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Optical intraday variability studies of 10 low energy peaked blazars

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ABSTRACT

We have carried out optical (*R* band) intraday variability (IDV) monitoring of a sample of 10 bright low energy peaked blazars (LBLs). 40 photometric observations, of an average of ∼4 h each, were made between 2008 September and 2009 June using two telescopes in India. Measurements with good signal-to-noise ratios were typically obtained within 1–3 min, allowing the detection of weak, fast variations using *N*-star differential photometry. We employed both structure function and discrete correlation function analysis methods to estimate any dominant time-scales of variability and found that in most of the cases any such time-scales were longer than the duration of the observation. The calculated duty cycle of IDV in LBLs during our observing run is ∼52 per cent, which is low compared to many earlier studies; however, the relatively short periods for which each source was observed can probably explain this difference. We briefly discuss possible emission mechanisms for the observed variability.

Key words: galaxies: active – BL Lacertae objects: general – galaxies: photometry.

1 INTRODUCTION

Blazars are a subclass of radio-loud active galactic nuclei (AGNs) characterized by strong and rapid flux variability across the entire electromagnetic (EM) spectrum and strong polarization from radio to optical wavelengths. Microvariability, or intraday variability (IDV) is commonly observed across much of the EM spectrum of AGNs but is particularly common in blazars. A change of flux of ∼1–15 per cent within a few minutes to hours reflect extreme physical conditions embedded in small subparsec scales. According to the usually accepted orientation based unified model of radio-loud AGNs, blazar jets usually make an angle $\leq 10^\circ$ to our line of sight (Urry & Padovani 1995). The Doppler boosting of the jet emission means that most of what we see from blazars arises in those jets. These jet dominated AGNs provide a natural laboratory to study the mechanisms of energy extraction from the vicinity of central supermassive black holes, the physical properties of jets and perhaps also accretion discs.

The radiation of blazars across the whole EM spectrum is predominantly non-thermal. At lower frequencies [through the ultraviolet (UV) or X-ray bands] the mechanism is almost certainly synchrotron emission while at higher frequencies it is very probably dominated by inverse Compton (IC) emission (Sikora & Madejski 2001; Krawczynski 2004). The spectral energy distributions (SEDs) of blazars have a double-peaked structure (Ghisellini et al. 1997; Fossati et al. 1998). Based on the location of the peak of their SEDs, blazars are often subclassified into the low energy peaked blazars (LBLs) and high energy peaked blazars (HBLs); the first component peaks in the near-infrared (NIR)/optical in case of LBLs and in the UV/X-rays in HBLs, while the second component usually peaks at GeV energies in LBLs and at TeV energies in HBLs.

The study of variability is one of the most powerful tools for revealing the nature of blazars and probing the various processes occurring in them. Based on their different time-scales, the variability of blazars can be broadly divided into three classes, IDV, short-term variability (STV) and long-term variability (LTV). Variations in the flux of source up to a few tenths of magnitude over a time-scale of a day or less is known as IDV (Wagner & Witzel 1995) or microvariability, or intranight optical variability. Variations of days to a few months are often considered to be STV, while those from several months to many years are usually called LTV (e.g. Gupta et al. 2004); both of these classes of variations for blazars typically exceed ∼1 mag and can exceed even 5 mag. Over the last two decades, the optical variability of blazars has been extensively studied on diverse time-scales (e.g. Heidt & Wagner 1996; Sillanpää et al. 1996a,b; Ciprini et al. 2003, 2007; Gupta et al. 2004, 2008a,b,c; Gupta, Srivastava & Wiita 2009, and references therein).

There are several theoretical models that might be able to explain the observed variability over wide time-scales for all bands, with the leading contenders all variants of models based upon shocks propagating down relativistic jets (Marscher & Gear 1985; Hughes, Aller & Aller 1991; Qian et al. 1991; Marscher, Gear & Travis 1992; Wagner & Witzel 1995). Some of the variability may arise

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from helical structures, precession or other geometrical effects occurring within the jets (e.g. Camenzind & Krockenberger 1992; Gopal-Krishna & Wiita 1992) and some of the radio variability is due to extrinsic propagative effects (Rickett et al. 2001). Hot spots or other disturbances in or above accretion discs surrounding the black holes at the centres of AGNs (e.g. Chakrabarti & Wiita 1993; Mangalam & Wiita 1993) are likely to play a key role in the variability of non-blazar AGNs and might provide seed fluctuations that could be advected into a rotating blazar jet and then be Doppler amplified.

Despite the large amount of information we have about blazars that is very briefly summarized above, we still lack sufficient understanding of basic parameters of the emission regions, such as jet composition, a quantitative assessment of beaming parameters, or the processes leading to the origin of shocks in the jets. These physical quantities are obviously important in understanding the physics of jets and their emission regions and additional IDV studies leading to statistically valid pictures of many blazars can help constrain them.

In this paper we present the results of an extensive IDV studies of a sample of 10 LBLs including six BL Lacs and four Flat Spectrum Radio Quasars (FSRQs). The work presented here is focused on intraday variations in the R passband magnitudes of these sources, which were the brightest blazars visible from ARIES, Nainital, India and PRL, Mount Abu, India. We also compare our observational results to some of those presented in the literature.

The paper is structured as follows. In Section 2, we present the observations and data reduction procedure. Section 3 provides our analysis and results. We present our discussion and conclusions in Section 4.

2 OBSERVATIONS AND DATA REDUCTION

We have carried out optical *R*-band photometric observations of 10 LBLs from 2008 September to 2009 June using two telescopes in India. The details of the telescopes and instruments used are given in Table 1 and the observation details are in Table 2.

For doing image processing, or data preprocessing, we generated a master bias frame for each observing night by taking the median of all bias frames; the master bias frame was subtracted from all flat and source image frames taken on that night. Then the master flat in each passband was generated by median combine of flat frames in that passband. Finally, the normalized master flat in each passband was generated. As usual, each source image frame was divided by the normalized master flat in the respective passband to remove pixel-to-pixel inhomogeneities (flat-fielding). Finally, cosmic ray removal was done from all source image frames. This preprocessing of the data was done by using standard routines in the Image Reduction and Analysis Facility[1] (IRAF) software.

Table 1. Properties of telescopes and instruments.

Site	ARIES Nainital	PRL Mount Abu
Telescope	1.04-m RC Cassegrain	1.20-m Cassegrain
CCD model	Wright 2K CCD	Andor EMCCD
Chip size	2048 × 2048 pixels	1024 × 1024 pixels
Pixel size	24 × 24 μm	13 × 13 μm
Scale	0.37 arcsec pixel^{-1}	0.18 arcsec pixel^{-1}
Field	13 × 13 arcmin^2	3 × 3 arcmin^2
Gain	10 e^- ADU^{-1}	5 e^- ADU^{-1}
Read out noise	5.3 e^- rms	4.9 e^- rms
Binning used	2 × 2	2 × 2
Typical seeing	1–2.8 arcsec	1–2.6 arcsec

Our data analysis, or processing of the data, utilizes Dominion Astronomical Observatory Photometry (DAOPHOT II) software to perform aperture photometry (Stetson 1987, 1992). We carried out aperture photometry with four different aperture radii, 1 × FWHM, 2 × FWHM, 3 × FWHM and 4 × FWHM. On comparing the results, we observed that aperture radii = 3 × FWHM provided the best signal-to-noise ratio, and we have adopted that in this work. For all of the 10 blazars, we observed more than three local standard stars. The magnitudes of the standard stars we used in the fields of our sources are given in Table 3. The multiple comparison stars were used to check that the usual standard stars were non-variable. We have used two non-varying standard stars from each blazar field and plotted their differential instrumental magnitudes in Figs 1–9. Finally, for the calibration of blazar data, we have used the one standard star that has a colour closer to the blazar from those two standard stars. The calibrated light curves (LCs) of the blazars are plotted in the same panel with the differential instrumental magnitudes of two standard stars.

3 ANALYSIS AND RESULTS

3.1 Variability parameters

We checked for the presence of microvariability both by using the F-test (de Diego 2010) and the variability detection parameter, C, for the sake of comparison with earlier papers, which nearly always used that approach. For two sample variances, say $s^2_{\rm Q}$, for the quasar differential LCs and $s^2_{\rm stS}$, for that of the standard star

$$F = \frac{s^2_{\rm Q}}{s^2_{\rm stS}}. \tag{1}$$

The F-statistic is compared with a critical value corresponding to the significance level set for the test. We have used the inbuilt F-test code available in R.[2] A p-value of $\leq$0.01 ($\geq$99 per cent significance level) is adopted for our variability detection criterion.

The variability detection parameter is defined as (e.g. Romero, Cellone & Combi 1999) the average of $C1$and $C2$ where

$$C1 = \frac{\sigma({\rm BL - starA})}{\sigma({\rm starA - starB})} \quad \text{and} \quad C2 = \frac{\sigma({\rm BL - starB})}{\sigma({\rm starA - starB})}. \tag{2}$$

Here (BL − starA) and (BL − starB) are the differential instrumental magnitudes of the blazar and standard star A and the blazar and standard star B, respectively, while σ(BL − starA) and σ(BL − starB) are the observational scatters of the differential instrumental magnitude of the blazar and star A and the blazar and star B, respectively. If $C \geq 2.57$, a conservative confidence level of a variability detection is >99 per cent, and we consider this to be a positive detection of a variation using this criterion. As noted by de Diego (2010) this C-statistic does not behave as a proper statistic should, but as it has been used in most of the IDV studies in literature, we also employed this test.

The percentage variation in the intraday LCs of LBLs is calculated by using the variability amplitude parameter, A, introduced by

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[1] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

[2] R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org.

Table 2. Observation Log.

Blazar name	Date of observation	Telescope	Filter	Data points	Duration (h)
3C 66A	2008 October 22	A	R	68	3.86
	2008 October 26	A	R	72	3.50
	2008 December 23	B	R	90	1.45
	2008 December 24	B	R	113	1.85
	2008 December 27	B	R	417	3.46
	2008 December 28	B	R	203	2.23
	2009 January 03	B	R	320	3.54
AO 0235+164	2008 October 20	A	R	98	6.30
	2008 October 23	A	R	45	2.60
	2008 December 26	B	R	248	1.23
PKS 0420−014	2008 October 23	A	R	18	1.94
	2008 December 26	B	R	29	0.73
S5 0716+714	2008 October 24	A	R	25	1.35
	2008 December 23	B	R	114	0.40
	2008 December 24	B	R	292	1.62
	2009 January 03	B	R	2685	3.73
PKS 0735+178	2008 December 23	B	R	90	0.63
	2008 December 28	B	R	300	3.20
	2009 January 04	B	R	50	1.02
	2009 January 20	A	R	67	3.98
OJ 287	2008 December 26	B	R	70	0.57
	2009 January 20	A	R	60	3.87
	2009 January 22	A	R	70	3.35
3C 273	2008 December 23	B	R	130	0.72
	2009 January 22	A	R	90	3.88
	2009 February 25	A	R	101	3.61
	2009 March 24	A	R	36	1.38
	2009 April 01	A	R	110	5.60
	2009 April 18	A	R	91	3.54
	2009 April 19	A	R	195	7.42
	2009 April 27	A	R	66	3.31
PKS 1510−089	2009 April 17	A	R	77	3.82
	2009 April 19	A	R	22	1.09
	2009 April 27	A	R	64	4.47
	2009 June 21	A	R	68	4.41
BL Lac	2008 September 04	A	R	83	5.10
	2008 October 26	A	R	73	4.25
	2009 June 21	A	R	62	2.98
3C 454.3	2008 October 24	A	R	55	3.01
	2008 October 28	A	R	65	4.25

A : 1.04-m Sampuranand Telescope, ARIES, Nainital, India
B : 1.20-m Telescope, PRL, Mount Abu, India.

Heidt & Wagner (1996), defined as

$$A = 100 \times \sqrt{(A_{\max} - A_{\min})^2 - 2\sigma^2}(\text{per cent}), \tag{3}$$

where $A_{\max}$ and $A_{\min}$ are the maximum and minimum magnitudes in the calibrated LCs of the blazar and σ is the average measurement error of the blazar LC. The calculated F-statistics, C-'statistics' and variability amplitude parameter, A, values are listed in Table 4.

3.2 Structure function

The first order structure function (SF) is a very useful tool to search for periodicities and time-scales of variability in time series data trains (Simonetti, Cordes & Heeschen 1985). Here we give only a very brief introduction to the method; for details refer to Rani, Wiita & Gupta (2009). The first order SF for a data train, a, is defined as

$$D^1_a(k) = \frac{1}{N^1_a(k)} \sum_{i=1}^{N} w(i)w(i+k)[a(i+k) - a(i)]^2, \tag{4}$$

where k is the time lag, $N^1_a(k) = \sum w(i)w(i+k)$, and the weighting factor, $w(i)$ is 1 if a measurement exists for the ith interval, and 0 otherwise.

The behaviour of the first order SF can be simply summarized. The SF curves for AGN usually at first rise with time lag. Following this rising portion, the SF will then fall into one of the following classes: (i) if no plateau exists, any time-scale of variability exceeds the length of the data train; (ii) if there are one or more plateaus, each one indicates a possible time-scale of variability; and (iii) if that plateau is followed by a dip in the SF, the lag corresponding to the minimum of that dip indicates a possible periodic cycle (unless such a dip is seen at a lag close to the maximum length of the data train, when it is probably an artefact). However, (iv) uncorrelated data produce a white noise behaviour, characterized by a constant slope (Ciprini et al. 2003).

We have carried out the SF analysis of all of those LCs which satisfy the variability detection criteria. Recently, some weaknesses of the SF method, including spurious indications of time-scales and

Table 3. Standard stars in the Blazar Fields.

Source name	Standard star	R magnitude (error)	References[a]
3C 66A	1	13.36(0.01)	5
	2	14.28(0.04)	5
	3	15.46(0.12)	5
	4	12.70(0.04)	6
	5	13.62(0.05)	6
AO 0235+164	1	12.69(0.02)	1
	2	12.23(0.02)	1
	3	12.48(0.03)	1
	6	13.64(0.04)	6
	8	15.79(0.10)	1
	C1	14.23(0.05)	6
PKS 0420−014	1	12.09(0.03)	4
	2	12.80(0.02)	5
	3	12.89(0.01)	5
	4	14.47(0.01)	5
	5	14.37(0.03)	4
	6	14.70(0.03)	4
	7	14.91(0.03)	4
	8	15.46(0.03)	4
	9	15.58(0.04)	4
S5 0716+714	1	10.63(0.01)	2
	2	11.12(0.01)	2, 3
	3	12.06(0.01)	2, 3
	4	12.89(0.01)	2
	5	13.18(0.01)	2, 3
	6	13.26(0.01)	2, 3
	7	13.32(0.01)	2
	8	13.79(0.02)	2
PKS 0735+178	A	13.14(0.05)	1
	C	13.87(0.06)	1
	D	15.45(0.06)	1
OJ 287	2	12.46(0.05)	1
	4	13.72(0.06)	1
	10	14.26(0.06)	1
	11	14.67(0.07)	1
3C 273	C	11.30(0.04)	1
	D	12.31(0.04)	1
	E	12.27(0.05)	1
	G	13.16(0.05)	1
PKS 1510−089	1	11.23(0.03)	5
	2	12.95(0.03)	5
	3	13.98(0.09)	5
	4	14.34(0.05)	5
	5	14.35(0.05)	4
	6	14.61(0.02)	4
BL Lac	B	11.93(0.05)	1
	C	13.69(0.03)	1
	H	13.60(0.03)	1
	K	14.88(0.05)	1
3C 454.3	A	15.32(0.09)	6, 9
	B	14.73(0.05)	6, 9
	C	13.98(0.02)	9, 10
	D	13.22(0.01)	9, 10
	E	14.92(0.08)	6, 9
	F	14.83(0.03)	4, 9
	G	14.83(0.02)	4, 9
	H	13.10(0.04)	6, 9
	C1	15.27(0.06)	6

[a] 1. (Smith et al. 1985); 2. (Villata et al. 1998); 3. (Ghisellini et al. 1997); 4. (Raiteri et al. 1998); 5. (Smith & Balonek 1998); 6. (Fiorucci & Tosti 1996); 7. Craine E.R.:Handbook of Quasistellar and BL Lacertae Objects, (Angione 1971); 8. http://www.lsw.uni-heidelberg.de/projects/extragalactic/charts/2251+158.html

periodicities have been discussed by Emmanoulopoulos, McHardy & Uttley (2010), so we cross check the SF results by using the discrete correlation function (DCF) method. The time-scales of variability calculated using the SF analysis are listed in Table 4.

3.3 Discrete Correlation functions

The DCF method was first introduced by Edelson & Krolik (1988) and it was later generalized to provide better error estimates (Hufnagel & Bregman 1992). Here we give only a brief introduction to the method; for details refer to Hovatta et al. (2007), Rani et al. (2009), and references therein.

The first step is to calculate the unbinned correlation (UDCF) using the given time series through (Hovatta et al. 2007)

$$\mathrm{UDCF}_{ij} = \frac{(a(i) - \bar{a})(b(j) - \bar{b})}{\sqrt{\sigma_a^2 \sigma_b^2}}. \qquad (5)$$

Here $a(i)$ and $b(j)$ are the individual points in two time series a and b, respectively, $\bar{a}$ and $\bar{b}$ are respectively the means of the time series, and σ_a^2 and σ_b^2 are their variances. The correlation function is binned after calculation of the UDCF. The DCF method does not automatically define a bin size, so several values need to be tried. If the bin size is too big, useful information is lost, but if the bin size is too small, a spurious correlation can be found. Taking τ as the centre of a time bin and n as the number of points in each bin, the DCF is found from the UDCF via

$$\mathrm{DCF}(\tau) = \frac{1}{n} \sum \mathrm{UDCF}_{ij}(\tau). \qquad (6)$$

The error for each bin can be calculated using

$$\sigma_{def}(\tau) = \frac{1}{n-1} \left\{ \sum [\mathrm{UDCF}_{ij} - \mathrm{DCF}(\tau)]^2 \right\}^{0.5}. \qquad (7)$$

A DCF analysis is frequently used for finding the correlation and possible lags between multifrequency AGN data where different data trains are used in the calculation (e.g. Raiteri et al. 2003; Villata et al. 2004; Hovatta et al. 2007, and references therein). When the same data train is used, so $a = b$, there is obviously a peak at zero DCF, indicating that there is no time lag between the two, but any other strong peaks in the DCF give indications of variability time-scales. The calculated t_v values using DCF analyses are listed in Table 4.

3.4 Intraday Variability of individual blazars

The R filter LCs of the blazars in which significant variability has been detected, along with their corresponding SF and DCF analysis curves, are displayed in Figs 1–7; the remaining non-variable LCs of the blazars are plotted along with the corresponding curves of the standard stars used for comparison in Figs 8 and 9. The complete observing log for the blazars is given in Table 3. The values of A-, C-, F-test along with any estimated time-scales of variability found using SF and DCF analysis methods on the individual blazar LCs are listed in Table 4. A detailed multiband optical STV study of the fluxes and colours of all of these blazars over the same time period of observation is reported in Rani et al. (2010b). There we showed that the colour versus brightness correlations seen in these sources support the hypothesis that BL Lacs tends to be bluer with increase in brightness while FSRQs show the opposite trend. We now report some key individual results for each of our sources, placed in the context of earlier work.

3C 66A: This is a LBL at redshift $z = 0.444$ (Lanzetta, Turnshek & Sandoval 1993) and belongs to the class of BL Lac objects. Since

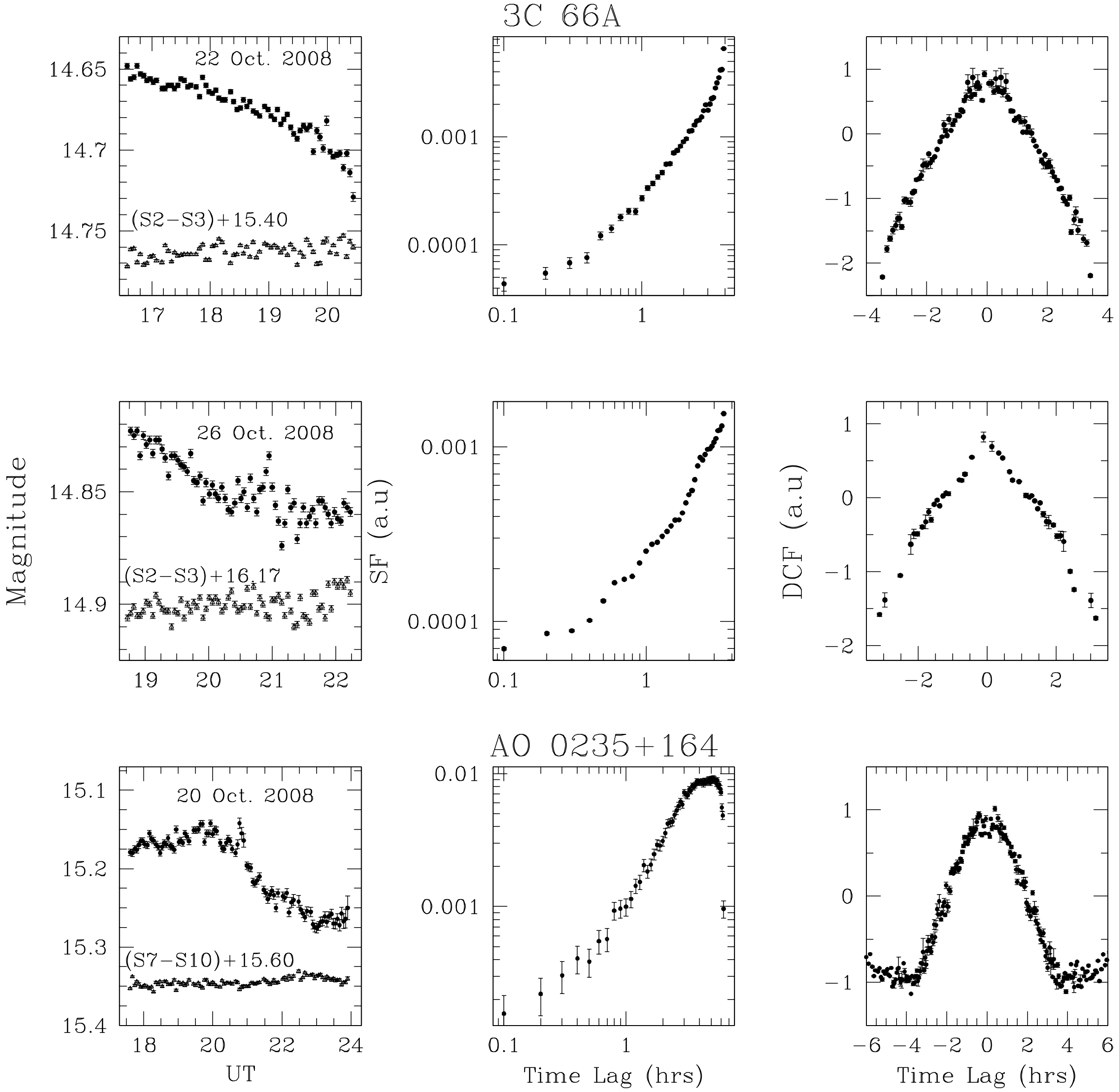

Figure 1. *R*-band optical IDV LCs of the blazars 3C 66A and AO 0235+164 and their respective SFs and DCFs.

its optical identification (Wills & Wills 1974), the source has been regularly monitored at many observable frequencies, although less regularly at radio frequencies (Aller, Aller & Hughes 1992; Takalo et al. 1996). Fan & Lin (1999, 2000) have studied the long-term optical and IR variability of the source and reported a variation of ≤1.5 mag at time-scales of ∼1 week to several years at those two frequencies. Böttcher et al. (2005) reported a large microvariability of ∼0.2 mag within 6 h; they also reported several major outbursts in the source separated by ∼50 d and argued that the outbursts seem to have a quasi-periodic behaviour. At the end of 2007 the source was found to be in an optically active phase, which triggered a new Optical-IR-Radio Whole Earth Blazar Telescope (WEBT) campaign on the source (Böttcher et al. 2009).

Our optical IDV observations of the source 3C 66A comprise a total of seven LCs, spanning a time period between 2008 October and 2009 January. During this period a change of ∼1 mag in brightness of the source is seen (Rani et al. 2010b). The source showed significant microvariability only on 2008 October 22 and 26 (Fig. 1). There is a continuous fading trend of ∼0.08 and ∼0.06 mag, respectively, on those two nights. The SF and DCF analysis of the LCs revealed that any time-scale of variability in this source at those epochs is greater than the lengths of our observations.

AO 0235+164: The blazar AO 0235+164 at $z = 0.94$ (Nilsson et al. 1996) was classified as a BL Lac object by Spinrad & Smith (1975). Over the past few decades this blazar has been seen to be highly variable over all time-scales and at all frequencies (Ghosh & Soundararajaperumal 1995; Heidt & Wagner 1996; Raiteri et al. 2001) and a very high fractional polarization of ∼40 per cent has been reported in the source both at visible and IR frequencies (Impey, Brand & Tapia 1982). By analysing 25 yr (1975–2000) of optical and radio data, Raiteri et al. (2001) argued that the source seemed to have an optical outburst period of ∼5.70 yr but the expected outburst in 2004 was not detected by a 2003–2005 multiwavelength WEBT observing campaign (Raiteri et al. 2006b). A more detailed long term optical data analysis suggested a possible outburst period of ∼8 yr in this source (Raiteri et al. 2006a) and

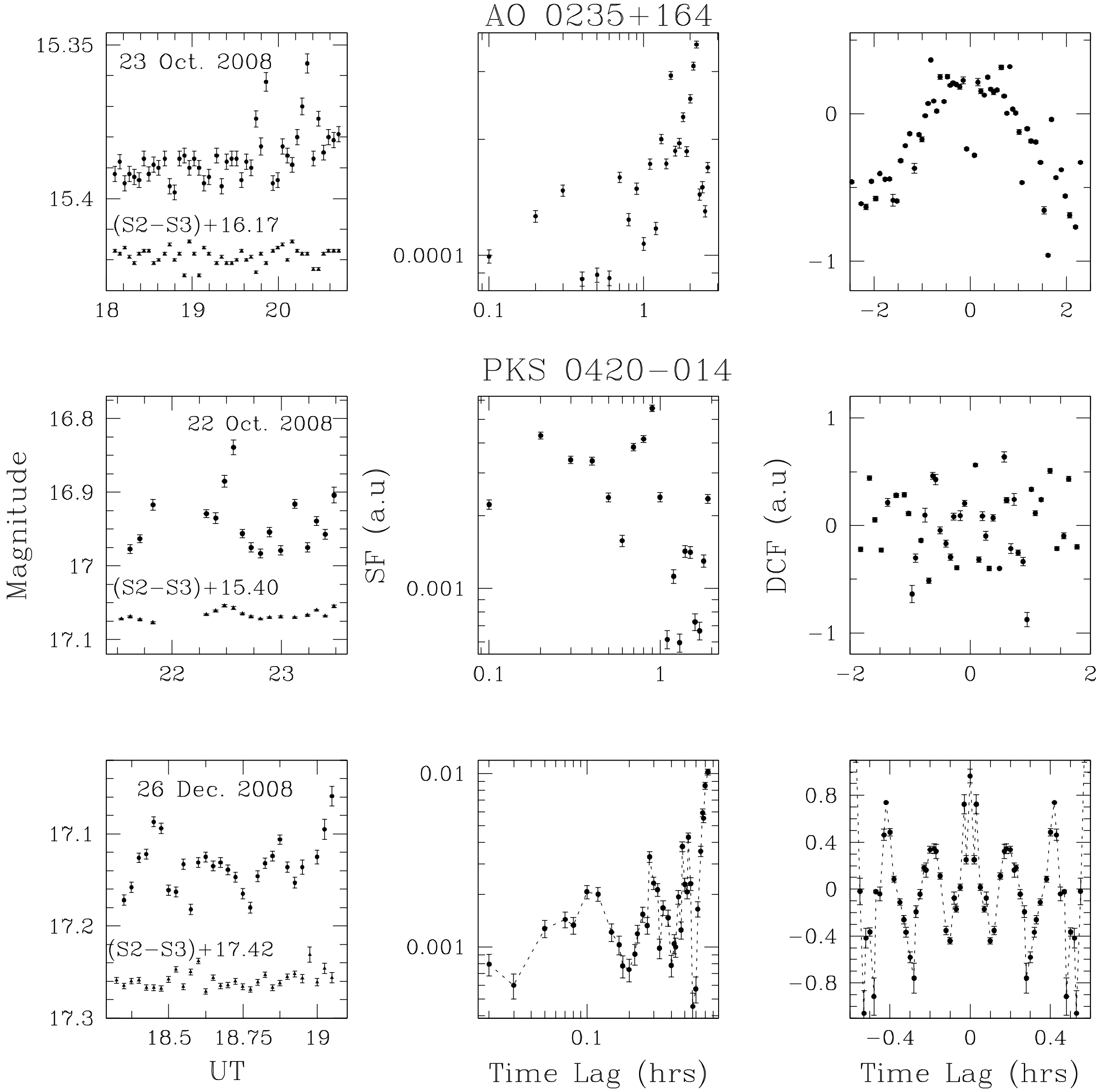

Figure 2. *R*-band optical IDV LCs of the blazars AO 0235+164 and PKS 0420−014 and their respective SFs and DCFs.

this period was supported by subsequent observations Gupta et al. (2008b). Strong IDV flux variations of 9.5 and 13.7 per cent during two nights were observed by Gupta et al. (2008b). Recently, Rani et al. (2009) reported the possible presence of nearly periodic fluctuations, with a time-scale of ∼17 d, in a 12.7-yr long X-ray LC of AO 0235+164 obtained by the All Sky Monitor (ASM) instrument on the *Rossi X-ray Timing Explorer* (*RXTE*) satellite.

We observed three IDV LCs of the source AO 0235+164 between 2008 October and 2009 January. The brightness of the source decayed by ∼2.2 mag during this period (Rani et al. 2010b). We found a significant flux variation in two out of three LCs. A continuous fading trend of ∼0.13 mag and both brightening and decaying of ∼0.04 mag were observed on 2008 October 20 (Fig. 1) and 2008 October 23 (Fig. 2), respectively. A possible time-scale of variability is ∼5.2 h (from the SF analysis) for the LC observed on October 20, while any such time-scale exceeds the length of our observation on October 23. However this putative time-scale is not supported by the DCF analysis.

PKS 0420−014: The blazar PKS 0420−014 is classified as a FSRQ and has a redshift of 0.915. It has been observed in optical bands since 1969. Several papers have reported multiple optically active and bright phases of the source and perhaps regular major flaring cycles (e.g. Villata et al. 1997; Webb et al. 1998; Raiteri et al. 1998, and references therein). Webb et al. (1998) reported that there were increases of ∼ 2–3 mag during the active phases of this blazar during their observations that stretched from 1969 December to 1986 January. Clements et al. (1995) have reported variations of Δmag ≅ 2.8 mag with a time-scale of ∼22 yr.

We found a variation of >0.1 mag within 2 h in the brief optical LCs of the source on both of the days of observation in 2008 October and December. During this period the source brightened by a factor of ∼0.7 mag (Rani et al. 2010b). The nominal time-scale of variability (from the peak of the SF) is 0.12 h for the LC observed on 26 December and multiple dips might indicate a possible periodicity around 0.18 h, which is weakly supported by the DCF curve. The other LC is irregular and shows no hint of a time-scale (Fig. 2).

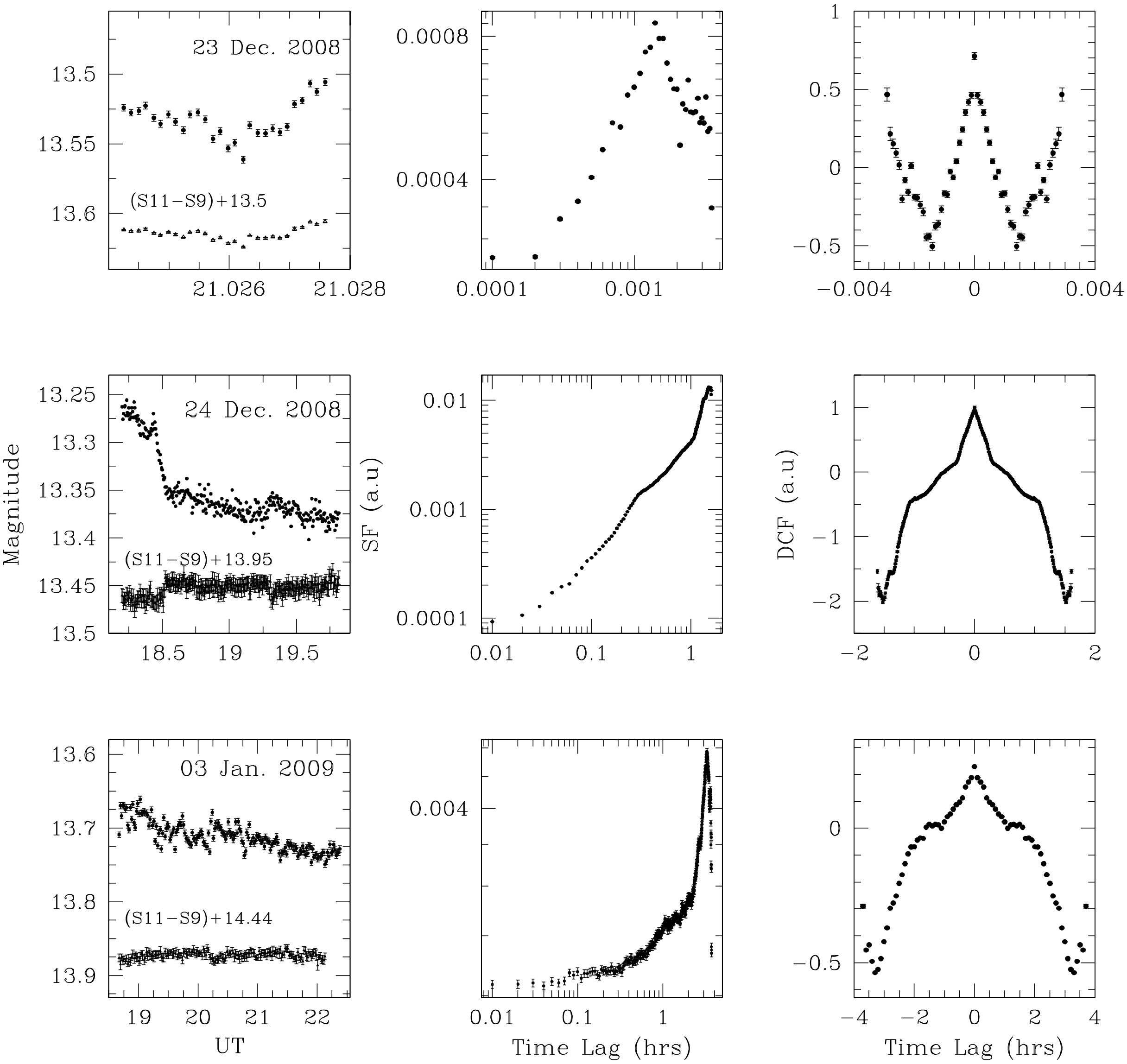

Figure 3. *R*-band optical IDV LCs of the blazar S5 0716+714 and their respective SFs and DCFs.

S5 0716+714: The blazar S5 0716+714 is classified as a BL Lac object. Nilsson et al. (2008) made a recent claim of redshift determination of the source to be $z = 0.31 \pm 0.08$. This source has been extensively studied at all observable wavelengths from radio to γ-rays on diverse time-scales (Wagner et al. 1990; Heidt & Wagner 1996; Villata et al. 2000; Raiteri et al. 2003; Foschini et al. 2006; Montagni et al. 2006; Ostorero et al. 2006; Gupta et al. 2008c,b). This source is one of the brightest BL Lacs in optical bands with an IDV duty cycle of nearly one. Unsurprisingly, it has been the subject of several optical monitoring campaigns on IDV time-scales (Heidt & Wagner 1996; Montagni et al. 2006; Gupta et al. 2008b). This source has shown five major optical outbursts (Gupta et al. 2008b) at intervals of $\sim$3.0 ± 0.3 yr. High optical polarizations of $\sim$ 20 – 29 per cent have also been observed in the source (Takalo, Sillanpaeae & Nilsson 1994; Fan et al. 1997). Gupta et al. (2009) reported good evidence for nearly periodic oscillations in a few of the intraday optical LCs of the source observed by Montagni et al. (2006). Good evidence of the presence of a $\sim$15-min periodic oscillation at optical frequencies has been reported by Rani et al. (2010a).

Our optical IDV observations of S5 0716+714 span a time period from 2008 October to 2009 January. The source brightened by a factor of $\sim$2 mag during this period (Rani et al. 2010b). We found significant microvariability of $\sim$0.1 mag in three out of four LCs of the source. The LCs observed on 2008 December 24 and 2009 January 03 show continuous fading trends of the order of $\sim$0.1 mag, though the former is abrupt while the latter is gradual. Both fading and brightening and fading trends of $\sim$0.05 mag were observed over just a few minutes on 2008 December 23. The calculated possible variability time-scales are listed in Table 4, but the lack of agreement between the SF and DCF possibilities leads us to discount their reality.

PKS 0735+178: The blazar PKS 0735+718 has been classified as a BL Lac object (Carswell et al. 1974). Papers concerning its redshift determination (Carswell et al. 1974; Falomo & Ulrich 2000) had set a lower limit of $z > 0.4$ and $z = 0.424$ was reported for the source using a *HST* snapshot image (Sbarufatti, Treves & Falomo 2005). Since its optical identification, the source has been

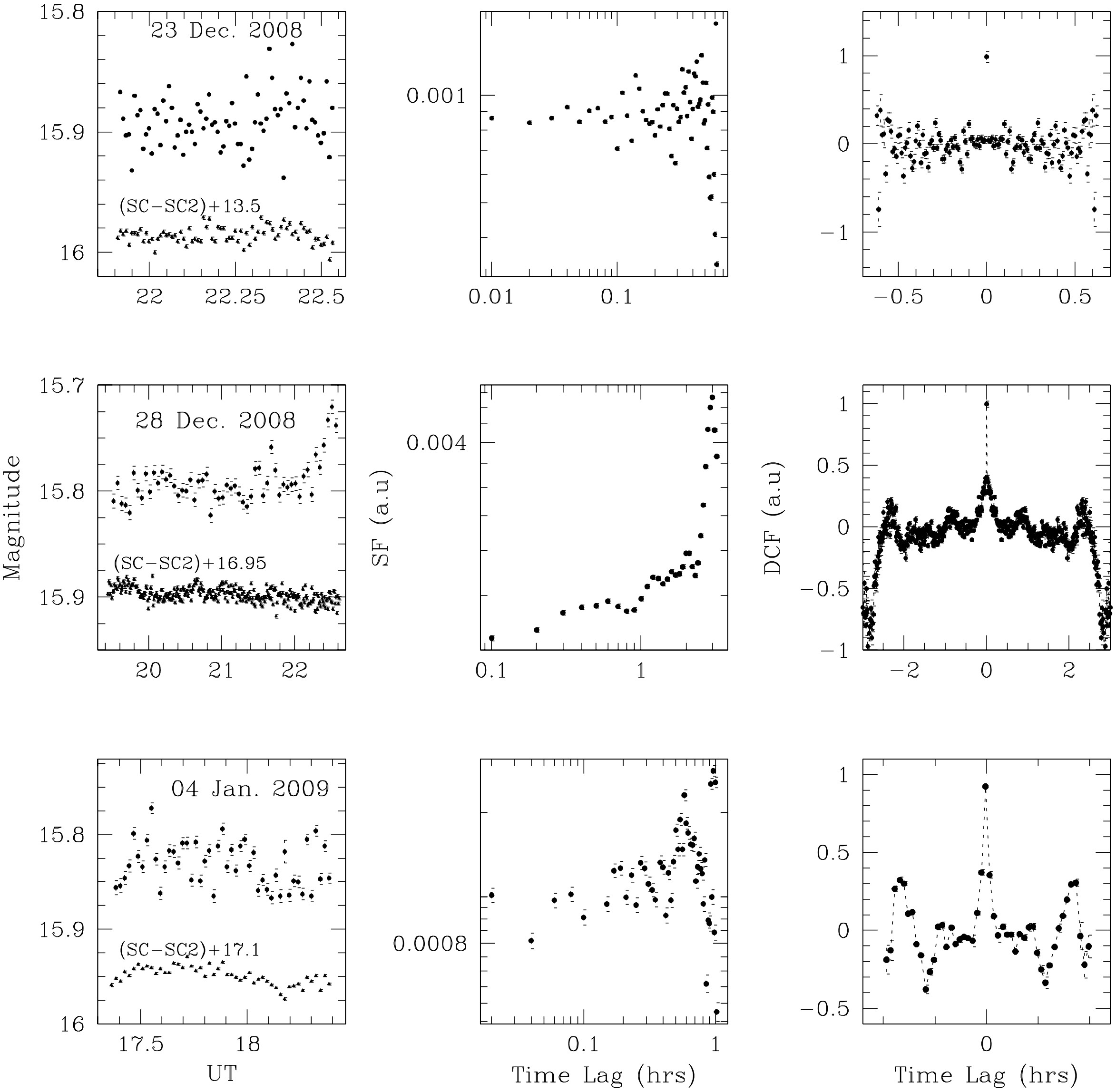

Figure 4. *R*-band optical IDV LCs of the blazar PKS 0735+178 and their respective SFs and DCFs.

extensively observed across the whole EM spectrum (Teräsranta et al. 2004; Gu et al. 2006; Gupta et al. 2008b; Ciprini et al. 2007). A periodicity of ∼14 yr has been suggested to be present in the source using a century long, but still sparse, optical LC (Fan et al. 1997). Optical variability on IDV and STV time-scales has been observed for 0735+178 (Xie et al. 1992; Massaro et al. 1995; Fan et al. 1997; Zhang et al. 2004; Ciprini et al. 2007; Gupta et al. 2008b). A significant amount of polarization (∼1–30 per cent) has been observed in the source both at optical and IR bands (Mead et al. 1990; Takalo 1991; Valtaoja et al. 1991a, 1993; Takalo et al. 1992a; Tommasi et al. 2001).

Our IDV observations of the source PKS 0735+718 comprise four LCs taken between 2008 December and 2009 January. The brightness of the source changes by ∼0.6 mag during this period (Rani et al. 2010b). We found significant microvariations of an order of ∼0.1 mag in three out of four observed LCs of the source (Fig. 4). The only conceivable hints of time-scales for variability from the SFs are ∼2.3 h for the LC observed on 2008 December 28 and ∼0.58 h for 2009 January 04. However, since both of these peaks are close to the total lengths of the observations they are not likely to be real, nor are they supported by DCF results.

OJ 287: The blazar OJ 287 at $z = 0.306$ is one of the most extensively observed and best studied BL Lac objects. It is also among the very few AGNs for which more than a century of optical observations are available (Sillanpää et al. 1996a,b; Fan et al. 1998; Abraham 2000; Gupta et al. 2008b; Fan et al. 2009). Using the binary black hole model (Sillanpää et al. 1988) for the long-term optical LC of the source, an outburst with a predicted ∼12 yr period was detected in the source by the OJ-94 programme (Sillanpää et al. 1996a; Valtonen et al. 2008). A very high optical polarization and variability in the degree and angle of polarization has been also reported for OJ 287 (Efimov et al. 2002). The observational properties of the source from radio to X-ray energy bands have been reviewed by Takalo et al. (1994). Recently, Fan et al. (2009), reported large variations in the source of ΔV = 1.96 mag, ΔR = 2.36 mag and ΔI = 1.95 mag during their observations spanning 2002 to 2007.

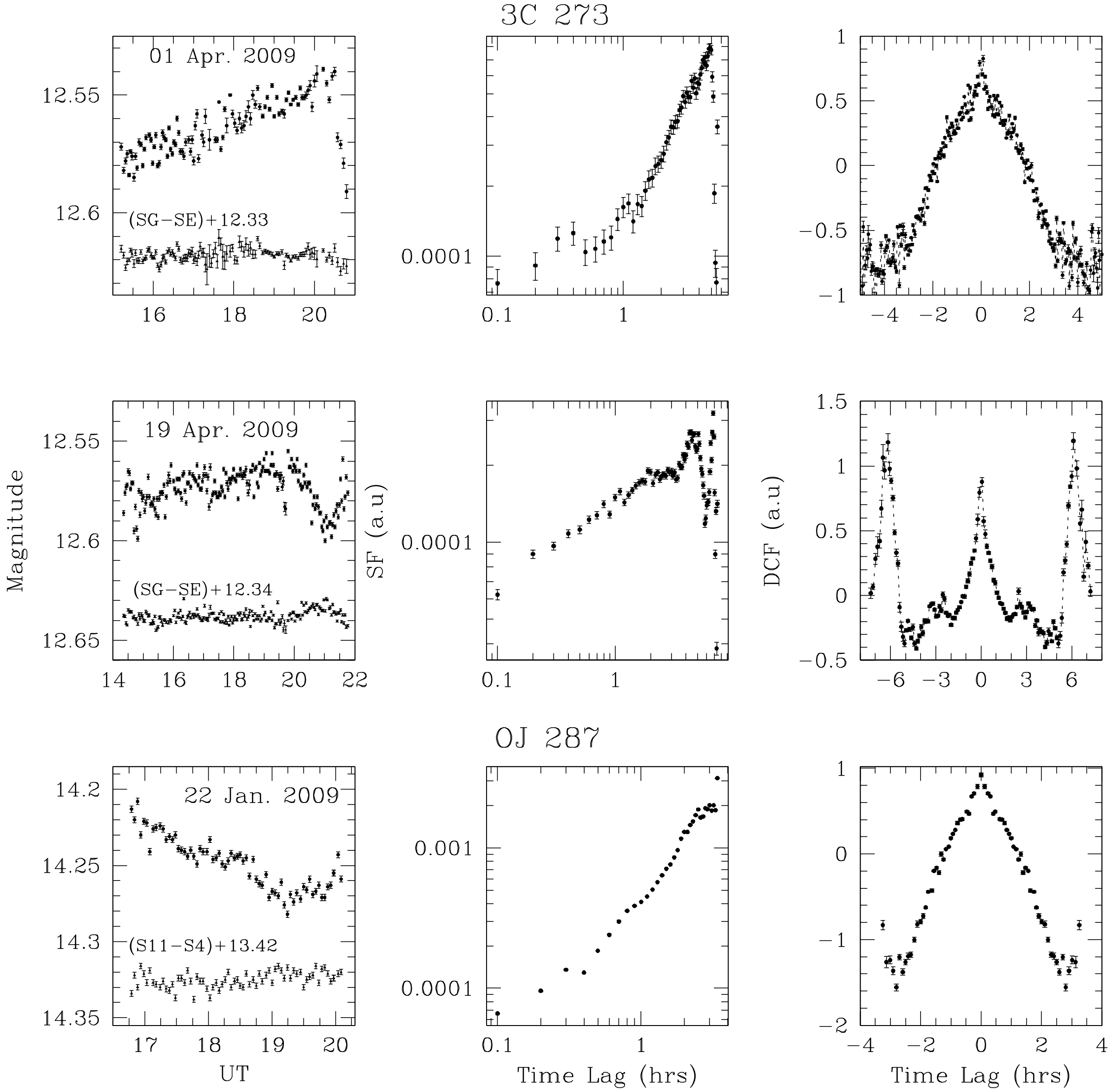

Figure 5. *R*-band optical IDV LCs of the blazars 3C 273 and OJ 287 and their respective SFs and DCFs.

Our observations of OJ 287 span a period from 2008 December to 2009 January, and during this time the brightness of the source changed significantly by ∼1 mag (Rani et al. 2010b). The source showed significant microvariations only in one out of three observed nightly LCs during which the brightness of the source continuously faded by ∼0.08 mag within 2 h (Fig. 5). The SF and DCF analysis showed that any time-scale of variability is longer than the time-scale of observation.

3C 273: The FSRQ 3C 273 was the first quasar discovered and has a redshift of 0.158 (Schmidt 1963). It is categorized as a LBL (Nieppola, Tornikoski & Valtaoja 2006) and its SED, correlations among different energy band flares and the approaching jet orientation have been extensively studied at all wavelengths. There are many papers covering the observational properties of the source in the optical band (Angione 1971; Sitko et al. 1982; Corso et al. 1985; Corso, Schultz & Dey 1986; Moles et al. 1986; Hamuy & Maza 1987; Sillanpää, Mikkola & Valtaoja 1991; Valtaoja et al. 1991b; Takalo et al. 1992b,a; Elvis et al. 1994; Lichti et al. 1995; Ghosh et al. 2000). An analysis of the optical LC of 3C 273 spanning over 100 yr can be interpreted to suggest a LTV time-scale of ∼13.5 yr (Fan, Qian & Tao 2001). Recently, the short-term optical variability and colour index properties of the source have been studied by Dai et al. (2009).

Our IDV observations of the source 3C 273 span the period from 2008 December to 2009 April during which a total of eight LCs were obtained. There is no change in overall flux of the source during this period (Rani et al. 2010b). This source showed microvariations (of ∼0.05 mag) in only two out of eight observed LCs (Fig. 5). On the night of 2009 April 19 there is a hint of a time-scale of variability of ∼6 h from both the SF and DCF approaches.

PKS 1510−089: The blazar PKS 1510−089 is classified as a FSRQ and has $z = 0.361$. It also belongs to the category of highly polarized quasars. Significant optical flux variations in the source were first reported by Lu (1972) over a time span of ∼5 yr. The historical LC of the source shows a large variation of $\Delta B = 5.4$ mag during an outburst in 1948 after which it faded by ∼2.2 mag within 9 d (Liller

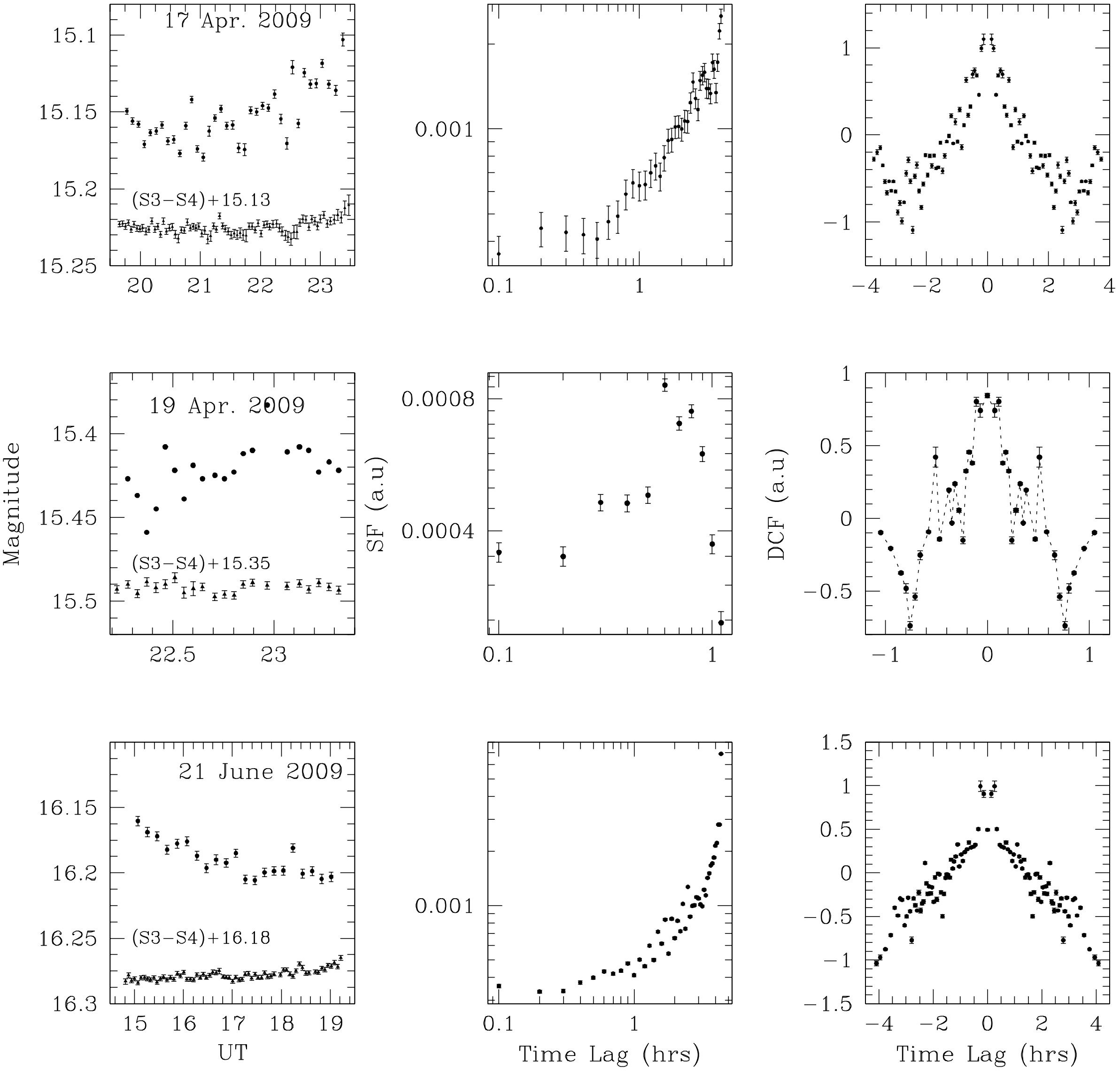

Figure 6. *R*-band optical IDV LCs of blazar PKS 1510−089 and their respective SFs and DCFs.

& Liller 1975). Strong variations on IDV time-scales also have been reported for PKS 1510−089; e.g. $\Delta R = 0.65$ mag within 13 min. (Xie et al. 2001), $\Delta R = 2.0$ mag in 42 min. (Dai et al. 2001), $\Delta V = 1.68$ mag in 60 min. (Xie et al. 2002b). In the optical LCs of this source, a few deep minima have been observed on different days (Dai et al. 2001; Xie et al. 2001, 2002a), that nominally correspond to a time-scale of ∼42 min, though no more than three such dips were ever seen in a single night. None the less, an eclipsing binary black hole model was actually proposed to explain the occurrences of these minima (Wu et al. 2005). Other observations by this group have yielded a claim of another possible time-scale between minima of ∼89 min (Xie et al. 2004).

We carried out IDV observations of the source from 2009 April to June. There is a large change in the brightness of the source during this period, with $\Delta R_{\rm mag} = 1.5$ (Rani et al. 2010b). We found significant microvariations of ∼0.05–0.08 mag in three out of four LCs (Fig. 6). We found that any time-scale of variability is larger than the time-scale of observations, except perhaps for the LC observed on 2009 April 19, for which it is formally ∼0.6 h from the SF curve and ∼0.5 h from the DCF; however, this LC has too few points to allow the production of a crisp SF or DCF, so this evidence is very weak.

BL Lac: The object BL Lac at $z = 0.069$ (Miller, French & Hawley 1978) is the archetype of its class. Observations over the past few decades have showed that its optical and radio emissions are highly variable and polarized and the polarization at those widely separated frequencies is found to be strongly correlated (Sitko, Schmidt & Stein 1985). It is among the very few sources for which more than 100 yr of optical data is available in the literature (Shen 1970; Webb et al. 1988; Fan et al. 1998). An optical variation of $\Delta \mathrm{B} = 5.3$ mag and a possible periodicity of ∼14 yr has been reported for BL Lac by Fan et al. (1998). Very recently, Nieppola et al. (2009) have studied the LTV of the source at radio frequencies and generalized the shock model that can explain it.

Our IDV observations of the source BL Lac were made between 2008 September and 2009 June. The brightness of the source faded by ∼1.6 mag during this period (Rani et al. 2010b). BL Lac faded by ∼0.05 mag within 1 h of observation on 2008 September 04, which had a nominal variability time-scale of ∼2.5 h according to

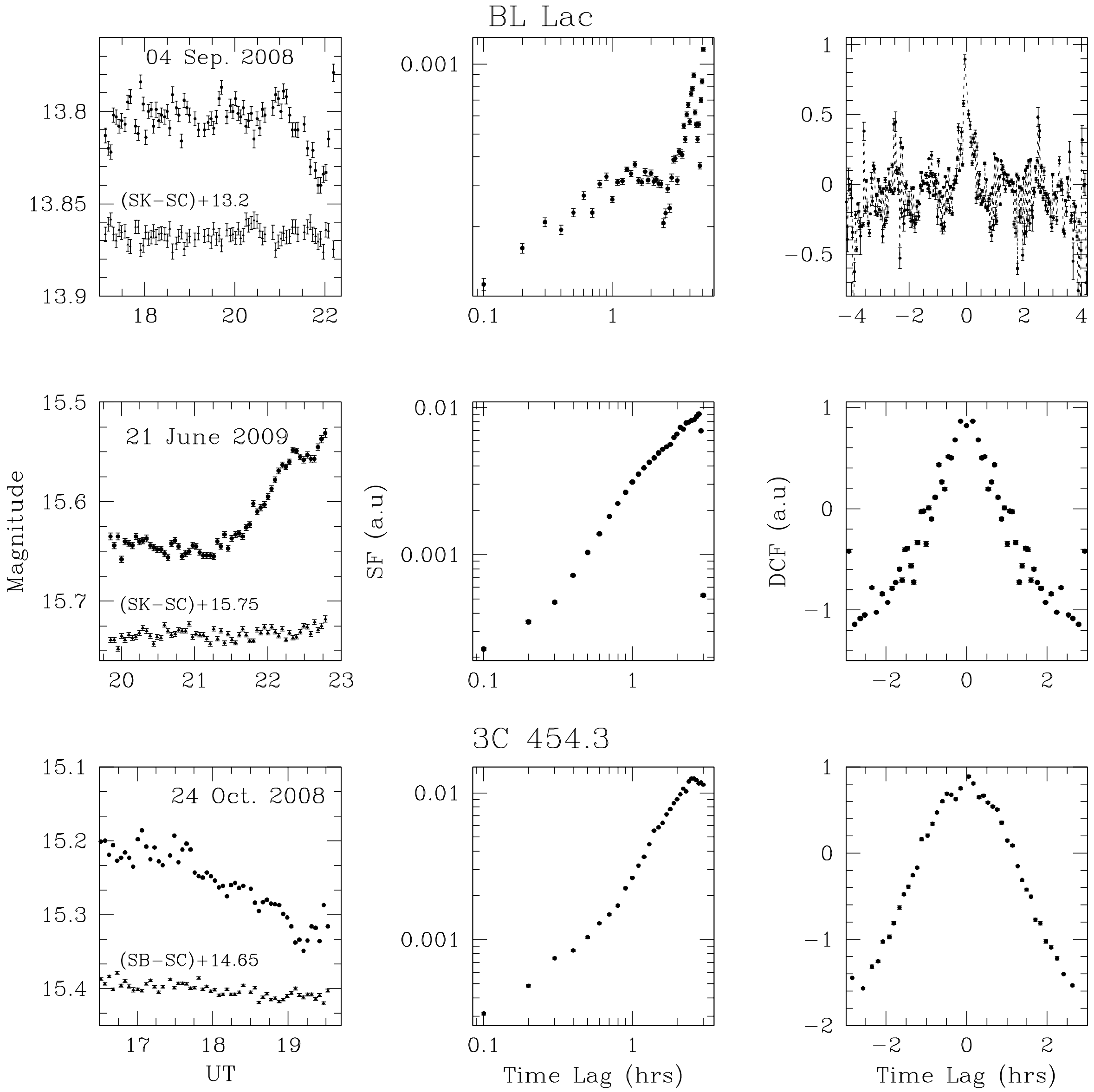

Figure 7. *R*-band optical IDV LC of the blazars BL Lac and 3C 454.3 and their respective SFs and DCFs.

both the SF and DCF plots (Fig. 7). A continuous rising trend of ∼0.1 mag in the LC of the source was observed on 2009 June 21, and the calculated time-scale of variability for the LC that night exceeds the time period of the observations.

3C 454.3: A FSRQ at a redshift of 0.859, 3C 454.3 is among the most intense and variable sources. The source has been detected in the flaring state in 2007 and 2008 July at γ-ray frequencies and those flares have been found to be well correlated with optical and longer wavelength flares (Ghisellini et al. 2007; Villata et al. 2007; Raiteri et al. 2008). The long term observational properties of the source at optical and radio frequencies have been well studied through multiwavelength campaigns (e.g. Villata et al. 2006, 2007). The IDV of the source was recently studied by Gupta et al. (2008b). They have reported that the amplitude varied by ∼5–17 per cent during their observing span. An extraordinary flaring activity above 100 MeV has been reported in the source in 2009 December (Striani et al. 2010).

We observed two IDV LCs of the source on 2008 October 24 and 28. During the period the brightness of the source increases by ∼0.4 mag (Rani et al. 2010b). The source showed significant microvariations of ∼0.13 mag on 2008 October 24 (Fig. 7) while no significant variations has been detected for the LC observed on 2008 October 28. The SF and DCF analysis revealed that any time-scale of variability exceeds the length of the observation on the first of those nights.

4 DISCUSSION AND CONCLUSIONS

We have carried out optical *R*-band IDV observations of 10 LBLs spanning over a time period of 2008 September to 2009 June. The sources PKS 0420−014 and PKS 1510−089 were in faint states; AO 0235+164, BL Lac and 3C 454.3 were possibly in post-outburst states; S5 0716+714 and 3C 66A were in pre-outburst states, while PKS 0735+178 and OJ 287 were in some intermediate states during

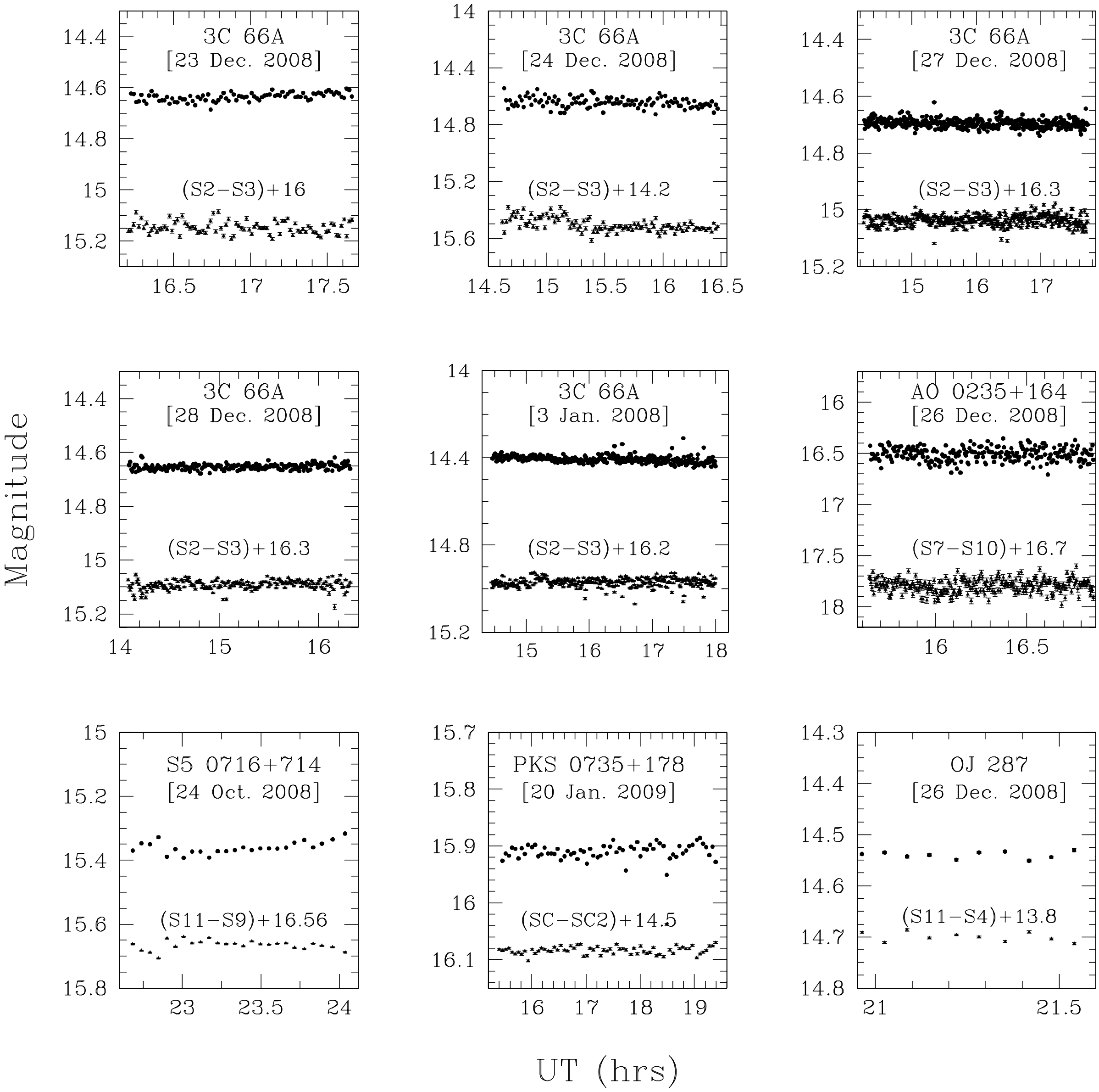

Figure 8. The *R* filter LCs of several blazars during which no significant variability has been detected, plotted along with the differential magnitudes of standard stars.

the observing run (Rani et al. 2010b). In our search of microvariations in 10 LBLs we found significant IDV in 21 out of 40 observed LCs; so the calculated duty cycle of IDV in LBLs during our observing run is ∼52 per cent. We performed the SF and DCF analysis to calculate the nominal time-scales of variability; however, we found that in most of the cases this time-scale of variability is longer than the length of observations and in a substantial majority of the cases where the SF indicated a possible time-scale the DCF did not support it.

The blazar emission mechanism in the outburst state is quantitatively understood by relativistic shocks propagating through a relativistic jet of plasma. In general, blazar emission in the outburst state is non-thermal Doppler-boosted emission from jets enhanced by that arising from shocks in the flows. (Blandford & Rees 1978; Marscher & Gear 1985; Marscher et al. 1992). The other models of AGNs that can explain the IDV in any type of AGN are optical flares, disturbances or hotspots on the accretion disc surrounding the black hole of the AGN (e.g. Mangalam & Wiita 1993, and references therein). Models based on the instabilities on the accretion disc could plausibly yield blazar IDV only when the blazar is in the very low state. When a blazar is in the low state, any contribution from the jets, if at all present, is very weak. So, we consider that the observed IDV in the sources AO 0235+164, BL Lac, 3C 454.3, S5 0716+714, 3C 66A, 0735+178 and OJ 287 is almost certainly related to a shock propagating through a relativistic jet (Blandford & Konigl 1979; Marscher & Gear 1985). Turbulence behind a shock propagating down such a jet is a very feasible way to explain the observed IDV (Marscher 1996). Since the blazars PKS 0420−014 and PKS 1510−089 were observed in relatively faint states, there is a chance that the observed optical IDV in these sources may be because of hotspots or any other enhanced emission on the accretion disc (Mangalam & Wiita 1993).

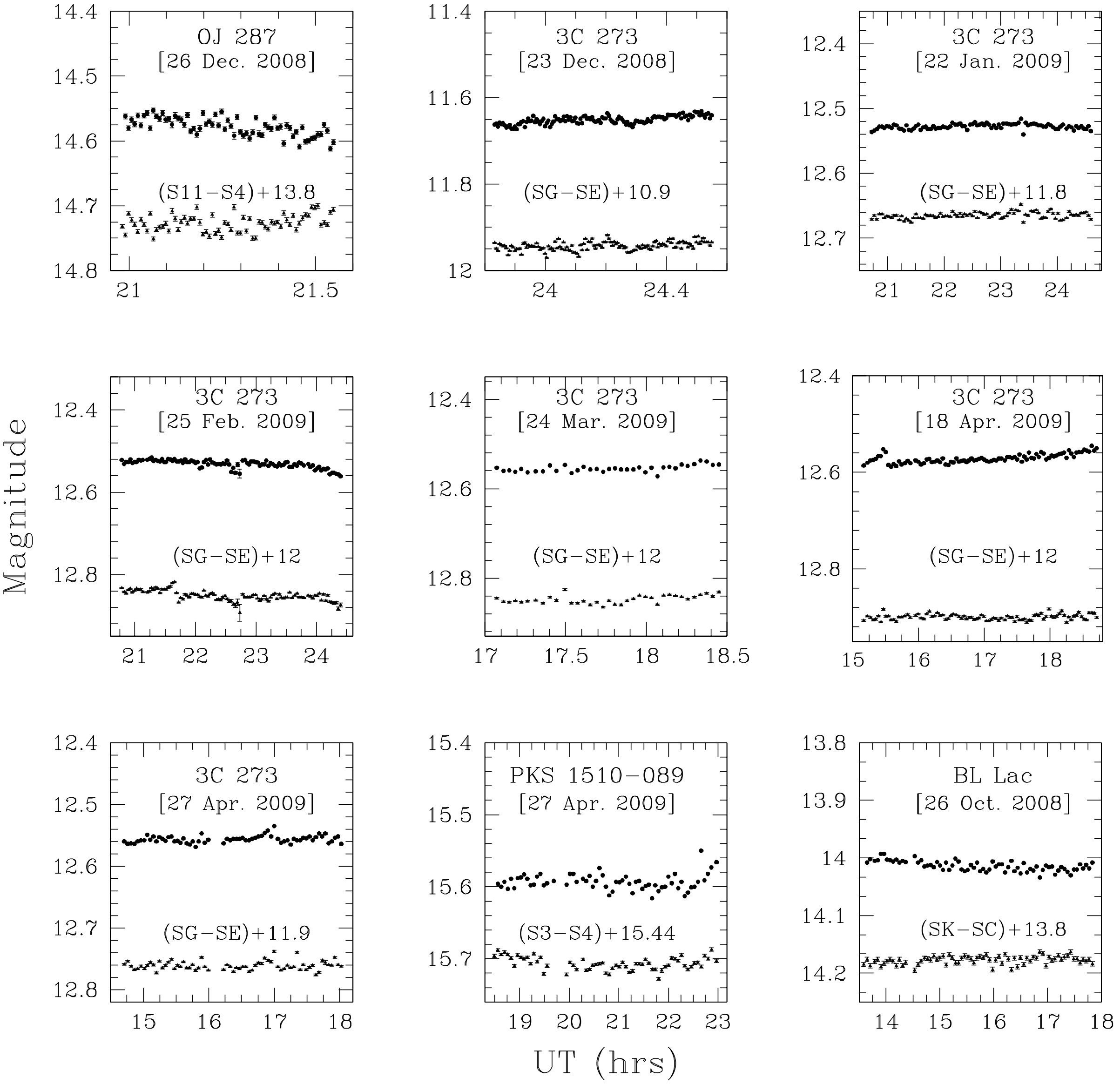

Figure 9. The *R* filter LCs of several blazars during which no significant variability has been detected, plotted along with the differential magnitudes of standard stars.

In one source, 3C 273, we are unable to classify the state of the source since this blazar has been in an essentially steady state for last six yr (Dai et al. 2009; Rani et al. 2010b). This source showed significant microvariations in two out of eight observed LCs and on both the days of observation the brightness of the source follows both rising and fading trends of ∼0.05 mag. Whatever may be the mechanism responsible for the origin of of microvariability in this source, it does not seem to be strong enough to introduce day-to-day variations in the flux of the source.

It is worth noting that an extrinsic mechanism can also be responsible for some of the observed IDV in blazars. Extrinsic IDV could be caused by refractive interstellar scintillation, which is only relevant in low-frequency radio observations, or microlensing, which is achromatic. We note that the blazar AO 0235+164 has two foreground galaxies at $z = 0.524$ and 0.851 (Cohen et al. 1987; Nilsson et al. 1996; Webb et al. 2000). The flux of this source is contaminated and absorbed by foreground galaxies, the stars of which can act as gravitational microlenses. Thus the observed optical IDV in AO 0235+164 could arise, at least partially, from gravitational microlensing. Using two separated telescopes to simultaneously observe 0716+714 Pollock, Webb & Azarnia (2007) showed that instrumental and atmospheric effects cannot account for the microvariations they measured for that blazar.

We found significant IDV in 21 out of 40 observed LCs of 10 LBLs; so the calculated duty cycle of IDV in LBLs during our observing run is ∼52 per cent. The average duration of our observation was 3.7 h per LC. The SF and DCF curves revealed that in ∼60 per cent of cases any time-scale of variability is longer than the time-scale of observations. In quite a few cases there were hints of time-scales in the data from the SF plots, but only a few of those hints were supported by the DCF plots.

Extensive IDV studies of different subclasses of AGNs revealed that the occurrence of IDV in blazars observed on a time-scale of <6 h is ∼60–65 per cent and if the blazar is observed more than 6 h then the possibility of IDV detection is 80–85 per cent (Carini 1990; Gupta & Joshi 2005, and references therein). If we consider

Table 4. IDV Results.

Blazar name	Date of observation	*C*-Test value	*F*-Test		V	A (per cent)	t_v	
			F-value	*p*-value			SF (h)	DCF (h)
3C 66A	2008 October 22	3.59	3.65	$3.1e^{-7}$	V	8.1	>3.86	>3.86
	2008 October 26	2.65	7.03	$1.9e^{-14}$	V	5.7	>3.50	>3.50
	2008 December 23	0.78	0.41	0.06	NV			
	2008 December 24	3.31	0.61	0.02	NV			
	2008 December 27	0.88	0.58	0.26	NV			
	2008 December 28	0.75	0.37	0.3	NV			
	2009 January 03	0.83	0.63	0.35	NV			
AO 0235+164	2008 October 20	8.32	76.84	$2.2e^{-16}$	V	13.4	5.20?	>6.30
	2008 October 23	3.23	10.53	$1.4e^{-14}$	V	4.2	>2.60	>2.60
	2008 December 26	1.09	1.43	0.04	NV			
PKS 0420−014	2008 October 23	5.44	31.44	$6.6e^{-15}$	V	14.4		
	2008 December 26	5.42	31.24	$6.1e^{-15}$	V	12.3	0.12,0.18	0.18
S5 0716+714	2008 October 24	0.92	1.57	0.27	NV			
	2008 December 23	3.47	7.77	$2.2e^{-16}$	V	9.1	0.0014	0.0028
	2008 December 24	4.51	3.07	$2.2e^{-16}$	V	14.6	>1.62	>1.62
	2009 January 03	3.71	1.26	$7.7e^{-7}$	V	31.6	3.28	>3.73
PKS 0735+178	2008 December 23	3.14	9.49	$2.2e^{-16}$	V	11.1		
	2008 December 28	4.22	18.36	$2.2e^{-16}$	V	19.3	2.90	2.30
	2009 January 04	2.31	4.64	$3.1e^{-7}$	V	9.8	0.58	0.60
	2009 January 20	1.30	1.99	0.055	NV			
OJ 287	2008 December 26	1.11	1.48	0.10	NV			
	2009 January 20	0.88	1.20	0.47	NV			
	2009 January 22	3.21	11.13	$2.2e^{-16}$	V	7.9	>3.35	>3.35
3C 273	2008 December 23	0.91	0.73	0.08	NV			
	2009 January 22	0.81	0.65	0.05	NV			
	2009 February 25	0.75	0.49	0.06	NV			
	2009 March 24	0.76	0.50	0.05	NV			
	2009 April 01	2.59	2.58	$1.2e^{-6}$	V	5.2	>5.2	>5.60
	2009 April 18	1.59	0.25	0.11	NV			
	2009 April 19	3.74	2.22	$4.7e^{-8}$	V	4.5	6.0	6.0
	2009 April 27	0.86	0.84	0.49	NV			
PKS 1510−089	2009 April 17	2.67	2.31	0.0003	V	9.3	>3.82	>3.82
	2009 April 19	2.72	7.11	$3.3e^{-5}$	V	7.6	0.60	0.50
	2009 April 27	1.27	1.54	0.09	NV			
	2009 June 21	4.46	2.65	0.0001	V	8.3	>4.41	>4.41
BL Lac	2008 September 04	2.73	5.71	$1.0e^{-13}$	V	8.7	2.5	2.5
	2008 October 26	1.05	1.56	0.06	NV			
	2009 June 21	2.87	7.34	$4.9e^{-13}$	V	12.9	>2.98	>2.98
3C 454.3	2008 October 24	5.14	22.95	$2.2e^{-16}$	V	16.3	>3.01	>3.01
	2008 October 28	1.42	2.09	0.01	NV			

observations over days to months, i.e., at STV time-scales then the observed duty cycle of variations is >92 per cent (e.g. Rani et al. 2010b) and at LTV time-scales it is almost 100 per cent, which confirms that the probability of detection of variability in blazars rises with the duration of the observations. Although the duty cycle from our current observations is less than that reported by Gupta & Joshi (2005), since the average duration of our observations is <4 h, this is unsurprising.

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