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ACTIVE GALACTIC NUCLEI

BL Lac object OJ 287: exploring a complete spectrum of issues concerning relativistic jets and accretion

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Abstract. BL Lacertae (BL Lac) object OJ 287 is one of the most dynamic blazars across the directly accessible observational windows: spectral, timing, polarization and imaging. Apart from behaviors, considered the characteristics of blazars, it exhibits peculiar timing features like quasi-periodicity in optical flux as well as radio-detected knots position and has shown diverse transient spectral features like a new broadband continuum dominated activity phase, Seyfert-like soft-X-ray excess, highly transient iron line absorption feature, a thermal-like continuum-dominated optical phase, large optical polarization swings associated with one of the timing features, etc., that are rare in blazars and contrary to currently prevailing view of BL Lacs. Theoretical considerations, supported by existing observations invoke scenarios involving a dynamical interplay of accretion and/or strong-gravity-induced events (tidal forces) in a binary supermassive black hole (SMBH) scenario to impact-induced jet and only jet activities. Many of these scenarios have some definite and quite distinctive observationally testable predictions/claims. These considerations make OJ 287 the only BL Lac to have an activity phase with dominance related to accretion and/or accretion-perturbation-induced jet activities. We present a brief overview of the unique spectral features and discuss the potential of these features in exploring not only relativistic jet physics, but also issues pertaining to accretion and accretion-regulated jet activities, i.e., the whole spectrum of issues related to the jet-accretion paradigm.

Keywords. BL Lac objects: individual: OJ 287—galaxies: active—galaxies: jets—radiation mechanisms: non-thermal—gamma-rays: galaxies.

1. Introduction

Astrophysical jets are a highly collimated outflow of material/plasma and large-scale jets, extending far beyond the sphere of influence of the source, though scarce, are a relatively common phenomenon associated with accreting systems. They have been observed in astrophysical systems of all masses, from stars (e.g., Anglada *et al.* 2018), X-ray binaries (e.g., Tetarenko *et al.* 2016) to galaxies (e.g., Blandford *et al.* 2019). For a successful outflow, the ejected material must leave the gravitational influence of the source, and thus, jets associated with highly compact objects are relativistic, and observations report/indicate a diverse range of jets—mild to relativistic, (mostly) transient jets in micro-quasars (e.g., Tetarenko *et al.* 2016), persistent relativistic jets in active galaxies (AGNs; e.g., Blandford *et al.* 2019), and highly transient, but ultra-relativistic in gamma-ray bursts (GRBs; e.g., Granot & van der Horst 2014). The emission is also extremely diverse with both thermal and non-thermal components, often showing dynamic co-evolution at different activity phases. Although almost every aspect related to relativistic jets and accretion, from jet triggering mechanisms to acceleration of particles to relativistic energies and broadband emission is yet to be understood (e.g., Romero *et al.* 2017), the apparent exclusive association of large scale jets with accreting systems, nonetheless, strongly indicates accretion as a primary driver, while the observed diversity implies a highly dynamic and complex multi-scale physics. The other ubiquitous

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ingredient indicated by the observations is magnetic fields (e.g., Zamaninasab *et al.* 2014).

The central region incorporating accretion and jet launching is extremely compact such that even for the nearest sources with the best existing resolution, e.g., the event horizon telescope (EHT; Event Horizon Telescope Collaboration *et al.* 2019a), it is still beyond our resolution scale. This leaves only spectral, timing, polarization and imaging (to a limited extent; e.g., superluminal and large-scale features) as the direct ways to peek into these sources and derive/infer scales as well as dynamics. Thus, in this overall accretion-jet paradigm, sources where accretion-powered emission primarily dominates the observed features represent the one end and the ones where jet emission dominates represent the other end, while sources where both can be seen during some activity phases and evolve to either end of the spectrum are ideal for investigating and understanding the missing links.

The most powerful accretion-powered sources in the universe are active galactic nuclei (AGNs) and a small fraction of these, designated as radio-loud, hosts the most powerful, persistent large-scale relativistic jets. Blazar is the AGNs subclass in which a jet points nearly to the Earth. They emit a featureless continuum that spans the entire accessible electromagnetic (EM) spectrum from radio to GeV/TeV gamma-rays (e.g., Hayashida *et al.* 2015; Ahnen *et al.* 2018), characterized by a broad double-humped spectral energy distribution (SED) and high and rapid variability of continuum and polarization on all feasible timescales being probed so far (e.g., Goyal *et al.* 2018). They are the most powerful persistent broadband emitter in the universe, and the radiation in every energy band is dominated almost entirely by the jet emission except for a few exceptions (e.g., PKS 1222+216; Tavecchio *et al.* 2011; Kushwaha *et al.* 2014). Even for most of these exceptional sources, the jet emission outshines other emission features during the bright activity phases (e.g., 3C 454.3; Raiteri *et al.* 2007).

The dominance of jet emission in all the accessible EM bands makes blazars the ideal sources to explore, understand and characterize relativistic jet emission, thereby offering a direct peek into jet physical conditions and extreme physics. However, the outshining of other likely emission components—either galaxy or various ingredients of accretion also presents formidable challenges vis-a-vis comparative studies with other accretion-powered sources where both thermal widely accepted to be associated with accretion and non-thermal broadband emission taken as the signature of jet emission is seen. This limits us to far fewer options and primarily to statistical inferences from studies of a sample of sources for comparative views. However, more than often, the outcomes from different approaches are conflicting. For example, from a spectral point of view, blazars are considered extreme AGNs with the jet continuum dominating in entirety, while from a flux variability point of view over the long-term, they appear similar to other accretion-powered sources (e.g., Kushwaha *et al.* 2016, 2017). At short timescales (minutes to hours), the trends are unclear (e.g., Kushwaha & Pal 2020; Bhattacharyya *et al.* 2020). Similarly, for some blazars, spectral classification based on SED is very different from that of the kinematic studies at radio, e.g., OJ 287 (Hervet *et al.* 2016).

The observed behavior of blazars covers an enormous range in each direct observational windows—emission spread over the entire EM spectrum from radio to GeV/TeV gamma-rays ($\gtrsim$17–20 orders of magnitude), flux variability on minutes and even less to decades and more ($\gtrsim$6–7 orders of magnitude in timing; e.g., Goyal *et al.* 2018), polarization degree (PD) variation from 0 to 50%, while polarization angle (PA) rotation of 360° and more (e.g., Marscher *et al.* 2010; Kiehlmann *et al.* 2016) and jet extending from the unresolvable compact site, probably even compact than our Solar system up to galaxy cluster scales (Mpc) covering $\gtrsim$10–24 orders of magnitude in spatial scale (e.g., Uchiyama *et al.* 2006; Marscher & Jorstad 2011). The enormous range and the requirement of contemporaneous coverage across the EM bands not only posses apparently insurmountable challenges for observations, but also theoretical investigations, requiring prohibitively huge computational resources. Even for the best cases where, to a zeroth level, the problem can be reduced to one parameter for some specific issues, coupling it with radiation immediately makes the problem wide open with far too many parameters (e.g., Event Horizon Telescope Collaboration *et al.* 2019b).

Notwithstanding the resource issue, the continued push and dedicated efforts with studies exploiting simultaneous[1]/contemporaneous multi-wavelength (MW) data, mostly a Fermi observatory initiated effort,[2] has revealed multitudes of trends from widely different observations, exploiting widely different methodologies that are now considered characteristic features of blazars and have been exploited extensively to explore

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[1] Note ‘simultaneous’ here is a misnomer, but often used in the literature. Different sensitivities in different energy bands bar a truly simultaneous multi-wavelength observation.

[2] https://fermi.gsfc.nasa.gov/ssc/observations/multi/programs.html.

diverse issues concerning the jet physics (e.g., Joshi & Böttcher 2011; Potter & Cotter 2012; Böttcher *et al.* 2013; Finke 2013; Ghisellini *et al.* 2014; Marscher 2014; Zamaninasab *et al.* 2014; Petropoulou & Mastichiadis 2015; Zdziarski *et al.* 2015; Hervet *et al.* 2016; Ghisellini *et al.* 2017; Raiteri *et al.* 2017; Zhang *et al.* 2018; Boula *et al.* 2019; Gao *et al.* 2019; Liodakis & Petropoulou 2020; Rodríguez-Ramírez *et al.* 2021, and references therein). These trends/characteristic features include—primarily stochastic flux variability (e.g., Sobolewska *et al.* 2014; Goyal *et al.* 2018) and similarity of statistical properties with accretion-powered sources in general (e.g., Kushwaha *et al.* 2016, 2017; Sinha *et al.* 2018; Tavecchio *et al.* 2020), intranight variability (e.g., Shukla *et al.* 2018; Goyal 2021; Liu *et al.* 2021), a broad double-humped spectral energy distribution (SED) with a highly stable location of the two peaks despite strong variations in flux as well as in Doppler boost, superluminal bright features (e.g., Lister *et al.* 2013; Hervet *et al.* 2016), inverted/flat radio spectra (MHz–GHz), usually high PD during flares, etc. There are exceptions to all these, but only a few. Polarimetric studies though are not as exhaustive as temporal and spectral studies, but the RoboPol[3] led systematic studies have made invaluable contributions to the general polarimetric behaviors; indicating some trends in polarization, especially a slow PA rotation during the brightest gamma-ray flares (Blinov *et al.* 2018; Blinov & Pavlidou 2019 and references therein).

Given the extreme and apparently insurmountable requirements, variability in the directly accessible observables (spectral, flux, polarization and imaging) is the only way to explore, infer and understand these sources. Though blazars are now firmly well known for flux and polarization variabilities, concurrent strong spectral changes indicating new emission components or drastic change in the spectral state are extremely rare, seen only in a few of the blazars and that too for a relatively very short duration, e.g., Mrk 501 (e.g., Pian *et al.* 1998; Ahnen *et al.* 2018), 3C 279 (e.g., Hayashida *et al.* 2015), etc. On the contrary, OJ 287 is the only blazar currently with a history of strong spectral changes persisting for comparatively much longer duration ($\gtrsim$4-year; e.g., Komossa *et al.* 2017; Brien & VERITAS Collaboration 2017; Kushwaha *et al.* 2018a, b, 2021a, b; Kapanadze *et al.* 2018; Komossa *et al.* 2020; Prince *et al.* 2021a, b; Singh *et al.* 2022). It also has been claimed to show a few recurring timing features both in flux (Sillanpaa *et al.* 1988; Dey *et al.* 2018) as well as radio images (Cohen 2017; Britzen *et al.* 2018), which is contrary to the general stochastic flux variability. Additionally, a few of the recently reported/discovered spectral features challenges our widely accepted view of BL Lac sources, e.g., break in the NIR-optical spectrum from its well-known (smooth) power-law form indicating a thermal component (Kushwaha *et al.* 2018a; Rodríguez-Ramírez *et al.* 2020), Seyfert-like soft X-ray excess (Pal *et al.* 2020), a highly transient iron line absorption feature indicating relativistic outflow (Komossa *et al.* 2020). The plausible implications of these features encompass every issue from accretion dynamics to energization of particles to ultra-relativistic energies and broadband emission, as elaborated and discussed in the following sections.

Observationally, the biggest advantage in the case of OJ 287, however, is the close coincidence of the spectral changes with the ∼12-yr quasi-periodic optical outbursts (QPOOs) and, hence, the predictability of expected sighting of these peculiar features, making coordination of MW monitoring relatively much easier with drastically fewer efforts when viewed in the context of challenges that plague observations and studies of transients. As stated above and elaborated below, these make OJ 287 the only blazar with much broader potential compared to a chosen few—suitable for exploration of some specific aspects of jet physics. In the next section, we briefly present the reported peculiar observational features with some comments on the models of QPOOs. We then focus on the exhibited spectral changes and argues their potential in exploring aspects of accretion (based on proposed scenarios in the literature) and jet physics—emission mechanisms, location of emission region, particle spectrum and constraints on highest energies from the optical-UV spectrum, and an outline of how these inputs further allow probe of other issues of the jet-accretion paradigm in Section 3. We finally summarized and conclude in Section 4. For an overview of the general observation behavior of OJ 287 across the directly accessible observational windows, we refer to our previous work—Kushwaha (2020).

2. OJ 287

OJ 287 is a BL Lacertae (BL Lac) type object located at a cosmological redshift of $z = 0.306$ (Sitko & Junkkarinen 1985; Nilsson *et al.* 2010). The BL Lac designation is the AGN classification scheme based on the strength of emission lines with respect to the underlying continuum and is attributed to those showing very weak or a complete absence of emission line features (equivalent

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[3] https://robopol.physics.uoc.gr/.

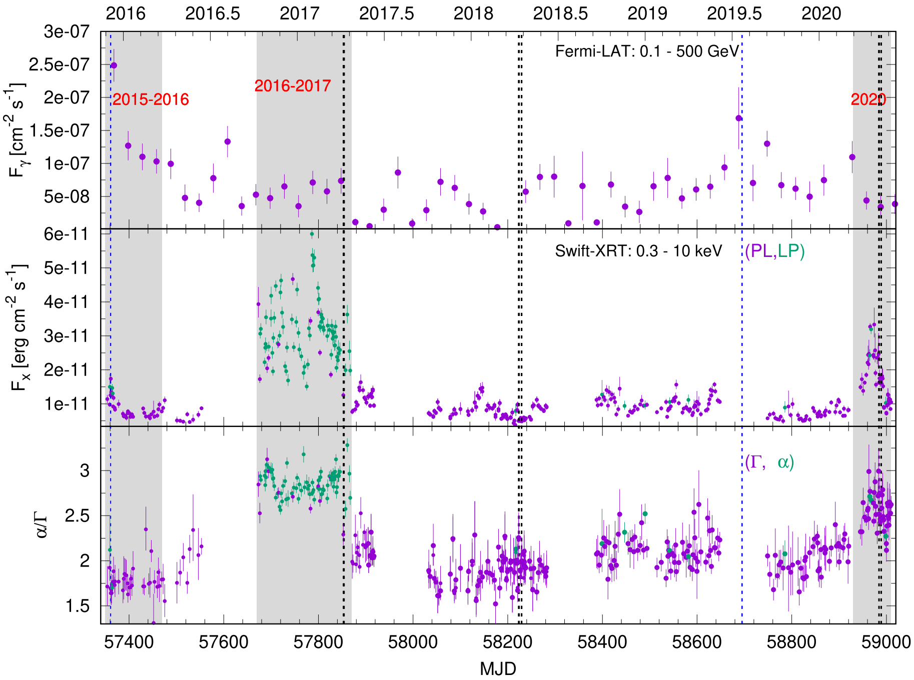

Figure 1. Monthly binned gamma-ray light curve from Fermi-LAT along with X-ray light curve and the corresponding best-fit spectral indices of OJ 287 from Neils Gherel Swift Observatory. The shaded regions mark the spectrally distinct high MW activity periods, while the non-shaded parts trace the spectral transition and its evolution. The blue vertical dashed lines are the claimed time of the impact flares (Valtonen *et al.* 2016; Laine *et al.* 2020), while the black vertical dashed lines represent long-exposure observations by the AstroSat (Kushwaha *et al.* 2021b; Singh *et al.* 2022).

width <5 Å; Stickel *et al.* 1991), but exhibits unusually high variations in both flux and polarization and have core-dominated inverted radio spectra. For OJ 287, emission lines have only been seen during its low optical flux states and these few observations suggest strong flux variations (Sitko & Junkkarinen 1985; Stickel *et al.* 1989; Nilsson *et al.* 2010; Huang *et al.* 2021).

OJ 287 is one of the best-explored sources, primarily due to its conducive location combined with observationally favorable features like high radio and optical brightness, highly dynamic and correlated MW variability, etc., making it the candidate source for characterization of the BL Lacertae class of sources (Sitko & Junkkarinen 1985). This in turn has culminated in one of the richest sets of data among blazars across the EM spectrum over a diverse range of timescales, taken either individually or in a coordinated fashion. Amongst blazars, it has the longest existing optical data going back to around 1890 (Visvanathan & Elliot 1973; Sillanpaa *et al.* 1988; Hudec *et al.* 2013).

In terms of blazars' SED-based classification, OJ 287 is categorized as a low-frequency/low-energy peaked blazar (Abdo *et al.* 2010). Early MW studies employing contemporaneous data do not show any appreciable change in the broadband SED state during high MW activity phases (e.g., Seta *et al.* 2009; Kushwaha *et al.* 2013). However, the MW activities since the end-2015 (e.g., Gupta *et al.* 2017; Kushwaha *et al.* 2018a) to date, turned out to be very different, especially in terms of spectral changes. An X-ray and MeV–GeV gamma-ray flux evolution of this duration, along with the best-fit X-ray spectral indices, are shown in Figure 1. Since X-ray spectra of OJ 287 have often shown a significant departure from a simple power-law description (e.g., Kushwaha *et al.* 2018a; Pal *et al.* 2020), we used both—a power-law and a log-parabola model, where the latter can capture this departure. The best-fit model was chosen on the basis of the F-test statistics. A strong spectral evolution at X-ray energies is visible in Figure 1 and the shaded regions mark these peculiar activity episodes.

MW data of the 2015–2016 activity revealed a sharp spectral break in the NIR-optical spectrum from its well-known (smooth) power-law form. A concurrent hardening of the MeV–GeV spectrum, as well as a shift in the location of the peak, was also observed (refer Figures 2 and 3; Kushwaha *et al.* 2018a). Soon after this, a new MW activity (Figure 1: 2016–2017) with strong optical to X-ray variations (e.g., Komossa *et al.* 2017, 2020; Kushwaha *et al.* 2018b) was reported, and detailed exploration revealed it to be due to the presence of a new additional HBL-like component (e.g., Kushwaha *et al.* 2018b, 2021a, b; Singh *et al.* 2022). This new state again reappeared (Figure 1: 2020) in a slightly weaker form in 2020 (Komossa *et al.* 2020; Kushwaha *et al.* 2021a; Singh *et al.* 2022). Furthermore, an absorption feature (highly transient) in the X-ray spectrum during the 2020 activity, (Komossa *et al.* 2020), a spectral cut-off in the high-energy end of the optical synchrotron spectrum during and after 2016–2017 activity (Kushwaha *et al.* 2021b; Singh *et al.* 2022) and a Seyfert-like soft X-ray excess before the 2015–2016 activity (Pal *et al.* 2020) have been reported.

Altough we have only recently had a quite dense follow-up of the ∼12-yr QPOOs across the EM bands, the close coincidence of the spectral changes reported above indicates a connection between the two. These provide strong constraints to the models proposed for the QPOOs when combined with the general behavior of the source as well as the BL Lacs. In short, based on the reported NIR-spectral break and its time of appearance, Kushwaha (2020) argues that Lehto & Valtonen (1996), see Dey *et al.* (2018) for the latest iteration of the model) model that invokes the impact of secondary SMBH ($1.5 \times 10^8\ M_\odot$) on the accretion disk of the primary ($1.8 \times 10^{10}\ M_\odot$) for the QPOOs is broadly favored over the simple jet precession interpretations. This and the claims of the high optical to X-ray MW activity driven by new HBL-like broadband as a likely tidal-disruption event (TDE; Huang *et al.* 2021) allows one to explore accretion and to a limit, connection with the jet in addition to the relativistic jet physics for which blazars are well known.

Regarding the ∼12-yr QPOOs, it should be noted that studies employing diverse and state-of-the-art timing methodologies (Goyal *et al.* 2018; Peñil *et al.* 2020) dispute the QPOO feature. However, observationally, flares in optical bands have been observed around the predicted times (Valtonen *et al.* 2016; Dey *et al.* 2018; Laine *et al.* 2020).

3. OJ 287 spectral changes: exploring jet-accretion paradigm in jetted-AGNs

BL Lacs show an entirely jet-dominated continuum and thus, they are widely accepted to lack the standard accretion disk and the putative IR-torus.[4] Hence, the sighting of a sharp break in the NIR-optical spectrum (relative to jet broadband emission; Kushwaha *et al.* 2018b, 2021a; Rodríguez-Ramírez *et al.* 2020) as well as a Seyfert-like soft X-ray excess (Pal *et al.* 2020), and the iron line absorption feature (Komossa *et al.* 2020) indicate OJ 287 as a peculiar BL Lac object. Such diverse spectral behaviors demand strong changes in physical conditions and an extremely efficient emission process with radiative output comparable to that of the jet/accretion.

3.1 *Accretion physics*

Figure 2 presents a glimpse of the diverse NIR-optical spectra exhibited by OJ 287. Panel (a) shows the NIR-optical spectra considered typical of OJ 287, (b) shows the sharp break between NIR-optical spectra—first reported by Kushwaha *et al.* (2018a), (c) shows yet unseen enigmatic variations in the NIR K-band data from the SMARTS facility, preceding the appearance of spectral break,[5] and (d) shows the broadband SEDs of a flaring and a quiescent (end) phase from the 2015 to 2016 MW activity. The NIR-optical spectral break is quite sharp ($\alpha_{\rm IJ}^{\rm max} \sim -2.5$; $F_\nu \sim \nu^{-\alpha}$) and is inconsistent with a (smooth) power-law shape, which is the typical spectrum of the source (as well as BL Lacs). Such a sharp break is indicative of a thermal feature—either thermal emission or a transition from optically thick to a thin emission regime. In addition, there is no indication of any shifting in the location of this spectral break throughout the activity period.

As stated above, the close coincidence of QPOOs and the spectral changes is indicative of a link between the two (e.g., Kushwaha 2020 and references therein)—also supported by limited records available in earlier studies (e.g., Isobe *et al.* 2001). Such strong spectral changes are inconsistent with the simple jet-precession scenarios (Britzen *et al.* 2018; Butuzova & Pushkarev 2020 and references therein) invoked for the QPOOs in which only achromatic flux boosting is expected without any spectral changes. If jet precession interpretation is indeed the case, it requires strong dynamical mechanisms with very efficient radiative output—like that of accretion or jet to account for these spectral features with dynamical forces peaking around the expected QPOOs to drive the spectral changes. On the other hand, the thermal-like NIR-optical spectral break (Kushwaha

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[4] Recently, Roychowdhury *et al.* (2021) reported an IR-torus for the first-time in a BL Lac source, but it is located at much longer distance from the central SMBH than the scale expected in the standard AGN paradigm.

[5] Variability is seen only in the SMARTS facility K-band data and is not in sync with variability seen in other NIR-optical bands and neither with the NIR data from INAOE, Mexico (Gupta *et al.* 2022) and thus, extreamly unusual. Further, it seems to persist for almost one season of observation from the SMARTS facility (MJD: ∼55500–55715).

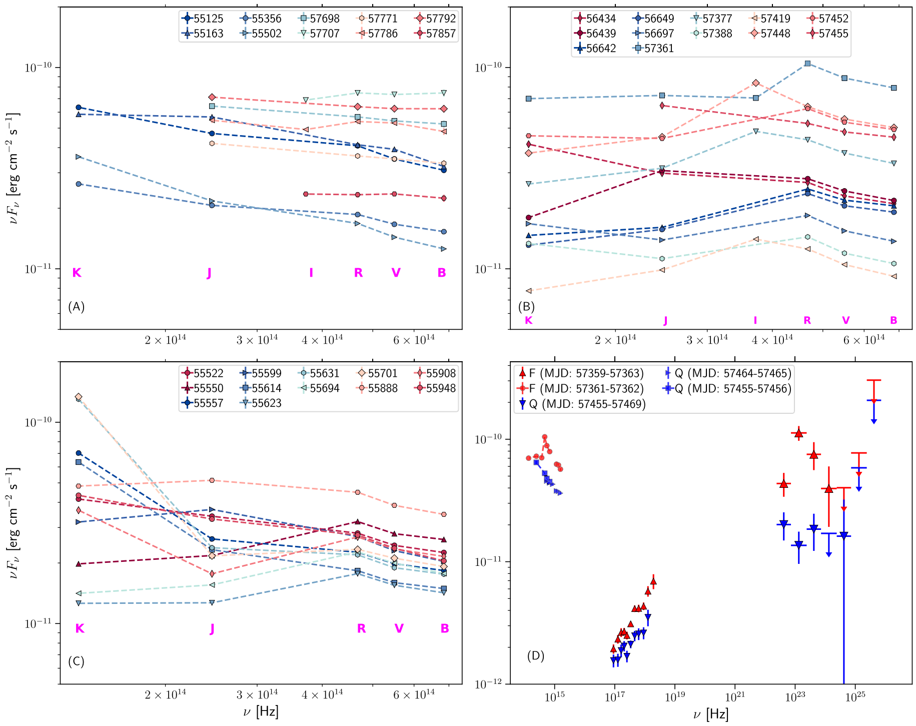

Figure 2. A glimpse of the diverse range of NIR-optical spectral states exhibited by OJ 287 to date. (A) NIR-optical spectra considered generic of the source—a simple power-law spectrum with/without smooth curvature at the either or both the ends. (B) Departure of the NIR-optical spectrum from its well-known simple power-law spectrum. (C) A strong odd variability only in the NIR-K band data from the SMARTS facility for an extended duration (MJD: 55500–55715), preceding the appearance of the NIR-optical spectral break. This is likely artificial as NIR data from INAOE, Mexico, do not support this (Gupta *et al.* 2022). (D) Broadband SEDs from a flaring (F) and a quiescent (Q) state of the source from its 2015–2016 activity. The flaring NIR-optical spectrum signifying why we termed the NIR-optical spectrum departure from a power-law form as break—too sharp compared to the general broadband spectrum of the source/blazars—closer to thermal emission spectrum (Kushwaha *et al.* 2018a; Rodríguez-Ramírez *et al.* 2020). Magenta colored labels (KJIRVB) in panels (A), (B) and (C) mark the optical-NIR filters.

et al. 2018a, 2021a), Seyfert-like soft X-ray excess (Pal *et al.* 2020), and iron line absorption feature (Komossa *et al.* 2020) are broadly consistent with the elements of the disk-impact BBH interpretation—the NIR-spectral break with a $\sim 10^{10}\ M_\odot$ SMBH accretion disk spectrum (Kushwaha *et al.* 2018a, 2021a; Kushwaha 2020) or even with the thermal bremsstrahlung (Rodríguez-Ramírez *et al.* 2020) proposition, while Seyfert-like soft X-ray excess (Pal *et al.* 2020) as well as iron absorption feature (Komossa *et al.* 2020), are expected in case of a standard accretion-disk and outflows. However, observations do not support the disk-impact model claim of bremsstrahlung as the driver of QPOOs and so do the optical polarization trends (Kushwaha 2020).

Another interesting spectral behavior related to the ∼12-yr QPOOs seems to be an extremely soft X-ray spectral state (Isobe *et al.* 2001; Komossa *et al.* 2017, 2020; Kushwaha *et al.* 2018b and references therein) with peculiar timing trends (Kushwaha *et al.* 2018b, 2021a; Komossa *et al.* 2020) and an HBL-like broadband SED (Kushwaha *et al.* 2018b, 2021a). Primarily, from the timing perspective, Komossa *et al.* (2021) claim this to be the impact-induced jet activity that is proposed in the disk-impact BBH scenario. It should, however, be noted that the broadband spectral state is very different (HBL-like) than the well-known LBL state to which the source belongs and the BBH model makes no comment on spectral state other than jet activity. On the other hand, recently Huang *et al.* (2021) claims this spectral state with associated peculiar timing feature as a tidal disruption event (TDE), likely associated with the secondary SMBH. These observations and the theoretical consideration make OJ 287, a unique laboratory to explore diverse aspects of not only extreme jet physics (refer Section 3.1.1), but accretion as well as the jet-accretion physics in jetted AGNs.

3.1.1 *Disk-impact binary BBH model vs. observations*

Though the disk-impact BBH interpretation is favored for the ∼12-yr QPOOs, both from timing, spectral and even polarization, many of the aspects are still ambiguous and contrary to the model claims. The foremost being the claim that thermal bremsstrahlung—an emission with a characteristically different spectral shape compared to the jet broadband emission (see also Kushwaha 2020) powers the QPOOs. The multi-band NIR-optical flaring spectra of 2005, 2006 and the most recent 2015 activities (Seta *et al.* 2009; Kushwaha *et al.* 2018a), however, do not support this interpretation (see also Valtonen *et al.* 2012). Additionally, the 2015 QPOO was the first flare with a true MW coverage from radio to gamma-rays and show not only optical outburst, but also flaring at X-rays and gamma-rays, indicating a non-thermal emission component. Not only this, the MeV–GeV spectra are also very different from the usual source spectra (refer Figure 2d; Kushwaha *et al.* 2018a).

Another perplexing feature is the large systematic optical PA rotation observed during the ∼12-yr QPOOs (Pursimo *et al.* 2000; Kushwaha *et al.* 2018a) despite a lower PD. In a thermal-emission-powered outburst, such a systematic PA swing is not expected in general. Further, neither the reported PD observations of all these QPOOs outbursts are consistent with being lower or close to zero (e.g., Seta *et al.* 2009) as expected for a thermal-emission-powered outburst. All these indicate additional dynamical processes in play. Note that a recent work based on this model by Dey *et al.* (2021) shows that the model can reproduce the radio PA swings. However, the one associated with thermal outbursts remains perplexing given the claim of thermal origin. The observation of the next predicted outburst in 2022 holds key to many of the features and further insight into the complexity of observed behaviors. Regarding the claim of the non-thermal soft-X-ray state (HBL-like component driven MW activities of 2016–2017 and 2020) as the impact-induced/triggered jet activity by Komossa *et al.* (2020) on the basis of timing perspective (both model and observational comparison with other sources), it should be noted that the timing comparison is drawn with respect to the optical outbursts that occur much later to the impact (e.g., ∼2.5 years for 2015 outburst)—once the claimed torn blob turns optically thin (Dey *et al.* 2018) and thus, taking QPOOs timing as a proxy for perturbations in disk seems unjustified in the context of comparison with other sources, where similar timing features have been seen.

3.2 *Jet physics*

The broadband emission and an enormous range of observed behaviors in all the observational windows are direct reflections/manifestations of extreme and highly dynamic physical conditions within the jet. These behaviors are directly related to the existence of ultra-relativistic non-thermal particles and the associated plausible emission channels. The former, in turn, is directly related to the interplay between magnetic fields and particles, while the latter is related to the matter constituents of the plasma—broadly whether primarily leptonic or hadronic or, if both, in what fractions.

Peeling the particle acceleration issue further down involves how the evolution and instabilities within the outflowing plasma led from (probably) magnetic dominated (e.g., Zamaninasab *et al.* 2014) to kinetic-dominated jet as indicated by SED modeling (Böttcher *et al.* 2013; Ghisellini *et al.* 2014). For the emission mechanisms, the fundamental issue remains is whether the high energy hump is primarily due to primary leptons—via inverse Compton scattering, or hadrons—primarily protons via proton-synchrotron and/or proton–proton, proton–photon-initiated cascades, and if both, the respective contributions' ratio (e.g., Romero *et al.* 2017; Murase *et al.* 2018; Gao *et al.* 2019).

The diverse range of broadband SED exhibited by OJ 287 (Kushwaha *et al.* 2018a, b, 2021a) provide potential constraints in exploring different emission scenarios—within standard blazar emission paradigm as well as scenarios inspired by QPOOs models. For the 2015–2016 broadband SEDs during quiescent and flaring part (refer Figure 1d), Kushwaha *et al.* (2018a) showed that overall emission can be reproduced in leptonic scenario, where the IC scattering of BLR photons (IC-BLR) is responsible for the hardening of MeV–GeV spectra and the shift of the high energy peak, while the NIR-optical spectral break can be reproduced by the standard accretion disk spectrum of a $\sim 10^{10}\ M_\odot$ SMBH in the flaring phase. In the quiescent case, the accretion-disk component is weakened (or disappeared) considerably that its no longer visible, while the IC-BLR component is weakened too—giving rise to a flat MeV–GeV spectrum. This interpretation is consistent with the report of increment of emission line strength during the previous cycle (2005–2008) of QPOOs (Nilsson *et al.* 2010 and references therein). Oikonomou *et al.* (2019), on the other hand, showed that MeV–GeV spectral hardening can also be reproduced in a hadronic scenario by $p\gamma$ channel. However, the NIR-optical break remains unexplained in the latter case.

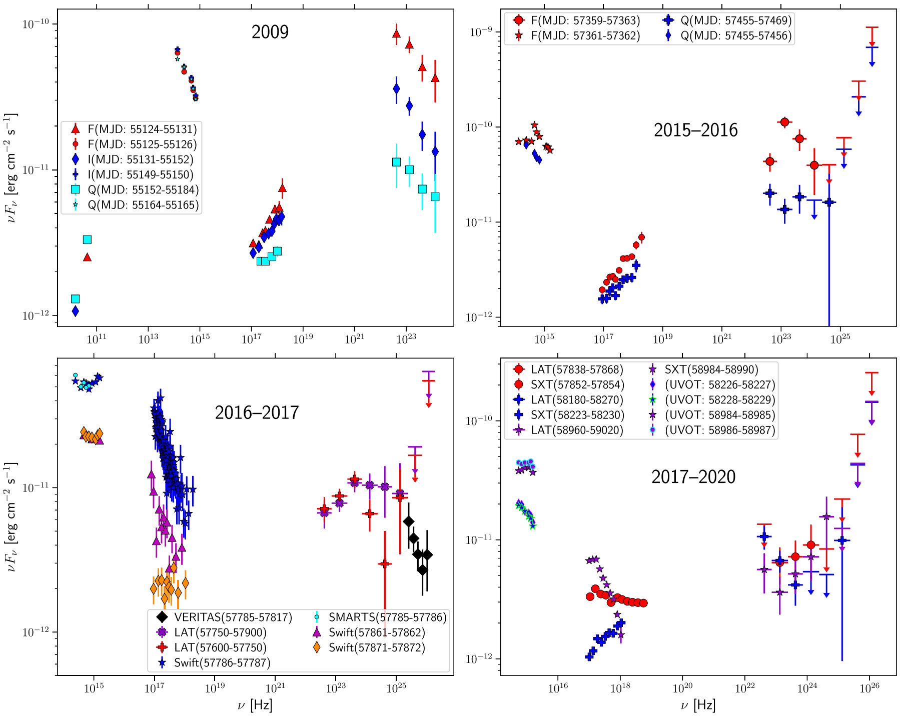

Figure 3. A plot summarizing the distinct broadband spectral phases exhibited by OJ 287. The year-label marked the calendar year of the broadband SEDs. The numbers in the parenthesis corresponding to the plot label are the MJD duration of the data from different facilities, while text F, I and Q refer to flaring, intermediate and quiescent MW flux state of the source. The plot labeled 2009 shows the broadband SEDs considered normal (LBL state) of the source (Kushwaha *et al.* 2013). The plot labeled 2015–2016 show the flaring and quiescent SEDs from the 2015–2016 MW activity (Kushwaha *et al.* 2018a). The 2016–2017 SEDs highlight the strong spectral changes in all bands from NIR-optical to MeV–GeV and VHE gamma-rays as a result of an HBL-like emission component (Kushwaha *et al.* 2018b), while the 2017–2020 show the source spectral state from disappearance of the HBL-like component in 2017-end to its reappearance in 2020 (Kushwaha *et al.* 2021b; Singh *et al.* 2022). The LAT spectra from 2015 onward have been re-analysed with Fermipy and reproduced here. The VERITAS VHE spectrum (Brien & VERITAS Collaboration 2017) has been corrected for EBL absorption following Domínguez *et al.* (2011).

In a completely different scenario inspired by disk-impact model of the QPOOs, Rodríguez-Ramírez *et al.* (2020) showed that the modified broadband SED with the NIR-optical spectral break and a hardened MeV–GeV spectrum can be self-consistently reproduced in a non-jetted disk-impact scenario via thermal bremsstrahlung and hadronic pp cascade, respectively. This is very different than the standard blazar hadronic emission scenarios, as it involves no boosting of emission. The model invokes outflows and is consistent with the report of absorption feature reported at X-ray energies (Komossa *et al.* 2020) as well as the Seyfert-like soft X-ray excess (Pal *et al.* 2020). Energetically too, the model fares better compared to blazar hadronic emission scenario due to the high density of thermal protons on account of the ejected optically thick blob that makes the pp interaction effective and thus requires lesser number of ultra-relativistic protons. In this scenario, it should be noted that the disk-impact BBH model predicts thermal emission only for the QPOO, (MJD 57361), while the NIR-spectral feature attributed to thermal bremsstrahlung in this model has been present much before (since MJD ∼ 56439; Kushwaha *et al.* 2018a; Kushwaha 2020).

For the broadband SEDs of the 2016–2017 and 2020 MW activities that show an additional emission component similar to HBL, Kushwaha *et al.* (2018b) have shown that the leptonic scenario can reproduce the overall spectrum. In this, the MeV–GeV is due to the combined effect of external Comptonization of IR photon and the synchrotron self-Compton component, where the latter is responsible for hardening of the MeV–GeV spectrum (see also Singh *et al.* 2022). The softening of the X-ray and the hardening of the optical-UV spectrum are due to the synchrotron emission of the HBL component that peaks at UV-soft X-ray region. The explanation is in line with the phenomenological explanation of the HBL sources and also the observational fact that the observed X-ray as well as EBL corrected very high energy (VHE) emission spectrum is similar to the low-state X-ray/VHE spectrum of the HBLs (Singh *et al.* 2022 and references therein).

Current studies and constraints suggest mainly a leptonic origin for GeV emission with a sub-dominant hadronic emission component (e.g., Murase *et al.* 2018; Gao *et al.* 2019; Oikonomou *et al.* 2019). In leptonic emission scenario, a highly contentious issue has been the location of the emission region, which is directly related to the soft photon field required for an effective inverse Compton scattering. From studies of the kinematics of superluminal and quasi-stationary features in radio along with correlation studies with gamma-ray, a parsec scale origin of the emission has been argued (Agudo *et al.* 2011; Hodgson *et al.* 2017). A similar inference is inferred from broadband SED modeling that requires an IR photon field (Kushwaha *et al.* 2013). More recent radio studies also indicate a systematic trend in quasi-stationary knots location (Britzen *et al.* 2018)—the claimed location of emission region or the blazar zone, over a year timescale. So if the knots are the location of high-energy emission, one expects an energy-independent flux variations and QPOs in all energy bands. Timing studies of the Fermi-LAT light curve (0.1–300 GeV) indicate a QPO (Kushwaha *et al.* 2020, but see Goyal *et al.* 2018; Peñil *et al.* 2020[6]), but low cadence observations in optical and X-ray bands do not allow such exploration without possible biases. These considerations combined with spectral properties allow one to locate the emission region that has direct implications on issues pertaining scales of energy dissipation and transformation, particle acceleration, etc.

On the spectrum and emitting particle spectrum front, blazars' broadband emission requires ultra-relativistic particle energies. Generally, it is believed to be a competitive interplay between the radiative cooling—the dominant loss mechanism and the acceleration process. Typical estimates of radiative cooling time scales suggest cooling timescales of a fraction of a minute (e.g., Kushwaha *et al.* 2014) indicating extremely efficient accelerating mechanisms and extreme physical conditions. Though time-dependent studies have broadened our general understanding of likely physical conditions (Marscher & Jorstad 2011; Marscher 2014; Zhang *et al.* 2014; Gao *et al.* 2019) and even attempts have been made to identify physical signatures of underlying acceleration processes (e.g., Zhang *et al.* 2018 and references therein) the issue remains the least understood. The diversity of the spectral changes reported in OJ 287 (Komossa *et al.* 2017, 2020; Brien & VERITAS Collaboration 2017; Kushwaha *et al.* 2018a, b, 2021a, b; Pal *et al.* 2020; Singh *et al.* 2022) and the densely monitored MW data combined with polarization properties (Valtonen *et al.* 2016; Gupta *et al.* 2017, 2019; Komossa *et al.* 2020) provide an excellent source to explore aspects related to particle acceleration processes, acceleration timescales, physical conditions, etc.

The other issue related to the emitting particle spectrum is the lowest and the highest achievable particle energies, i.e., the two extreme ends of the particle spectrum. In this direction, the diverse optical-UV to X-ray spectra of OJ 287 offer excellent inputs[7] (e.g., Figures 1, 3 and 4), especially the strong spectral softening/cut-off revealed by the long-exposure observation by AstroSat during a low X-ray flux state as reported in Singh *et al.* (2022) (see also Kushwaha *et al.* 2021b). Under the blazar paradigm, it provides a lower bound on the highest particle energies. The observation of steepening when combined with the general optical-UV and X-ray evolution of the source also establishes that most of the X-ray spectral change in the LBL state of the source is due to evolution of the synchrotron component (Singh *et al.* 2022), which is reflective of the strong evolution in the high-energy-end of the underlying particle spectrum. A similar spectral sharpening/cut-off can be inferred during the low X-ray flux phase of the HBL-driven MW activity from the spectral shape of the optical-UV and the X-ray spectra (Kushwaha *et al.* 2018b, 2021a; Singh *et al.* 2022). Interestingly, the onset of spectral steepening is almost at similar energies, indicating a similar acceleration process or even the same sites for both cases. What is further intriguing is that the cut-off is seen in the low flux state of the source. In general, if the radiative loss dominates over accelerating (and often used in the literature as a proxy for the highest particle energies, e.g., de Jager *et al.* 1996), the cut-off should be expected during the bright phases. This suggests that the spectral shape and energies are shaped primarily by the local conditions within the jet rather than by cooling alone. Not only this, the observation of HBL-like emission component in an LBL has implications for the blazar spectral sequence.

On the issue of jet-disk connection and the accretion-jet paradigm, the report of an additional HBL-like new broadband emission component (Kushwaha *et al.* 2018b, 2021a; Prince *et al.* 2021a) with peculiar timing properties (Kushwaha *et al.* 2018b, 2021a; Komossa

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[6] Used >1 GeV light curve.

[7] Gamma-ray too, but the weakness of the source do not allow short-time evolution history like those of optical to X-rays.

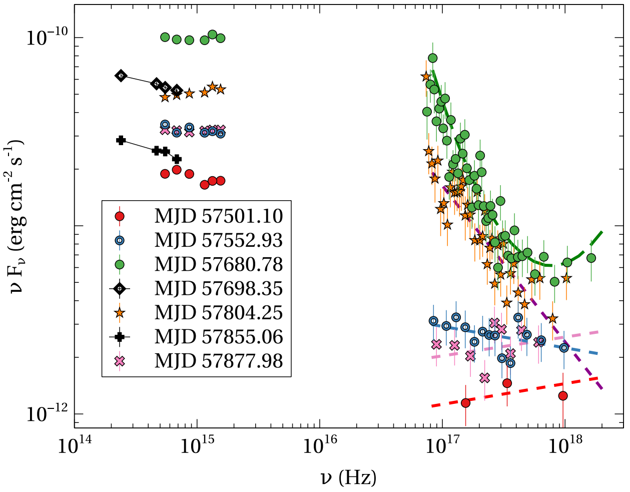

Figure 4. A peek into a sequence of diverse optical to X-ray spectral phases exhibited by OJ 287, highlighting the very dynamic and evolutionary nature of the source spectra. The optical-X-ray part is the direct tracer of evolution of the high-energy end of the particle spectrum.

et al. 2020) and claim of this as a TDE and/or disk-impact triggered jet activities offer a potential way to explore jet-disk connection issues, propagation and evolution, and much more.

In short, the multitude of observed features reported in OJ 287 across the directly accessible observational windows makes it the most promising blazar and jetted-AGNs to investigate not only jet physics, but accretion as well as accretion-regulated jet activities. The dense MW monitoring of the most spectrally dramatic activity between 2015 and 2020 when combined with time-dependent modeling and investigations, holds the potential to deepen our existing understanding. The source is now an EHT target, and the studies and MW observations are expected to significantly broaden our existing understanding.

4. Summary and conclusions

We presented a brief overview of peculiar features exhibited by OJ 287 since 2013 and implications in these contexts of the standard blazar emission paradigm as well as the scenarios motivated by the proposed model of ∼12-yr QPOO. A summary is as follows:

- The optical-NIR spectral break is too sharp when seen in the context of the well-known jet spectrum. Its timing and spectral shape broadly favor the disk-impact model over the simple jet precession scenarios. However, many of its predictions/claims are at odds with observations, e.g., the bremsstrahlung origin of flare and a simultaneous flaring at X-ray and gamma-rays, large systematic swing in optical PA for a thermal-emission-powered flare (the 2015 and outbursts), etc. Jet precession may be admissible, but, requires a dynamical model that may allow strong spectral changes.
- Jet precession inferred from radio knots' position and the claim of these knots as the origin of high-energy emission provide an additional way to constrain the location of emission region through correlated timing studies across the EM bands.
- The observation of sharp steepening of the high-energy-end of the optical-UV spectrum combined with the associated X-ray spectrum during a low-flux state of the source questions the often used assumption that constraining the highest achievable energy of the particle spectrum by equating to radiative losses. The finding rather indicates local jet conditions as the primary driver. This is also supported by similar steepening inferred for the low state of the HBL-like activity. The steepening also settles that most of the X-ray spectral evolution in the LBL state of the source is due to the synchrotron component, i.e., a direct reflection of the evolution of the high-energy end of the underlying particle spectrum.
- Broadband SED modeling of different spectral states and during different activity phases, supports the leptonic origin of the MeV–GeV emission with external Comptonization as the main driver. The explanation of SEDs of the 2015–2016 MW activity in a non-jetted hadronic scenario, supported by many observational clues, can be further tested with future observations.
- The consistency of many elements of the disk-impact model and the claim of an HBL-like emission component as TDE offer a potential candidate to explore accretion physics and jet-disk connection in addition to jet physics.

The MW observations of the expected 2022 QPOO hold additional clues and inputs on these issues. The diversity of observed peculiar behaviors/trends, their expected time of occurrence, and the implications of these on almost all issues pertaining to jet-accretion paradigm makes OJ 287 an ideal candidate for coordinated MW observations for further insight on the issues of complex accretion dynamics and jet physics.

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