RAPID OPTICAL VARIABILITY IN BLAZAR S5 0716+71 DURING 2010 MARCH

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ABSTRACT

We report rapid optical variability for the blazar S5 0716+71 during 2010 March 8–10 and 19–20 in the CCD observations made from Mt. Abu Infrared Observatory. The light curves are constructed for a duration longer than 3 hr each night, with very high temporal resolution (∼45 s in the R band). During 2010 March 8, the source smoothly decayed by about 0.15 mag in 2.88 hr; apart from a fast flicker lasting about 30 minutes. S5 0716+71 brightened during March 9 and 10, showing high activity, while it was relatively faint (∼14 mag in the R band) albeit variable during March 19–20. During March 9 and 10, rapid flickers in the intensity modulated the long-term intra-night (∼3 hr) variations. The present observations suggest that the blazar S5 0716+71 showed night-to-night and intra-night variability at various timescales with a 100% duty cycle for variation along with microvariability at significant levels. On a night-to-night basis, the source exhibits mild bluer-when-brighter nature. The interaction of shocks with local inhomogeneities in the jet appears to cause intra-night variations, while microvariations could be due to small-scale perturbations intrinsic to the jet.

Key words: BL Lacertae objects: individual (S5 0716+71) – galaxies: active – galaxies: photometry – methods: observational

Online-only material: machine-readable table

1. INTRODUCTION

Blazars are an extreme subclass of active galactic nuclei (AGNs), seen at a small angle (<10°) to the relativistic jet emanating from very close to the black hole (Urry & Padovani 1995). They are characterized by strong variability in flux and polarization at almost all frequencies in the electromagnetic spectrum and their variability is often used to probe the central engine and nature of physical processes in AGNs. Blazars are known to show variations on different timescales ranging from years to months to days to hours and minutes. The variations that occur during the course of a night (few hours) are known as intra-night variations (INOVs), while microvariability is a change of a few tenths of magnitude in brightness during hours or less. Some authors use these terms interchangeably (Wagner & Witzel 1989). Fast variation, or microvariability, was first discovered in 1960s by Matthews & Sandage (1963), who found that the brightness of the BL Lac object 3C48 changes by 0.04 mag in the V band in 15 minutes, but their result was not taken seriously due to instrumental errors. However, now microvariability has been confirmed as an intrinsic feature of AGNs, especially blazars (Miller et al. 1989; Villata et al. 2008; Impiombato et al. 2011), and has become a subject of intensive study as its physical mechanisms are not understood well. Several models (e.g., Gopal-Krishna & Subramanian 1991; Mangalam & Wiita 1993; Marscher & Gear 1985; Qian et al. 1991; Marscher 1996; Gopal-Krishna & Wiita 1992) have been proposed in order to explain such fast variations. In order to constrain these models, long-term continuous observations with high temporal resolution (few minutes) are required.

The blazar S5 0716+71 (PKS 0716+714, redshift z = 0.31) is one of the brightest BL Lac objects that is highly variable from the radio to γ-rays with a very high duty cycle (Wagner & Witzel 1995). This source has been the target of a number of monitoring campaigns (e.g., Wagner et al. 1996; Qian et al. 2002; Raiteri et al. 2003; Villata et al. 2008). For the first time, INOV was detected in this source by Heidt & Wagner (1996). A decay in J-band brightness by 0.5 mag during 2003 December 10–12 was reported by Bailyan et al. (2005). Variations on various timescales have also been reported by many authors (e.g., Gupta et al. 2009; Montagni et al. 2006; Stalin et al. 2009, and references therein). Neschi et al. (2002) reported 0.02 mag hr⁻¹ variations during their 52 night observation. Very recently, Carini et al. (2011) reported the B- and I-band microvariability study of S5 0716+71 based on their five-night observation during 2003 March 5–9. In their systematic statistical study, they detected variations at several timescales from days to few tens of minutes. Zhang et al. (2008) claim microvariability down to a 6 minute timescale but their sampling time is large (4–7 minutes). In the present paper, we report day-to-day and rapid variations in the optical brightness of the BL Lac object S5 0716+71 obtained in high temporal resolution observations during five nights in 2010 March.

The paper is organized as follows: Section 2 describes the observations and data analysis procedures, while Section 3 presents the results and their discussion. Conclusions from the study are presented in Section 4.

2. OBSERVATIONS AND DATA ANALYSIS

The photometric observations were carried out by using the liquid nitrogen cooled CCD Camera mounted at the f/13 Cassegrain focus of the 1.2 m Telescope at Mt. Abu Infrared Observatory, Gurushikhar, Rajasthan, operated by the Physical Research Laboratory, Ahmedabad, India. The PIXELANT CCD Camera has 1296 × 1152 pixels² each of 22 μm size and a total read out time of about 13 s. With a scale of 0.29 arcsec pixel⁻¹, the total field of view is about 6.5 × 5.5 arcmin². The CCD read-out noise is four electrons and the dark current is negligible when cooled. The CCD-photometric system is equipped with a Johnson–Cousins UBVRJ filter set.

The source was observed in two observing slots: during 2010 March 8–10 and 2010 March 19–20. All the observation nights were photometric with a seeing better than 1″. Several
bias frames were taken every night at the beginning and the end of the observations. To construct master flats, we have taken a large number of evening twilight sky flats in all the bands each night. The observation strategy was to take four frames each in the $B$, $V$, $R$, and $I$ bands and then to monitor the source in the $R$ band for several hours. The field of view was large enough to accommodate several standard stars in the target frame to facilitate calibration. The exposure times were 30 s in the $I$, $R$, and $V$ bands and 60 s in the $B$ band.

Table 1 presents the details of the observations, giving the date, time (UT) of the starting observation, duration of monitoring (hours), and total number of observation points on the source. The data reduction is performed using standard routines in the IRAF 1 software. On the bias-subtracted, flat-fielded images, differential aperture photometry was performed using DAOPHOT package available in IRAF. The photometry is carried out using several aperture radii, ranging from 1 to 9 times the FWHM. The right size of the aperture is chosen, keeping in mind the optimum value of signal-to-noise ratio ($S/N$) and the prescription of Cellone et al. (2000) to avoid spurious variations. Based on these criteria, we use 4.5 arcsec as the aperture radius for the target and other stars used in the differential photometry. We have used standard stars 6 ($R = 13.26$ mag) and 5 ($R = 13.18$ mag) from Villata et al. (1998), having apparent magnitudes close to that of the source to check the variability of the blazar. Such a choice of comparison and control stars is necessary to avoid any disparity in the measured dispersions of the target-comparison and comparison-control light curves (Howell et al. 1988) due to photon statistics. One star is used to correct the source magnitude and the other as a control star to check the stability.

To check the significance of intra-night variability, we performed the $F$-test incorporated in the $R$ statistical package. The $F$-statistic is the ratio of the sample variances, or $F = S_2^2/S_C^2$, where $S_2^2$ is the variance in the blazar magnitude and $S_C^2$ is that in the standard stars during the whole night of observations. For all the five nights, the $F$-values are greater than 9 with a significance level of 0.999995 or $>5\sigma$. We have also calculated the intra-night variability amplitude, which is given by

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

where $A_{\text{max}}$ and $A_{\text{min}}$ are the maximum and minimum values in the light curves and $\sigma$ is given as

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

Figure 1. Nightly averaged $B$, $V$, $R$, and $I$ magnitudes for S5 0716+71 at a function of time during 2010 March 8–10 and 19–20. Most of the error bars ($\pm\sigma$) lie within the symbol. where $m_i = (m_{S6} - m_{S5})$, is the differential magnitude of stars 6 and 5 for the $i$th observation point, while $\bar{m} = (m_{S6} - m_{S5})$ is their differential magnitudes averaged over the entire data set, and $N$ is the number of observation points obtained that night in a particular band. As the errors are subtracted from the total measured variability, Equation (1) gives a fairer estimate of the amplitude of variability in the source. The results from such analysis of our data for each night are discussed in the following section.

### 3. RESULTS AND DISCUSSION

The light curves for the source were obtained by adopting the abovementioned analysis procedure. The observed magnitudes of the source in the $B$, $V$, $R$, and $I$ bands are calculated with respect to standard star 5 and nightly averaged values are plotted as a function of time in MJD in Figure 1 for 2010 March 8–10 and 19–20. In Figure 2, we plot $R$-band light curves showing intra-night variations during individual nights. The bottom curve in each panel shows the differential light curve of the stars. The observational uncertainties are the rms errors of the nightly differential magnitudes of calibration star 5 and check star 6 as given in Equation (2). The typical rms errors for the $R$ band are less than 0.008 mag. These $R$-band magnitudes for S5 0716+71 for all the nights of observation are given in Table 2 in truncated form. The full data table is available electronically in a machine-readable form in the online version of the journal.

Table 3 lists the result of the $F$-test, giving the date of observation, $F$-value, standard deviation in the differential magnitudes of stars, and the amplitude of variation in the source each night. On March 19, we have five data points at the beginning and 24 data points at the end of the night, covering about 3.5 hr. The $F$-value for this night, therefore, is obtained from these limited measurements. The tabulated values for all the nights indicate that the source is significantly variable during the present observing run, showing 100% duty cycle for variation. A similar result has been reported by other workers (e.g., Wagner & Witzel 1995). The $F$-test results are in very good agreement with the values obtained from the variability test (Jang & Miller 1997). Here, the confidence level of variability is defined by the parameter $C = \sigma_T/\sigma$, where $\sigma_T$ is the standard deviation in the differential light curve of the source and comparison star. The source is considered variable at the 99% confidence level if $C \geq 2.576$. Our values for the variability parameter for March 8, 9, 10, and 20 are, 7.66, 3.35,

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1 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
Figure 2. R-band light curves showing INOV for S5 0716+71 on 2010 March 8, 9, 10, and 20. The lower curve in each panel shows differential light curve for comparison and control stars plotted with appropriate offsets.

Table 2

| Date       | MJD (55200 +) | Mag | σ (mag) |
|------------|---------------|-----|---------|
| 2010 Mar 8 |               |     |         |
| 63.39160   | 13.211        | 0.007 |
| 63.39210   | 13.215        | 0.007 |
| 63.39260   | 13.211        | 0.007 |
| 63.39310   | 13.208        | 0.007 |
| 63.39360   | 13.204        | 0.007 |
| 2010 Mar 9 |               |     |         |
| 64.38170   | 13.054        | 0.006 |
| 64.38220   | 13.041        | 0.006 |
| 64.38270   | 13.048        | 0.006 |
| 64.38320   | 13.049        | 0.006 |
| 64.38370   | 13.045        | 0.006 |
| 2010 Mar 10|               |     |         |
| 65.38520   | 12.906        | 0.005 |
| 65.38570   | 12.911        | 0.005 |
| 65.38630   | 12.914        | 0.005 |
| 65.38680   | 12.921        | 0.005 |
| 65.38730   | 12.920        | 0.005 |

Table 3

| Date       | F-value | σ (mag) | Amp(%) |
|------------|---------|---------|--------|
| 2010 Mar 8 | 38.82   | 0.006   | 16.8   |
| 2010 Mar 9 | 11.27   | 0.006   | 9.1    |
| 2010 Mar 10| 20.51   | 0.005   | 9.9    |
| 2010 Mar 19| 98.54   | 0.004   | 12.8   |
| 2010 Mar 20| 19.73   | 0.008   | 14.4   |

The intra-night variability of S5 0716+71 for 52 nights and claimed a variation rate of 0.02 mag hr$^{-1}$ along with a maximum rising rate of 0.16 mag hr$^{-1}$, while Montagni et al. (2006) reported equally fast variation rates of 0.1–0.16 mag hr$^{-1}$. In the following, we discuss results obtained in the present study.

3.1. Inter-night Variations

Figure 1 shows nightly averaged B, V, R, and I magnitudes as a function of time (MJD) for all five nights. It is evident that S5 0716+71 brightens by 0.34, 0.3, 0.3, and 0.24 mag in the B, V, R, and I bands, respectively, during 2010 March 8–10. During March 19–20, the source decreases in brightness by 0.23, 0.22, and 0.21 mag in the B, R, and I bands, respectively. Evidently, during our observations the blazar S5 0716+71 was brightest on March 10 ($R \approx 12.914 \pm 0.008$ mag) and faintest on March 20 ($R \approx 14.179 \pm 0.006$ mag). The figure also gives clear indication that the source is mildly bluer when brighter and redder when fainter. During the period of eight days (March 11–18), when we do not have observations, S5 0716+71 became fainter by about 1.10 (R band) and 1.49 (B band) mag, clearly showing an increase in the amplitude of variation with the frequency.
3.2. Intra-night Variations (INOVs)

From the light curves in Figure 2, it is evident that the blazar S5 0716+71 is showing significant INOVs on almost all of the nights it was monitored. Here we discuss the variability behavior night by night.

On 2010 March 8, the source brightens up to \( R \approx 13.185 \) mag at MJD = 55263.40. It then decays to \( R \approx 13.335 \) mag at MJD = 55263.52, a variation of 0.15 mag during 2.88 hr (decay rate \( \approx 0.052 \) mag hr\(^{-1}\)). This smoothly falling curve is superposed by a flicker (between MJD55263.44 and MJD55263.46) that brightens the source by more than 2\( \sigma \) within a timescale of about 15 minutes.

The blazar S5 0716+71 appears to be very active during the night of 2010 March 9 (cf. Figure 2). The source is in the brightening phase with several rapid fluctuations modulating a smoothly varying intra-night light curve. During the first microvariability event of the night, the source fades by 0.032 mag (<5\( \sigma \)) with a timescale of \( \approx 15 \) minutes. It then brightens to its highest value \( (R = 12.976 \) mag) at MJD = 55264.46 within a time span of about 1.24 hr (rise rate \( 0.063 \) mag hr\(^{-1}\)). The source then decays by 0.05 mag within 0.48 hr toward the end of the observations.

The statistical analysis of the light shows fast variation rates (up to \( \approx 0.38 \) mag hr\(^{-1}\)) for several segments on March 10. During the entire night, the source remains in a bright state with rapid fluctuations in the intensity. We have recorded the most rapid fluctuation during this night. For the most significant peak, we have calculated the rise and fall rates to be \( \approx 0.38 \) mag hr\(^{-1}\) and \( \approx 0.08 \) mag hr\(^{-1}\), respectively. Toward the end (from MJD 55265.502 to MJD 55265.539), S5 0716+71 brightens by 0.09 mag in the \( R \) band within about 53 minutes. The source also shows several microvariability events on a timescale of about 15 minutes. On March 19, we have few observation points in the beginning and end of the night. However, the trend shows significant variation, about 0.1 mag in 3.5 hr of duration. The light curve for this night is not shown here. On March 20, the source is initially stable but later (at MJD = 55275.43) starts brightening, changing by 0.12 mag in 1.68 hr (0.07 mag hr\(^{-1}\)). The source is generally faint during these two nights and microvariability, if any, is washed out in the relatively large scatter (0.008 mag).

Let us now discuss our results in detail. The present observations reveal significant variability at intra-night (1.24–2.88 hr) and inter-night (night-to-night to nine nights) timescales, as well as microvariability (15 minutes or more) or fast fluctuations. Similar behavior for S5 0716+71 is reported by Carini et al. (2011) in their 2003 March 5–9 observations made in the \( B \) and \( I \) bands. As mentioned above, to avoid the spurious variations caused by the variation in the seeing and/or contamination by the thermal emission from the unresolved host galaxy, we have carefully chosen aperture and comparison/control stars. In order to delineate small-scale fluctuations, we have used the best temporal resolution (\( \approx 45 \) s) reported so far. Many authors have reported INOV and microvariability for this source at similar timescales (e.g., Quirrenbach et al. 1991; Villata et al. 2008; Carini et al. 2011) but with few minutes to tens of minutes temporal resolutions. Zhang et al. (2008) have reported fast variations at 6–33 minute timescales with an unusually large (>1 mag) amplitude of variations. They do not mention the aperture size adopted but have used exposures ranging from 4 to 7 minutes and have calibrated the source magnitude with the brightest star in the field. Some of these are prescriptions for spurious variations as investigated by Cellone et al. (2000).

The observed optical emission in blazars originates in a part of the accretion disk and the inner (pc-scale) regions of the jet. In light of this, one can discuss the possible reasons behind the variations over various timescales. We should also keep in mind that optical variability timescales shorter than a few hours would imply emitting regions to be smaller than the Schwarzschild radius for certain objects, depending upon their mass. There are a host of models to explain extrinsic and intrinsic variability in blazars: microlensing effect (Chang & Refsdal 1979), light house effect (Camenzind & Krockenberger 1992), accretion disk models (Chakrabarti & Wiita 1993; Mangalam & Wiita 1993), and shock-in-jet model (Marscher & Gear 1985). As far as our observations are concerned, we notice mild chromatic behavior (bluer when brighter) in the inter-night light curves. Our intra-night light curves do not show any symmetry or periodicity and the variability timescales are short, ranging from few tens of minutes to few hours. Such fast variations with amplitude of the variations reported here are difficult to explain using the accretion disk models. Since the blazar emission is dominated by the jet radiation, we concentrate on relativistic jet models.

A mild chromatic behavior in the long-term variation is explained by Villata et al. (2004) and Papadakis et al. (2007) for BL Lacertae, using the data obtained during several Whole Earth Blazar Telescope (WEBT\(^2\)) campaigns covering the period from 1997 to 2002, by the variation in the Doppler factor due to the change in the viewing angle. They interpreted flux variability in terms of two components: a long-term (few days timescale) variation component as a mildly chromatic event and a fast (intra-day) varying component characterizing strong bluer-when-brighter chromatic behavior. If the intrinsic source spectrum is well described by a power law, a Doppler factor variation does not imply a color change. But mildly chromatic behavior could be due to Doppler factor variation on a spectrum slightly deviating from a power law. A change in the Doppler factor changes both the flux \((F \propto \delta^4)\) and the frequency \((\nu \propto \delta)\) of emission. The inter-night variations reported here for S5 0716+71, which show mild chromatic behavior, could be the result of the change in the Doppler factor.

Rapid variability can be produced when a relativistic shock wave or a blob propagates down the jet with turbulent plasma (Marscher et al. 1992; Qian et al. 1991). Synchrotron emission gets enhanced when the shock encounters particle or magnetic field overdensities. The amplitude and the timescale of the variation depend on the turbulence and shock thickness. Fast variations thus require shocks to be very thin and emission to originate from very close to the central engine. Based on our shortest intra-night variation timescale \((t_\nu)\) of 1.24 hr, the upper limit on the size of the emission region, with Doppler boosting and cosmological corrections, is \( R \approx t_\nu c/(1 + z) \approx 10^{15} \) cm, where \( c \) is the speed of light and \( \delta \) is the Doppler factor (taken as 10 here). Considering this size as a bound on the Schwarzschild radius of the central engine, one can estimate its mass using \( M \approx (c^2/R)/3G \), which comes out to be \( \approx 1.1 \times 10^9 \) \( M_\odot \). However, estimation of black hole mass using such fast optical variations must be taken with caution (Quirrenbach et al. 1991). The variations shorter than INOV (microvariations) amounting to few tens of minutes as reported here and by many other authors cannot possibly be explained by the shock-in-jet model. These are perhaps due to small fluctuations intrinsic to the jet or imprint by a small fraction of black hole horizon

\(^2\) http://www.to.astro.it/blazars/webt/
4. CONCLUSIONS

Here we have reported intra-night variations and microvariability in the blazar S5 0716+71 as observed in the high temporal resolution observations carried out during 2010 March 8–10 and 19–20. We note that the source was variable with a 100% duty cycle at various timescales. Inter-night behavior of the source appears to be bluer when brighter from the limited observations. It is evident that S5 0716+71 was highly active during 2010 March 9, 10, and 20 with rapid flickers superposed on the slowly varying intra-night light curves. On March 19, it shows substantial decay but we do not have full coverage of the night to comment on the behavior of nightly variation.

The source shows various timescales for the variation, ranging from close to 2 hr to 15 minutes. The inter-night variations showing mild bluer-when-brighter nature could be due to variations in the Doppler factor. While intra-night variations with few-hour timescales are probably due to the interaction of fast-moving shocks in the jet with local small-scale inhomogeneities, it is very difficult to associate faster variations with the spatial extent of the emitting region. Perhaps these variations originate in a small region of the blob. Taking the shortest intra-night variability timescale of 1.24 hr, the linear size of the emitting region is estimated to be $\approx 10^{15}$ cm and with the corresponding Schwarzschild radius, $\approx 1.1 \times 10^9 M_\odot$ is the mass of the black hole.

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