



Optical Variability in IBL S5 0716+714 during the 2013–2015 Outbursts

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Abstract

With an aim to explore optical variability at diverse timescales in BL Lac source S5 0716+714, it was observed for 46 nights during 2013 January 14 to 2015 June 01 when it underwent two major outbursts. The observations were made using the 1.2 m Mount Abu InfraRed Observatory telescope mounted with a CCD camera. On 29 nights, the source was monitored for more than 2 hr, resulting in 6256 data points in the *R* band, to check for the intra-night variability (INV). Observations in the *B*, *V*, and *I* bands with 159, 214, and 177 data points, respectively, along with daily averaged *R*-band data are used to address inter-night and long-term variability and the color behavior of S5 0716+71. The study suggests that the source shows significant INV with a duty cycle of more than 31% and night-to-night variations. The average brightness magnitudes in the *B*, *V*, *R*, and *I* bands were found to be 14.42 (0.02), 14.02(0.01), 13.22(0.01), and 13.02(0.03), respectively, while S5 0716+714 was historically brightest with *R* = 11.68 mag on 2015 January 18, indicating that the source was in a relatively high state during this period. A mild bluer-when-brighter behavior, typical of BL Lacs, supports the shock-in-jet model. We noticed larger amplitudes of variation when the source was relatively brighter. Based on the shortest timescale of variability and causality argument, the upper bound on the size of the emission region is estimated to be 9.32×10^{14} cm, and the mass of the black hole is estimated to be $5.6 \times 10^8 M_{\odot}$.

Key words: BL Lacertae objects: general – BL Lacertae objects: individual (S5 0716+714) – galaxies: active – methods: observational – techniques: photometric

1. Introduction

Blazars are a subclass of active galactic nuclei (AGNs) with their relativistic jet oriented toward the observer’s line of sight (Blandford & Königl 1979; Urry & Padovani 1995), leading to the Doppler-boosted emission from the jet. They show extreme variability in their brightness and polarization over the timescale of minutes to tens of yr. Owing to these properties, their study serves as a tool to probe deeper into the central engine to understand the structure and emission processes in AGNs. The continuum spectral energy distribution (SED) of blazars is dominated by the nonthermal emission with two broad peaks covering the entire electromagnetic spectrum (EMS), ranging from radio to high-energy γ -rays. The first peak in the SED lies in the submillimeter to X-ray region and is known to be due to the synchrotron process in which the relativistic electrons gyrate in a strong magnetic field present inside the jet (Urry & Mushotzky 1982) and radiate by cooling. The second, high-energy peak is understood to be due to inverse Compton scattering of low-energy photons, the origin of which is not understood well. Under the leptonic scenario (see Böttcher 2007 for a review), inverse Compton scattering of the low-energy photons by the relativistic electrons, which gave rise to the synchrotron emission, is responsible for the high-energy peak. The seed photons, which are upscattered, could be synchrotron photons (self-synchrotron Compton (SSC)); external photons from the accretion disk, broad-line region, molecular torus, cosmic microwave background, etc. (external Compton (EC)); or a combination of both (Maraschi et al. 1994 and references therein). The exact source of these seed photons is still an open question. As an alternative approach, hadronic models (Mannheim & Biermann 1989) are

also used to explain the high-energy component in the SED (Zdziarski & Böttcher 2015).

Blazars consist of flat-spectrum radio quasars (FSRQs) and BL Lac objects, with FSRQs differentiated from BL Lacs by the presence of broad emission lines in their spectra (with equivalent width (EW) >5 Å; Urry & Padovani 1995; Laurent-Muehleisen et al. 1999). Depending upon the frequency of the synchrotron peaks in their SEDs, BL Lacs are further classified into three categories (Abdo et al. 2010): low-, intermediate-, and high-energy peaked BL Lacs, abbreviated as LBL, IBL, and HBL, respectively. The synchrotron peak frequency, ν_{sync}^p , for LBL lies below 10^{14} Hz; for IBL, between 10^{14} and 10^{15} Hz; and for HBL, $\nu_{\text{sync}}^p > 10^{15}$ Hz. Fossati et al. (1998) found an anticorrelation between the synchrotron peak frequency and synchrotron peak luminosity in the blazar. Also, the Compton dominance parameter, which is the ratio of inverse Compton peak luminosity to synchrotron peak luminosity, decreases from the high-luminosity (FSRQs) to low-luminosity blazars (BL Lacs). This could be due to the presence of external seed photons, from broad line region (BLR) or torus, leading to higher inverse Compton luminosity (Sikora et al. 1994). It was, therefore, noticed that the luminosity, degree of polarization, and γ -ray dominance decrease from FSRQ to LBL, IBL, and HBL, while the ratio of the nonthermal to thermal component and the synchrotron peak frequency increase, indicating a blazar sequence (Maraschi et al. 1994; Fossati et al. 1998; Ghisellini & Tavecchio 2009).

Since AGNs are not resolvable by any existing telescope facility, understanding their structure and emission mechanisms poses a big challenge. Blazars, which are variable over diverse timescales across the whole spectrum, provide a viable tool, as their variability timescales, correlated variations among multifrequency light curves

(LCs), color variations, and SEDs are used as probes (Ciprini et al. 2007; Marscher 2008; Marscher et al. 2010; Jorstad et al. 2010; Dai et al. 2015, and references therein). The temporal variability in blazars has been classified into three categories, namely, long-term variability (LTV; months to years; Fan 2005; Fan et al. 2009), short-term variability (STV; a few days to months), and intra-night variability (INV) or microvariability (a few minutes to several hours within a night; Wagner & Witzel 1995; Kaur et al. 2017b). Though the mechanisms responsible for the variability remain largely unclear, LTV could be due to the disk perturbation/instability or structural changes in the jet, e.g., precession or bending of the jet (Marscher & Gear 1985; Nottale 1986; Kawaguchi et al. 1998; Nair et al. 2005). The STV in optical flux, including inter-night variability, could be caused by intrinsic and extrinsic processes, e.g., injection of fresh plasma into the jet, shock moving down the turbulent jet, changes in the boosting factor due to a change in the viewing angle, gravitational microlensing etc., and sometimes results in the spectral changes (Ghisellini et al. 1997; Villata et al. 2002; Hong et al. 2017). The INV, also known as microvariability, could be due to shock compression of the plasma in the jet, a shock interacting with local inhomogeneities, a blob passing through a quasi-stationary core, changes in the viewing angle in a jet-in-jet scenario (Narayan & Piran 2012), or other processes causing small-scale jet turbulence (Marscher & Gear 1985; Marscher 2008; Chandra et al. 2011; Kaur et al. 2017b). However, the exact processes responsible for variability, in particular INV, are not well understood, and a significant amount of work is required to have a better understanding of this complex phenomenon.

The intermediate BL Lac object S5 0716+714 is one of the most active blazars and makes a perfect candidate for a variability study of the blazars at diverse timescales (Aliu et al. 2012). It is available in the sky for a longer time during the night (due to its high declination) and is almost always active and fairly bright; hence, it can be observed with moderate facilities. It was discovered by Kuehr et al. (1981) in the NRAO 5 GHz radio survey with a flux larger than 1 Jy⁵ and, due to its featureless spectra (Biermann et al. 1981), was categorized as a BL Lac source. Nilsson et al. (2008) derived a redshift of 0.31 ± 0.08 by taking the host galaxy as a standard candle, but recently, Danforth et al. (2013) put a statistical upper limit of $z < 0.322$ (with 99% confidence) on its redshift. The source S5 0716+714 has been observed across the EMS, including its discovery as a TeV candidate in 2008 by the MAGIC collaboration (Anderhub et al. 2009), when a strong optical and γ -ray correlated activity was noticed.

The source S5 0716+714 shows a high duty cycle of variation (DCV), as reported by Chandra et al. (2011 and references therein). Due to all of these properties, it has been the target of several multiwavelength campaigns around the globe (Wagner & Witzel 1995; Villata et al. 2002; Nesci et al. 2005; Raiteri et al. 2005; Montagni et al. 2006; Gupta et al. 2008; Dai et al. 2015), focusing on INV and STV. After being reported in its high phase, the object was followed by Bachev et al. (2012), who claimed historical maxima and minima of 12.08 (MJD 56194) and 13.32 (MJD 56195), respectively, in the *R* band. Rani et al. (2013) found the γ -ray emission to be correlated with optical and radio, supporting the SSC mechanism responsible for the high-energy emission.

However, an orphan flare in X-rays indicated the limitation of such a simple scenario.

Investigating the LTV trend, Nesci et al. (2005 and references therein) reported a decreasing average brightness of the source during 1961–1983, followed by an increasing one up to 2003, superposed with short-term flares. They extracted source brightness data from photographic plates obtained from the Asiago Observatory, POSS1, and Quick V surveys dating back to 1953 to generate long-term LCs. It underlined the importance of the astronomical data, even if taken for some other purpose. Based on these data, they even predicted a decrease in the mean brightness of the source during the next 10 yr, i.e., after 2003. Indeed, the source was inferred, from the 2003–2014 optical data, to be in a decreasing-brightness phase by Chandra (2013), Baliyan et al. (2016), and the present work, suggesting a precessing jet with increasing viewing angle.

The blazar S5 0716+714 has undergone several optical outbursts in the past, superposed on the mean decreasing or increasing long-term trends, as reported by many workers (Raiteri et al. 2003; Gupta et al. 2008; Nesci et al. 2005; Larionov et al. 2013). Microvariability (INV) on timescales of a few hr to 15 minutes is reported (Chandra et al. 2011; Rani et al. 2013; Man et al. 2016 and references therein), with S5 0716+714 showing bluer-when-brighter (BWB) behavior in general. On the other hand, Raiteri et al. (2003) found a weak correlation with color, while others did not find any correlation between color and brightness (Wu et al. 2005; Stalin et al. 2009; Agarwal et al. 2016). The blazar S5 0716+714 has also been reported to show (quasi-) periodic variations (QPVs) in the optical at several epochs and at many timescales ranging from subhours to years (Raiteri et al. 2003; Gupta et al. 2008). However, Bhatta et al. (2016) did not find 3 and 5 hr QPVs as genuine. Recently, Hong et al. (2018) reported 50 minute QPVs when the source was relatively fainter during 2005–2012, ascribing it to the activity in the innermost orbit of the accretion disk.

The blazar S5 0716+714 was reported to be achieving new historical brightness levels (11.68 in the *R* band) in the optical on 2015 January 18 by Chandra et al. (2015a, 2015b), reassuring us that it will never stop surprising us. Therefore, it justifies continuous coverage of the source to help us understand the nature of blazars in general and S5 0716+714 in particular. Keeping this objective in mind, and to understand the variability characteristics, chromatic behavior, and relationship between variability amplitude and brightness of the source, here we present our results obtained from the observations during 2013 January to 2015 June. Section 2 describes the observations and data analysis, Section 3 presents the results and discussions, and Section 4 summarizes the work.

2. Observations and Data Reduction/Analysis

To investigate intra-night and inter-night variability in BL Lac source S5 0716+714, we carried out optical observations using the 1.2 m telescope of the Mount Abu InfraRed Observatory (MIRO), operated by the Physical Research Laboratory, Ahmedabad. The observatory is located at Gurushikhar mountain peak, about 1680 m above sea level, in Mount Abu (Rajasthan), India, with a typical seeing of 1''. The observations were taken with a liquid nitrogen-cooled Pixcellent CCD camera as the back-end instrument, equipped

⁵ 1 Jy = 10^{-23} erg cm⁻² s⁻¹ Hz⁻¹.

with a Johnson–Cousins optical *BVRI* filter set. The dimension of the CCD array is 1296×1152 pixels of size $22 \mu\text{m}$ each. The field of view is about $6.5 \times 5.5 \text{ arcmin}^2$ with a plate scale of $0''.29 \text{ pixel}^{-1}$. The CCD readout time is 13 s with readout noise of four electrons and negligible dark current when cooled to a temperature of about -120° .

In order to study INV (microvariability), as a strategy, we monitored the source for a minimum of 2 hr in the Johnsons *R* band with a high temporal resolution (less than a minute) to resolve any rapid flare, while for STV and LTV in the source brightness and color, 4/5 images were taken in the *B*, *V*, and *I* bands every day during the campaign period. The source and its comparison/control stars, as they appear in the finding chart available at the website of Heidelberg University⁶ having a brightness close to that of the source (Howell & Jacoby 1986), were kept in the same observed frame. Differential photometry was performed to minimize the effect of nonphotometric conditions (however, the majority of the observations were made during photometric nights), like minor fluctuations due to turbulent sky and other seeing effects. The exposure time was decided by keeping the counts well below the saturation limit and in the linear regime of our CCD (Cellone et al. 2000). Several twilight flat-field and bias images were taken on each observation night to calibrate the science images. By following the abovementioned strategy, a total of 6256, 159, 214, and 177 images in the *R*, *B*, *V*, and *I* bands, respectively, were obtained and subjected to analysis.

The observed data were checked for spurious features, if any, and reduced using IRAF⁷ standard tasks-bias subtraction, flat fielding, cosmic-ray treatment, etc. The comparison stars 5 and 6,⁸ present in the source field, were chosen to perform differential photometry. Other stars (stars 2 and 3) in the field were too bright to be used for differential photometry, as they could introduce errors (from differential photon statistics and random noise, like sky; Howell et al. 1988). An optimum aperture size, three times the FWHM, was used based on the prescription by Cellone et al. (2000), as smaller apertures can give better signal-to-noise ratios but might lead to spurious variations if the seeing is not good, while a larger aperture would have significant contribution from the host galaxy thermal emission (Cellone et al. 2000) and might suppress the genuine variations in the blazar flux. Aperture photometry on the blazar S5 0716+714 and comparison stars 5 and 6, using the same aperture size, was performed using the DAOPHOT package in IRAF on photometric nights.

The aperture photometry technique was employed on a total of 6806 images in the *BVRI* bands, and the source magnitudes were calibrated with the average magnitude of the comparison stars 5 and 6, which were also used to check for the stability of the sky during observations, as described in Equations (1) and (2). No correction for the host galaxy of S5 0716+714 was applied, as the host galaxy is much fainter with an *R* band $>20 \text{ mag}$ (Montagnani et al. 2006) than the central bright source. The differential LCs were constructed to detect INV, while *BVI*- and *R*-band long-term LCs were generated from daily averaged values in each band. To quantify the INV nights, we

applied several statistical tests, for example, the confidence parameter test (C-test) and amplitude of variability (A_{var}) test, as discussed in the next section.

3. Results and Discussion

As already mentioned earlier, the photometric data obtained after the aperture photometry were used to plot the intra-night and inter-night LCs. Though the LCs themselves are not sufficient to reveal the complexities of the variability and blazar phenomena, they are good indicators of the emission mechanism and can help put constraints on various models. The nature of most of the LCs differs from one night to another, indicating the emission from random and turbulent processes in the jet. Since the physical mechanisms that trigger blazar variability, especially on intra-night timescales, are still debatable, any detailed study of LCs should add to our understanding.

In order to identify and characterize the nights showing INV, we performed variability amplitude and confidence parameter (C-test) tests. In the following, we also discuss the STV, LTV, and color behavior of the source during the period of our observing campaign.

3.1. Intra-night Variability

Blazars show rapid variability, which can sample very compact sizes of their emission regions. To determine the number of INV nights, we first excluded the not-so-photometric nights when sky conditions were changing drastically and those with less than 2 hr of monitoring. We were left with 29 nights that fit this criterion during 2013 January–2015 June. The LCs for S5 0716+714, being very complex with a number of features, made it very difficult to infer the INV from just visual inspection, barring a few clear cases. To resolve this problem, the following statistical methods are used to quantify the INV.

Confidence parameter test (C-test). The C-test was first introduced by Jang & Miller (1997) and further generalized by Romero et al. (1999). It is basically a ratio between calibrated source magnitudes and the differential magnitude of the comparison stars, given as

$$C = \frac{\sigma_{S-C_{5,6}}}{\sigma_{C6-C5}}, \quad (1)$$

where $C_{5,6}$ is the average of the difference in the instrumental and standard magnitudes of stars 5 and 6, and $\sigma_{S-C_{5,6}}$ and σ_{C6-C5} are the standard deviations of the differential LCs. We consider the source to be variable when the confidence parameter is greater than 2.57 (i.e., $C > 2.57$) for more than 3σ confidence (or 99% confidence level; Jang & Miller 1997). The standard deviation σ for differential LCs is given by

$$\sigma = \sqrt{\frac{\sum (m_i - \bar{m})^2}{N - 1}}, \quad (2)$$

where $m_i = (m_2 - m_1)_i$ is the differential magnitude of the two objects, $\bar{m} = \overline{m_2 - m_1}$ represents the differential magnitude averaged over the night, and N is the total number of data points.

F-test. The F-test, also known as the Fisher–Snedecor distribution test, measures the sample variances of two quantities, i.e., the variance of the calibrated source magnitudes

⁶ <http://www.lsw.uni-heidelberg.de/projects/extragalactic/charts/0716+714.html>

⁷ The Image Reduction and Analysis Facility (IRAF) is a data reduction and analysis package by the NOAO, Tucson, Arizona, operated by AURA under agreement with the NSF.

⁸ Stars taken from the sequence A, B, C, D by Ghisellini et al. (1997) and the corresponding sequence 2, 3, 5, 6 by Villata et al. (1998).

and of the differential magnitudes of the comparison stars. To test the significance of variability during each night, it is written as

$$F = \frac{\sigma_B^2}{\sigma_{CC}^2}, \quad (3)$$

where σ_B^2 and σ_{CC}^2 are the variances in the blazar magnitudes and differential magnitudes of the standard stars for nightly observations, respectively. An F -value of ≥ 3 implies variability with a significance of more than 90%, while an F -value of ≥ 5 corresponds to 99% significance level.

Amplitude of variability (A_{var}): The intra-night amplitude of variability in the source is calculated by using the expression given by Heidt & Wagner (1996),

$$A_{\text{var}} = \sqrt{(A_{\text{max}} - A_{\text{min}})^2 - 2\sigma^2}, \quad (4)$$

where A_{max} and A_{min} are the maximum and minimum magnitudes in the intra-night calibrated LC of the source and σ is the standard deviation in the measurement. For a night to be considered as variable, A_{var} should be more than 5%.

3.1.1. INV LCs and DCV

After performing statistical tests on the entire data set, we get nine out of a total of 29 nights that are found to be variable based on all of the abovementioned criteria, i.e., $C \geq 2.57$, $F \geq 5$ for the more than 99% confidence level, and $A_{\text{var}} \geq 0.05$ mag. Figure 1 shows the LCs for these INV nights, where the time in Modified Julian Date (MJD) is plotted along the X-axis and the brightness magnitude in the R band is along the Y-axis. The lower curve is the differential LC for the two comparisons (5 and 6) to check the stability of that particular night, thus providing the extent of uncertainty in the source values. The rms values of these differential LCs for comparison stars are a measure of accuracy in our magnitude measurements. The upper curve (filled circles) shows the calibrated brightness magnitudes for the source. The plotted photometric errors are of the order of a few millimagnitudes.

The INV LCs (Figure 1) feature a monotonic rise or fall and slow rise or decay with rapid fluctuations superimposed on them, along with a few LCs indicating a possibility of quasi-periodic oscillations with short timescales. It can be noted that the shapes of most of the nightly LCs are different, as also reported by several other authors (Chandra et al. 2011; Kaur et al. 2017b; Hong et al. 2018 and references therein), indicating that the emission processes are stochastic and complex in nature. A symmetric flare in an LC would mean the cooling timescale is much shorter than the light-crossing timescale. On the night of 2013 February 12 (Figure 1), the brightness decays slowly with no distinct peak, with a total change in the amplitude of variation of about 7.5%. In the same figure, a slow increase in flux by about 0.07 mag in about 2.6 hr, with several rapid fluctuations superimposed (including one with 0.04 mag in about 30 minutes), is noticed on 2013 March 6. The next day, the LC starts with a slight decreasing trend but begins brightening up at MJD 56358.88, with a rapid increase after 1.44 hr leading to 0.06 mag ($>2\sigma$). The flux decreases up to MJD 56607.0 and then remains stable within the errors on 2013 November 11. The INV LC on 2013 March 12 shows interesting features with a brightening by 0.11 mag in about 30 minutes, followed by a decay of about 0.17 mag in about 1 hr. It starts increasing again, reaching the initial level of

about 13.41 mag. A slow decrease in flux and then a relatively faster increase by about 0.07 mag within about 70 minutes characterizes the LC on 2013 December 28 (Figure 1). A significant increase in flux by 0.13 mag within about 2.9 hr is noticed on 2013 December 30, while on 2014 December 02, the brightness decreases continuously, with no peak. On 2014 December 3, the flux rises by 0.08 mag within 2.4 hr during the total monitoring time of about 6 hr.

However, it is difficult to determine variability timescales accurately only from visual inspection of LCs; therefore, in the next section, we introduce and use structure functions (SFs) and later analyze them to estimate the required parameters.

Duty cycle of Variation (DCV). Most of the blazars show a very high probability of variation even on intra-night timescales, with an amplitude of variation of a few tenths of a magnitude, for example, CTA 102 (Bachev et al. 2017), 3C 66A (Kaur et al. 2017b and references therein), and S5 0716+714 (Chandra et al. 2011). In order to quantify the probability of variation in a source, DCV is often used. The DCV is defined as the fraction of the total number of nights the source is monitored for, which are found variable (Romero et al. 1999). An expression to estimate DCV is given by

$$\text{DCV} = 100 \frac{\sum_{i=1}^n (N_i / \Delta t_i)}{\sum_{i=1}^n (1 / \Delta t_i)} \%, \quad (5)$$

where $\Delta t_i = \Delta t_{i,\text{obs}} (1+z)^{-1}$ is the duration of monitoring in the rest frame of the source, and N_i is 0 or 1, depending on whether the source is nonvariable or variable, respectively.

Several authors (Wagner & Witzel 1995; Chandra et al. 2011; Dai et al. 2015 and references therein) have reported an INV DCV for S5 0716+714 ranging from 40% to 100% during their observations, which indicates that the source is almost always active. In our case, nine nights out of a total of 29 nights monitored for more than 2 hr are detected as confirmed variable ones. Thus, based on our observations during 2013–2015, we get a value of 31% as the duty cycle, which is on the lower side. Reasons could be that we monitored the source, by chance, when it did not show much activity, or our duration of monitoring may not be sufficient. Hong et al. (2018) monitored the source for less than 1 hr and reported a DCV of 19.57%, and, in another study done over 13 nights during 2012 January–February, a value of 44% (Hong et al. 2017) was estimated when the source was monitored for about 5 hr. In order to check for any connection between the INV shown by the source and the duration over which it was monitored, we calculated the duty cycle with more than a 1 or 2 hr monitoring period.

Out of the total of 46 nights of observation during 2013–2015, we find 35 and 29 nights monitored for a minimum of 1 and 2 hr, respectively. Based on these, we obtained INV duty cycle values for S5 0716+714 as 26% and 31%, respectively, in the two cases. This therefore indicates that the longer the duration of monitoring, the higher the probability of finding a source variable, i.e., a higher DCV, will be.

Rise and fall rates of variation in INV LCs. To investigate the extent of the INV of the source, we determined the rate of change in magnitude (rise/fall) on each INV night for S5 0716+714 by fitting a line segment to LCs. These rates of variation are given in Table 1.

During our observations, 2013 February 12 and 2013 December 28 represent the nights with minimum and maximum rates of

Table 1
Details of the Rates of Rise/Fall in the Magnitude for INV Nights

Date	Trend	Rise/Fall mag (Δm_+ / Δm_-)	Duration (minutes)	Rate = $\Delta m / \Delta t$ (mag hr ⁻¹)
2013 Feb 12	Fall	0.05 (Δm_-)	198	0.015
2013 Mar 06	Flickering over a monotonic rise	0.08 (Δm_+)	>150	0.02
2013 Mar 07	Fall	0.05 (Δm_-)	72	0.03
2013 Mar 12	Rise	0.12 (Δm_+)	144	0.05
	Sine-like pattern	0.10 (Δm_+)	30	
		0.20 (Δm_-)	72	
2013 Nov 11	Fall	0.08 (Δm_-)	>72	0.04
	Fall with flickering	0.08 (Δm_-)	72	
		0.02 (Δm_-)	>20	
2013 Dec 30	Monotonic rise	0.14 (Δm_+)	144	0.07
2014 Dec 02	Monotonic fall	0.02 (Δm_-)	216	0.05
2014 Dec 03	Sine-like	0.08 (Δm_-)	288	0.02

Note. Δm_+ , Δm_- Represent the Source Brightening or Dimming, Respectively

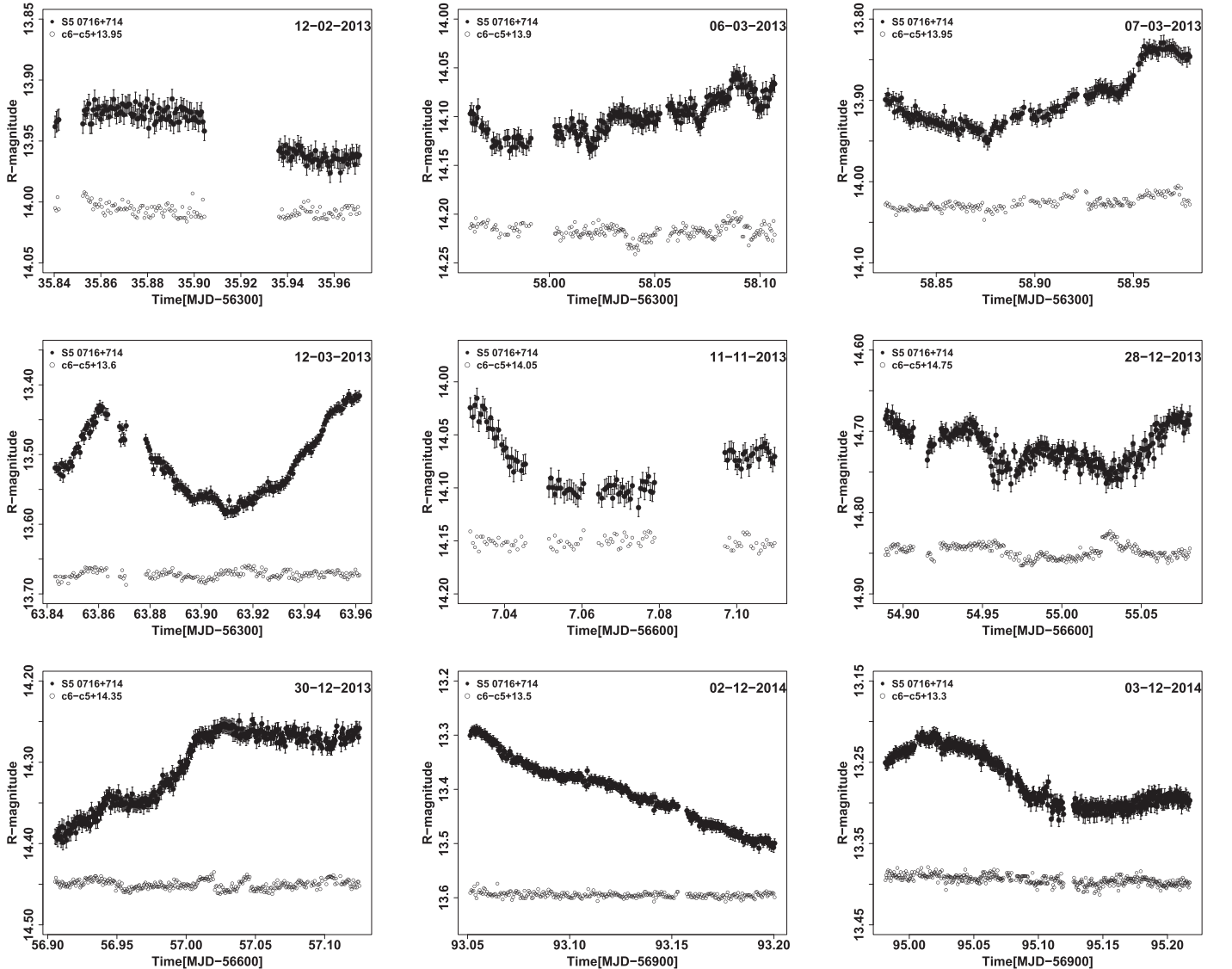


Figure 1. Intra-night LCs for the source S5 0716+714 on various nights during 2013 January to 2015 June.

change in the magnitudes of the source, with 0.015 and 0.381 mag hr⁻¹ (see Table 1), respectively. The rate of brightness change on 2013 December 28 happens to be one of the fastest for this source. Earlier, Chandra et al. (2011) and Man et al. (2016) reported 0.38 and 0.35 mag hr⁻¹ rates, respectively. A rate of change in the brightness magnitude as high as 0.43 hr⁻¹ has been reported for PKS 2155–304 (Sandrinelli et al. 2014). The source showed a smooth decline in its brightness by 0.05 mag on February 12 with 7.60% amplitude of variability. On 2013 March 6, S5 0716+71 became brighter by 0.08 mag in 3 hr with rapid fluctuations (few tens of minutes duration) superposed over the daylong trend showing 7.58% amplitude of variation in the LC. On 2013 March 7, the brightness decreases from 13.90 mag to almost 13.95 mag within 1 hr, after which the source brightened by more than 0.1 mag in the next 3 hr with a rate of change of 0.03 mag hr⁻¹, as mentioned in Table 1. On 2013 March 12, the LC shows a sine-like feature, with rising (0.1 mag in 30 minutes)—declining (0.2 mag in 72 minutes)—rising (>0.2 in about 72 minutes) trends in brightness over a duration of more than 3 hr.

The LC on 2013 December 28 showed sharp rise/fall magnitudes over two peaks and again showed a rising trend with an overall change in magnitude of 0.38 mag hr⁻¹ (see Table 1). However, the features in the LCs are asymmetric in nature, which rules out variation being caused by extrinsic/geometric mechanisms. The variability in blazars is stochastic in nature at almost all timescales. The flares, therefore, appear to be produced independently, and any similarity or difference might reflect different scales of particle acceleration and energy dissipation (Nalewajko et al. 2015). The variations in blazars are caused largely in the jet, but it is difficult to ascertain whether these are intrinsic or geometric in nature. Intrinsic variations are dissipative and irreversible in time. Hence, they should cause asymmetric flares. The geometric variations, on the other hand, are symmetric in time (Bachev et al. 2012) and achromatic in nature. The intrinsic variability could be due to fast injection of relativistic electrons and radiative cooling and/or escape of the particles or radiation from the emission zone. The symmetric flares, however, might result if the cooling timescale is much shorter than the light-crossing time (Chatterjee et al. 2012).

The INV LCs are, in general, asymmetric and complex, indicating the random/turbulent nature of the flow inside the jet. Based on the visual inspection of these curves, we identify three observed trends.

- (a) Rapid intra-night changes in the source flux indicate the violent, evolving nature of the shock formed in the jet. It might be due to either the presence of oblique shocks or instabilities in the jet.
- (b) The steady rise or fall in the LC during a night indicates that the light-crossing timescale is shorter than the cooling timescale of the shocked region. It is when a data series is shorter than the characteristic timescale of variability. The cooling times shorter than the light-crossing time would have resulted in symmetric LCs (Chiaberge & Ghisellini 1999; Chatterjee et al. 2012).
- (c) The small-amplitude rapid fluctuations (asymmetric in shape) superimposed over slowly varying LCs suggest small-scale perturbations in the shock front or oscillations in the hot spots downstream the jet and may not be associated with the size of the emission regions.

3.1.2. Variability Timescale, Size of Emission Region, and Black Hole Mass

It is important to know the characteristic timescale of INV, which can constrain the emission size and structures of the blazar emission zones. If we consider the shape of the jet as conical close to its origin, the opening angle and the extent of vertical expansion of the jet can provide us a rough estimate of the location of the emission region with respect to the supermassive black hole (Ahnen et al. 2017; Kaur et al. 2017a).

The rapid variations with durations of a few hours originate, perhaps, in the close vicinity of the central engine where jets are launched and might be caused by a combination of accretion disk instability, shock propagating within the jet, and/or particle acceleration and consequent radiative cooling near the base of the jet (Ulrich et al. 1997). This assumption is also used to estimate the mass of the black hole, which is difficult to determine otherwise, as BL Lacs do not show emission lines. Since the INV LCs are complex, we use statistical tools, described here, to discuss features in the intra-night LCs and estimate INV timescales and any possible quasi-periodicity.

Structure function. The SF described by Simonetti et al. (1985) and Gliozzi et al. (2001) provides information about the characteristic timescale of variability for flat- and steep-spectrum radio sources by analyzing their LCs. In order to estimate the characteristic variability timescale, we used first-order SF for a magnitude data series, defined as

$$SF(\tau_i) = \frac{\sum [M(t + \tau_i) - M(t)]^2}{N}, \quad (6)$$

where $M(t)$ is the magnitude at time t and τ_i is the time lag. The χ^2 method is used to fit the SF where-from the minimum variability timescale and corresponding errors are estimated (Zhang et al. 2012). The SF reveals the extent of the changes in the magnitude as a function of time between two observations. In this curve of growth of variability with time lag, a plateau (change of slope or saturation of SF) might indicate the presence of a characteristic time,

$$SF(\tau) = \begin{cases} k\tau^\beta, & \tau \leq \tau_o, \\ C, & \tau > \tau_o, \end{cases} \quad (7)$$

where τ_o is the characteristic timescale with 1σ uncertainty and $\beta = \frac{d \log(F)}{d \log(\tau)}$ is the logarithmic slope in the τ -SF plane characterizing the nature of the variability and physical processes. If the value of β is close to 0, it indicates flickering noise, while $\beta \geq 1$ indicates turbulent processes in the jet (or shot noise) responsible for the changes.

Figure 2 shows the SFs for the INV nights. It is seen that first-order SF for several nights does not show any plateau, which means that the characteristic timescale of the variability is longer than the length of the observational data (Dai et al. 2015). The local maximum following the smooth rise in the SF- τ plane reveals a timescale of variability introduced by the presence of minimum and maximum or vice versa in the curve. If the SF consists of more than one plateau with slopes (β) following a power-law trend, the presence of multiple timescales is inferred. If periodicity is present, it will be seen as local minima in SF after the occurrence of a local maximum. The difference between two minima gives the time period.

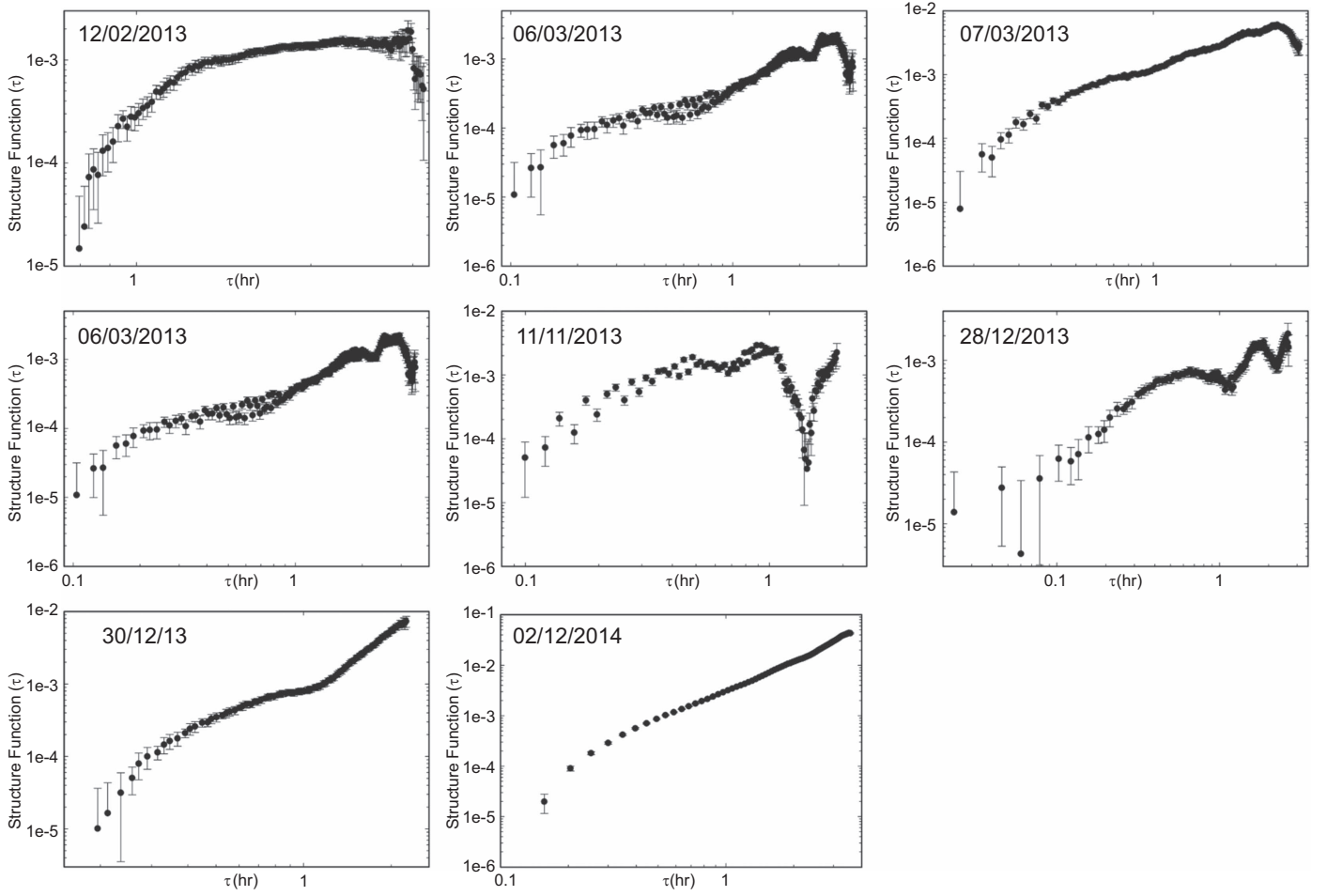


Figure 2. SFs for the INV nights plotted for the source S5 0716+714 during 2013–2015. The X-axis represents the time lag in hours.

Table 2
Details of the INV Nights for the Source S5 0716+714 during 2013–2015

Date of Observation (1)	MJD (2)	T_{start} (hh:mm:ss) (3)	Duration (hr) (4)	N^a (5)	$\bar{m} \pm \sigma$ (6)	C (7)	A_{var} (%) (8)	t_{var} (9)	k (10)	β (11)
2013 Feb 12	56335.84038	20:10:09	3.28	195	13.94 ± 0.02	2.63	7.60	>2.36 hr	0.31	4.82
2013 Mar 06	56357.96250	23:06:00	3.46	237	14.10 ± 0.02	2.72	7.58	>1.68 hr	0.99	1.67
2013 Mar 07	56358.82424	19:46:54	3.71	203	13.90 ± 0.03	4.46	11.38	2.04 hr	1.71	1.81
2013 Mar 12	56363.84308	20:14:02	2.83	229	13.50 ± 0.05	8.90	15.61	1.11 hr	0.08	1.21
2013 Nov 11	56607.03115	00:44:51	1.88	139	14.08 ± 0.02	4.62	9.75	0.96 hr	3.61	1.33
2013 Dec 28	56654.88889	21:20:00	2.48	284	14.72 ± 0.02	2.65	11.89	0.76 hr	1.14	0.97
2013 Dec 30	56656.90536	21:43:43	2.26	350	14.30 ± 0.05	7.55	15.38	3.1 hr	0.88	1.31
2014 Dec 02	56993.05133	01:13:05	4.58	284	13.41 ± 0.06	12.37	20.50	3.54 hr	2.29	2.34
2014 Dec 03	56994.98155	01:13:55	5.97	454	13.27 ± 0.03	5.23	10.07	3.89 hr	2.32	2.41

Note. Columns 1–11: date, MJD, observation start time, duration, number of images, average magnitude with error, test parameter C , amplitude of variation, variability timescale, SF parameters k and β .

^a Number of data points.

On several nights (2014 December 02, 2013 March 07, 2013 November 11, and 2013 February 13), the SF shows a continuous increase with no or a feeble plateau, indicating that the characteristic timescale of variability is longer than the monitoring period, giving only a lower limit of the variability timescale. While the LC for the night of 2013 March 12 shows several features, the SF shows only one plateau and then a dip at about 2.2 hr. On 2013 December 13, the SF shows a

discernible peak with a timescale of 3.11 hr, followed by a rise. The SF for the INV night of 2014 December 14 shows a plateau at 2.89 hr. As can be seen, the INV night of 2013 December 28 shows a plateau in its SF, giving it the shortest characteristic timescale of variability of about 45.6 minutes during our observing campaign.

The quantitative values of various parameters related to INV nights, including SF parameters, are given in Table 2. In this

table, columns 1 and 2 represent the date of observation (in yyyy mm dd and MJD format, respectively), column 3 represents the start time of the observations, the duration of monitoring and the number of data points (images) are given in columns 4 and 5, column 6 presents the average magnitude and associated errors in the source brightness, and columns 7 and 8 contain the values of the statistical parameters, i.e., C and A_{var} , respectively. The variability timescales for INV nights are shown in column 9, along with the SF parameters, normalization constant (k) and logarithmic slope (β), in columns 10 and 11, respectively.

The INV LCs feature several complete events with specific timescales. Applying light travel time arguments, these timescales can be used to put limits on the size of the emission regions responsible for the variation in flux. The shortest characteristic timescale puts a constraint on the size of the emission region (Elliot & Shapiro 1974). Using the characteristic timescales obtained from LC and SF analysis, the size of the emission region is

$$R \leq \frac{\delta c \Delta t_{\text{var}}}{(1+z)}, \quad (8)$$

where c is the speed of light, Δt_{var} is the minimum timescale of variability, δ is the Doppler factor, and z is the redshift of the source ($z = 0.32$). When considering long-term behavior, various authors have used different values of the Doppler factor, δ . Bach et al. (2005) used Doppler factors 13–25 when the viewing angle changed from 5° to $0^\circ.5$. Nesci et al. (2005) adopted a value of 20, while Fuhrmann et al. (2008) applied a range of 5–15 for the Doppler factor. We have assumed a value of 15 in this work, based on the values adopted in other works and the brightness of the source during the observed period. Thus, using $\Delta t_{\text{var}} = 45.6$ minutes as the characteristic timescale of variability, the estimated size of the emission region is of the order of $\approx 10^{15}$ cm. Apart from this shortest timescale of variability, other timescales estimated on other nights indicate different sizes of emission regions in the jet. The longest timescale of variability detected in the present study is 3.89 hr, which corresponds to a size of 4.8×10^{15} cm in the source frame. All these emitting regions are very compact and close to the black hole within the BLR region.

Mass is one of the most important properties of a black hole. There are two categories of methods to determine the mass of a black hole in AGNs: primary and secondary. While there are direct, primary methods applicable to nearby black hole systems where the motion of the surrounding stars and gas under the influence of the black hole are traceable (Vestergaard 2004), it is very difficult to have an estimate of their masses at high redshifts. In the secondary methods, the mass of the black hole is estimated by resorting to approximations, e.g., using a parameter with which black hole mass is correlated. There are several methods that fall into this category. However, for the sources that do not show any emission lines and whose host galaxy is also weak/nondetectable, which is the case for BL Lac-type sources, it becomes extremely difficult to estimate the mass of the black hole. For such systems, the variability timescale can provide a rough estimate of the black hole mass, assuming that the shortest timescale of variation is governed by the orbital period of the innermost stable orbit around a Kerr (maximally rotating) black hole. Miller et al. (1989) claimed the origin of microvariability to arise from a location very close

to the central engine based on the fast variability timescales, while Marscher et al. (1992) associated their location somewhere down the jet and perhaps near the submillimeter core, caused by turbulence.

Many authors have estimated the masses of black holes residing in the BL Lac sources following the earlier (Miller et al. 1989) approach using the shortest variability timescales (Xie et al. 2002; Liang & Liu 2003; Fan 2005; Gupta et al. 2008; Rani et al. 2010; Chandra et al. 2011; Dai et al. 2015; Kaur et al. 2017b). Here we use this method to estimate the mass of a Kerr black hole at the center of S5 0716+71 using the expression (Abramowicz & Nobili 1982; Xie et al. 2002)

$$M = 1.62 \times 10^4 \frac{\delta \Delta t_{\text{min}}}{1+z} M_\odot, \quad (9)$$

where c is the speed of light, z is the redshift, and δ is the Doppler factor. Taking the shortest variability timescale, $\Delta t_{\text{min}} = 45.6$ minutes, and the Doppler factor as 15, we estimate the mass of the Kerr black hole to be $5.6 \times 10^8 M_\odot$, which is in close agreement with other values, including a value of $1.25 \times 10^8 M_\odot$ (Liang & Liu 2003) obtained by using optical luminosity. Bhatta et al. (2016) linked a plateau in the LC to the characteristic timescale for developing outflow within the jet base, equivalent to the innermost stable orbit, and obtained the value of the black hole mass as 4×10^9 (maximally spinning black hole) and $3 \times 10^8 M_\odot$ (lowest-spin black hole). Agarwal et al. (2016) obtained a value of $2.42 \times 10^9 M_\odot$ for the black hole mass in S5 0716+714. Hong et al. (2018) estimated the mass of the black hole as $5 \times 10^6 M_\odot$ using 50 minute QPVs originating from the innermost orbit of the accretion disk.

Using the black hole mass, M_{BH} , estimated here, the Eddington luminosity can be estimated from the following expression given by Wiita (1985),

$$L_{\text{Edd}} = 1.3 \times 10^{38} (M/M_\odot) \text{ erg s}^{-1}, \quad (10)$$

which, in the case of S5 0716+71, comes out to be about $7.28 \times 10^{46} \text{ erg s}^{-1}$.

Quasi-periodic variability. Another very interesting, albeit highly debatable, issue is the possible presence of periodicity in the blazar LCs. Claims for its existence have been made in optical bands (Lainela et al. 1999; Fan & Lin 2000). A few INV LCs indicate the presence of possible QPV, also noticed in this source by Wu et al. (2005), Gupta et al. (2008), Poon et al. (2009), Rani et al. (2010), and Man et al. (2016), with periods varying from 15 minutes to 1.8 hr. The presence of such features, if genuine, can be explained by the lighthouse effect (Camenzind & Krockenberger 1992), plasma moving in a helical magnetic field, the microlensing effect, etc. Recently, Hong et al. (2018) obtained 50 minute QPVs from the observations during 2005–2012 when S5 0716+71 was in a relatively fainter state. They opined that the QPV is caused by the activity in the innermost orbit of the accretion disk. In the present case, the variations seen on timescales of a few hours with asymmetric profiles rule out the possibility of microlensing as the mechanism. Here flares could be caused by a sweeping beam whose direction changes with time due to helical motion. To estimate variability timescales and/or periodicity (if present) in our LCs, we use SF and periodogram analysis.

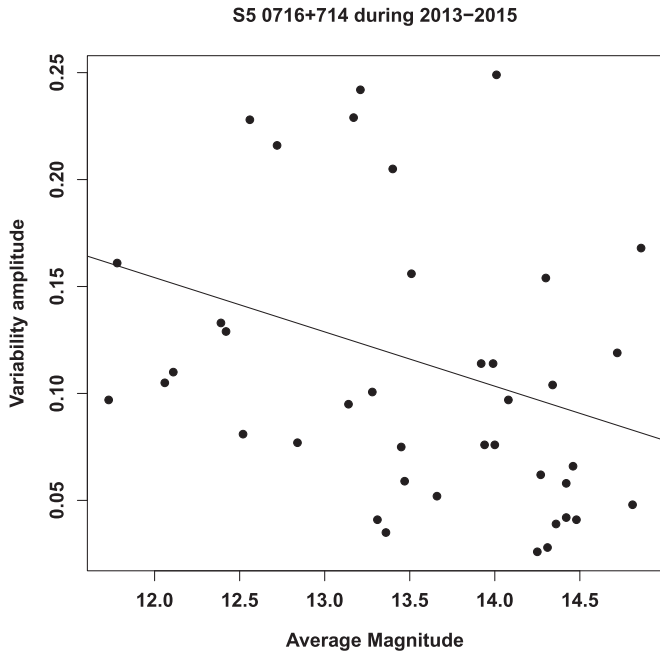


Figure 3. Amplitude of variability as a function of the average R -band brightness during 2013–2015.

The SF for the night of 2013 March 12 shows only one minimum at about 2.2 hr, while that for 2013 December 28 gives two minima at 1.25 and 2.3 hr, giving a possible period of about 1.2 hr.

However, since these periods are either closer to the length of the data series and/or the flux enhancements are less than 3σ , the existence of periodicity is doubtful. Also, these features may not significantly represent a departure from a pure red-noise power spectrum. Though the quality of the LC presented here, in particular its dense sampling, is good enough for a search of hour-long QPVs, the fact that we did not find such a QPV at a significantly high level to claim the detection is meaningful in itself. It implies that no persistent periodic signal exists in the source within the analyzed variability timescale domain.

3.1.3. Variability Amplitude (A_{var}) and the Brightness State of the Source

In order to find out whether the extent of the variability has any dependence on the brightness of the source, we calculated the amplitude of variability (A_{var}) in the R band for all the nights monitored for a long enough time to show a minimum of 3% amplitude variation (see Equation (4)). The values of A_{var} are plotted against nightly averaged brightness magnitudes in the R band (Figure 3) for the duration of 2013 January to 2015 June. We notice larger-variability amplitudes when the source is brighter. In blazars, the A_{var} is indicative of the environment where turbulent plasma in the jet interacts with frequent shock formations where relativistic electrons are accelerated in the magnetic field, which then cools down, leading to synchrotron radiation. During this period (2013–2015), the source was in a relatively more active phase, showing an average R -band magnitude of 13.22 ± 0.01 mag (historical average $R = 14.0$); therefore, one would expect a larger amplitude of variation in the active jet. When the source is relatively faint, thermal emission from the host galaxy is expected to dilute the intrinsic variation in the jet emission, resulting in smaller A_{var} . Several authors

have reported a behavior similar to what we have noticed. Agarwal et al. (2016) and Yuan et al. (2017) noticed a very mild trend of larger A_{var} when the source was brighter. Montagni et al. (2006) estimated rates of magnitude variation for 102 nights during 1996–2003 for S5 0716+71 and found faster ($\sim 0.08/\text{h}$) rates when the source was brighter ($R < 13.4$), though the dependence was weak, compared to the average rate of change ($\sim 0.027 \text{ mag/h}$) irrespective of the state of the source brightness.

However, just the opposite behavior has been detected by Kaur et al. (2017b) in another IBL, 3C 66A, i.e., a larger amplitude of variability when the source was relatively fainter. A similar trend was reported by Chandra (2013) and Baliyan et al. (2016) in a long-term (2005–2012) study of the blazar S5 0716+714, reporting a larger amplitude of variation when source was relatively fainter. Perhaps more extensive study of several blazars is needed to address this issue.

The behavior of the amplitude of variation as a function of the source brightness also provides a clue to how the LTV and INV could be related. When the source is bright, it indicates that the relativistic shock is propagating through the larger-scale jet, leading to enhanced flux at the longer timescale (LTV; Romero et al. 1999). The interaction of the shock with local inhomogeneities (small-scale particle or magnetic field irregularities) or turbulence interacting with the shock (Marscher et al. 1992) is perhaps giving rise to the intra-night variations (INV). Since we notice an increase in the amplitude of INV with an increase in the mean brightness of the source, later being seen due to LTV, there is perhaps a relation between LTV and INV. A statistical study of a number of sources with good-quality long-term data showing INV, STV, and LTV on a large number of nights would, perhaps, reveal whether INV amplitudes really have any correlation with the long- and short-term variability amplitudes. Certainly, S5 0716+714 would qualify as one such candidate for the study.

3.2. Long-term Variability

The long-term optical LC constructed for the period 2013 January–2015 June for S5 0716+714 is shown in Figure 4, with time in MJD and B , V , R , and I brightness in magnitude. A total of 46 nights with 6256, 159, 214, and 177 data points in the R , B , V , and I bands, respectively, are used in generating these LCs. The source was in its faintest state with $14.85(0.06)$ mag in the R band on MJD 56663.02 (2014 January 6) and in its brightest state with $11.68(0.05)$ mag almost 1 yr later on MJD 57040.90 (2015 January 18). The source S5 0716+71 has undergone several outbursts and flares during its 2.5 yr journey, with two major outbursts peaking in 2013 March and 2015 January having a duration of about 350 and 510 days, respectively (see Figure 4). An outburst here is defined as a significant (more than 1 mag) enhancement in the flux over a considerable duration—tens of days to a few months or longer. In our case, limited by the observational data (ours and those from Steward Observatory), we have estimated the outburst duration, looking at the trend of long-term variation, based on the above criterion. These outbursts are superposed by a number of fast flares. We estimate LTV amplitudes of about 2.5 and 3.45 mag with timescales of 250 and 360 days, respectively, during these two outbursts. These LTV timescales are estimated with respect to the minimum and maximum brightness values of the source during the two outbursts. During the 2015 January outburst, S5 0716+714 reached its unprecedented brightness

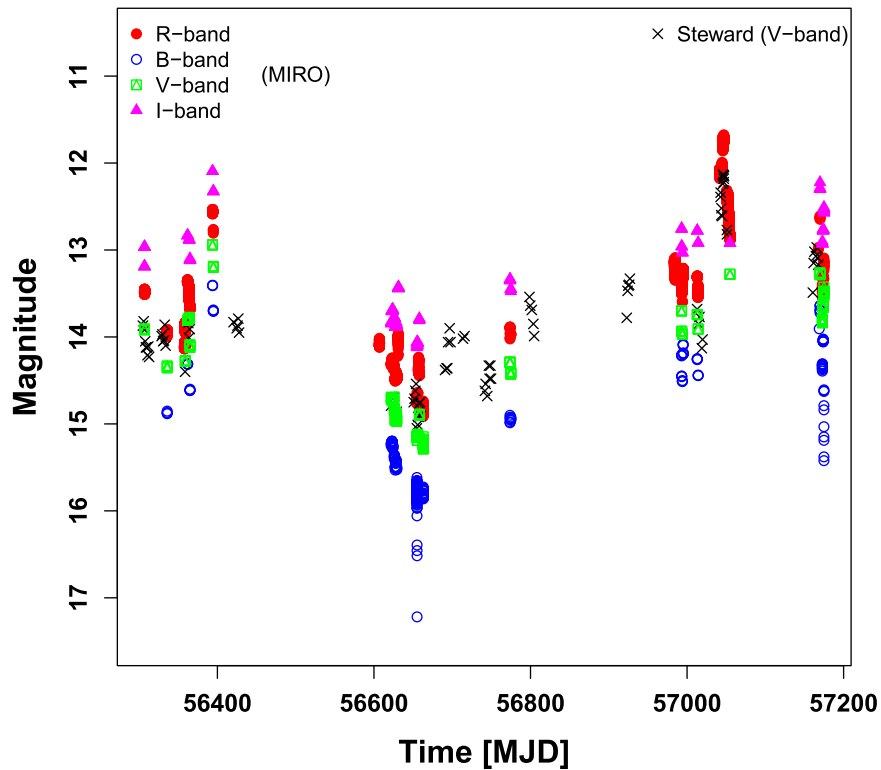


Figure 4. Long-term *B*-, *V*-, *R*-, and *I*-band LCs of S5 0716+714 for the duration 2013 January–2015 June. Data used are from MIRO and the Steward Observatory. The source has undergone the brightest and faintest phases during 2013–2015, exhibiting *R*-band magnitudes of 11.68(0.05) and 14.85(0.06), respectively.

level (Chandra et al. 2015a, 2015b). Using multiwavelength data from *Fermi*-LAT, *Swift*-XRT, *Swift* UVOT, MIRO (optical *R*-band), Steward optical *R*-band, and polarization data, we (Chandra et al. 2015b) detected two subflares contributing to this major 2015 January outburst. In the optical, the source brightened by 0.8 mag in 6 days (MJD 57035–57041) and, post-flare, decayed over the next 4 days at a rate of $0.13 \text{ mag day}^{-1}$. A very sharp drop in brightness within a day (MJD 57040–57041) and a subsequent rise in brightness the very next day (MJD 57042) indicated the presence of two subflares with almost the same peak flux during the outburst. A rapid swing in the position angle of polarization indicated the magnetic reconnection (Zhang et al. 2012) in the emission region, causing the outburst.

In the long term, the source became fainter within 1 yr from its average brightness, $R = 13.5$ mag in 2013 to $R \sim 15$ mag in 2014 January. It was then in the brightening phase during 2014–2015 with intermittent flaring activity. The source S5 0716+71 attained the brightest flux value in 2015 January and started its journey toward the fainter side later, as reflected in all of the *B*-, *V*-, *R*-, and *I*-band (from $R = 11.68$ to 13.20 mag, a 1.52 mag decay in five months, cf. Figure 4) LCs. In addition to major outbursts, there are at least nine flares with a duration ranging from 20 to 30 days leading to changes in the brightness of the source from a few tenths of a magnitude to as much as more than 1.5 mag in the *R* band. The frequent large gaps in the data restrict us from appropriately characterizing these flares, which indicates that the source remains almost always active with substantial brightness changes. During our observation period, S5 0716+714 was brightest on 2015 January 18 (MJD = 57040.90) with a value $R = 11.68 \pm 0.05$ and faintest on 2014 January 06 (MJD = 56663.02) with a value $R = 14.85 \pm 0.06$.

There are several approaches to explain the variation at various timescales, long as well as short. The intrinsic variations could be caused by the instability and hot spots in the disk or its outflow (Chakrabarti & Wiita 1993; Kawaguchi et al. 1998) and activities in the relativistic jet (Marscher & Gear 1985; Marscher 2008). Variations could also be caused by the processes extrinsic to the source, e.g., interstellar scintillation, that are highly frequency dependent and normally affect long-wavelength radio observations. Gravitational microlensing might cause long-term variations in some sources but will result in achromatic, symmetric LCs. The latter is less likely to cause INV (Wagner & Witzel 1995). Since S5 0716+714 was in a relatively bright phase and emission is strongly jet-dominated, the most probable source of variation should be processes in the jet. The shock-in-jet model (Marscher & Gear 1985; Marscher 2008) is normally able to explain a variety of variability events with some modifications (Camenzind & Krockenberger 1992; Zhang et al. 2015), where a shock propagates down the jet interacting with a number of particle overdensities or stationary shocks/cores distributed randomly in the parsec-scale jet. Such standing shocks are formed due to a pressure imbalance between the jet plasma and interstellar medium. In trying to maintain a balance, an oblique shock is created perpendicular to the jet axis. The relativistic shocks interacting or passing through such regions energize the particles in the presence of the magnetic field, which then radiates synchrotron emission while cooling. Either the jet moves in a helical motion or the blob moves in a helical magnetic field, causing a change in the viewing angle and thus changing the Doppler factor, which significantly enhances/reduces the intrinsic flux variation, depending upon the decrease/increase in the angle. The model can explain rapid variations by resorting to a jet-in-jet scenario

Table 3
Observation Log and Photometric Results for S5 0716+714 in the *R* Band during 2013 January–2015 June

Date (yyyy mm dd)	T_{start} (hh:mm:ss)	MJD	N^a	$\bar{m}$ (avg. mag)	$m(\sigma)$ mag	E_{phot} mag	Variable (Y/N)
2013 Jan 14	21:30:14	56306.89600	785	13.478	0.01	0.01	N
2013 Feb 12	20:10:09	56335.84038	195	13.943	0.02	0.01	Y
2013 Mar 06	23:06:00	56357.96250	237	14.007	0.10	0.03	Y
2013 Mar 07	00:03:50	56358.00266	203	13.996	0.10	0.01	Y
2013 Mar 10	19:37:50	56361.81794	231	13.356	0.01	0.003	N
2013 Mar 12	20:14:02	56363.84308	229	13.505	0.05	0.004	Y
2013 Mar 13	23:38:51	56364.98531	160	13.660	0.01	0.005	N
2013 Apr 11	19:49:09	56393.82580	182	12.563	0.03	0.02	N
2013 Apr 12	19:46:43	56394.82411	5	12.780	0.02	0.02	N
2013 Nov 11	00:44:51	56607.03115	139	14.078	0.02	0.003	Y
2013 Nov 26	03:20:25	56622.13918	13	14.310	0.01	0.003	N
2013 Nov 27	01:48:39	56623.07545	25	14.259	0.01	0.01	N
2013 Nov 28	01:13:25	56624.05098	169	14.275	0.01	0.01	N
2013 Nov 29	01:07:09	56625.04663	247	14.337	0.01	0.01	N
2013 Nov 30	02:29:12	56626.10361	107	14.357	0.01	0.008	N
2013 Dec 01	03:08:06	56627.13063	112	14.485	0.01	0.02	N
2013 Dec 02	02:32:13	56628.10571	200	14.417	0.01	0.04	N
2013 Dec 03	02:12:03	56629.09170	242	14.463	0.01	0.03	N
2013 Dec 05	00:19:24	56631.01347	230	14.011	0.03	0.02	N
2013 Dec 28	21:20:00	56654.88889	284	14.718	0.02	0.007	Y
2013 Dec 30	21:43:43	56656.90536	350	14.304	0.04	0.005	Y
2014 Jan 01	00:18:37	56658.01293	183	14.423	0.01	0.004	N
2014 Jan 05	02:10:57	56662.09094	50	14.816	0.01	0.005	N
2014 Jan 06	00:43:03	56663.02990	349	14.855	0.06	0.006	N
2014 Apr 26	20:26:39	56773.85184	10	13.924	0.05	0.006	N
2014 Apr 27	20:08:22	56774.83914	05	13.969	0.01	0.008	N
2014 Nov 22	20:08:34	56983.83929	49	13.143	0.02	0.002	N
2014 Nov 23	18:47:49	56984.78321	207	13.212	0.06	0.005	N
2014 Dec 02	01:13:55	56993.05133	284	13.404	0.06	0.01	Y
2014 Dec 03	01:16:34	56994.05317	454	13.276	0.04	0.006	Y
2014 Dec 22	01:41:07	57013.07022	579	13.456	0.08	0.01	N
2015 Jan 18	18:15:04	57040.90131	105	11.681	0.05	0.05	N
2015 Jan 19	16:32:33	57041.68927	442	12.114	0.02	0.006	N
2015 Jan 20	18:49:11	57042.78417	06	12.087	0.04	0.002	N
2015 Jan 22	14:42:59	57044.61319	100	12.063	0.02	0.004	N
2015 Jan 23	16:37:47	57045.69292	934	11.776	0.03	0.004	N
2015 Jan 24	22:06:24	57046.92112	240	11.727	0.02	0.01	N
2015 Jan 28	17:19:42	57050.72202	557	12.398	0.02	0.002	N
2015 Jan 29	19:03:20	57051.79399	401	12.518	0.01	0.01	N
2015 Jan 30	15:40:12	57052.65292	513	12.416	0.02	0.01	N
2015 Jan 31	16:35:46	57053.69152	727	12.726	0.05	0.01	N
2015 Feb 01	20:38:28	57054.86005	44	12.837	0.02	0.01	N
2015 May 25	21:49:50	57167.90961	02	12.979	0.07	0.005	N
2015 May 27	20:35:16	57169.85782	05	12.626	0.01	0.02	N
2015 May 30	20:38:38	57172.86016	10	13.449	0.04	0.01	N
2015 May 31	20:22:47	57173.84916	15	13.315	0.01	0.003	N
2015 Jun 01	20:13:27	57174.84267	18	13.171	0.05	0.003	N

Note. Columns are date of observation, time (UT and MJD), number of data points, average magnitude with standard deviation and photometric errors, and variable (Y/N).

^a Number of data frames.

(Camenzind & Krockenberger 1992; Zhang et al. 2015). The small flares before the outburst indicate acceleration/cooling of the relativistic particles due to plasma blobs interacting with the shock front and ongoing activity in the jet due to the superposition of all the events leading to LTV in the source. In our study, after the second outburst, the source enters into a faint state again.

Several studies have been carried out to address the long-term behavior of the source. Raiteri et al. (2003) and Nesci et al. (2005) used the historical data, including from the

literature, during 1953–2003 and noticed alternate trends of decreasing and increasing mean brightness on a tentative period of about 10 yr, claiming precession of the jet to be responsible for them. It should be noted that even during these slow trends of increasing/decreasing mean brightness levels, the source was very active, with a large number of flares superposed on the longer trends. Again, a decreasing trend was noticed by Chandra (2013) beginning in 2003 that continued up to 2012; they also predicted an increase in average brightness after 2014. Agarwal et al. (2016) observed the source for 23 nights

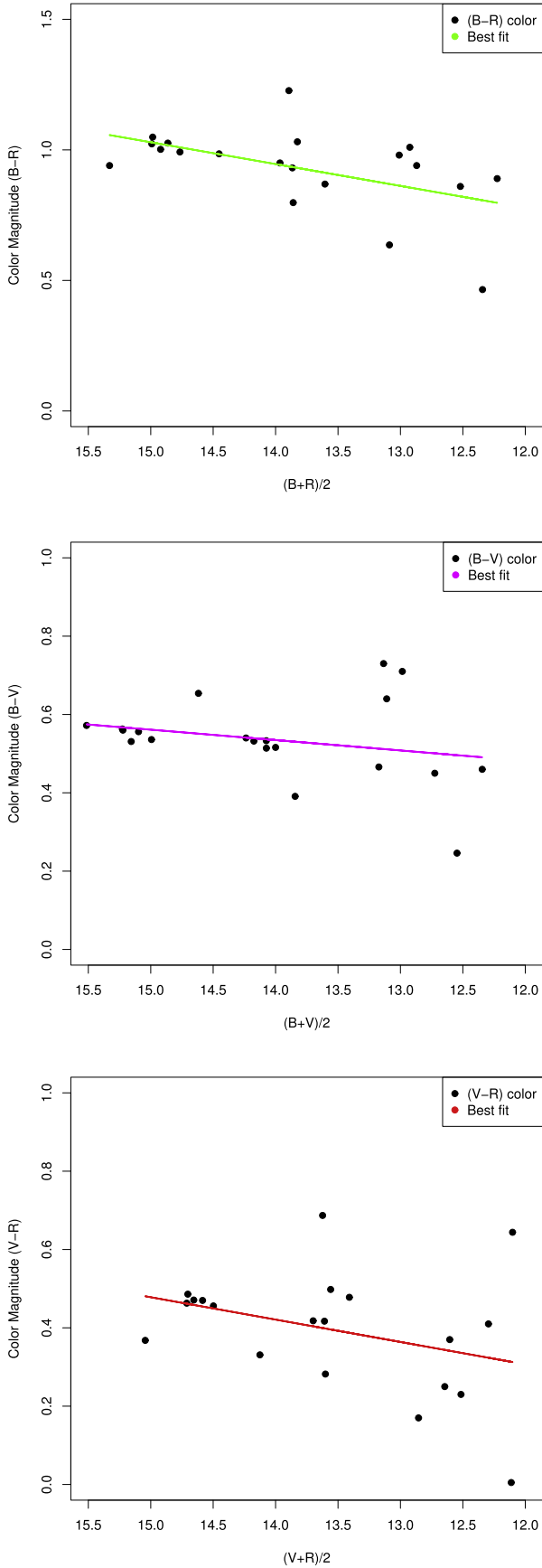


Figure 5. Color–magnitude plot for the source S5 0716+714 during 2013–2015, showing the BWB trend. The fit is obtained by performing the linear regression analysis, and values for the parameters are given Table 4.

during 2014 November–2015 March and found the source in a bright state, showing INV for seven out of eight nights and STV with a 1.9 mag change during about 28 days (MJD 57013.86–57041.34). In their long-term work for the period 2004–2012, Dai et al. (2015) reported STV at 10 days’ timescale and 11 INV nights out of 72 nights observed with an average magnitude of $R = 13.25$ and an overall change of 2.14 mag.

A complete observation log, along with the daily averaged R -band photometric magnitudes for S5 0716+714 and the nature of the night, are provided in Table 3.

3.2.1. Spectral Behavior of S5 0716+71

The variation of color with the brightness of the source provides useful clues to constrain the blazar emission models (Hao et al. 2010). To investigate the spectral behavior of S5 0716+714 over a long timescale, i.e., from 2013 to 2015, the color–magnitude diagrams, $(B-R)$ versus $(B+R)/2$, $(B-V)$ versus $(B+V)/2$, and $(V-R)$ versus $(V+R)/2$, are plotted using nightly averaged magnitudes in the B , V , and R bands, respectively. The minimum and maximum values of the color indices for the better-sampled case of $B-R$ versus $(B+R)/2$ are 0.40 and 1.3, respectively, while the color average is $\langle B-R \rangle = 0.6$ mag, with a standard deviation $\sigma = 0.14$ mag.

Figure 5 shows the spectral behavior of the source with the brightness during 2013–2015. The first panel shows the $(B-R)$ spectral color versus its average magnitude. Similarly, the middle and bottom panels display the $(B-V)$ and $(V-R)$ spectral behavior with their average brightness magnitudes, respectively. To quantitatively determine the correlation between the color index with brightness in Figure 5 (color versus magnitude), we performed regression analysis by fitting a straight line, $y = mx + c$ (y = color index, x = average magnitude), using the linear model in the R software package and extracted various parameters, such as intercept (c), slope (m), correlation coefficient (r^2), p -value, etc. The values for these parameters are given in Table 4.

It is clear from Figure 5 and the values of various parameters obtained from regression analysis (see Table 4) that the source showed a weak positive correlation for the $B-V$ and $V-R$ color indices plotted against brightness magnitudes, with a Pearson correlation coefficient (r^2) of 0.06 and 0.12 along with a p -value of 0.29 and 0.13, respectively. However, a comparatively stronger positive correlation for the $B-R$ color index versus the average magnitude of the source with a Pearson coefficient r^2 of 0.26 and null hypothesis probability $p = 0.02$ are noticed. Thus, the present study suggests a BWB color for S5 0716+71 (cf. Figure 5), as also reported by many workers (Poon et al. 2009; Wu et al. 2009; Chandra et al. 2011; Man et al. 2016). Li et al. (2017) statistically studied the data for S5 0716+71 during 1995–2015; addressed the issue of LTV, STV, and INV behavior of the symmetry in flares and color; and found flares asymmetric in general and BWB color on all the timescales considered. The spectral changes in S5 0716+714, and blazars in general, are complicated and difficult to explain. The source was reported with a strong BWB trend over long timescales (Poon et al. 2009) and during its flaring phase (Ghisellini et al. 1997; Wu et al. 2005, 2009; Gu et al. 2006). Wu et al. (2005) and Agarwal et al. (2016) discussed color trends in their studies but did not find any change on the intra-night or long-term timescales. Raiteri et al. (2003), on the other

Table 4

The Values of the Regression Parameters for Variations in Color Indices as a Function of Brightness (Figure 5) and Time (Figure 6) for S5 0716+714 during 2013–15

Color Index	versus Brightness				versus Time			
	m	c	r^2	p	m	c	r^2	p
$B-R$	0.08 ± 0.03	-0.22 ± 0.45	0.26	0.02	$1e-03 \pm 1e-04$	$-0.002 \pm 1e-04$	0.025	0.01
$B-V$	0.02 ± 0.02	0.16 ± 0.34	0.06	0.29	0.004 ± 0.01	-0.01 ± 0.02	0.10	0.33
$V-R$	0.05 ± 0.03	-0.37 ± 0.48	0.12	0.13	$1e-03 \pm 1e-04$	$0.002 \pm 1e-04$	0.017	0.01

Note. m = slope of regression line, r^2 = square of Pearson correlation coefficient, p = probability for null hypothesis.

hand, noticed all possible scenarios, i.e., BWB, RWB, and no trend at all, in their studies. Stalin et al. (2009) found sources showing no color dependence with brightness on both the long and short timescales, albeit a BWB color on intra- and inter-night timescales was noticed. The fresh injection of high-energy particles in the emission region inside the jet might lead to BWB behavior (Ghisellini et al. 1997; Raiteri et al. 2003; Gu et al. 2006). The BWB behavior can be explained by the shock-in-jet model (Marscher & Gear 1985; Marscher 2008), where the propagation of a disturbance downstream from the jet gives rise to the shock formation and the lag between the emissions at different wavelengths provides information on their relative spatial separations. In the case of BL Lacs, the higher-frequency electrons close to the shock front undergo faster radiation losses than the low-frequency ones. The BWB behavior basically means that the flux enhancements are produced either during the episodes of intense particle acceleration or, alternatively, by the fluctuating magnetic field superimposed on the local, steady electron energy distribution. The redder-when-fainter trend indicates that when the jet is not dominant, the contribution from the disk emission or the host galaxy becomes relevant. These cases show the complex color behavior of the source with brightness. However, in the case of S5 0716+714, where the host galaxy is several magnitudes fainter, $R > 20$ mag (Montagni et al. 2006), thermal contribution from the host is negligible.

Spectral variation with time. The long-term optical LCs of blazars manifest significant details on the nature of the source, as these contain various phases in their brightness, color changes during flares, outbursts, and fainter states. Several authors have looked at spectral variations with time on intra-night and inter-night timescales for blazars (Raiteri et al. 2003; Wu et al. 2005; Stalin et al. 2009; Rani et al. 2010; Gaur et al. 2012; Agarwal et al. 2016) and reported mixed behavior, with some sources showing color dependence while others showed no change in color over considered timescales. Agarwal et al. (2016), during their 130 day study, found a change of about 0.3 mag in spectral color with no significant dependence on the time or brightness phase. Yuan et al. (2017) reported a complex pattern for spectral index with time without any specific trend during the period 2000–2014. The color variations are caused by differential cooling of energetic electrons behind the shock front. The relativistic shock moving down the jet accelerates electrons to high energies at the sites of high magnetic field or electron density, giving rise to emission at diverse frequencies. In BL Lacs, higher-energy electrons cool faster with a larger change in flux with time during a flare. Since the regions of the plasma overdensities or quasi-stationary shocks are randomly distributed in the jet, the interaction of the relativistically moving knot with existing features in the large-scale jet gives rise to multiple outbursts

that evolve individually and perhaps differently. The processes involved give rise to changes in the spectral behavior with time.

In order to understand the spectral behavior of S5 0716+714 with time (2013 January to 2015 June), we plot the color index ($B-R$), ($B-V$), and ($V-R$) against the time in MJD for this period in Figure 6. To get the correlation between the color index and time (MJD), we also performed regression analysis by fitting a straight line, $y = mx + c$ (y = color index, x = time in MJD), using a linear regression software package and extracted various parameters, such as intercept (c), slope (m), correlation coefficient (r^2), and p -value, which are given in Table 4. A nicely sampled LC in different optical bands should give a clear picture of the temporal evolution of S5 0716+714. However, our data suffer from substantial gaps, and the observations in different bands are not truly simultaneous.

Figure 6 shows mixed behavior. While we notice a significantly bluer spectral behavior with time in the ($B-V$) color-versus-time plot, indicating the source getting brighter at higher frequencies during this period of 2.5 yr, we see a very mild bluer trend in ($B-R$) versus time. However, the color index ($V-R$) shows a mild redder color with time. We therefore conclude, based on our data during 2013 January and 2015 June, that the source S5 0716+714 does not show any strong chromatic behavior, barring ($B-V$) showing a bluer behavior during this period. This mixed spectral behavior with time is in line with other studies. The source was in a relatively bright phase during 2013, in low phase during 2014, and in its brightest phase in 2015 January.

4. Conclusions

The IBL blazar S5 716 was observed for 46 nights with high temporal resolution during a period of more than 2 yr (2013–2015) in the optical $BVRI$ wavelength bands from MIRO. It was monitored for more than 2 hr during 29 nights to address INV. The nightly averaged B -, V -, R -, and I -band brightness magnitudes with 6256, 159, 214, and 177 data points were used to discuss LTV and color behavior of the source. The source exhibited intra-night, as well as inter-night, variability at significant levels. From the present study, the following conclusions are drawn.

1. The source showed variability over diverse timescales, i.e., a few tens of minutes to months, and a DCV of more than 31%. The DCV appears to be dependent upon monitoring time. Two major outbursts with ~ 370 and 500 days' duration superimposed with several flares are noticed.
2. The SF analysis leads to the shortest variability timescale of 45.6 minutes, based on which upper limit on the size of the emission region of the order of 10^{15} cm is estimated. There are several timescales longer than this, indicating multisized emission regions in the jet. Based on the

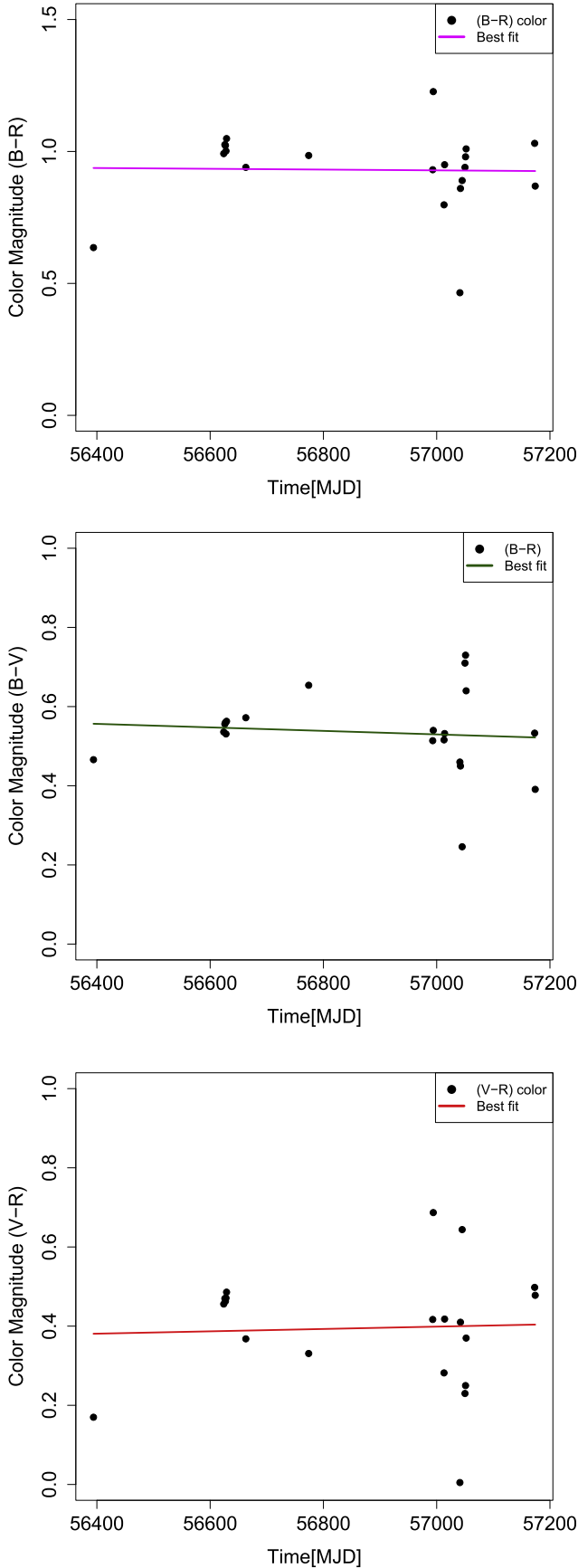


Figure 6. Color of the source S5 0716+714 plotted as a function of time (MJD) during 2013–2015. The solid line is the best fit obtained using linear regression analysis of the data.

longest timescale, the size of the emission region is estimated as 4.8×10^{15} cm.

3. Assuming the rapid variations to be originated in the vicinity of the central engine, the black hole mass is estimated to be $5.6 \times 10^8 M_\odot$ using the shortest variability timescale.
4. The SF analysis is used to infer a period of about 1.2 hr on the night of 2013 December 28. However, it could easily be a red-noise signature, as flux enhancements are within 3σ .
5. The source exhibited a BWB spectral behavior in the long-term LC, which supports a shock-in-jet model.
6. The brightness of S5 0716+71 shows a mild increase with time during 2013 January–2015 June along with a mild bluer color.
7. A larger amplitude of variation when the source was in a relatively brighter state is detected, indicating synchrotron-dominated jet emission. It perhaps indicates that LTV and INV are linked.

It should be noted that these inferences are drawn from the data with large gaps. However, the data presented here should be very useful for other related statistical and modeling studies on this very interesting source.

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Facilities: MIRO:1.2m(PRL-CCD), MIRO:ATVS.

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