1. Name and last name: Gopal Bhatta

2. Academic degrees:

December 2012	Ph. D. in Physics, Florida International University, USA Dissertation Title: *The Nature of Microvariability in the Blazar S5 0716+714* Advisor: Prof. James R. Webb
July 2000	M. Sc. in Physics, Tribhuvan University, Kathmandu, Nepal Dissertation Title: *Null and time-like geodesics in Kerr–de Sitter space-time* Advisor: Prof. Udayraj Khanal

3. Academic positions held:

2013 August -Present	Postdoctoral Associate, High Energy Astrophysics Astronomical observatory of Jagiellonian University
Jan 2013 -Aug 2013	Adjunct Faculty Physics Department, Florida International University, USA
Jan-Dec 2012	Dissertation Year Fellow Physics Department, Florida International University, USA
Jan 2007 -Dec 2011	Graduate Teaching Fellow Physics Department, Florida International University, USA
Jan 2003 -Dec 2006	Physics Lecturer Capital College and Research Center, Kathmandu, Nepal

4. Work of significant scholarly merit, according to: art. 16 ust. 2 ustawy z dnia 14 marca 2003 r. o stopniach naukowych i tytule naukowym oraz o stopniach i tytule w zakresie sztuki (Dz. U. nr 65, poz. 595 ze zm.):

4.1. Title of the academic achievement:

Multi-wavelength variability study of blazars: a journey into the innermost regions of blazars

4.2. Main refereed publications

H1. **Bhatta, G.**, 2018, Galaxies, 6, 136
Detection of periodic radio signal from the blazar J1043+ 2408

H2. **Bhatta, G.**, Mohorian, M., & Bilinsky, I. 2018, A&A, 619, A93
Hard X-ray properties of NuSTAR blazars

H3. **Bhatta, G.**, Stawarz, L., Markowitz, A., et al. 2018, ApJ, 866, 132
Signatures of the disk-jet coupling in the Broad-line Radio Quasar 4C+74.26

H4. **Bhatta, G.**, & Webb, J. 2018, Galaxies, 6, 2
Microvariability in BL Lac: "Zooming" into the Innermost Blazar Regions

H5. **Bhatta, G.** 2017, ApJ, 487, 7B
Radio and γ-Ray Variability in the BL Lac PKS 0219--164: Detection of Quasi-periodic Oscillations in the Radio Light Curve

H6. **Bhatta, G.**, Zola S., Stawarz, L., et al. 2016, ApJ, 832, 47
Detection of Possible Quasi-periodic Oscillations in the Long-term Optical Light Curve of the BL Lac Object OJ 287

H7. **Bhatta, G.**, Stawarz, L., Ostrowski, M., et al. 2016, ApJ, 831, 92B
Multifrequency Photo-polarimetric WEBT Observation Campaign on the Blazar S5 0716+714: Source Microvariability and Search for Characteristic Timescales

4.3. Academic achievement – overview of scientific motivations and results:

Active galactic nuclei (AGN) are the most luminous sources in the universe. They are widely believed to be powered by accretion on to the supermassive black holes. A sub-class of radio-loud AGN with its relativistic jet aligned close to the line of sight is known as blazar. Blazar sources are identified by their extreme properties such as high luminosity, rapid flux and polarization variability, and a large output of high energy emission, e. g. X-ray and gamma-ray. Although, with the advancement of the telescopes and the detectors, we have a fair understanding of the sources, the details of the processes occurring near the central region, e.g. the nature of accretion processes, disk-jet connection and the role the magnetic field in launching the jets, are still relatively poorly understood.

In blazars, the flux modulations due to disk processes could easily be swamped by the Doppler boosted emission from jets. However, the imprint of the modulations should, in principle, propagate along the jet so that the traces of their characteristic timescales should be revealed by the suitable time series analyses – such as the breaks or peaks in the power spectral density (PSD) of long term light curves of blazars. Such time scales then can be linked to the various processes in the jet and the accretion disk such as dynamical, thermal, and viscous processes (Czerny, 2004). For example, for blazars with typical masses between $\sim 10^8 - 10^9 M_\odot$ the dynamical, thermal and viscous time scales are in the order of a few hours to a few years.

Some AGN models predict quasi-periodic oscillations (QPO) in the flux with the characteristic timescales also ranging from a few hours to a few years. In fact, recently there are numerous reports of the detection of QPOs in various kinds of AGNs including radio-loud and radio-quite ones (see Bhatta, 2017 and Bhatta et al. 2016b). In addition, QPOs are also seen in the recent numerical studies involving simulations of the relativistic jets (McKinney et al. 2012). For instance, in the scenario of highly magnetized accretion disk playing a key role in launching the jets in AGN, commonly known as *magnetic flux paradigm*, various magnetohydrodynamical instabilities at the interface of the disk and the magnetosphere might give rise to QPOs. These QPOs then could propagate along modulating the jet emission, and could be detected in the multi-wavelength observations. In the similar context, the highly magnetized optical flare discovered by Bhatta et al. 2015 might be a signature of dominance of magnetic field near blazar cores, so called magnetically arrested disk (MAD) scenario (see Narayan et al. 2003).

Out of the 12 reviewed papers that were published after my doctoral degree in late 2012, here I include and briefly discuss 7 works in the track record. These works, in my opinion, exemplify my main research activities over the years, contributing consistently to the fields of multi-wavelength (MWL) blazar variability studies. The selected publications illustrate the diversity in the research methodology and approach adopted by me and my colleagues in carrying out the analysis. The methods often include the original design and conduct of observational campaigns, data acquisition, observational data processing, analytical calculations, and numerical modeling.

4.3.1. General Introduction of the field:

Blazars, and in general AGN, are believed to harbor monstrously giant black holes, billions times massive than the sun, squeezed within a volume as small as the solar system. The surrounding accretion disk constantly feeds the black hole with tremendous amount of matter which makes the nuclei extremely bright and consequently, it outshines the whole galaxy. The central engine spews out matter nearly at the speed of the light that form relativistic jets. The jets beaming upon us shine brightly in non-thermal emission covering a wide electromagnetic spectrum - from radio to most energetic γ-rays. The broadband spectral energy distribution (SED) of blazars can often be identified with a double-peaked feature in the frequency-flux plane. The lower peak, usually found between the radio and X-ray, arises as a result of the synchrotron emission by the energetic particles accelerating in the jet magnetic field; whereas the origin of the high frequency component, extending from X-rays to TeV energies, is still a debated topic. In leptonic models, e.g., Maraschi et al. (1992); Bloom & Marscher (1996) it is resulted due to the inverse-Compton scattering of the soft seed photons by the energetic particles. In the synchrotron self-Compton scenario (SSC), the same population of the high energy electrons responsible for the synchrotron emission up-scatter the photons to higher energy. However, in the external Compton scenario (EC), the seed photons might originate at the various components of an AGN, e.g., accretion disk (AD; Dermer & Schlickeiser 1993), broad-line region (BLR; Sikora 1994), and dusty torus (DT; Błażejowski et al. 2000). Hadronic models, on the other hand, ascribe the high energy emission from blazars to the interaction of relativistic protons in the presence of radiation fields (e.g., Mannheim & Biermann, 1992; Aharonian, 2000; Mücke et al., 2003)

Blazars consists of further two sub-classes: flat-spectrum radio quasars (FSRQ) and BL Lacertae (BL Lac) sources. The more luminous sources, FSRQs, show emission lines over the continuum and their synchrotron peak is in the lower frequency. As the sources are found to have abundant seed photons due to the AD, BLR, and DT, the high energy emission is most likely due to the EC process as opposed to SSC (Ghisellini et al., 2011). BL Lac objects constitute less powerful subclass that has weak or no emission lines over the continuum and the synchrotron peak in these objects lies in the UV to X-rays bands. BL Lacs represent an extreme class of sources with an excess of high energy emission (hard X-rays to TeV emission) resulting from the synchrotron and inverse-Compton (IC) processes. However, their apparent low luminosity could be due to lack of strong circum-nuclear photon fields and relatively low accretion rates. Blazar sources can have further subdivision based on the frequency of the synchrotron peak (ν_s): high synchrotron peaked blazars (HSP; $\nu_s > 10^{15}$ Hz), intermediate synchrotron peaked blazars (ISP; $10^{14} < \nu_s < 10^{15}$ Hz), and low synchrotron peaked blazars (LSP; $\nu_s < 10^{14}$ Hz) (see Abdo et al., 2010). In the unifying scheme known as blazar sequence, the bolometric luminosity decreases as we move from FSRQ to HSP but γ-ray emission increases (Fossati et al., 1998; Ghisellini et al., 2017). This means that while FSRQs are γ-ray dominated, in HSP sources synchrotron and γ-ray emission become comparable. In other words, with the increase in their bolometric luminosity, blazars become redder and Compton dominant as the ratio of the luminosities at the Compton peak to the synchrotron peak frequency increases. More recently, blazar TXS 0506+056 was associated with the first non-stellar neutrino emission detected by the IceCube experiment (Padovani et al., 2018).

The jets are believed to be powered by Blandford-Znajek process (see Blandford & Znajek, 1977) i. e. extraction of the rotational energy of the black holes with the help of disk magnetic field that is twisted in helical shapes around fast spinning black holes, and thereby, pave the path for streams of relativistic particles that plough through the intergalactic medium up to several Mpcs away. Consequently, any changes in the accretion rate or other inner-structure configuration such as accretion rate and magnetic field could lead to the changes in the flux observed as multi-frequency flux variation. Blazar continuum emission is characterized by broadband emission which is variable, both flux and polarization, on diverse timescales. The variability timescales can be broadly classified as long-term, short-term and intraday/night variability. The long-term variability, typically in the timescale of a few years, might arise due to variable accretion rates; the short-term variability, which are usually identified with flaring episodes lasting a few weeks to a few months, could be the result of the passage of the shock waves propagating down the blazar jets; and the intraday variability might be resulted due to the turbulence in the innermost region of the jets (e.g., Bhatta et al., 2013; Marscher & Travis, 1996). In general, the variability shown by AGNs appears predominantly aperiodic in nature, although quasi-periodic oscillations on various timescales have been detected for a number of sources (see Bhatta, 2017; Bhatta et al., 2016c; Zola et al., 2016). Generally, signatures of (quasi-)periodic oscillations can be revealed as the large peaks in the periodograms of the source light curves. QPOs could also arise near the disk-magnetosphere interface due to the processes directly related to the activities in the vicinity of the black hole. The QPOs could result in various scenarios such as binary supermassive black holes, disk and jet precession, Lense-Thirring precession around the Kerr-black holes and therefore bear the signatures of the nature of the space-time near the fast spinning black holes.

4.3.2. Research methodology:

Generally, source variability displayed in the light curve can be quantified in two ways: The variability amplitude (VA) estimated using two extrema flux of the light curve measures peak-to-peak oscillation, and is expressed as in Heidt & Wagner (1996),

$$\mathrm{VA} = \sqrt{(A_{max} - A_{min})^2 - 2\bar{\sigma}^2}, \quad (1)$$

where A_{max}, A_{min}, and $\bar{\sigma}^2$ are the maximum, minimum magnitudes, and the mean of the magnitude error square in the light curves, respectively. Whereas to estimate mean variability during the observational period, fractional variability (FV) is more suitable. For a mean flux of $\langle F \rangle$ with S^2 variance and $\langle \sigma_{err}^2 \rangle$ mean squared uncertainties, the fractional variance, as in (Vaughan et al., 2003), is given as

$$F_{var} = \sqrt{\frac{S^2 - \langle \sigma_{err}^2 \rangle}{\langle F \rangle^2}}. \tag{2}$$

The error in the fractional variability can be expressed as

$$\sigma_{F_{var}} = \sqrt{F_{var}^2 + \sqrt{\frac{2}{N}\frac{\langle \sigma_{err}^2 \rangle^2}{\langle F \rangle^4} + \frac{4}{N}\frac{\langle \sigma_{err}^2 \rangle}{\langle F \rangle^2} F_{var}^2} - F_{var}} \tag{3}$$

The research methodology is chiefly based on the central idea that MWL blazar properties can be utilized to make inferences about the physical processes occurring at the innermost regions of blazars, or in general AGN. For this purpose, blazar observations from various telescopes operating in a wide range of electromagnetic spectrum - in particular, Owens Valley Radio Observatory (OVRO), optical telescopes, Swift, NuSTAR and Fermi/LAT- spanning up to decades are analyzed, and subsequently several methods of time series analysis are performed to constrain their statistical properties. Particularly, the power spectrum in both time and frequency domain were studied to search for the features, e.g. power spectral break, that possibly can indicate the characteristic timescale in the light curves. The studies were conducted in collaboration with my colleagues from the Boston Blazar Group[1], the whole earth blazar telescope (WEBT[2]) and the Long-term AGN Monitoring group at Astronomical Observatory of Jagiellonian University[3]. The methods of the time-series analysis employed in the studies are briefly discussed below.

Time series analyses:

i. Discrete Fourier periodogram: For a time series $f(t_j)$ sampled at times t_j with $j = 1, 2, .., n$, the discrete Fourier power at a given angular frequency ω is expressed as

$$P(\omega) = \frac{1}{N}\left|\sum_{j=1}^{n} f(t_i)\, e^{-i\omega t_j}\right|^2 . \tag{4}$$

For a total time length of the observations, L, the normalization factor $N = 2L/(n\bar{f})^2$ is chosen such that the unit of the periodogram is $(rms/mean)^2/d$. The discrete Fourier transform is performed using $n/2$ frequencies with the minimum frequency $\omega_{min} = 2\pi/L$ and $\omega_k = \omega_{min}k$ where k=1, 2, ., $n/2$.

ii. Lomb-Scargle Periodogram: Lomb-Scargle Periodogram (Lomb, 1976; Scargle, 1982) is one of the most extensively employed methods that approaches the periodicity analysis from multiple directions e.g. *Fourier analysis, least-squares method, Bayesian probability theory*, and *bin-based phase-folding* techniques and therefore has advantage over traditional discrete Fourier periodogram (see VanderPlas, 2018). To account for the problem with unevenly spaced data-sets, the Lomb-Scargle method modifies the above periodogram such that the least-square fitting of sine waves of the form $X_f(t) = A\cos\omega t + B\sin\omega t$ is minimized (Lomb, 1976; Scargle, 1982). The *modified periodogram* is expressed as

$$P = \frac{1}{2}\left\{\frac{[\sum_i x_i \cos\omega(t_i - \tau)]^2}{\sum_i \cos^2\omega(t_i - \tau)} + \frac{[\sum_i x_i \sin\omega(t_i - \tau)]^2}{\sum_i \sin^2\omega(t_i - \tau)}\right\}, \tag{5}$$

where τ is given by $\tan(2\omega\tau) = \sum_i \sin\omega t_i / \sum_i \cos\omega t_i$.

iii. Weighted wavelet z-transform: When used in the periodicity analysis, the above two methods expect the periodic signal to persist through out the entire data. However, in many astrophysical systems the periodicities are rather transitory, i. e. quasi-periodic oscillations. In such cases, wavelet analysis becomes

[1] https://www.bu.edu/blazars/research.html
[2] www.to.astro.it/blazars/webt/
[3] http://www.oa.uj.edu.pl/

a more preferable tool. In the method, the sinusoidal waves, localized in both time and frequency domains, can be scaled in frequency and shifted in time to fit the data. In weighted wavelet Z-transform (WWZ; Foster 1996) method, most suitable for the unevenly sampled observations, the functions can be viewed as weighted projections on the following trial functions

$$\phi_1(t) = \mathbf{1}(t), \quad \phi_2 = \cos[\omega(t-\tau)], \quad \text{and} \quad \phi_2 = \sin[\omega(t-\tau)] \tag{6}$$

The weight given as $w_i = e^{-c\,\omega^2(t_i-\tau)^2}$ where c acts as a fine tuning parameter. With V_x and V_y as weighted variations of the data and the model function, respectively, the WWZ power can be written as,

$$WWZ = \frac{(N_{eff} - 3)\,V_y}{2\,(V_x - V_y)}, \tag{7}$$

where N_{eff} is the effective number of the data points.

iv. Discrete cross/auto-correlation function: The discrete correlation function (DCF) described in Edelson & Krolik (1988), is most extensively used to investigate cross-correlation between two time series with uneven spacing (see Bhatta & Webb, 2018). The unbinned DCF can be estimated as,

$$UDCF_{ij} = \frac{(x_i - \bar{x})\,(y_j - \bar{y})}{\sqrt{(\sigma_x^2 - e_x^2)\,(\sigma_y^2 - e_y^2)}} \tag{8}$$

where $\bar{x}$ and $\bar{y}$, σ^2, e^2 correspond to the mean, variance and the uncertainties in the magnitudes of the two light curves, respectively. These discrete pairs can be binned of bin width comparable to the sampling widths of the light curves. Then the average DCF including the M pairs within a given bin width is written as,

$$DCF(\tau) = \frac{1}{M} UDCF_{ij} \tag{9}$$

The sampling distributions of DCF, however, are highly skewed making the estimation of DCF uncertainties by the sample variances unreliable. However, the z-transformed DCFs (ZDCFs), i.e.

$$z = \frac{1}{2} log\left(\frac{1+r}{1-r}\right),\; r = tanhz, \tag{10}$$

where r = DCF, follow closely normal distribution with known mean and standard deviation. With the transformation, the estimation of ZDCF uncertainties becomes more robust (see Alexander (2013)). When we let $x = y$ in the Equation 8, then it becomes auto-correlation function.

v. Structure function: First order structure function (SF; Simonetti et al. 1985) is also widely used in the astronomical time series analysis. For a signal x(t) and a signal offset τ, the first order structure function is given by

$$SF(\tau) = \left\langle [x(t) - x(t+\tau)]^2 \right\rangle \tag{11}$$

General interpretations of the SF features are discussed in Hughes et al. (1992). The SF can be treated as equivalent to the PSD of a light curve calculated in the time domain instead of frequency domain. One of the main advantages of the SF over PSD is that SF method is less sensitive to irregular sampling in the time series and therefore it is relatively free of artifacts similar to windowing and aliasing in frequency domain (e.g. Lainela & Valtaoja, 1993; Paltani et al., 1997). This makes SF one of the favored tools in time series analysis widely applied in the search for periodicity in AGN light curves.

vi Epoch folding: First worked out by Leahy et al. (1983), epoch folding is frequently discussed method of time series analysis. This time domain based method was later improved by a number of authors (e.g. Davies, 1990, 1991). Unlike traditional discrete Fourier periodogram, which expects periodic components to be of the sinusoidal shape, the method is less sensitive to the modulating shape of the periodic components. Also, this method is largely unaffected by the irregularity in the sampling of the observations and therefore well suited for the periodic search in the data with gaps. In this method, a time

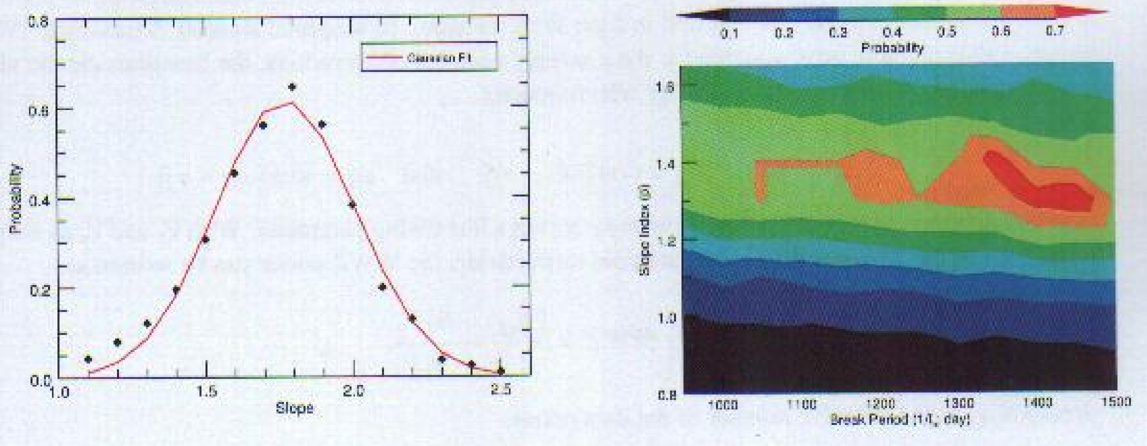

Figure 1: Examples of the statistical tools employing MC simulations. The figures present a method of estimation of probability that a model PSD with given parameters represents the periodogram of the analyzed light curve. *Left panel*: The black symbols represent the probability as a function of the slope index for the model power-law of the form$P(f) = Cf^{-\alpha}$, where C is a constant (from Bhatta et al., 2016b). *Right panel*: Probability contours in the $f_b - \alpha$ (break frequency – slope index) plane for the power-law of the form $P(f) = C(f/f_b)^{-\alpha}$(from Bhatta et al., 2016c)

series with N data points and varying about a mean value of $\bar{x}$ is folded on several trial periods and phase bins. Then, a quantity χ^2 expressed as

$$\chi^2 = \sum_{i=1}^{M} \frac{(x_i - \bar{x})^2}{\sigma_i^2}, \tag{12}$$

is estimated, where x_i and σ_i represent the mean and standard deviation, respectively, of each of M phase bins. For the observations distributed as Gaussian noise, we generally find $\chi^2 \sim M$. However in case of the observations containing periodic signals, χ^2 takes a value which is significantly different (or the maximum) from the average value (see Larsson, 1996).

4.3.3. Significance Estimation: Power spectrum response method (PSRESP)

In astronomical time series analysis a number of artefacts including red-noise like behavior, discrete data, finite observation length, and uneven data sampling potentially could interfere with the analysis and produce spurious features which could be mistaken as real signals. Therefore to estimate the significance of the spectral features such effects should be analyzed in detail, especially when searching for QPOs. In addition, there is a pitfall that blazar variability is, in general, of a colored noise type, with larger amplitude fluctuations at longer variability timescales; with such, high amplitude peaks in the lower frequency region of the periodograms can sometimes pose as QPO features (Press et al., 1978). To address these issues, we adopted the power spectrum response method (PSRESP; see Uttley et al., 2002), a method involving intensive Monte Carlo (MC) simulations. The method is aimed at estimating the power spectral density (PSD) shape that best represents periodogram of an unevenly spaced light curve. The method properly takes account of a number of artefacts, usually unavoidable in frequency domain analysis, such as *red-noise leak*, *aliasing* and PSD distortion due to unevenly spaced sampling. In addition, it provides a measure for goodness of fit and, thereby, estimates uncertainties in the model parameters. The method is fully described in Uttley et al. 2002 (see also Bhatta et al. 2016b and Appendix in Chatterjee et al. 2008); here, for completeness, we briefly summarize the method as following:

i) For a given time series $f(t_j)$ sampled at times t_j with $j = 1, 2, ..., N$ during an observational period T, the periodogram at a given frequency ν is estimated using the expression

$$P(\nu) = \left| \sum_{j=1}^{N} f(t_i)\, e^{-i2\pi\nu t_j} \right|^2 . \tag{13}$$

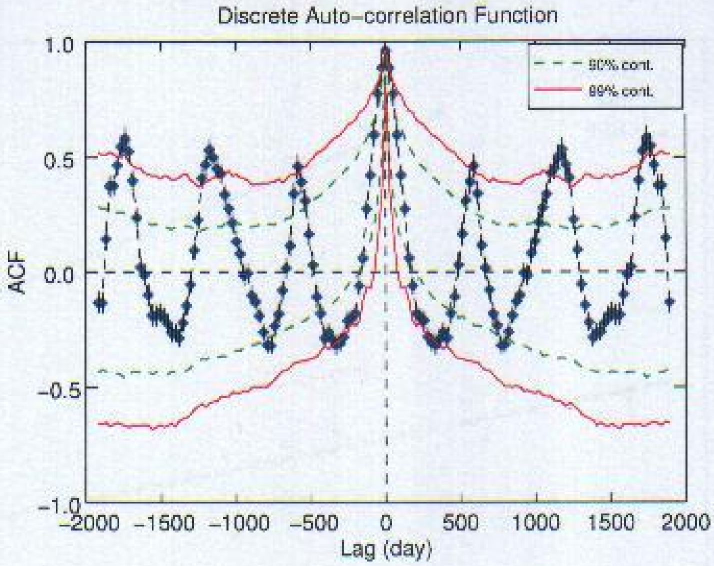

Figure 2: z-transformed discrete auto-correlation function of the ~ 10.5 years long 15 GHz observations of the blazar J1043+2408. The re-occurring peaks suggest of underlying ~ 560 day periodic radio signal. The dashed green and red curves represent the 90 and 99% significance levels, respectively (from Bhatta, 2018).

Often, to express the variability power in terms of fractional variation, a normalization of the kind $N^2\mu^2/2T$ is applied, where μ stands for the mean flux during the entire observational period. The periodogram is computed at regular frequency grid starting from the minimum frequency ν_{min}=1/T to maximum (Nyquist) frequency $\nu_{max} = N/2T$.

ii) To estimate power-law index that best represents a given periodogram, a large number of light curves (typically 1000) are simulated based on a power-law model of the form $P(f) = \nu^{-\beta} + C$, where β and C stand for power-law index and the Poisson noise. Thus simulated light curves, subsequently, are re-sampled according to the source light curve before periodogram for each one of them is calculated.

iii) For each of the simulated light curve, a χ^2-like quantity is constructed which is given as

$$\chi_i^2 = \sum_{\nu_{\min}}^{\nu_{\max}} \frac{\left[\overline{P_{\rm sim}(\nu)} - P_i(\nu)\right]^2}{\overline{\Delta P_{\rm sim}(\nu)}^2}, \tag{14}$$

where $\overline{P_{\rm sim}(\nu)}$ and $\overline{\Delta P_{\rm sim}(\nu)}$ represent the mean periodogram and the standard deviation of the simulated periodograms; a similar quantity for the observed periodogram, $\chi^2_{\rm obs}$, is also evaluated by replacing P_i with $P_{\rm obs}$.

iv) Step iii) is repeated for a number of indices of the power-law model.

v) The goodness of fit between the mean simulated periodogram and the observed periodogram is estimated by comparing $\chi^2_{\rm obs}$ with χ^2_is. In particular, to quantify the goodness of the fit for a given index, the ratio of the number of χ^2_is greater than χ^2_{obs} to the total number of χ^2_is in all simulations is defined as the probability that the model, with the given index, best represents the source periodogram.

The above method of estimating the significance of a spectral peak provides *local* estimates as it represents the significance only at a particular period. Since we do not have *a priori* knowledge of where the significant peak might occur, a more robust measure of the significance can be *global significance* which is associated with the fraction of the simulated powers at any period below the observed power at the period of our interest (see Bhatta, 2017 and Bell et al. 2011).

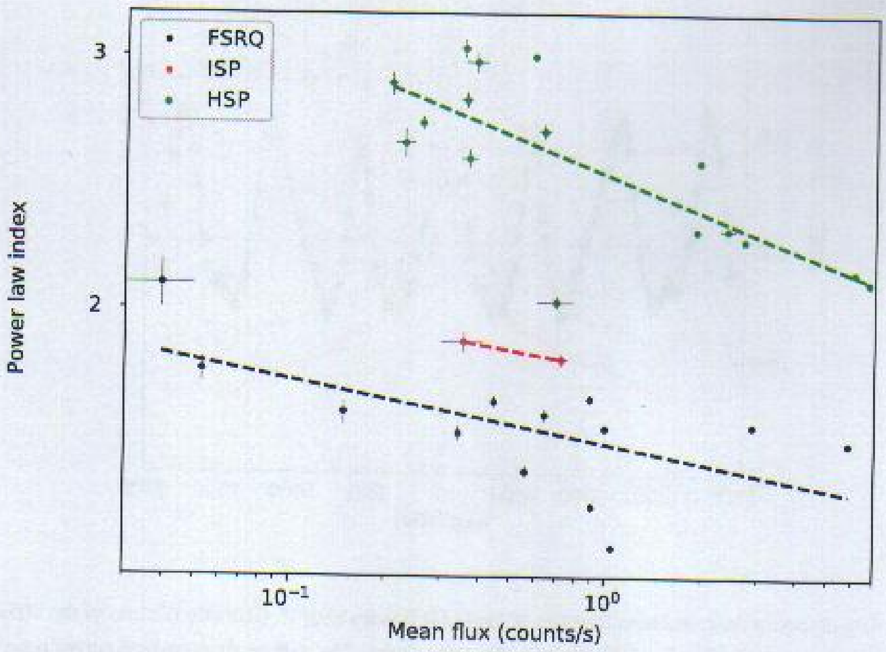

Figure 3: Distribution of the *NuSTAR* power-law photon indexes over the mean fluxes for flat spectrum radio quasars (black), intermediate frequency synchrotron peaked blazars (red), and high frequency synchrotron peaked blazars (green). The dashed lines represent the corresponding linear best fits. The distribution reveals the blazar sub-classes (from Bhatta et al., 2018c).

4.3.4. Overview of individual publications:

H1. Detection of periodic radio signal from the blazar J1043+2408

In this most recent work of mine, I discovered a repeating radio signal in the blazar J1043+2408. I performed multiple methods of time series analysis, including epoch folding, Lomb-Scargle periodogram, and discrete auto-correlation function, on the radio observations from OVRO spanning ~10.5 years. To robustly account for the red-noise processes usually dominant in the blazar variability and other possible artifacts, a large number of Monte Carlo simulations were performed. All three methods consistently revealed a repeating signal with a periodicity of ~ 560 days. Using PSRESP method I estimated a high significance (99.9% local and 99.4% global) against possible spurious detection. After discussing a number of possible scenario, I concluded that the observed periodic oscillations could most likely be originated in binary supermassive black hole system with a secondary to primary black hole mass ratio 0.01–0.1, and with a separation of a few parsecs Such a close binary supermassive black hole system would undergo gravitational coalescence within a few centuries accompanied with the emission of gravitational waves of the frequency ~ 10^{-2} μHz

H2. Hard X-ray properties of NuSTAR blazars:

This work was a result of collaboration with the foreign students who visited us under 'Summer Internship Program for Astronomy and Physics'. I spent six weeks supervising and teaching them blazar X-ray analysis. In this work, one of the most comprehensive work using NuSTAR observations, we investigated the hard X-ray emission properties of blazars as an attempt to understand the central engine of the sources and associated jet process. In particular, simultaneous spectral and timing analyses of the intraday hard X-ray observations provide us a means to peer into the compact innermost blazar regions. The main objective of the work was to associate the observed hard X-ray variability properties in blazars with their flux and spectral states, thereby, based on the correlation among these states, extract the details about the emission regions and processes occurring near the central engine. We carried out timing, spectral, and cross-correlation analysis of 31 NuSTAR observations of 13 blazars. We investigated the spectral shapes of the sources in the give band using single power-law, broken power-law, and log-parabola models and used F-test to estimate the best-fit spectral shape. We also studied the co-relation between

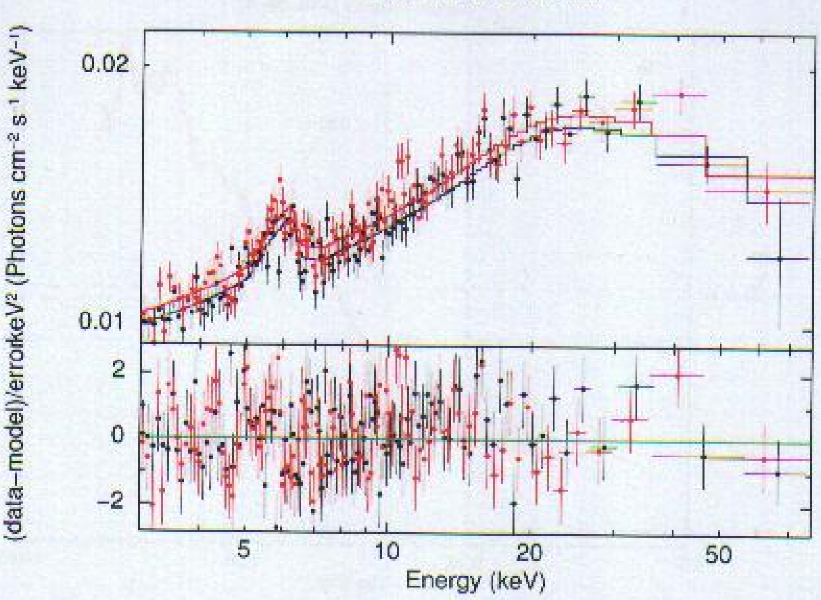

Figure 4: Spectral modeling of the NuSTAR data for the giant radio galaxy 4C+74.26, assuming the relativistic reflection model (upper panel), with the corresponding residuals (lower panel). The modeling assumes the X-ray emission originating from the innermost accretion disk where the effects of the strong gravity and fast rotation of supermassive black hole prevail. Red and black symbols/curves correspond to the NuSTAR modules FPMA and FPMB (from Bhatta et al., 2018b).

the soft (3-10 keV) and hard emission (10-79 KeV) using z-transformed discrete correlation function. In addition, we attempted to constrain the smallest emission regions using minimum variability timescales derived from the light curves. We found a number of interesting results:

- We observed that, for most of the sources, the hard X-ray emission can be well represented by the log-parabola model and that the spectral slopes for different blazar sub-classes are consistent with the so-called blazar sequence.
- We also reported the steepest spectra with photon index ~ 3 in the BL Lacertae PKS 2155-304 and the hardest spectra with photon index ~ 1.4 in the flat- spectrum radio quasar PKS 2149-306.
- In addition, we noted a close connection between the flux and spectral slope within the source subclass in the sense that high flux and/or flux states tend to be harder in spectra.

Furthermore, in BL Lacertae objects, assuming particle acceleration by diffusive shocks and synchrotron cooling as the dominant processes governing the observed flux variability, we constrain the magnetic field of the emission region to be a few Gauss; whereas in flat-spectrum radio quasars, using external Compton models, we estimate the energy of the lower end of the injected electrons to be a few Lorentz factors.

H3. Signatures of the disk-jet coupling in the Broad-line Radio Quasar 4C+74.26:

4C+74.26 is a quasar having unimaginably giant radio lobes that extend up to ~ 3 million light years from the central black hole. The target is unique in that its radiative output at radio wavelengths is dominated by a moderately-beamed nuclear jet, at optical frequencies by the accretion disk, and in the hard X-ray range by the disk corona. we explore the disk-jet connection by conducting cross-correlation analysis of the long-term MWL light curves and discovered that the optical emission was delayed behind radio emission by ~ 250 days. Since relativistic jets in active galactic nuclei (AGN) are widely believed to be launched by magnetic fields supported by the disks and entering the ergospheres of spinning black holes, the flux changes could be naturally identified with magnetic perturbations within the innermost parts of the accretion disk. Therefore, to further zoom into the central engine, we performed spectral analysis the source using hard X-ray observations from NuSTAR space telescope. The spectra were analyzed within the framework of coronal emission reflected by a fast rotating inner regions of the accretion disk that

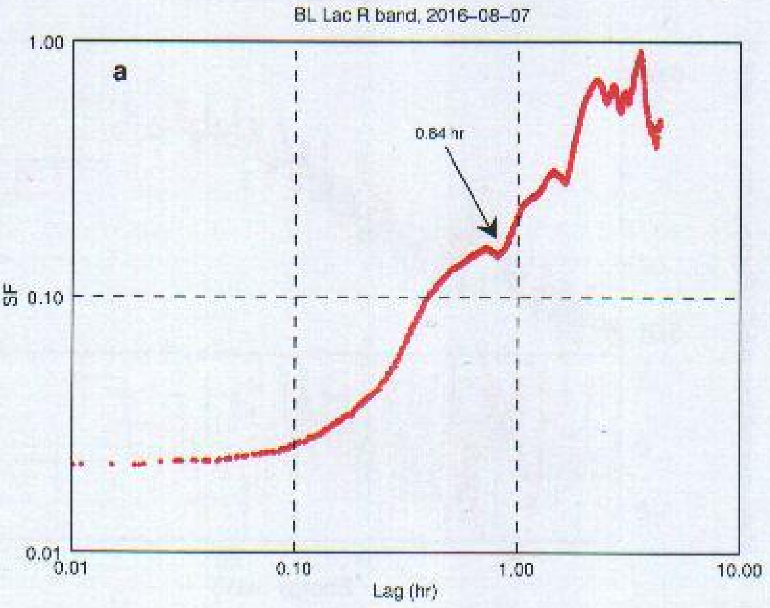

Figure 5: The structure function of intranight observations of the blazar BL Lac showing a possible characteristic timescale of ~ 1 hr from Bhatta & Webb (2018).

boosts the energy of the photon to higher energies, in particular, hard X-ray. The modeling accounted for some of the exotic events including bending of the light and space-time drag near the fast rotating supermassive black holes. This scenario is supported by the analysis of the NuSTAR data, modeled in terms of a relativistic reflection from the disk illuminated by the coronal emission, which returns the inner disk radius $R_{\rm in}/R_{\rm ISCO} = 35^{+40}_{-16}$. We discussed the global energetics in the system, arguing that while the accretion proceeds at the Eddington rate, with the accretion-related bolometric luminosity $L_{\rm bol} \sim 9 \times 10^{46}\,{\rm erg\,s^{-1}} \sim 0.2L_{\rm Edd}$, the jet total kinetic energy $L_{\rm j} \sim 4 \times 10^{44}\,{\rm erg\,s^{-1}}$, inferred from the dynamical modeling of the giant radio lobes in the source, constitutes only a small fraction of the available accretion power.

H4. Microvariability in BL Lacertae: "Zooming" into the Innermost Blazar Regions

In this work, we presented the results of our multi-band microvariability study of the famous blazar BL Lac. We performed microvariablity observations of the source in the optical VRI bands for 4 nights in the year 2016. We closely studied the intranight flux and spectral variability of the source in detail with an objective to characterize microvariability in the source, a frequently observed phenomenon in blazars. We used the methods of time series such as structure function and z-transformed auto-correlation function to characterize the statistical properties of the variable blazar. In addition, we studied multi-band cross correlation in the source. The results showed that the source often displayed rapid flux variability with an amplitude as large as 0.2 magnitude within a few hours, and that the color variability in the similar time scales can be characterized as "bluer-when-brighter" trend. We also notices markedly curved optical spectrum during one of the nights. Furthermore, the correlation between multi-band emission showed that in general the emission in all the bands are highly correlated; and in one of the nights V band emission was found to lead the I band emission by 20 minutes. The search for characteristic timescale using auto-correlation function and the structure function analyses reveals characteristic timescale of ~ 48 minutes in one of the R band observations. We explained the observed results in the context of the passage of shock waves through the relativistic outflows in blazars.

H5. Radio and γ-Ray Variability in the BL Lac PKS 0219-164: Detection of Quasi-periodic Oscillations in the Radio Light Curve:

In this work, I studied the long-term variability properties of the blazar PKS 0219-164 using the radio and the γ-ray observations from the period 2008–2017. The radio observations were obtained from the

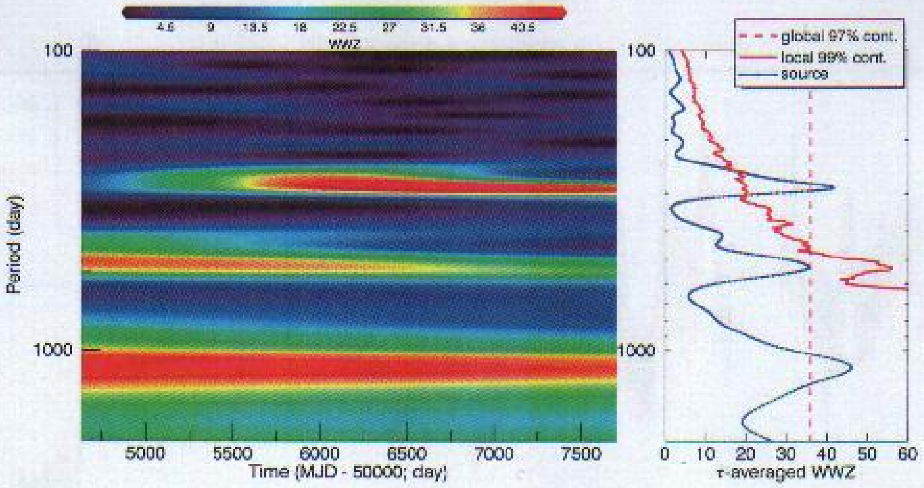

Figure 6: Weighted wavelet z-transform of OVRO light curve for the blazar PKS 0219-164. The left panel shows the distribution of color-scaled WWZ power in the time-period plane, and the right panel shows the time averaged power (blue curve) as a function of period. The red curve and the magenta line show the 99% local significance and 97% global significance contours, respectively, from the MC simulations (Bhatta 2017).

OVRO 15 GHz telescope whereas the γ-ray observations were gathered from the Fermi/LAT telescope. The analysis resulted three main results:

i) γ-ray emission was found to be more variable than the radio emission. This could imply that γ-ray emission possibly originated in more compact regions while the radio emission represented continuum emission from the large-scale jets.

ii) The source exhibited spectral variability, characterized by the softer-when-brighter trend, a less frequently observed feature in the high-energy emission by BL Lacs.

iii) The radio observations studied using Lomb-Scargle periodogram and weighted wavelet z-transform revealed the presence of a strong QPO signal with a periodicity of ~ 270 days with possible harmonics of ~ 550 and ~ 1150 day periods.

I concluded that at a time when detection of QPOs in blazars are still under debate, the observed QPO with high statistical significance (97–99 %) global significance over underlying red-noise processes) and persistent over nearly 10 oscillations could make one of the strongest cases for the detection of QPOs in blazar light curves. In addition I discussed relevant blazar models that might lead to the γ-ray and radio variability, the QPO, and the achromatic behavior seen in the high-energy emission from the source.

H6. Multifrequency Photo-polarimetric WEBT Observation Campaign on the Blazar S5 0716+714: Source Microvariability and Search for Characteristic Timescales:

This work is an effort to conduct a most detailed study of small sub-structures of blazar jets using multi-band observations with unprecedented time resolution. After the success of the WEBT campaign in 2009[4], we wanted to further study one of the highly variable blazar S5 0716+71 using multiband photo-polarimetric simultaneous observations. I coordinated the Whole Earth Blazar Telescope photo-polarimetric campaign targeting the the source in 2014 March to monitor the source simultaneously in BVRI and near-IR filters[5]. The campaign resulted in an unprecedented data set spanning 110 hr of nearly continuous, multiband observations (shown in Figure 7), including two sets of densely sampled polarimetric data mainly in the R filter. During the campaign, the source displayed pronounced variability with peak-to-peak variations of about 30% and bluer-when-brighter spectral evolution, consisting of a day-timescale modulation with superimposed hour-long microflares characterized by 0.1 mag flux changes. We performed an in-depth search for quasi-periodicities in the source light curve; hints for the presence of oscillations on timescales of 3 and 5 hr did not represent highly significant departures from a pure

[4] http://www.oato.inaf.it/blazars/webt/webb.html

[5] http://www.oato.inaf.it/blazars/webt/gopal.html

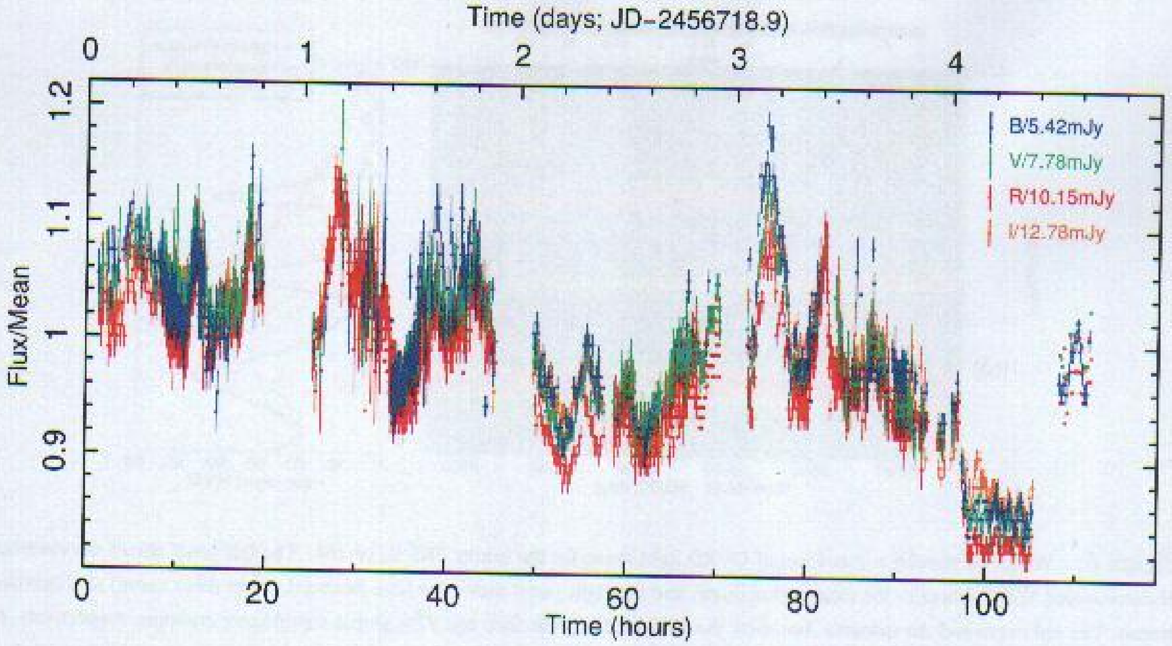

Figure 7: Simultaneous multiband (BVRI) light curve of the blazar 0716+714 spanning 130 hrs from the WEBT campaign 2014 (Bhatta et al., 2016c)

red-noise power spectrum. We observed that, at a certain configuration of the optical polarization angle (PA) relative to the PA of the innermost radio jet in the source, changes in the polarization degree (PD) led the total flux variability by about 2 hr; meanwhile, when the relative configuration of the polarization and jet angles altered, no such lag could be noted. The microflaring events, when analyzed as separate pulse emission components, were found to be characterized by a very high PD (> 30%) and PAs that differed substantially from the PA of the underlying background component, or from the radio jet positional angle. The analyses resulted a number of interesting results about the innermost structures of the relativistic jets. Some of the results can be listed as below.

- The overall statistical nature of the microvariability closely resembled a red-noise type processes of the form $P(\nu) \propto \nu^{-\alpha}$. In addition, the previous claims of the QPOs in the time scales of few hours were proven to be inconclusive.
- Discovery of some of the highly polarized micro-flares suggested the presence of isolated but highly magnetized regions such as magnetic islands.
- The correlation between flux, polarization and the polarizing angle revealed magnetic field geometry was found to complex configured in a way dependent on the relative orientation of the ambient magnetic field and the jet base.

H7. Detection of Possible Quasi-periodic Oscillations in the Long-term Optical Light Curve of the BL Lac Object OJ 287:

Blazar OJ 287 is one of the most fascinating sources famous for its double-peak feature in optical light curve that repeats every ~ 12 years. It is the first blazar widely believed to be a binary supermassive black hole system. Astronomers have been monitoring the source for more than a century. Our research group is also monitoring the source from our observatories in Suhora and Krakow in Poland for more than a decade taking exceptionally well-sampled observations. This project primarily used the data from our own observations performed at the Mt. Suhora and Krakow Observatories in Poland. Again, the Lomb-Scargle periodogram and the weighted wavelet z-transform methods were employed to search for possible quasi-periodic oscillations in the resulting optical light curve of the source. It was interesting to find that apart from the ~ 12-year-period modulations, the methods yielded another quasi-periodic signal around the periods of ~400 days and along with a possible harmonics of ~800 days. The significance of the observed spectral features were estimated using PSRESP method. A number of likely scenarios trying

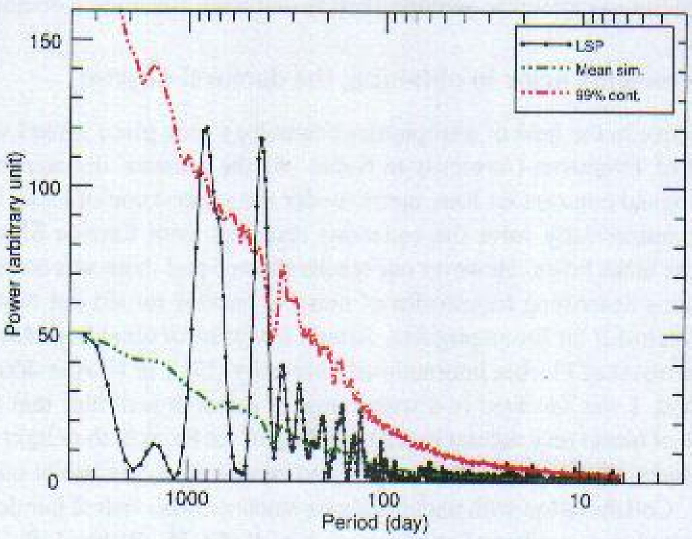

Figure 8: A ~ 400 d QPO with a possible harmonics of ~ 800 d was detected in the ~ 9.2 years optical light curve of the blazar OJ 287. The black curve represents the Lomb-Scargle Periodogram of the long-term light curve, the green curve shows the mean periodogram of 10000 simulated light curves and the red curve outlines the 99% significance contour (from Bhatta et al., 2016c).

to explain quasi-period are discussed in the literature, e.g. binary black hole, jet precession, wobbling jet, Lense-Thirring precession of the innermost parts of accretion disks etc. can result QPOs of various timescales. But for a QPOs of the timescales of few years, with preference given to a modulation of the jet production efficiency by highly magnetized accretion disks.

Final remarks:

The optical studies revealed that the statistical nature of the intra-day variability can be characterized by a single power-law PSD in the Fourier space; and that the multi-band observations are strongly correlated with an occasional lead/lag of a few tens of minutes between the wave bands. The results suggests that rapid variability most likely originates in highly magnetized compact substructure of the blazar jets, and the rapid particle acceleration and cooling mechanisms can be associated with either *shock-in-jet* model or magnetic reconnection in turbulent jets. From the distribution of the emission sizes derived from the minimum timescales, we found that some of the emission regions were smaller than the gravitational radius (r_g) of an AGN with a typical black hole mass of ~ 10^9 $M_\odot$. This can be possible either if the flux modulations occur at a fraction of the entire black hole region or in the scenario where the fluctuations reflect small-scale magnetohydrodynamic instabilities with the turbulent structures moving relativistically in random directions. Alternatively, high bulk Lorentz factors (e.g., $\Gamma \sim 100$) associated with the emitting regions, such as in *jets-in-a-jet* model, can make the size of these regions appear comparable to r_g. In BL Lacs, hard X-ray emission might represent the synchrotron emission from the high energy tail of the power-law distribution of the electrons. In such a case, the Lorentz factors for the highest energy electrons can be constrained as ~ 10^6, and the variability timescales can be directly linked to the particle acceleration and cooling timescales. Whereas in FSRQs, the emission could be result of the inverse-Compton of the circum-nuclear photon field (e.g. from dusty torus and broad-line region) by the low energy end of the distribution. In such a scenario, the energy of the particle turns out to be a few tens of Lorentz factors.

Our multi-wavelength long-term variability studies in a number of blazars conclude that the statistical long-term variability properties are still consistent with power-law PSD. But several sources exhibit QPO on top of the power-law continuum. Detailed analysis of such flux oscillations are of immense importance as the signals bear imprints of the processes occurring near the central engine, which is mostly inaccessible to our direct view. The oscillations can originate in various scenarios e.g. binary supermassive black hole, jet and disk precession. However, multi-frequency spectral and timing analysis of a sample of blazar would be necessary to single out the exact causes.

5. Summary of other scientific achievements:

Below I described my additional scientific activities before and after obtaining a doctoral degree.

5.1. Research achievements prior to obtaining the doctoral degree:

My first research experience in the field of astrophysics/cosmology took place when I was a Masters' student in the Physics Department of Tribhuvan University in Nepal. As the Masters' dissertation project, I investigated the effect of the cosmological constant on Kerr metric under the supervision of Prof. Udayraj Khanal. During the project, we tried to numerically solve the equations resulting from Kerr-de Sitter metric describing the trajectory of light near the black holes. However our results showed that there was no significant change in their trajectories. The equations describing trajectories of massive particle turned out to much more complicated, and we had to defer its treatment for future projects. After a few years of obtaining Masters' degree in Physics, I joined the Physics Department of Florida International university (FIU) in USA in 2007 for my further studies.

As a FIU PhD student, I was involved in a wide range of research activities that included making optical observations of a sample of blazar on a regular basis, modeling of the flares in their light curves and writing code, help undergraduate students with their research project and contribute to the public outreach programs such as 'Evening with the stars'. Collaboration with undergraduate students, who visited our department under *Summer Research Program*, resulted in a number of publications e.g. Rafle, H., Webb, J. R., Bhatta, G., *Determining cell sizes in the Turbulent Jet of Blazar S5 0716+714*, 2012, JSARA, vol. 7, p. 33-36 and Dhalla, S, Webb, R., Bhatta, G., & Pollock, J., *The Nature of Microvariability in Blazar 0716+714*, 2010, JSARA, vol. 4, p. 7-11. In addition, I collaborated with an international team of astronomers studying the spectral and timing properties of the blazar 0716+714. I contributed to the research by making optical observation of the source during several nights using SARA 0.9m telescope. The results of the multi-frequency campaign are published in 'Villata M, Raiteri, C. M., Larionov, V. M., et al. *Multifrequency monitoring of the blazar 0716+714 during the GASP-WEBT-AGILE campaign of 2007*, 2008, A&A 481, L79L82'

Blazar intranight variability studies conducted using single site observations are limited by the length of the night. Consequently, the variability properties of the sources in the timescales 8-24 hours (greater than the typical length of a night) are unconstrained. To address this issues, we adopted a novel approach to making observations. Then I along with my PhD supervisor Prof. James Webb coordinated a multi-site WEBT observation campaign and collected observations for 72 hrs without major interruption. Subsequently, we applied the resulted light curve our microvariaibity model and obtained the physical parameters including size of the turbulent regions and injection parameters. The results of the study are published in 'Bhatta, G., et. al. *The 72-h WEBT microvariability observation of blazar S5 0716 + 714 in 2009*, 2013, A&A, 558A, 92B' and the details of the campaigns and the modeling are included in my dissertation '*The nature of microvariability in the blazar 0716+714*'.

5.2. Research achievements after obtaining the doctoral degree:

After obtaining my doctoral degree in December 2012, I came to Poland to begin the postdoctoral position in the Astronomical observatory of Jagiellonian University, in the High Energy Astrophysics group led by Prof. Michal Ostrowski. Ever since I have been collaborating with the group. Over the years, we conducted many interesting research in the field of high energy astrophysics often making use of the observations from several space and ground based telescopes including Fermi/LAT, NuSTAR, OVRO and optical telescopes. We performed timing, cross correlation and spectral analysis of several blazars. My research in the observatory resulted in a number of papers including the ones listed above. Besides, we reported *Discovery of a Highly Polarized Optical Microflare in Blazar S5 0716+714 during the 2014 WEBT Campaign*, 2015 ApJ, 809L, 27B. The scientific cooperation with prof. Ostrowski and prof. Stawarz has continued up to present.

In addition, I am also a part of Cosmic-Ray Extremely Distributed Observatory (CREDO) collaboration that aims studying the signatures of extremely high energy cosmic rays through a global network of instruments. The detail of the science, instruments and collaboration are presented in CERN Proceedings (arXiv:1804.05614). Similarly, the results of the study simulating the pre-super shower due to a high energy photon that passes through the Sun's magnetic field is ready to be submitted soon (Dhital et al. in preparation, arXiv:1811.10334).

Last year, I won the NCN grant SONATA 13 Poszukiwanie charakterystycznych skal czasowych oraz quasi-periodycznych oscylacji w blazarach: oddzialywanie dysk - dzet. (PI: G. Bhatta): that will fund me as a PI for 3 years (2018–2021). Feeling re-energized, I started to analyze Fermi blazars and so far I detected periodic variations in the flux of Mrk 501. (Bhatta, G., Blazar Mrk 501 shows rhythmic oscillations in its γ-ray emission, arXiv:1808.06067). The findings were reported by the international media including phys.org.

5.3. Ongoing works and Future plans:

As part of the proposed NCN research, my current works are centered around 'MWL variability study of blazar' as an probe of the central black hole, disk-jet connection and jet physics. I am performing a systematic study of γ-ray light curve of a number of blazars systematically searching for QPOs and characteristic timescales, utilizing the decade-long Fermi/LAT observations. Once the analysis in the γ-ray domain concludes, the future works will be oriented in conducting a statistical study of light curves (of the same sources) in other electromagnetic bands e.g. radio, optical and X-ray and thereby looking for the spectral feature that is common to two ore more wave bands. The possible outcomes, in combination with previously estimated physical parameters such as mass, luminosity and accretion rate, can help gaining a comprehensive understanding of blazar processes.

In addition, currently I am involved in the timing and spectral analysis of one of the famous blazar Mrk 421. To obtain high resolution multi-band observations, I coordinated the WEBT campaign in January 2019[6]. The campaign was organized during the long look by AstroSat instruments as per the successful AstroSat proposal by my colleague Alex Markowitz. The global collaboration is participated by several instruments such as IRAM 30m Millimeter Radio telescope, Metsahovi Radio Observatory (37 GHz), Owens Valley Radio Observatory (OVRO), WEBT (radio, near-infrared and optical) and MAGIC telescope. The work is in progress.

6. Bibliometric data (until 11th March 2019):

Number of citations;
from the Web of Science (WoS) database: 156 (126 without self-citations)
from the ADS database: 211

h-index :
according to WoS: 6
according to ADS: 7

The total Impact Factor for all the publications
according to the Journal Citation Reports (JCR) list: 44.45

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