearance at the end of May, 2013 (MJD 56439) is in close coincidence with the time of impact predicted by the disk-impact binary SMBH model. This spectral and temporal coincidence with the model parameters of the disk-impact binary SMBH model provides independent evidence in favor of the model over the geometrical models which argue for a total central-engine mass in the range of  $10^{7-9} M_{\odot}$ . On the other hand, the MeV-GeV spectral change is naturally reproduced by the inverse Compton scattering of photons from the broad-line region and is consistent with the detection of broad emission lines during the previous cycles of quasi-periodic outbursts. Combining this with previous SED studies suggests that in, OJ 287, the MeV-GeV emission results from external Comptonization.

**Keywords:** BL Lac objects; individual; OJ 287–galaxies; active–galaxies; jets–radiation mechanisms; non-thermal–gamma-rays; galaxies

## 1. Introduction

Non-thermal emission is ubiquitous with jets hosted by compact astrophysical objects being one of the most prominent emitters. One of the most powerful and persistent jets are those found in active galactic nuclei (AGNs) designated radio-loud, characterized by a large scale, highly collimated, relativistic jets of plasma. In particular, the subclass called blazar–AGNs with bipolar relativistic jets of plasma aligned to our line of sight has its entire emission almost fully dominated by the jet emission. They have been found to emit across the entire electromagnetic (EM) spectrum, from radio to GeV–TeV energies ( $\sim 17$ – $20$  orders of magnitude; e.g., [1]), variable on all timescales from orders of a few  $10$  s

of minutes and even less to decades<sup>1</sup> ( $\sim 6$ – $7$  orders of magnitude; e.g., [2]). Their radio and optical emission is highly polarized and have been observed to vary often with the source flux, all the way from 0 to  $> 50\%$ . Imaging in radio, infra-red (IR), optical, and X-ray, on the other hand, have shown an extremely well collimated jet extending up to Mpc scales ( $\sim 9$ – $13$  orders of magnitude; e.g., [3,4]) with frequent sighting of superluminal features in high-resolution imaging of the core. Taken together with the observational and theoretical understanding of other astrophysical objects combined with their high and rarely repeating observational behavior indicates that they are the site of complex, multi-level, multi-scale physics and thus are normally called extreme sources among non-catastrophic events.

Though studies in different energy bands finally culminated into a unified scheme for radio-loud AGNs [5], it also revealed that AGNs need well-coordinated multi-wavelength (MW) observations to go beyond the limits associated with individual bands. The launch of the gamma-ray survey observatory *Fermi*-LAT (Large Area Telescope) with an unprecedented MeV-GeV sensitivity [6] has revolutionized studies of  $\gamma$ -ray emitting sources, especially blazars. The *Fermi* AGN monitoring program<sup>2</sup> supported by a host of observatories across the globe, working in different energy bands and supplementing and coordinating *Fermi* observations currently serves as the best archive of (relatively) unbiased data. The *Fermi*-LAT survey catalog, as was expected, revealed blazars (and AGNs) as the largest source population, making  $> 60\%$  of the detected sources (4FGL; [7]). This allowed a detailed spectral, temporal, polarization, and imaging characterization of blazars, as well as exploration of correlations between them, thereby greatly enhancing our understanding of these sources and physical conditions within the relativistic jets.

Spectral and temporal studies, in particular, high energy (HE) emission mechanisms and search for (quasi) periodic modulation has been one of the focuses of intensive research, in addition to characterization based on these. Temporal studies of flux variability have firmly established it to be stochastic with statistical properties [2,8,9] broadly similar to those exhibited by other-accretion powered sources [10]. Though a few cases of firm quasi-periodic signals have been observed, significance of most of the detected signal is still marginal (e.g., [11], and references therein). Broadband spectral studies, on the other hand, revealed a characteristic broad double-humped spectral energy distribution (SED). This feature culminated in a new classification scheme for blazars based on the frequency ( $\nu_p$ ) at which the low-energy component peaks [1,12]. Thus, sources with  $\nu_p < 10^{14}$  Hz,  $10^{14} < \nu_p < 10^{15}$ , and  $\nu_p > 10^{15}$  are respectively called low-synchrotron peaked (LSP), intermediate-synchrotron peaked (ISP), and high-synchrotron peaked (HSP) blazars. Thus far, only BL Lacs (BLLs) subclass of blazars have been found to exhibit the three spectral classes, referred to respectively as low-frequency-peaked BL Lacs (LBLs), intermediate-energy-peaked BL Lacs (IBLs), and high-frequency-peaked BLLs (HBLs) [12], whereas flat spectrum radio quasars (FSRQs) so far are exclusively LSP sources.

The low-energy hump of the blazars SED extends from radio to ultraviolet (UV)/X-ray energies, attaining a maximum in between NIR to soft-X-rays and is widely regarded as the synchrotron emission from relativistic non-thermal electrons in the jet. The high-energy hump spans X-rays to GeV-TeV energies, peaking in MeV-GeV energies, but its origin remains uncertain. The uncertainty is a direct reflection of lack of constraint on the matter content of the jet plasma, whether mainly electrons (leptonic) and/or hadrons (protons primarily) and particle acceleration. Within the limit of current observational constraints, both the models have been successful in explaining observed broadband SEDs (e.g., [13–16]), though the exact cause and the level of contribution/dominance remains a matter of debate. In the leptonic scenario, entire broadband emission is attributed to the primary electrons, via synchrotron at radio to UV/X-ray energies and via inverse Compton (IC) scattering from X-ray up to TeVs (e.g., [16–18]). Until recently, this has been the most favored interpretation of blazar emission due to the photon rich environment offered by the AGNs constituents for IC scattering e.g., accretion

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<sup>1</sup> currently feasible with observing facilities and available data.

<sup>2</sup> Multi-wavelength support program—<https://fermi.gsfc.nasa.gov/ssc/observations/multi/programs.html>.

disk (AD) close to the source, broad-line region (BLR) with extension up to sub-parsec scales, infra-red torus on parsec (pc) scales, and the omnipresent cosmic microwave background (CMB), in addition to the synchrotron photons. The respective IC scattered radiation, in the blazar community, are referred to as EC-AD [19], EC-BLR [20], EC-IR [20], EC-CMB, and synchrotron self-Compton SSC; [21], where EC stands for External Comptonization–IC scattering of photon field external to the jet. Depending on the location of the emission region, one or many of the photon fields can contribute and/or dominate the scattering process. In general, FSRQs require EC to explain their  $\gamma$ -ray emission while SSC is sufficient for most of the BLLs (IBLs and HBLs). Given the current understanding of emission lines strength in the sub-classes of blazar ([22], and references therein), it seems that, to a broad basic level, the traditional sub-classification of blazars based on rest-frame equivalent width (EW) of optical emission lines into BL Lacartae objects (BLLs,  $EW < 5 \text{ \AA}$ ) and flat spectrum radio quasars (FSRQs,  $EW > 5 \text{ \AA}$ ) nicely integrate into the interpretation that, in BLLs, the high-energy hump is primarily powered by SSC while it is by EC in FSRQs.

The hadronic scenario attributes the HE hump to proton synchrotron (purely electromagnetic process) and/or cascade initiated as a result of interaction of ultra-relativistic protons ( $\geq EeV$ ) with photons and/or protons<sup>3</sup> (e.g., [14]). The recent detection of a  $\sim 290$ -TeV neutrino (IceCube-170922A) by the *IceCube* observatory in the direction of blazar TXS 0506+056 [23,24], spatially and temporally coincident with its flaring MW activity provided the first clear evidence in favor of hadronic emission. Further investigation of data revealed neutrinos detection in the same direction during a quiescent state of the source [23]. Though interpretations of these neutrinos are still under debate ([25], and references therein) modeling of SEDs corresponding to the neutrino episodes suggests an overall sub-dominant hadronic contribution [26].

A majority of the blazars' MW activities have been observed to be simultaneous within the observational cadence. With radio to optical emission being synchrotron, the standard leptonic scenario provides the simplest, natural, and logical explanation to such highly correlated variability, though more complex physical processes may be involved and thus more involved interpretations can be offered (e.g., [27]). For BLLs, in the standard leptonic picture, an SSC interpretation has been generally favored in the literature for their HE hump due to a weak or absent BLR field. However, increasing number of studies suggest that this may not be true for LBLs and instead argue EC-IR for the MeV–GeV emission [22,28,29]. For example, in the case of 2009 flare of LBL OJ 287, Kushwaha et al. [28] has shown the infeasibility of SSC in explaining MeV–GeV emission through a systematic modeling of SEDs within the observational constraints while for LBL AO 0235+164, Ackermann et al. [22] have argued the EC interpretation based on energetics and the luminosity of the detected emission lines. The inability of SSC to reproduce the X-ray and  $\gamma$ -ray emission in the case of OJ 287 was already apparent from the work of Seta et al. [30], with the only exception being the lack of a contemporaneous MeV–GeV spectrum. The EC-IR interpretation of MeV–GeV gamma-ray emission in these two is consistent with inferences drawn from the study of broadband SEDs of a sample of LBLs with good quality  $\gamma$ -ray spectra from *Fermi*-LAT [29]. A similar (EC-IR) interpretation is favored for FSRQs from the lack of spectral cutoff at  $\gtrsim 20$  GeV, expected due to the  $\gamma - \gamma$  interaction, in the spectra extracted from  $\sim 7.3$ -yr of *Fermi*-LAT [31]. However, this interpretation has an important caveat in the case of FSRQs. FSRQs are believed to have a rich IR torus field and the expected spectral cutoff due to  $\gamma - \gamma$  interaction for it will occur at very high energies (VHEs,  $E > 100$  GeVs). Thus, spectra extracted from data integrated over a long duration may contain moments when the emission has mainly happened at parsec scales (EC-IR) for which the mentioned cutoff will not lie in *Fermi*-LAT band and thus may hide/suppress the cutoff feature.

In the present work, we focus on the blazar OJ 287—a potential binary SMBH candidate system. In particular, we discuss the implications of the new spectral features observed during its 2015–2017

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<sup>3</sup> being the biggest constituent, almost exclusively.

MW activity on the source central engine models discussed in the literature and high energy emission (MeV–GeV) mechanisms—one of the fundamental debates in the blazar community and a focus of intensive studies. First, we present a brief historical account of the source general properties as gleaned from observations and models/interpretations offered, if any, for its unique features in the next section. In Section 3, we discuss the implications of the reported features in the context of the main theme of the work with a summary in Section 4. We have assumed a  $\Lambda$ CDM cosmology with  $\Omega_M = 0.286$ ,  $\Omega_\Lambda = 0.714$ , and a Hubble constant  $H_0 = 69.6$  km/s/Mpc. With this, an OJ 287 redshift of 0.306 corresponds to a luminosity distance of 1.6 Gpc and an angular diameter scale of 4.556 kpc/arcsec.

## 2. OJ 287

OJ 287, as it is called now, was first reported in the second section of the VRO (Vermilion River Observatory) survey at 610.5 MHz (VRO 20.08.01; [32] and its optical association was identified by Blake [33]). Spectroscopic attempts following its identification failed to reveal any emission and or absorption features [34,35] and was firmly established only later at  $z = 0.306$  when it was in a low flux state [36,37]. However, photo-polarimetric studies in radio to optical bands, in general, found it to be similar to other radio sources with a star-like appearance in optical images, inverted radio spectrum, variable brightness, polarized, and variable non-thermal continuum [34,35,38–41]. These findings and resemblance of its flux and polarization variations with the archetypal source BL Lacertae led it to being classified as a BL Lac type object [34]. These observations also found it to be the most dynamic among them all, with comparable variations over a broad range of wavelengths (radio and optical; [34]). As a result, OJ 287 became the key source to characterize and understand the BL Lac class [36]. Subsequently, many focused as well as coordinated multi-wavelength studies were carried out in both photometric and photopolarimetric modes (e.g., [35,39,41,42]).

Initial concerted efforts revealed a tantalizing  $\sim 39.2$ -minute periodic signal in an optical observation while a historical data archive revealed data going back to 1890 with four clear high activity duration of several months [41]. OJ 287, however, became famous after the discovery of persistent quasi-periodic outbursts (QPOs) of  $\sim 12$ -yr in the optical band by Sillanpaa et al. [43]. Various models have been proposed in the literature for this repeating modulation and can be broadly grouped into two classes: dynamical and geometrical. The dynamical models attribute the recurring outbursts to accretion dynamics in a supermassive binary black holes (SBBHs) system [43–45], while geometrical models attribute it to Doppler boosted jet emission resulting from the jet precession (e.g., [46–48], and references therein).

The very first model by Sillanpaa et al. [43] postulated OJ 287 as an SBBH system. The outbursts in the model were a result of enhanced accretion to the primary as a result of perturbation caused by the secondary when transiting the periastron in an orbit coplanar with the primary's accretion disk. It was based on the similarity of flare profiles and its structure to that of an accreting system [49]. The model successfully passed its first observational test by correctly predicting the 1994 optical outburst [50]. However, the intensive monitoring of the 1994 outburst revealed double-peaked flares with rather sharp substructures within it compared to what was expected from an accretion flow [51]. Furthermore, the Sillanpaa et al. [43] model failed to explain the twin nature of the outbursts. This led Lehto and Valtonen [44] to propose the twin outbursts to the impact of the secondary SMBH on the accretion disk of the primary twice every orbit (see also Sundelius et al. [52]). It attributed the outbursts to hot bubbles of gas, torn off from the disk as a result of the impact, which when it expands and becomes optically thin, emits strongly in optical-UV bands via thermal bremsstrahlung. The flare emission is thus completely unpolarized. Another model in the dynamical class is by Tanaka [53]. It is based on theoretical studies and numerical hydrodynamic/magneto-hydrodynamic simulations of nearly equal-mass binary SMBH systems going around each other in an orbit coplanar with their circumbinary disk. For OJ 287, it assumes a total mass of  $\sim 10^9 M_\odot$ . The QPOs occur due to leakage of gas into this cavity once every orbit. Though the model generates double flares, it has not been investigated in

detail vis-à-vis the vast amount of available observational data on OJ 287. Thus, although it remains a plausible interpretation, the details are still to be worked out and tested with the available data.

Several other models, mainly based on geometrical interpretations, have been proposed in the literature with the earliest ones based solely on the recurrent double-peaked optical outbursts [46,54] while subsequent ones considering other observed inputs of OJ 287 like radio measurements [55,56], optical polarization [57], morphological changes [47] and jet kinematic features on parsec scales [48,58]. Except for Valtaoja et al. [55] and Villforth et al. [57] models, the recurring outbursts in these models are attributed to the Doppler boosting caused by systematic changes in the jet orientation with respect to our line of sight as a result of precession. In the model of Katz [46], the gravitational torque of the secondary induces precession in the primary's accretion disk which in turn leads to jet precession and causes the first flare. It attributes the second outburst to the nodding motion. The Villata et al. [54] model argues that both the SMBH have precessing relativistic jets. The interaction between jet plasma and the ambient medium leads to the bending of the jets and the double-peaked outbursts arise when the bent jets are aligned towards us as the result of precession. Valtaoja et al. [55] proposed a hybrid interpretation for the twin outbursts based on the radio variability where they found that the first optical outburst has no radio counterpart while the second shows simultaneous radio and optical flares. They attributed the first flare to the disk impact and the second to the jet, resulting from the propagation of impact disturbances to the primary's jet. Another double jet model is proposed by Shi et al. [56] by additionally considering variability in radio and "double minimum" in the optical data. They interpret the double-peaked flares to the synchrotron emission from the double helix jet, which appears partially merged at radio, giving rise to a broad temporal profile in radio bands.

The most recent and detailed models in the series of geometrical interpretations are by Britzen et al. [47] and Qian [48]. Britzen et al. [47] found a  $\sim 22$ -yr periodicity in the morphological features of the parsec-scale jet. Assuming no abrupt changes in these kinematic features, they interpreted both the recurrent outbursts in optical and radio bands to Doppler boosted jet emission as a result of precessing and jet rotation. They further argue that a binary system is not needed and even a precessing accretion disk can generate the jet precession. Qian [48], on the other hand, showed that the trajectories of superluminal radio knots seen at 15 GHz and 43 GHz can be explained in a binary SMBH scenario with both SMBHs having precessing jets. Using the correlation between OJ 287 high activity and ejection of superluminal knots, Qian [48] further showed that the QPOs can be explained by the motion of a few of these knots. A completely different interpretation for the recurrent outbursts is proposed by Villforth et al. [57] from the study of optical photopolarimetric properties from 2005 to 2009. They attributed the observed features to the 'magnetic breathing' of the disk causing accretion of magnetic field lines and claimed that there should be no more such outbursts in the future.

As stated above, OJ 287 is a very dynamic source and the diversity of peculiar features have made it the best-monitored BLL blazar over a wide range of scales in all the domains of observation e.g., spectral: [27,28,39,59,60]; temporal: [2,43,59,61–64]; imaging: [4,65]; polarization: [59,66–68] on the aspects of jet, accretion physics, and a test of the general theory of relativity. Below, we list different observational facets of the source from the literature in each of the domains and inferences from these. It should, however, be noted that for some of the domains there is no clear boundary due to the method of detection used in some of the energy bands (e.g., radio measurement are primarily imaging and thus observation at different epoch provide temporally-sequenced data, thereby mixing the two). Furthermore, the list of literature cited/mentioned in the context of observational features is neither exhaustive nor complete, but rather a practical consideration. In addition to citing studies reporting new features/properties and/or performing extensive analysis, we have followed a simple guiding principle where only references with earliest and latest observations are mentioned if the reported features/properties are similar.

## 2.1. Spectral

The general broadband SEDs of the source is typical of LSP/LBL subclass of blazars with emission up to GeV energies [1,28]. Reported SEDs suggest the low-energy component peak at  $\lesssim$  NIR bands and  $\lesssim$  100 MeV for the high-energy component [1,28,59]. Thus far, no shift in the location of the peak of the low-energy component has been observed, though additional emission component, similar to an HBL SED [27] was recently seen during its first-ever reported VHE activity [69]. Studies in different energy bands at different flux states of the source, however, have reported a wide variety of spectral features.

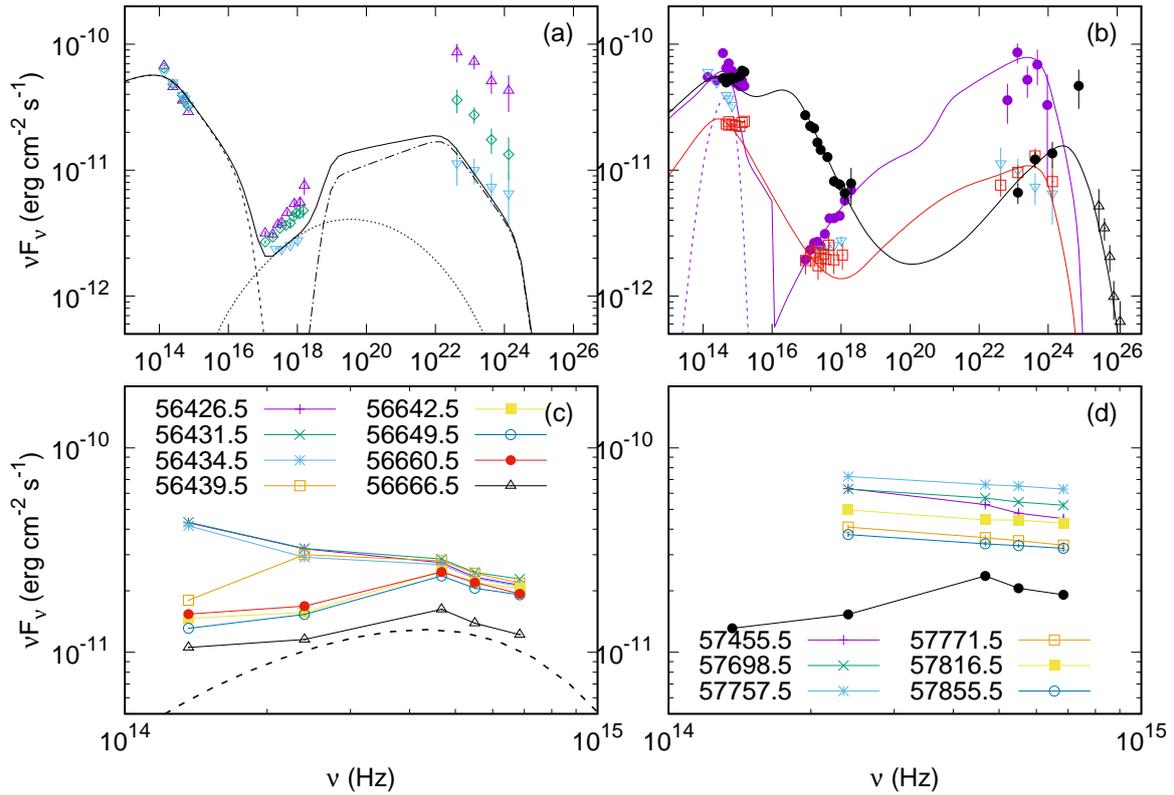
At radio centimeter wavelengths, it shows a convex (positive curvature) spectra [33], typical of the synchrotron self-absorbed quasi-stellar sources. This changes to power-law spectra representing optically thin synchrotron emission at mm wavelengths [35,70]. At NIR-Optical-UV energies, reported spectra can be separated into two groups. The first group corresponds to the duration before mid-2013 (MJD < 56,439) when data in these bands are smoothly connected, irrespective of the source flux state and occasionally show hints of smooth curvature at either or both ends [28,30,35,39,59,63,66,70–72]. This includes spectra measured during the epochs of outbursts claimed to have a thermal origin in the binary SMBH model of Lehto and Valtonen [44]. All these are consistent with synchrotron emission from a power-law particle distribution. From mid-2013 (May 2013, MJD 56439, Figure 1c) until February 2016 (MJD~57455; Figure 1d), a spectral break was observed at the junction of the NIR-optical region [60]. After February 2016, it again returned to its typical pre mid-2013 spectral state.

In contrast, at X-ray energies, it has been observed with most of the major X-ray facilities and has exhibited drastic spectral variations compared to the other EM bands. The observed spectra cover all the possible spectral phases. In addition to its typical LBL spectra described by a power-law photon spectral index of  $\Gamma \sim 1.5\text{--}1.7$  ( $f_\nu \sim \nu^{-\Gamma}$ ; [28,30,60,73,74]), it has shown a flat ( $\Gamma \sim 1$ ; [27,28,63,75]), extremely soft ( $\Gamma > 2$ ; [27,69,73], and references therein) as well as mixture of these [27,74,76]. Interestingly, most of the extremely soft spectral state seems to have been around (within a few years) the period of optical outbursts claimed to be thermal bremsstrahlung emission [44,77]. The latest steep X-ray spectral state was seen during the VHE activity of the source in 2017 [69] which also corresponds to the highest-ever reported X-ray emission from OJ 287 ([27], and references therein).

Spectral inferences at gamma-rays before *Fermi*-LAT have only been indirect. A probable detection was claimed in the *Compton Gamma-Ray Observatory* (CGRO) energy band on board the *EGRET* during a high optical state of the source in 1994 [75]. Though photon statistics prevented spectral analysis, it was argued to be in a “hard” state based on the number of detected GeV photons. In the *Fermi*-LAT era, on the contrary, it is one of the bright MeV-GeV sources detected in the first three months of its operation with spectrum being consistent with a power-law profile [1]. Up to now, all the reported MeV-GeV spectra before its latest activity starting November 2015 show a power-law [28] profile and suggest an SED peak at  $\lesssim$  100 MeV. The November 2015 MW activity revealed a hardened MeV-GeV spectrum with a shift in the HE SED peak and is yet to revert to its generic form as per the latest records [27,60,69]. It also registered its first VHE activity [69] in 2016, accompanied by a change in MeV-GeV spectral state which is consistent with the extrapolated VHE spectrum [27]. The VHE activity was a transient phase, lasting about six months with source HE spectrum being of an LBL+HBL source [27]. Following this, OJ 287 has been added to the TeV source catalog<sup>4</sup>. A snippet of different spectral states exhibited by OJ 287 is shown in Figure 1.

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<sup>4</sup> <http://tevcat.uchicago.edu/>.



**Figure 1.** Broadband and optical SEDs showing the spectral phases exhibited by OJ 287 to date. (a) Typical broadband SEDs of OJ 287 from a 2009 observation [28] showing three different flux states: Flare (magenta, MJD: 55124–55131), moderate (green, MJD: 55131–55152) and quiescent (cyan, MJD: 55152–55184) MW emission. The solid curve is the total emission with synchrotron, SSC and EC-IR component shown respectively in dashed, dotted, and dot-dashed curves (see [28], for modeling details). (b) Broadband SEDs of the source in its new spectral phase during 2016–2017 with magenta (MJD: 57359–57363; [60]) showing a flare SED, black (MJD: 57786; [27]) showing a typical SED during the VHE phase and red (MJD: 57871; [27]) showing the quiescent SED state after the VHE activity with the lowest flux across EM spectrum. For reference/comparison, the quiescent SED (cyan) from panel (a) is also shown. The solid curves are the model produced spectrum (see [27,60], for details), while the dotted curve is the standard accretion-disk spectrum of a  $\sim 10^{10} M_{\odot}$  SMBH; (c) NIR-optical spectrum highlighting the timing of the appearance of spectral break [60]. The dashed curve is the accretion-disk spectrum drawn again for clarity. (d) NIR-optical SEDs before (MJD 57455.5), during and after the VHE activity of OJ 287, showing return to the typical power-law NIR-optical spectrum. For comparison, one of the SED (black) from (c) is also shown.

## 2.2. Temporal

OJ 287 has shown variability on all time scales (e.g., minutes-to-hours: [59,78], days: [28,59], months-to-years: [41,59,62], decades: [43,61]) across the entire electromagnetic spectrum (e.g., [27,28,60,70]). On short time scales ( $<$  months), it normally exhibits variation from NIR to MeV-GeV  $\gamma$ -ray energies which have been simultaneous within the observational cadence (e.g., [27,28,60]). An exception to this was the August 2016–July 2017 (MJD: 57600–57950) period when simultaneous variation was seen only at optical to X-rays energies but statistically no variability at Fermi-LAT energies [27].

Over long term, MW variations, in general, are more pronounced at optical energies than X-rays but show no relation/pattern between the two [63]. In the Fourier domain, MW variations show flicker/colored-noise spectra on all timescales with  $\gamma$ -ray variation being different from the others. Statistical analyses of the radio to X-ray light curves show colored-noise power spectral densities

(PSDs) for all and are consistent with each other. Gamma-ray time series from LAT, on the other hand, shows both white and color noise PSD with the transition occurring on a timescale of 150 days [2]. Apart from stochastic variations, OJ 287 has also exhibited (quasi) periodic modulation and, in fact, is the only blazar/AGN with the most numerous claims of QPOs of different duration in different energy bands e.g., optical:  $\sim 40$  min [41,79], 40–50 days [80],  $\sim 400$ -days [81],  $\sim 11.65$  years [43,47]; radio:  $\sim 16$ min [82], 1.12 up 6–7 years ([47], and references therein).

### 2.3. Imaging

At radio wavelengths, OJ 287 exhibits a one-sided jet with complex patterns on parsec [65,83] and kilo-parsec scales. Morphologically, it appears as an FR I source but energetically exhibits an FR II power. On Very Long Baseline Array (VLBA) resolution scales, it presents very complex dynamical patterns [65] with a core–jet structure [83,84], changes in jet position angle as well as overall morphology on parsec scales [65,67,84]. A study of kinematic features by Tateyama and Kingham [84] at 8 GHz has reported a clockwise change of  $\sim 30^\circ$  in jet position angle and argues for a ballistic precessing jet for this while Agudo et al. [65] have reported a sharp swing in jet position angle by  $> 100^\circ$  within the 0.4 mas ( $\sim 1.8$  pc) inner region between 2004–2006 at 43 GHz. Based on structural changes Agudo et al. [65] have instead argued for an erratic wobbling of the jet along with superluminal motions in non-radial directions. The Cohen [85] and Britzen et al. [47] study of VLBA observations at 15 GHz, on the contrary, argues for a precessing jet with a period of  $\sim 30$  years and  $\sim 22$  years, respectively. From the analysis of the ridgeline of contours, the former has argued the jet to be a rotating helix. In contrast, a reanalysis of the same by data Britzen et al. [47] in combination with other observations have reported additional yearly variations under the assumption that observed changes are smooth. Based on these morphological changes, Britzen et al. [47] have favored a precessing jet for the cause and claims that this can explain both radio and optical variations within this framework. Correlation studies between mm radio time series with other bands (optical to  $\gamma$ -rays) have found a strong connection between these during the high activity periods with the increased activity associated with radio-flaring in quasi-stationary features and ejection of superluminal features [86,87].

At X-ray energies, deep exposure with the *Chandra* observatory shows a curved jet with a de-projected extension of  $> 1$  Mpc and many bright X-ray knots/hot-spots. The location of these knots are consistent with the radio ones but follow a complex brightness profile while only the bright core is visible at NIR-optical energies [4]. Claims of detection of the host galaxy, so far, have been ambiguous [88,89] but argued to have an optical-V band magnitude of 18 ([90], but see also [91]).

### 2.4. Polarization

Like the other domains of observation, in polarization too, OJ 287 exhibits frequent and high variation in the degree of linear polarization (PD) as well as electric vector polarization angle (EVPA) at radio (e.g., [67,86]) and optical energies [59,62,66,78]. The reported PD range spans  $\sim 0$ –40% at optical,  $\sim 1.5$ –20% at IR [42,78,86] and  $\sim 0$ –30% at radio (e.g., [86]) while PA changes of up to  $\sim 250^\circ$  have been observed (e.g., [59,78]).

A detailed study by Villforth et al. [57] has reported a preferred direction for optical EVPA which is consistent with the radio measurements. They successfully decomposed the EVPA variations and found that the preferred EVPA is due to the optically polarized core which is variable on timescales of a year with a chaotic jet component superimposed on it. Similar PA in radio and optical has also been reported by Sasada et al. [92] from the analysis of quasi-simultaneous radio and optical observations. Holmes et al. [42] have reported a complex variation of polarization showing variation with time as well as frequency (energy). Contrarily, a close synchronous change of optical and radio polarization has also been observed (e.g., [68,93]). Though generally optical PD follows the source flux state, systematic to chaotic and then back to systematic changes in fractional Stoke polarization during high flux states has also been observed [66]. A study of EVPA time series by Cohen et al. [67] over 40 years, assuming smooth changes, has found four rotation reversals in EVPA:  $\sim 180^\circ$  anti-clockwise swing followed by

a clockwise swing by the same amount. The swings have taken place over timescales of a few weeks to a year.

### 3. Discussion

The observational results listed above clearly demonstrate that OJ 287 is a very dynamic BLL object with activity over vast scales and across the observational domains. Except for a few rare cases, these results, in general, appear to be random events without any connections, reflective of stochastic variations of blazars as well as the lack of a comprehensive jet theory. Additionally, it also highlights the complexity of exploring nonlinear dynamics involving a multitude of scales both theoretically and observationally (e.g., [94]). The best example of this complexity in the present case can be understood from studies of source with VLBA. The Agudo et al. [65] study of 1995–2011 radio images at 43 GHz argues for an erratic jet variation. On the contrary, an analysis of 15 GHz VLBA images between 1995–2017 by Britzen et al. [47] have reported a periodicity of  $\sim 22$  years assuming that observed changes are smooth while Cohen [85] have argued a periodicity of  $\sim 30$  years using the same 15 GHz images but between 1995–2015 and employing ridge-line contours as an observational indicator. Thus, given our current understanding of AGNs constituents, their energy-dependent emission, and observational indications of a multitude of scales, both long and short term monitoring across the EM bands is essential to unravel the various facets and the source as a whole.

As stated already, the  $\sim 12$ -yr QPOs have been one of the most explored features of the source. Regarding the two class of models/interpretations for the  $\sim 12$ -yr QPOs, the model of Lehto and Valtonen [44] which attributes the outbursts to thermal bremsstrahlung emission as a result of disk-impact is dynamical and predictive (the timing of the outbursts). Thus, the predicted timing of the outbursts, separation between the two outbursts, optical PD (unpolarized), and outbursts' temporal profile can be compared with observations (e.g., [62,77,95]). Though it predicts the outbursts to be unpolarized, given the underlying jet emission, PD is expected to be systematically low compared to its state before the outburst. From the timing of these outbursts [61], the model derived SMBH masses are  $1.83 \times 10^{10} M_{\odot}$  and  $1.5 \times 10^8 M_{\odot}$  for primary and secondary, respectively [62,77,96]. The extreme mass of the primary, inconsistent with estimates from other methods (e.g., [47], and references therein) is, in fact, the biggest criticism of this model. The alternative interpretation i.e., the geometrical class of models attributes the QPOs to Doppler boosted jet synchrotron emission resulting from the jet precession (e.g., [46–48,54,56]). Furthermore, geometrical models are kinematic in the sense that they are mainly concerned with reproducing the QPOs and lack any predictive power of the timing of these outbursts. These models mainly argue the central engine mass in the range of a few  $\times (10^7 - 10^9) M_{\odot}$  [47,48,56]. However, it should be noted that the system mass in these models is not dynamically connected with the model parameters and has been mainly inferred or argued using other observations ([47,56], and references therein). Thus, if the geometrical interpretation is true, the outbursts should be, in general, highly polarized. In addition, there should be a coherent simultaneous rise of emission across the EM spectrum with similar temporal profiles. An important caveat in this interpretation, however, is that even jet emission has been observed to show low PD during flares and thus needs statistically relevant polarization data to test either class of models. Additionally, OJ 287, being a BLL object, knowing the expected time of outburst allows for a targeted observation campaign to study HE emission mechanisms—one of the focuses of intense research in the blazar community in the *Fermi* era. In the context of these two, the MW observation of the 2015 outburst provides new, independent clues as argued below.

As per the prediction for the 2015 outburst in the disk-impact SBBH model November 2015–January 2016 [97], an outburst with the expected signature—flux peak coincident with a dip in the PD ( $< 10\%$ ; [62,78]) and broadly following the expected temporal profile of a sharp rise followed by a slower decline with multiple smaller outbursts was observed on 5 December 2015 (MJD: 57361; [45,62]). Additionally, a coincident large systematic swing of  $\sim 200^{\circ}$  in the optical EVPA was also observed, similar to the EVPA swing during the 1994 outburst [59]. The most important point about 2015 outburst,

however, was that it was the first QPOO with a true broadband coverage from radio to MeV-GeV energies, thanks to the *Fermi*. Previous observation by *CGRO* of the 1994 outburst only claimed a probable detection in a “hard state” without any spectral study [75] while 2007 observations by the VHE facility *MAGIC* resulted in only an upper limit [30]. A detailed systematic study of broadband activity around the 2015 QPOO by Kushwaha et al. [60] reported rise/outburst at X-ray and MeV-GeV energies as well. The observed MW variations were typical of the source and showed simultaneous variability from NIR to  $\gamma$ -ray energies [60], but broadband SEDs revealed a new spectral state of the source characterized by a break in the NIR-optical SED and a hardening of MeV-GeV emission with a shift in its peak emission. Further spectrottemporal analyses revealed that the NIR-optical break first appeared on 27 May 2013 (MJD 56439) within the available NIR-optical data and is fairly well constrained in the sense that records just before this i.e., MJD 56434 and before do not show such spectral break. It should, however, be noted that the data gaps before and after MJD 56439 do not allow for tracking the spectral evolution, which at first sight appears as though the spectral break is due to drop off of the two data points (J & K bands; ref Figure 1c). In fact, a power-law spectrum from these two data points already hints at a marginal excess even before MJD 56439 but is unreliable given low-energy hump peaks near these energies and may wash out the intrinsic spectrum due to smoothing by change in the spectral shape.

As for spectral changes and HE emission is concerned, multiple explanations have been proposed. Kushwaha et al. [60] showed that an EC-BLR reproduces the MeV-GeV emission while NIR-optical break nicely fits the description of a standard disk emission of a  $\sim 10^{10} M_{\odot}$  SMBH (refer to Figure 1b). Subsequently, Qian [98] argued that NIR-optical break is actually a shift in synchrotron peak and is in tune with the shift observed in HE SED peak while Oikonomou et al. [99] has proposed a hadronic scenario for the MeV-GeV. However, as shown in Kushwaha et al. [100], the SED corresponding to the impact flare has similar NIR and X-ray emission and lacks any spectral change vis-à-vis 2009 jet SEDs [28]. This rules out Qian [98] interpretation and also the previous EC-IR explanation for the MeV-GeV emission [100]. The hadronic model, on the other hand, mainly focuses on the interpretation of the MeV-GeV emission and the NIR-optical break remains unexplained. The optically thin bremsstrahlung emission from a 25 eV thermal plasma responsible for QPOOs, as argued in Valtonen et al. [101], is also not consistent with the NIR-optical break, though it may have a sub-dominant contribution. Optically thin bremsstrahlung emissivity has a spectral index of  $\sim 0$  ( $F_{\nu} \sim \nu^{-a}$ ). Thus, in the blazar SED representation ( $\nu F_{\nu}$ ), it will have a spectral index of  $\sim -1$ , contrary (rising) to the observed optical-UV (declining) SED (e.g., see [96]). At most, the maximum possible contribution can be the lowest flux value observed in the NIR-UV bands i.e., UVOT-w2 band ( $1.5 \times 10^{15}$  Hz). With this, the flux contribution at NIR-optical junction ( $\sim 10^{14}$  Hz) will be an order of magnitude below the UVOT-w2 band, contrary to the observed SED (see Figure 1b). Furthermore, for IC, bremsstrahlung (and accretion-disk) photons energy density will appear de-boosted by a factor of the square of the bulk Lorentz factor ( $\Gamma$ ) of the emission region. In addition, the IC spectrum peak ( $\nu_p$ ) will be at  $\nu_p = \delta / (1 + z) \gamma_b^2 (\nu^* / \Gamma)$ , where  $\delta$  is the Doppler factor,  $\gamma_b$  is the Lorentz factor corresponding to the break in a broken power-law particle distribution normally assumed to model blazars SEDs,  $z$  is the source redshift, and  $\nu^*$  is the frequency at which the seed photon spectrum peaks (e.g., [28]). Using  $\nu^* \sim 7.2 \times 10^{15}$  Hz from eq 68, Pihajoki [95] results in  $\nu_p \sim 2.2 \times 10^{22}$  Hz assuming  $\delta = \Gamma$  and  $\gamma_b = 2000$  [28,60] while the observed HE SED peak is at  $\sim 10^{24}$  Hz [60]. An additional clue against a dominant contribution of bremsstrahlung photons in IC is that the MeV-GeV spectral profile remains as it was during the 2015 QPOO [27] even after the disappearance of the NIR-optical spectral break around 3 March 2016 (MJD 57455; Figure 1d).

Among the discussed HE emission mechanisms, the EC-BLR explanation seems the best description in the view of the observational records in the literature during the previous QPOOs. The interpretation is consistent with the detection of broad emission lines during the previous cycles (1984, 2005–2008) of the  $\sim 12$ -yr optical outbursts as well as the strong changes observed in its level of emission [102]. Thus, if we combine the current EC-BLR origin of MeV-GeV emission [60] with the previous EC-IR [28]

and the inability of SSC to reproduce the X-ray and  $\gamma$ -ray emission [28,30], these results imply that in OJ 287 the MeV-GeV emission is due to EC, both on long and short timescales. Additionally, this also provides the first clear observational evidence on the ongoing debate of the location of the blazar zone at sub-parsec and parsec scales. Furthermore, if we extrapolate current inferences of OJ 287 HE emission with inferences from the modeling of neutrino event SEDs of blazar TXS 0506+056 [26], it seems that MeV-GeV emission in all blazars is likely IC in origin i.e., leptonic in origin.

The 2015 QPOO was followed by yet another new and peculiar MW activity, as reported in detail by Kushwaha et al. [27]. It started almost immediately after the settling of the activity associated with the December 2015 outburst. The source was found to be in a historic high state in X-rays and was contemporaneously detected at VHEs [69]. The systematic study of broadband SEDs presented by Kushwaha et al. [27] established this to the presence of an additional HBL emission component with the low-energy component peak in the UV-soft-X-ray region. They further showed that the broadband SEDs are broadly consistent with a two-zone leptonic model with one emitting the typical OJ 287 emission with the modified MeV-GeV spectrum and the other an HBL spectrum. An important aspect during this activity was the further hardening of the MeV-GeV gamma-ray spectrum compared to the previous December 2015 activity and also a change of fractional polarization from systematic to chaotic and then back to systematic trends [66].

The interpretation of the NIR-spectral break with an accretion disk emission has direct implications on the ongoing debate over the central engine of OJ 287. The consistency of the spectral break with an accretion disk spectrum of a  $\sim 10^{10} M_{\odot}$  SMBH provides independent evidence from the energy-spectrum domain in favor of the disk impact SBBH model, which is based solely on the QPOOs timing [62]. Additional strong evidence in its favor is the close coincidence between the time of appearance of the spectral break in May 2013 (MJD 56439) and the impact time predicted by the model in the SMBH frame [77]. This is in stark contrast with the geometrical class of models which argues for a total system-mass in the range of  $\times(10^7 - 10^9) M_{\odot}$ . However, the geometrical models are still plausible as the system-mass is not dynamically related to the model parameters. Thus, precessing jet models with a total central-engine mass of  $\sim 10^{10} M_{\odot}$  are still consistent with the currently available data/results [60] in the view of the lack of statistically relevant polarization information. The biggest challenge with geometrical models, however, is their failure to explain the sharpness of the outbursts [45]. Thus, if the geometrical interpretation represents the real physics behind the phenomena, the sharpness of profile during the recurring outbursts would indicate some special physical processes happening during these repeating outbursts e.g., [48]. Another result contrary to the geometrical class of models is the lack of a similar temporal profile at radio and optical [47].

The peculiarity and uniqueness of the  $\sim 12$ -yr QPOOs are further supported by the X-ray records in the literature during and around these outbursts. Though the concurrent NIR-optical observations during the previous cycles of  $\sim 12$ -yr QPOOs do not show any spectral break [39,59,71], an extremely soft X-ray spectral state seems to be a generic feature within the limits of observational records. It seems to be present within a few years around these optical outbursts and shows strong variations in spectral extent, strength, and the time of appearance [30,73] and references therein, thereby suggesting a relation between the two. The 2016–2017 MW activity showing an additional transient HBL component appears to be the continuity of this trend. The peculiarity of these QPOOs is also noted from time series analysis [47]. Finally, it should be noted that all the models are primarily based on the observed periodicity and none currently reproduce all the observational features seen during these outbursts e.g., Sillanpaa et al. [51]. The disk-impact model lacks proper accounting of magnetic field effects, which is essential for polarization properties. Though the phenomenological interpretation for the observed PD during the 2015 outburst in Valtonen et al. [62] seems justified, it lacks the explanation of the large systematic EVPA swing.

#### 4. Conclusions

The new spectral features seen during the 2015–2017 MW high activity of OJ 287 have provided some tantalizing, independent clues in settling two of the active ongoing debates on the source related to its central engine and MeV–GeV emission mechanism. Though different interpretations may be possible, the spectral coincidence of the NIR-optical spectral break with a standard accretion-disk emission of a  $\sim 10^{10} M_{\odot}$  SMBH and its first appearance in close coincidence with the impact time predicted by the disk-impact binary SMBH model in SMBH frame support/favor the disk-impact binary SMBH model over the geometrical class of models. However, geometrical models still cannot be ruled out confidently as the mass of the central engine is not dynamically tied with the model parameters and hence are still plausible within the limits of currently available observational data. In this case, the sharpness of QPOOs, as well as non-similarity of optical and radio time series, need an explanation. Future observations of these outbursts, particularly the duration between the twin outbursts and polarization, hold the key to breaking this degeneracy.

Similarly, the change of the MeV-GeV spectrum is reproduced by both hadronic and leptonic scenarios. The leptonic scenario via EC-BLR, however, seems natural, consistent with the detection of broad emission lines during the previous impact duration and strong changes in its luminosity [102]. This with the inferences from the systematic broadband SEDs modeling during its previous activity [28] implies that in OJ 287 the MeV-GeV emission is due to EC, both on long and short timescales. These results also provide the first clear evidence on the debate of the location of the blazar emission region at parsec and sub-parsec scales. The extremely soft X-ray spectral states around the QPOOs make it an ideal target for the Cherenkov Telescope Array (CTA)—the next generation, ground-based gamma-ray observatory.

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#### Abbreviations

The following abbreviations are used in this manuscript:

AGNs	Active Galactic Nuclei
BLL	BL Lacartae
BLR	Broad Line Region
CTA	Cherenkov Telescope Array
EVPA	Electric Vector Polarization Angle
FSRQ	Flat Spectrum Radio Quasar
HSP (HBL)	High-Synchrotron Peaked (High-Frequency Peaked BL Lac)
IC	Inverse Compton
ISP (IBL)	Intermediate-Synchrotron Peaked (Intermediate-Frequency Peaked BL Lac)
LSP (LBL)	Low-Synchrotron Peaked (Low-Frequency Peaked BL Lac)
MW	Multi-Wavelength
NIR	Near-Infrared
PD	Polarization Degree
QPO	Quasi-Periodic Outburst
QPOO	Quasi-Periodic Optical Outburst
SED	Spectral Energy Distribution
SMBH	Supermassive Black Hole
VHE	Very High Energy ( $E > 100$ GeV)

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