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Multi-wavelength Study of Blazars Using Variability as a Tool

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Active galactic nuclei (AGN) are too compact to be resolved by any existing optical telescope facility, making it difficult to understand their structure and the emission processes responsible for their huge energy output. However, variability, one of their characteristic properties, provides a tool to probe the inner regions of AGN. Blazars are the best candidates for such a study, and hence a considerable amount of effort is being made to investigate variability in these sources across the electromagnetic spectrum. Here, using the Mt. Abu infrared observatory (MIRO) blazar monitoring program, we present intra-night, inter-night, and long term aspects of the variability in S5 0716+71, 3C66A, and OJ 287. These stars show significant variability on short (a few tens of mins, to a few hours, to a few days) to long term (months to years) timescales. Based on the light travel time argument, the shortest variability timescales (micro-variability) provide upper limits to the size of the emission region. While S5 0716 shows a very high duty cycle of variability (> 80 %), 3C66A shows a much lower intra day variability (IDV) duty cycle (< 20 %). All three show rapid variations within 2.5 to 3.5 hr, which, perhaps, are generated near the vicinity of black holes. Assuming this, estimates of the masses of the black holes are made at ~10^9, 8×10^8, and 2.7×10^9 $M_\odot$ for S5 0716+71, 3C66A, and OJ 287, respectively. Multi-wavelength light-curves for the blazar PKS 1510-089 are discussed to infer the emission processes responsible for the recent flaring episodes in this source.

Keywords: active galactic nuclei, blazars, optical photometry

1. INTRODUCTION

Blazars, a sub-class of active galactic nuclei (AGN), have their relativistic jet pointed towards the line of sight of the observer and hence their emission is Doppler boosted and jet dominated (Urry & Padovani 1995). Though almost all AGN show variations in their flux, blazars are extremely variable across the whole electromagnetic spectrum. The variability time scales range from a few minutes to several years (Chandra et al. 2011). Since AGN are very compact and at high red-shift, their central engines, responsible for high and variable emission, are not spatially resolvable. This is one of the main hurdles in attempts to understand the structures and physical processes that lead to their emissions. Variability in blazars provides a useful tool to study the innermost regions of the central engine because these bodies are seen at a very small angle to the direction of the jet that emanates from the close vicinity of a black hole (Ciprini et al. 2003, 2007). Blazars' multi-wavelength light-curves and spectral energy distribution are the essential parameters to constrain the models proposed for their emission. The nature and shape of the blazar continuum spectral energy distributions (SEDs) can be sub-classified into flat spectrum quasars (FSRQ), low energy peaked BL Lacs (LBL), intermediate energy peaked BL Lacs (IBL), and high energy peaked BL Lacs (HBL). While FSRQs show significant emission lines, these lines are rare or very weak in other subclasses. In their two humped SED, the location of first component (synchrotron) peak frequency is used to distinguish LBL, IBL, and HBL; the peak frequency increases from LBL to HBL. While the first component results from synchrotron emission due to the presence of relativistic

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electrons in the magnetic field, the second component is due to up-scattering of the low energy (seed) photons, the origin of which is still debatable, by the relativistic electrons. Long term, high temporal resolution, (quasi-) simultaneous data across the electromagnetic spectrum are required to generate high quality light-curves; spectral energy distributions are required to understand the origin of these photons. In spite of the large number of coordinated campaigns involving space and ground facilities (e.g. Böttcher et al. 2005), our understanding of these sources has not been satisfactory and a lot needs to be done to collect the maximum possible amount of information about these sources.

We are conducting a blazar monitoring program at the Mt. Abu infrared observatory (MIRO) which houses 1.2 m and 0.5 m telescopes; at this facility, a sample of sources is being observed. The program aims to study the microvariability as well as the long term trends in the light curves of these sources. In this study, we discuss some of the results for S5 0716+71, one of the most active blazars, and results for 3C66A and OJ 287, the only confirmed binary black hole system which flared up during 2015-16. Multi-wavelength light curves provide insight into the emission processes responsible for the blazar emissions. We present and discuss recent flares in PKS1510-089 using data from *Swift*, *Fermi*, and our own optical data.

2. OBSERVATIONS AND DATA ANALYSIS

The photometric observations of S5 0716+71, 3C66A, and OJ 287 were performed using the liquid nitrogen cooled CCD-camera mounted on the f/13 Cassegrain focus of the 1.2 m telescope at the Mt. Abu infrared observatory, Gurushikhar, Rajasthan, operated by the physical research laboratory, Ahmedabad, India. The PIXELLANT CCD camera has 1,296×1,152 square pixels, each with 22 micron size, and a total readout time of about 13 seconds. With a scale of 0.29 arcsec per pixel, the total field of view is about 6.5×5.5 $arcmin^2$. In October 2014, the MIRO 1.2 m was mounted with an iKon ANDOR CCD camera (2,048×2,048). The CCD in this camera is cooled to -80°C via thermoelectric cooling to keep the dark current very low. The CCD-photometric system is equipped with a Johnson-Cousin UBVRI filter set. The general observation strategy was to take about 4 frames in the B, V, R, and I bands and then monitor the source in the R-band for a few hours, keeping the number of standard stars in the same field as the source. The followings are details of the observations for each source.

S5 0716+71 :

This has been one of the most active blazars, and has been the favorable target of many campaigns (e.g. Wagner & Witzel 1994; Dai et al. 2015), and it's activity is still surprising. The observations used here were made during December 2005 – November 2012. Out of 162 total nights of observation, 68 nights were monitored with more than two hours of duration to estimate the duty cycle of the variability which corresponds to the number of nights when the source showed intra-night (micro-) variations. To check the color information, observations in the BVR and I optical bands were made.

3C66A :

During our observation campaign from November 06, 2005 to February 01, 2015, 3C66A was observed for a total of 132 nights in the BVRI bands; during this period, to address intra-night variations, 3C66A was monitored for at least 1 hr with a temporal resolution of better than 1 min in the R band for 65 nights to address intra-night variations, leading to a total of 11,973 data points for the source. The number of data points obtained in B, V and I bands are 511, 1,189 and 769, respectively, during the period of the campaign.

OJ 287 :

For this source, we report only the observations made during the recent flaring. As predicted by Valtonnen et al. (2012), OJ 287 was to undergo a new phase of outburst beginning in November 2015. We, therefore, started observing the source on nights available to us from October 21, 2015 to January 2, 2016. The observations were made mostly in the R band but other bands were also used to obtain color information. On a few nights, source was monitored for more than two hours to check for IDV.

Data reduction was performed using standard routines in IRAF software. All CCD frames were subject to data reduction with batch procedures, using standard methods, to correct each raw image for bias signals and flat fielding. The aperture photometry was carried out using the correct size of aperture chosen carefully considering the optimum value of the S/N ratio and the prescription of Cellone et al. (2000) to avoid spurious variations.

Calibration of the source magnitude was performed with respect to comparison stars in the same field. We used one of the three stable stars close to the source in brightness as a comparison star and the rest were used as control stars to construct differential light curves.

To assess the intra-day variability of the blazar under consideration, a C statistical test for days on which the source was monitored for at least 1 hr was carried out. The variability parameter, C, first employed by Jang & Miller (1997) and generalized by Romero et al. (1999), is defined as follows:

$$C = \frac{\sigma_{BL-C}}{\sigma_{C1-C}} \qquad (1)$$

where $\sigma_{BL\text{-}C}$ and $\sigma_{C1\text{-}C}$ are the standard deviations of the (source – comparison star) and the (control star – comparison star), respectively. A value of $C > 2.576$ is the criterion on which the source is classified as variable at the 99 % confidence level for the corresponding night. In addition to this, for intra-night variability, we also constructed structure functions for all the sources on the nights when these were monitored. Structure functions provide information on whether source is variable and help estimate the time scale of variation.

PKS 1510-089 is an FSRQ at a redshift of 0.361 and showed a large number of flares during the period of 1 January 2006 (day 1 in the plot) to June 2012. We obtained publicly available data for X-ray and UV from *Swift*, Gamma-ray data from the LAT on board the *Fermi*, and 2 cm data from MOJAVE (Lister et al. 2009). Standard analysis procedures were used to analyze the data in the respective energy regimes.

3. RESULTS AND DISCUSSION

The photometric data obtained after the differential photometry, using the same aperture for the photometry of source and comparisons, were used to plot differential light curves for (source - comparison star) and (comparison star - control star) in the R-band. Apparent brightness magnitudes were obtained for the sources (S5 0716+71, 3C66A, and OJ 287) to address their long term behavior and color. In the following we discuss these results for each individual source.

3.1 S5 0716+71

The criterion for the source to show intra-night variations is that the source should be observed for more than two hours during a night that is free from large variations in observation. 68 nights met this condition. The total number of nights that passed the C-test (a value greater than 2.576) and the number of nights that showed amplitude of variation larger than 0.05, were 50 (F-test was also used) and 57, respectively. Thus, the duty cycle of variability values, in the two cases, were estimated at 74 % (99 % confidence) and 84 %, respectively. The results are shown in Fig. 1. In Fig. 2, we plot the differential light curve for January 20, 2012 as a representative of all the light curves of the 68 nights. S5 0716+71 shows a variation of 0.22 of magnitude in the R band within a 2.3 hr timescale. Based on the light crossing timescale, this rapid variability puts an upper limit on the size of the emission region of 2×10^{15} cm. Assuming that these variations are manifestations of events taking place in the vicinity of the central engine, the mass of the black hole comes out to be ~ $10^9\ M_\odot$. During this period of about 7 yr, we looked at how the amplitude of variation changed with the average brightness of the source. Normally, one would expect that because the jet is the dominant contributor to the emission, the amplitude of variation would be larger

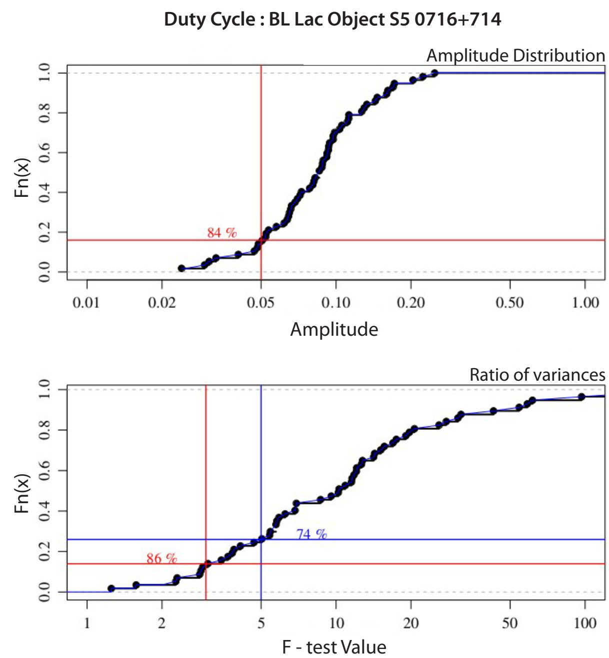

Fig. 1. Duty cycle of intra-night variations for S5 0716+71. Both extent of amplitude variation (> 0.05 mag) and F-test are used.

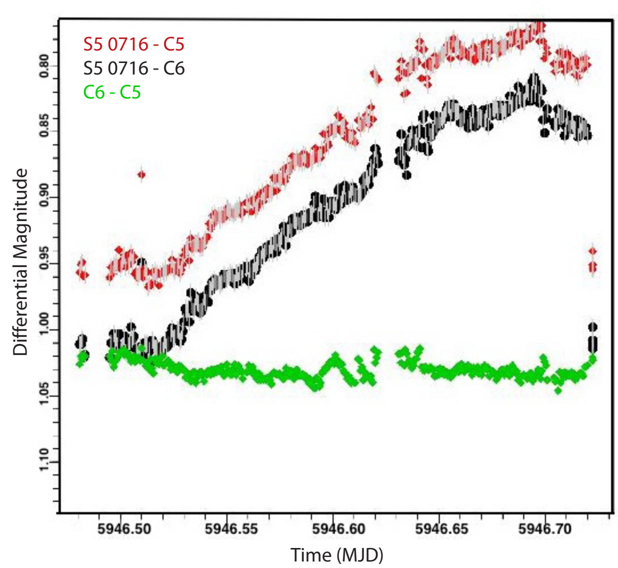

Fig. 2. Intra-night variation in S5 0716+71 on January 20, 2012, showing a variation of ~0.21 mag in R-band at a time scale of 2.30 hr. The red, black and green differential light-curves are for (S5 0716+71 - C5), (S5 0716+71 - C6) and (C6 - C5), respectively.

when the source was brighter. Contrary to this, we noted that the amplitude of variation was larger when the source was fainter; however, the source was found to be variable on a smaller number of days in this case. Fig. 3 shows the amplitude of variation as a function of the average brightness magnitude. It is very difficult to understand this behavior and more data for the sample are required. If the jet emission is dominant, the source should either have larger amplitude of variation during the bright phase or at least similar values of amplitude of variation in both cases. In the faint state, variability might be reduced slightly due to thermal emission if the host galaxy is sufficiently bright.

During the period of our observations, we also noticed a mild decrease in the average brightness of the source in all the bands. It should be pointed out that Nesci et al. (2005) showed the average brightness in the source increased over the period from 1995 to 2003. Earlier data also showed trends of decrease and increase in the brightness over a period of 10 yr or so. This variability was ascribed to precession of the jet, which affected the viewing angle: when the angle is decreasing the source will be seen to be brighter, while increasing the viewing angle will result in the fainter source. Fig. 4 shows the long term behavior of the source during the period of 2005-2012; it can be seen that there are a number of large flares superposed on a slowly decreasing trend. These flares could be due to shock moving down the jet and interacting with local inhomogeneities or stationary/slowly moving blobs.

3.2 3C66A

Over the period of observations, 3C66A shows two major outbursts and a number of large flares superposed over these outbursts. The differential light curves obtained for the IDV show the source with an IDV duty cycle of about ~14 % only—much lower than that of S5 0716. Out of the 65 nights monitored for IDV, only 9 showed variability. On the 7th of November 2010, 3C66A was found to vary by 0.2 magnitude over a period of 2.88 hr (cf. Fig. 5). This time scale of variability indicates that the size of the emission region is smaller than 3.24×10^{15} cm and that the mass of the black hole is estimated to be $8\times10^{8}\ M_{\odot}$, which is in agreement with the value obtained by Böttcher et al. (2005).

3.3 OJ287

OJ287 is the only blazar confirmed to have a binary black hole system at its center. The rotation about the common center and the piercing of the primary black hole accretion disk by the secondary black hole results in twin outbursts in the light-curve with a (quasi-) periodicity of about 12 yr (Valtonen et al. 2012; Pihajoki 2014). The last outburst happened during the period of 2005-07, and was nicely traced. The next outburse was predicted to begin in November 2015 and a campaign to capture it was organized. Fig. 6 shows the light-curve during the period of October 21, 2015 – January 02, 2016 as observed from MIRO. This curve

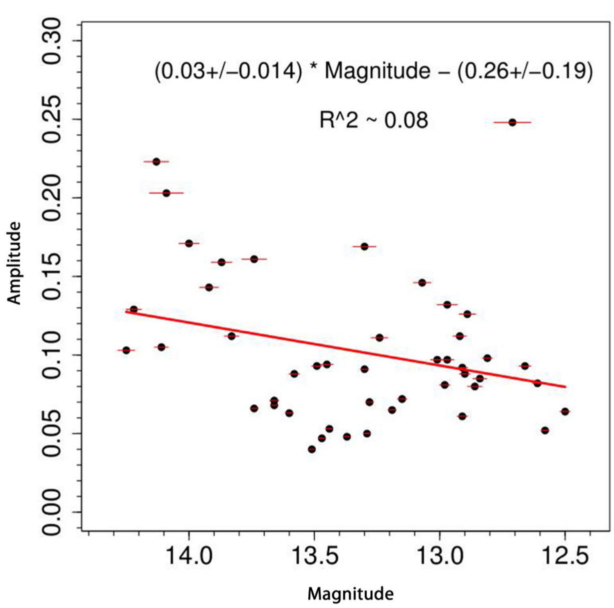

Fig. 3. Amplitude of variability as a function of average R band brightness magnitude of S5 0716+71 during the period from December 2005 to November 2012. It can be seen that the amplitude of variation is larger when the source is relatively fainter; however, IDV events are less frequent.

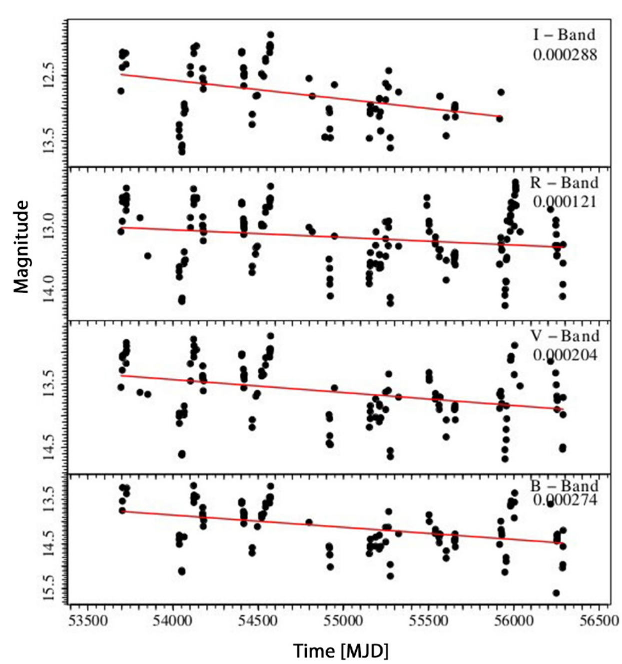

Fig. 4. Brightness magnitude vs. time in MJD during 2005-2012. A mild decreasing trend in the average brightness of S5 0716+71 is noticeable.

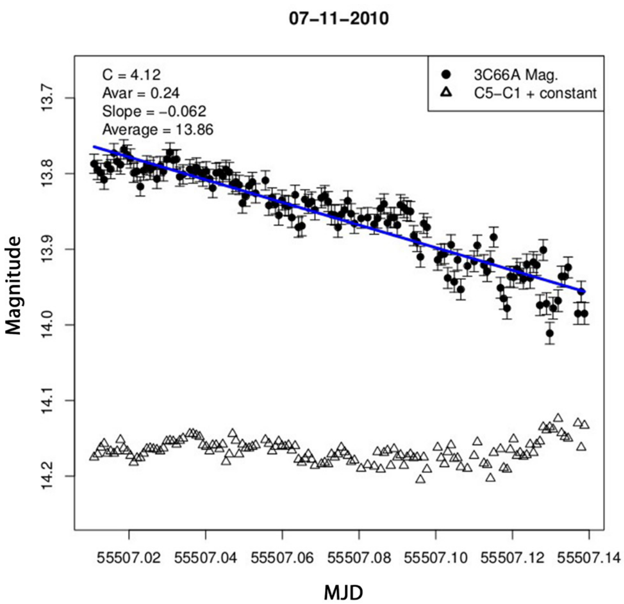

Fig. 5. IDV in 3C66A light-curve on 7 November, 2010. The timescale of variability is 2.88 hr.

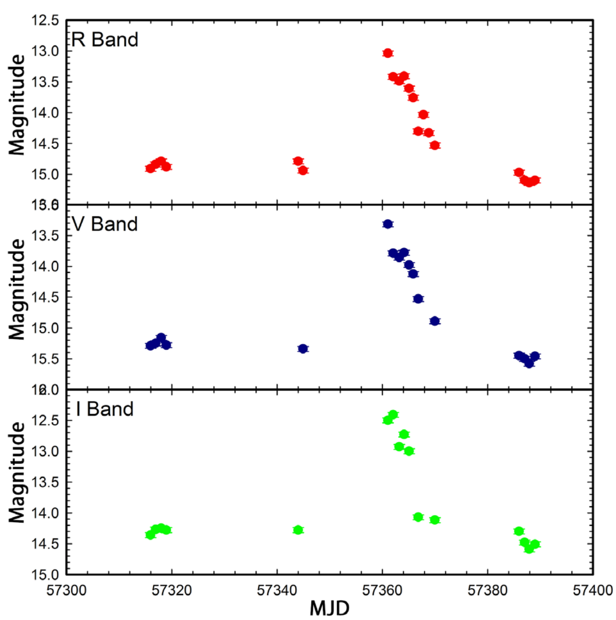

Fig. 6. OJ 287 in new outburst. The outburst peaked on 5 December 2015, with R-band magnitude of about 13.04. MIRO covered the peak and decaying part of the flare.

clearly shows the flare peaking on December 5, 2015 and decaying thereafter. The intra-night observations made on several nights during this period show that the source had an IDV on December 13, 2015, with a timescale of 3.35 hr, during which OJ287 brightened by 0.25 mag in R. Based on this, the upper limit on the size of the emission region and the resulting mass of the black hole were estimated to be 7.23×10^{15} cm and 2.7×10^{9} $M_{\odot}$, respectively, taking a Doppler

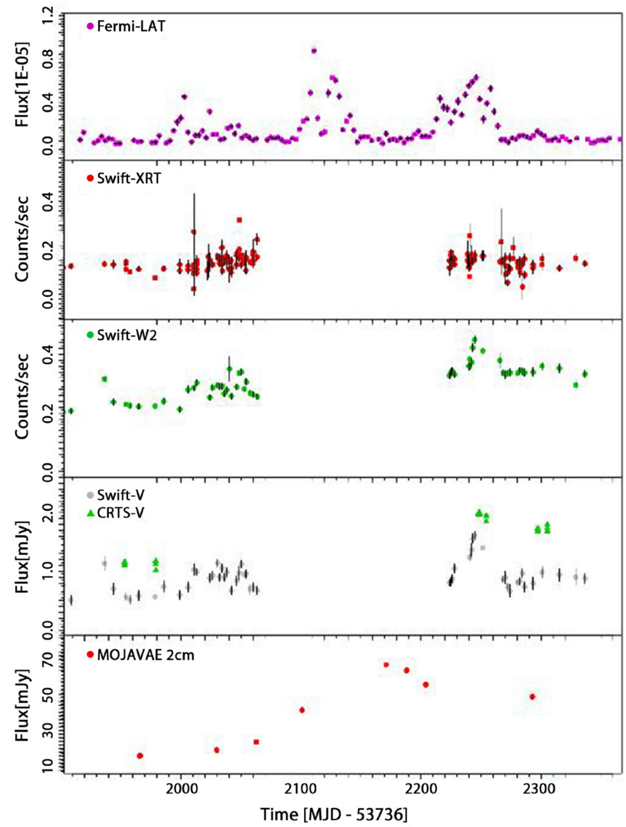

Fig. 7. Light curve of FSRQ PKS1510-089 during period of 24 February 2011 – 19 May 2012. X-axis shows days since 1 January, 2006. Data source and energy domains are given in each panel.

factor of 15. This is in agreement with the typical values obtained using the binary black hole model. Because this flare and the variation thereof are the result of emission from heated material due to the impact of the secondary black hole on the primary accretion disk, variability in flux is due to thermal activity in the disk. This might lead to a non-thermal flare when the ejected material is injected into the jet.

3.4 PKS1510-089

PKS1510-089 showed a number of flares during the period of January 1, 2006 (day 0:MJD 53736) – June 8, 2012 (day 2500:MJD 56086), during which intense episodic activities in all the bands were noticed. Flares are caused by moving disturbances (emission features) in the jet, passing through stationary cores, bends, or other density enhancements. This can also happen at the upstream of the core when a blob moves down the jet in a spiral streamline, passing through the collimation/acceleration zone which has a helical field. There are some flares that do not have counterparts in other bands; these are the so-called 'orphan flares'. Here we discuss the multi-wavelength light-curve during the period of February 24, 2011 (MJD 55616) – May 19, 2012 (MJD 56076) as shown in Fig. 7. There are three sets of multi-flares in gamma-rays, an enhanced X-ray, a large optical/UV flux, and the onset of a radio outburst on July 14, 2011 (day 2020). The first set of gamma-ray flares with 10 times the average flux, is an orphan flare caused by, perhaps, a shock (emission feature) passing through a region of low energy photons (IR/Opt/UV) or local ambient seed photons at the periphery of the jet. The second gamma-ray flare, centered on day 2110, showed a value of twenty times the averaged flux, and was not covered by the *Swift*, but is accompanied by enhanced radio flux (almost non-variable). The third set of multi-flares in the gamma-ray band, centered on day 2250 (February 29, 2012) could be nicely traced by optical/UV emission and enhanced X-ray flux. The radio outburst is in a decaying phase. The enhanced multi-frequency emission could be the result of the emission feature passing through a sub-mm core or a slowly moving blob.

4. CONCLUSIONS

Blazars are enigmatic sources due to their unresolved, highly compact sizes, long distances, and huge emission across the electromagnetic spectrum, whose emission is highly variable in nature. Keeping these properties in mind and using the observables, e.g., the variability in flux and polarization, spectral energy distribution, and correlated flux variability between various energy domains, one can attempt to infer the nature of these sources. Such an attempt is discussed in this work for S5 0716+71, 3C66A, OJ287, and PKS1510-089; results indicate that with simultaneous, high temporal multiwavelength data, it is possible to constrain the models of variability in terms of flux. It is also possible to determine blazar spatial extent, and to make rough estimates of the central engine masses and probable regions of the emitted flux. We conclude that S5 0716+71 is extremely variable, showing variability at levels from several hours to several years; it has a very high IDV duty cycle and a trend of alternating slow decay and rise in average flux. 3C66A shows many outbursts and has a low IDV duty cycle, and it has a lower mass of its black hole compared to those of S5 0716+71 and OJ 287. The recent outburst phase of OJ287 is discussed along with intra-day variation, which indicates that the size of the emission is 5.5×10^{15} cm and the mass of the primary black hole is in agreement with that obtained using the binary black hole model. PKS1510-089 shows a number of flares in different energy regimes, which are mostly simultaneous. Orphan flares could be a result of up-scattering of the low energy ambient photons at the periphery of the jet.

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