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Multi-Wavelength Intra-Day Variability and Quasi-Periodic Oscillation in Blazars

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Abstract: We reviewed multi-wavelength blazars variability and detection of quasi-periodic oscillations on intra-day timescales. The variability timescale from a few minutes to up to less than a days is commonly known as intra-day variability. These fast variations are extremely useful to constrain the size of the emitting region, black hole mass estimation, etc. It is noticed that in general, blazars show intra-day variability in the complete electromagnetic spectrum. However, some classes of blazars either do not show or show very little intra-day variability in a specific band of the electromagnetic spectrum. Blazars show rarely quasi-periodic oscillations in time series data in optical and X-ray bands. Other properties and emission mechanisms of blazars are also briefly discussed.

Keywords: active galaxies; BL Lacertae object: BL Lac; quasars: flat spectrum radio quasars; jets, accretion disk

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1. Introduction

It is commonly accepted that super massive black holes (SMBHs, with masses between 10^6 and 10^{10} $M_\odot$ [1]) are present in the nuclei of all galaxies with stellar bulges. At any given time, a few percent of these SMBHs are fed with a sufficient amount of gas that they will possess significant accretion discs. The emission of these discs is comparable to the total emission of stars in the entire host galaxy because of a very high efficiency for the conversion of matter into radiation as it spirals into a BH. This is the fundamental mechanism underlying the "active galactic nucleus" or AGN.

Roughly 85–90% of AGNs have very little radio emission ($F_{5\mathrm{GHz}}/F_B \leq 10$, here $F_{5\mathrm{GHz}}$ = flux at radio 5 GHz and F_B = flux at optical B band 4400 Å) and are therefore called radio-quiet AGNs (RQAGNs). The remaining ∼10–15% of AGNs are radio-loud AGNs (RLAGNs). It has been proposed that different types of AGNs can be explained by the idea that different line of sight (LOS) angles can play an important role in understanding their different properties [2,3].

Blazars belongs to the RLAGN class, and their LOS is pointed close to the observer. Blazars show rapid variability at almost all wavelengths of the electromagnetic (EM) spectrum with the emission being strongly polarized (optical linear polarization ≥3%). Due to their strong and large amplitude variability nature in the complete EM spectrum, they are considered as transient astronomical objects. Blazars include two sub-classes: BL Lacertae objects (BLLs) and flat spectrum radio quasars (FSRQs). BLLs show featureless optical continua (no prominent emission or absorption lines), while FSRQs show prominent emission lines in their optical spectra. The radiation from blazars is dominated by non-thermal emission at all wavelengths, consisting of two broad spectral bumps [4,5]: a low-frequency component from radio to the UV or X-rays, generally agreed to be due to synchrotron radiation from relativistic electrons in the jet, and a high-frequency component from X-rays to γ-rays, which can be either due to inverse Compton scattering of lower-frequency radiation by the same relativistic electrons (leptonic models i.e., [6]) or due to interactions of ultra-relativistic protons in the jet (hadronic models), either via proton synchrotron radiation [7] or via secondary emission from the photo-pion and photo-pair production process ([8] and the references therein).

Blazars can be classified into three sub-classes, depending on the peak frequency of their synchrotron emission: LSPs (low-synchrotron-peaked blazars), consisting predominantly of LBLs (red or low energy or radio selected blazars) and defined by a peak of their synchrotron component at $\nu_{sy} < 10^{14}$ Hz, ISPs (intermediate-synchrotron-peaked blazars) or IBLs, consisting mostly of intermediate blazars, defined by 10^{14} Hz $< \nu_{sy} < 10^{15}$ Hz, and HSPs (high-synchrotron-peaked blazars), all of which are HBLs (blue or high energy or X-ray selected blazars) and which are defined through $\nu_{sy} > 10^{15}$ Hz [9]. The high-energy component of the spectral energy distribution (SED) of blazars extends up to γ-rays, peaking at GeV energies in LSPs and at TeV energies in HSPs. Blazar properties are consistent with relativistic beaming, i.e., bulk relativistic motion of the jet plasma at small angles to the line of sight, which gives rise to a strong amplification and rapid variability in the observer's frame.

The study of variability is one of the most powerful tools for understanding the nature and processes occurring in blazars. The variability of blazars can be broadly divided into three classes. Significant variations in flux may occur over a few tens of minutes to the course of less than a day, often called micro-variability, intra-night variability or intra-day variability (IDV) [10]. Short-term variability (STV) can range time scales from days to a few months, and long-term variability (LTV) can have time scales of several months to several years [11].

The variability of observations on IDV timescales in AGN is the most puzzling. The variability of blazars on IDV timescales can provide important clues to the physics of the innermost nuclear regions in these objects. Blazar properties are consistent with relativistic beaming caused by bulk relativistic motion of the jet plasma at small angles to the line of sight, which gives rise to a strong amplification and rapid variability in the observer's frame. Simultaneous multi-wavelength observations of blazars in the entire EM spectrum are an important tool to test several possible models for IDV: shock-in-jet models, accretion-disk-based models, models based on plasma instabilities in shear layers, etc.

2. Intra-Day Variability in Different EM Bands

There have been several dedicated monitoring campaigns in which the IDV of blazars has been studied over the entire EM spectrum (e.g., [12–43]; and the references therein).

There are several methods that can be used to find the genuine IDV and variability parameters in time series data. These methods are described by different groups, and relevant source references are cited in their papers. [44] introduced the C-test, which is used by several groups (e.g., [23,30,38,45,46]; and the references therein). However, later, [47] explained that the C-test statistic is too conservative of an approach for IDV detection. IDV detection results can be tested using the F-test, which is a distributed statistic [47]. The F-test is also used by several groups (e.g., [30,38]; and the references therein). A better method called the power enhanced F-test was introduced by [48,49]. This method takes care of large brightness differences in a blazar and comparison/standard stars or large brightness differences in comparison/standard stars. It was used by [32]. The χ^2-test (as explained by: [30,38] also provides evidence of the presence of IDV in time series data. The analysis of variance (ANOVA) test is a very robust test to investigate the variability in the light curves (LCs) (e.g., [27,30,38,50]; and the references therein). Percentage amplitude variation in the time series data was introduced by [18] and used in several papers (e.g., [23,27,30,38]; and the references therein). Another method called excess variance and fractional rms variability amplitude were introduced by [51,52] and extensively used for getting the variability in AGN LCs (e.g., [37,42,53,54]; and the references therein).

IDV in blazars can be intrinsic to the source or due to extrinsic origin. Interstellar scintillation and gravitational microlensing are the main extrinsic causes of IDV. Interstellar scintillation is only relevant in low-frequency radio observations. Gravitational microlensing is only applicable in a few blazars, which are lensed systems, e.g., the blazar AO 0235+135 at z = 0.94 has revealed foreground-absorbing systems at z = 0.524 and z = 0.851 [55,56]. In the blazars where IDV is detected, low-frequency radio observations or gravitationally-lensed sources can also have some intrinsic origin; to find that, we need to observe simultaneous multi-wavelengths of the blazar, and co-related variability in different EM bands will be helpful to find the nature of the variability.

IDV in the high state (pre/post the outburst state) of blazars can be explained by jet-based models, e.g., helical instabilities in the jet [57,58] or turbulence behind the shock in the jet [59]. Jet-based models can explain IDV over the entire range of EM wavelengths. Other theoretical models seek to explain IDV in blazars (mainly in their low-state) involving accretion-disk-based models. These models include pulsations of the gravitational modes of the gaseous disk [60,61] or orbital signatures from "hot-spots" in the gas surrounding the black hole, either from the disk itself or the corona above it [62,63]. Accretion-disk-based models can explain the variations in optical, UV and X-ray bands, but are difficult to connect to the observed rapid variability in γ-rays. Plasma instabilities in the jet (e.g., Kelvin–Helmholtz-type instabilities due to the interaction of a fast inner spine of the jet with a slower, outer layer) could play an important role in the production of IDV at a variety of wavelengths [64].

2.1. IDV in Gamma-Rays

Most of the ground- and space-based gamma-ray experiments are not sensitive enough to observe blazars with a few minutes time resolution. Therefore, it is extremely difficult to do IDV studies of blazars. However, there is an excellent IDV observation of the blazar PKS 2155–304 in an exceptionally very high energy gamma-ray flare observed on 28 July 2006 using HESS (High Energy Stereoscopic System). The IDV LC obtained with a time resolution of 1 min and IDV is seen down to the 10-min scale, which gives a Doppler factor of more than 100. The average flux at >200 GeV during outburst was ~7-times the flux observed from the Crab Nebula [22]. The LAT (Large Area Telescope) on board the Fermi gamma-ray space telescope (Fermi-LAT; [65]) has been observing the sky in the gamma-ray spectrum since its launch in June 2008. Fermi-LAT covers 20 MeV–300 GeV energies and made a revolution in the discovery of the gamma-ray emission of blazars. It has observed several blazars in flaring state and detected strong IDV ([33–36,41,66–68]; and the references therein). Fermi-LAT LCs with a time resolution of minutes of blazars were presented by [33,41], while [34–36,66–68] presented Fermi-LAT LCs of blazars with a few hours time bin. [33] searched for IDV in three FSRQs, 3C 454.3, 3C 273 and PKS B1222+216, in the energy $E > 100$ MeV and set the upper limit on the observed characteristic time scales, which were of the order of <2–3 h, which suggests that the location of the γ-ray emission region could be within the broad-line region (BLR). Based on the 3.75 years of data of the FSRQ PKS 1510–089 in the energy range 0.1–300 GeV, [66] reported the doubling time in flare rise stage as 1.3 ± 0.12 h, while 1.21 ± 0.15 h during flare decay. [34] reported Fermi-LAT LC of the blazar PKS 1222+216 with a 6-h time bin showing the asymmetric rise profiles, but rapid decline during the April 2010 flare. Paliya et al. (2015) reported the giant γ-ray outburst observed in the FSRQ 3C 279 in March–April 2014 using Fermi-LAT. They reported γ-ray flux (1.21 ± 0.10 ph cm^{-2} s^{-1} in the energy range 0.1–300 GeV and flux doubling time as 1.19 ± 0.36 h. [41] reported γ-ray IDV in 3C 279, which showed a giant outburst on 16 June 2015 with a peak flux of $\sim 3.6 \times 10^{-5}$ ph cm^{-2} s^{-1} at >100 MeV and flux doubling times of less than 5 min. The same flare in 3C 279 on 16 June 2015 was also studied by Paliya 2015 with the observations taken for 16 days (four days before the flare started and six days after the flare ended), and the shortest doubling time was measured as 2.2 ± 0.3 h with $\sim 9\sigma$ significance, from $\gamma\gamma$ pair opacity arguments; the minimum Doppler factor is reported to be 14; and the location of the γ-ray emitting region is claimed to be either at the outer edge of BLR or farther out from it. [67] reported a twin γ-ray flare in 3C 279 in December 2013, which had similar intensity as the flare in April 2014 [35], but less intense than the April 2015 flare. The γ-ray flux doubling time of 3.04 ± 0.77 h was detected. [68] studied γ-ray flares of 3C 279 observed during December 2013–April 2014. Results reported in [68] and [67] are in good agreement.

2.2. IDV in X-Rays

A pilot project on searching for IDV in blazars was initiated ([28,37,42,43,54]; and the references therein). A sample of four HBLs observed on 23 occasions by XMM-Newton was studied; IDV timescales ranging from 15.7–46.8 ks were found on eight occasions; in 13 cases, IDV timescales were longer than the data length, and the hint of weak quasi periodic oscillations (QPOs) was observed on one LC each of blazars ON 231 and PKS 2155–304 [28]. Reference [69] took the sample of 104 nearby AGN ($z < 0.4$) observed with XMM-Newton. The AGN sample also includes several blazars. They did power-spectrum density (PSD) analysis of all those LCs and reported IDV variability parameters. The LBL 3C 273 observed on 24 occasions during 2000–2012 with XMM-Newton and on IDV timescales have shown occasionally small amplitude variability [37]. A complete sample of 12 LBL and IBL with 50 IDV LCs taken with XMM-Newton was compiled [37,54]. It is noticed that the duty cycle of genuine IDV detection in LBL and IBL in the X-ray band is only 4% (two out of 50 LCs) [54]. It is concluded that probably the peak of the spectral energy distribution seems to be responsible for the IDV properties [54]. In a recent study, [42] reported the search for X-ray IDV in five TeV blazars using NuStar . Four TeV blazars have shown large amplitude IDV, using the auto-correlation function (ACF). The IDV timescale in the range of 2.5–32.8 ks was reported in eight LCs of Mrk 421; a timescale of about 8.0 ks for one LC in Mrk 501; and timescales of 29.6–57.4 ks in two LCs of PKS 2155–304. In general, soft (3–10 keV) and hard (10–79 keV) LCs were well correlated, which indicated that the same population was emitting soft and hard X-rays. IDV timescales are used to calculate δ the Doppler factor, B the magnetic field, γ the Lorentz factor and R the size of the emitting region (see Table 4, [42]. Recently, in another search for X-ray IDV, 83 LCs of the TeV blazar Mrk 421 taken during 1999–2015 with Chandra were studied [43]. IDV timescales ranging 2.4–30.0 ks, IDV duty cycle $\sim$77%, soft (0.3–2.0 keV) and hard (2.0–10.0 keV) LCs well correlated with zero lag were found. IDV timescales were also used to calculate δ the Doppler factor, B the magnetic field, γ the Lorentz factor and R the size of emitting region for the blazar Mrk 421 [43]. For Mrk 421, we found that shortest IDV timescale $\approx$2.4 ks, δ = 25, $B > 0.26\ \nu_{18}^{-1/3}$ G, where ν_{18} = critical synchrotron emission frequency in terms of 10^{18} Hz for the Chandra satellite, electron Lorentz factor $\gamma \geq 1.92 \times 10^5\ \nu_{18}^{2/3}$ and the radius of the emitting region $R \leq 1.7 \times 10^{15}$ cm [43].

2.3. IDV in Optical and Infrared Bands

The first evidence of optical micro-variability was reported in BL Lacertae by [12]. The result of this paper motivated several groups around the globe to start dedicated projects to search for optical micro-variability in blazars. Optical IDV in blazars was pioneered by the U.S. group in which they studied optical micro-variability in five blazars (e.g., [12–16]) and reported that the probability of finding genuine micro-variability is about 80% for the blazar continuously monitored for <8 h. An extensive search for optical IDV in a sample of 34 BLLs from the 1 Jy catalog was done by [18]. IDV was detected in 28 out of 34 BLLs (82%), and 75% of the variable BLLs changed significantly over a time span <6 h. However, these data lack continuity in the LCs. [70] compiled the optical IDV studies of blazars till $\sim$2004 and noticed that the occurrence of IDV of blazars if observed for less than 6 h was about 60–65%. If the blazar were observed for more than 6 h, then the possibility of IDV detection was about 80–85%. Several hundred nights of optical IDV searching in blazars were done by different Chinese groups (e.g., [71–88]; and the references therein). Significant IDV was detected in most of these observations, but in several papers, the data lack continuity in the LCs. Indian groups also performed extensive searches for optical/IR IDV in blazars with collaborators around the globe (e.g., [11,20,23,24,26,27,29–32,38–40,89–94]; and the references therein). There are some other collaborations world wide that are performing searches for optical/NIR IDV of blazars (e.g., [19,95–109]; and the references therein). The important results reported in these papers are: (i) LBLs and IBLs show large amplitude IDV with high duty cycles; (ii) HBLs either do not show IDV or if they do, the amplitude of variability and the duty cycle of IDV detection are less compared to LBLs and IBLs; (iii) cross-correlation analysis in different optical bands on IDV timescales in general shows strong correlation with zero lag, which implies that the emissions in different optical bands are co-spatial, but occasionally, a few minute time lags are also reported; (iv) optical color variation on IDV timescales shows a range of properties, e.g.: sometimes, no color variation is seen; on some occasions, BLLs are bluer when brighter (BWB) and FSRQs are redder when brighter trend (RWB); and rarely, the opposite trend is also noticed; (v) IR/optical SED in general fits to a power-law, but occasionally shows a big blue bump (BBB), which shows the signature of thermal emission from the accretion disk; (vi) IDV LCs are used to get a variable timescale, which gives a clue about the size of the emitting region, black hole mass estimation of the blazar; etc. [110].

2.4. IDV in Radio Bands

IDV in radio bands are a mixture of intrinsic and extrinsic origins. Mostly, observations at centimeter and meter wavelengths have dominant extrinsic variability, which is due to interstellar scintillation of radio waves caused by the turbulent interstellar medium of the Milky Way, while IDV are in the millimeter wavelength of the intrinsic origin. Radio IDV studies of blazars were pioneered by the 100-m Effelsberg radio telescope in Germany, as well as other radio and mm wavelength telescopes (e.g., [17,25,102,111–121]; and the references therein).

Reference [111] did simultaneous optical and radio monitoring of blazars. Reference [17] reported for the first time the correlated optical and radio IDV in the blazar S5 0716+714. To test the inverse-Compton (IC) catastrophe scenario in the blazar S5 0716+714, extensive observational campaign in the radio and mm wavelengths were coordinated [102,112,115], and the lower limits to the brightness temperature were derived from the inter-day variations exceeding the 10^{12} K IC-limit by up to 2–4 orders of magnitude. Reference [113] reported radio IDV of the blazar J 1128+5925 in three frequencies, i.e., 2.7- and 10.45-GHz observations using the 100-m Effelsberg radio telescope in Germany, and 4.8-GHz observations using the 25-m radio telescope in Urumqi, China. The observed frequency-dependent IDV in the source was in good agreement with the prediction from interstellar scintillation. VLBA observation of the blazar J1128+592 was reported by [114], and with VLBA observations, they detected an east-west-oriented core-jet structure with no significant motion in its jet. Radio IDV in blazars was studied where the variability characteristics have changed abruptly by interstellar scintillation [116,117]. Radio IDV at 4.8 GHz using the 25-m Urumqi, China telescope for the blazars S5 0716+714 and 1156+295 was reported by [118,119]. Simultaneous IDV in the X-ray, four optical bands and three frequencies in the radio spectrum were reported by [25]. IDV was detected in all three radio frequencies, and it was also noticed that low and high frequency correlations do not peak at zero lag, which shows that low frequency radio observation is the combined effect of an intrinsic and an extrinsic mechanism. Optical and radio IDV observations were carried out by [121]. IDV observation along with VLBI analysis was carried out for the blazar S4 0917+624 [120].

3. Quasi Periodic Oscillations in Intra-Day Time Series Multi-Wavelength Data

Detection of quasi-periodic oscillations (QPOs) in time series data are very rare in AGN. In the last decade, several detections of QPOs in AGN on diverse timescales ranging from as short as a few minutes and as long as a few years using γ-ray, X-ray, optical and radio time series data were made (e.g., [122–139]; and the references therein). However, only a few claims of QPO detection on IDV timescales using X-ray and optical monitoring data of a few blazars have been reported [123–125,127].

There are several methods that can be used to search for QPO or periodic signals in time series data. These methods are described by different groups, and relevant source references are cited in their papers. Reference [122] used power spectral density (PSD) and data folding. Reference [123] used wavelet analysis, whereas [124] used wavelet plus randomization technique. Weighted wavelet z-transform (WWZ) and the Lomb–Scargle periodogram (LSP) were used by [139]. Multiple analysis techniques, e.g., structure function (SF), wavelet analysis, data folding, PSD and multi-harmonic AoV periodogram (mhAoV), were used by [125]. SF and the auto-correlation function (ACF) were used to get the variable timescale and QPOs [28,42]. One or multiple methods used in these papers were used in other searches for QPOs.

QPOs in blazars on IDV timescales can be explained by several standard models of AGN. One of the simplest models by which the central BHs of AGN would have the QPOs attributed can be explained by the presence of a single dominating hot-spot on the accretion disk (e.g., [63,140]. Using QPO or a nearly periodic signal, the period can be used to estimate the BH mass for non-rotating (Schwarzschild) BH and maximally-rotating (Kerr) BH. The detailed explanation is given in [124]. Other alternative possible mechanisms for QPOs in blazars on IDV timescales can also have a disk origin or can arise from relativistic jets. The former class includes small epicyclic deviations in both radial and vertical directions from exact planar motions within a thin accretion disk (e.g., [141]) and trapped pulsational modes within a disk (e.g., [123,142]). Using the detailed explanation of [142], one can also get the BH mass of the blazar. There are various jet models that also can explain the QPO detection in blazars on IDV timescales, e.g., a shock propagating down a jet in which the jet structure is quasi-helical and changes in electron density or magnetic field can produce QPO, and a short-lived QPO can be due to turbulence behind the shock in the relativistic jet (e.g., [59,143,144]).

3.1. In the Optical Band

Reference [124] selected 20 optical IDV light curves of the blazar S5 0716+714 from a database of 102 lights curves taken in a three-year span [21]. They used wavelet analysis along with the randomization test and found strong evidence for nearly periodic variations on five light curves with a probability >99%. The period for these five light curves was found in the range of 25 min–73 min, which led to BH mass ranging 2.47–7.35 $\times$ 10^6 $M_\odot$ and 1.57–4.67 $\times$ 10^7 $M_\odot$ for non-rotating BH and maximally-rotating BH, respectively. Another piece of evidence of QPO detection in the optical band on the same blazar S5 0716+714 was reported by [127]. They found a QPO period of $\sim$15 min using various techniques (e.g., SF, LSP, PSD, data folding). This period yields the BH mass 1.5 $\times$ 10^6 $M_\odot$ and 9.6 $\times$ 10^6 $M_\odot$ for non-rotating BH and maximally-rotating BH, respectively.

3.2. In X-Rays

Using the wavelet technique, Reference [123] analyzed 19 observations of 10 AGN observed with the EPIC/pn detector on board XMM-Newton and detected a QPO period of 3.3 ks in one light curve of the blazar 3C 273. The QPO period is used to get the black hole (BH) mass of the blazar. They estimated the BH mass of the blazar to be 7.3 $\times$ 10^6 $M_\odot$ and 8.1 $\times$ 10^7 $M_\odot$ for non-rotating BH and maximally-rotating BH, respectively. In another observation of EPIC/pn of XMM-Newton for the blazar PKS 2155–304, Reference [125] detected a QPO period of 4.6 h that was present for $\sim$3.8 cycles. This QPO detection was verified by various techniques (e.g., SF, PSD, MHAoV, data folding and wavelet). The BH mass of the blazar was estimated to be 3.29 $\times$ 10^7 $M_\odot$ and 2.09 $\times$ 10^8 $M_\odot$ for non-rotating BH and maximally-rotating BH, respectively.

4. Conclusions

With the extensive studies of IDV in the radio to optical bands in approximately the last three decades and in high energies (X-ray and γ-rays) in the last decade, we reach the following conclusions:

- Blazars show large amplitude IDV in radio bands, which is basically the mixture of extrinsic and intrinsic mechanisms.
- LBLs and IBLs show large amplitude IDV in optical/IR bands with a high duty cycle.
- HBLs either do not show optical/IR IDV or if they do, the amplitude is low and the duty cycle is very small compared to LBLs/IBLs.
- In general, blazars do not show color variation on IDV timescales; however, occasionally this is seen.
- Optical inter-band cross-correlation shows that in general, there is no time lag in different optical bands. On some occasions, the time lag of a few minutes is reported in different optical bands.
- Optical/IR SEDs are well fitted to a single power law.

- Sometimes optical/IR SEDs show a big blue bump, which is a signature of emission from the accretion disk.
- In X-rays, HBLs show large amplitude IDV, and the duty cycle is high.
- In X-rays, LBLs/IBLs either do not show IDV or if they do, the amplitude is less. The duty cycle of X-ray IDV for LBLs/IBLs is much less compared to the duty cycles for HBLs.
- In general, hard and soft X-ray LCs of blazars show strong cross-correlation with zero lag, which implies that the emissions in the hard and soft bands are co-spatial.
- IDV timescales in different EM bands are used to get the black hole mass of the blazars, the size of the emitting region and the Doppler factor δ.
- In general, the sensitivity of very high energy γ-ray facilities is poor, but occasionally, blazars are observed on time resolutions of a few minutes to a few hours. The best time resolution γ-ray light curves give a high Doppler factor of $\sim$100 for the blazar PKS 2155–304.
- QPOs in blazars on IDV timescales are rare.
- Occasionally, QPOs on IDV timescales are detected in a few blazars in the X-ray and optical bands.

5. Future Projects

In the last three decades, there have been several attempts to search for IDV in blazars, but still, we need many new observations in the complete EM spectrum to better understand the IDV properties of various sub-classes of blazars and detected QPOs in blazars. Below, I list a few projects that I think need focused effort to search for IDV and QPOs in blazars.

- Simultaneous low and high frequency radio IDV should be studied with other EM bands with almost a similar time resolution. This will help us to separate out the extrinsic component of low-frequency IDV, which is responsible for the high brightness temperature. For such observations, instead of using single-dish radio telescopes, interferometric telescopes will be a much better option.
- For a large sample of blazars, IDV studies in IR bands are not yet performed with focused effort, which needs to be done.
- With the help of the Fermi-LAT and VHE gamma-ray facilities, a large number of new HBLs has been discovered. Extensive IDV of HBLs in the optical bands should be done to see if the IDV duty cycle is really much less for HBLs in optical bands in comparison to LBLs and IBLs.
- Extensive IDV studies for LBLs and IBLs are not yet done in X-rays and γ-rays, which can be done to see if the IDV properties in these bands for LBLs and IBLs are similar to HBLs.
- Still, there are only a few pieces of evidence when blazars are observed in γ-rays on IDV timescales. Upcoming CTA can contribute to this project.
- QPO is rarely detected in blazars on diverse timescales in different EM bands. It is even much rarer to detect QPO in blazars on IDV timescales. A focused effort with high time resolution and good S/N data is required to search for QPOs on IDV timescales in various EM bands.

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