Mon. Not. R. Astron. Soc. **404,** 1992–2017 (2010) doi:10.1111/j.1365-2966.2010.16419.x

Short-term flux and colour variations in low-energy peaked blazars

Bindu Rani,[1⋆] Alok C. Gupta,[1] A. Strigachev,[2] R. Bachev,[2] Paul J. Wiita,[3,4] E. Semkov,[2] E. Ovcharov,[5] B. Mihov,[2] S. Boeva,[2] S. Peneva,[2] B. Spassov,[2] S. Tsvetkova,[2] K. Stoyanov[2] and A. Valcheva[5]

[1]*Aryabhatta Research Institute of Observational Sciences (ARIES), Manora Peak, Nainital 263129, India*
[2]*Institute of Astronomy, Bulgarian Academy of Sciences, 72 Tsarigradsko Shosse Blvd., 1784 Sofia, Bulgaria*
[3]*Department of Physics and Astronomy, Georgia State University, PO Box 4106, Atlanta, GA 30302–4106, USA*
[4]*Department of Physics, The College of New Jersey, PO Box 7718, Ewing, NJ 08628, USA*
[5]*Department of Astronomy, University of Sofia, 5 James Bourchier, 1164 Sofia, Bulgaria*

Accepted 2010 January 26. Received 2010 January 25; in original form 2009 December 21

ABSTRACT

We have measured multiband optical flux and colour variations for a sample of 12 low-energy peaked blazars (LBLs) on short, day-to-month, time-scales. Our sample contains six BL Lacertae objects (BL Lacs) and six flat spectrum radio quasars (FSRQs). These photometric observations, made during 2008 September to 2009 June, used five optical telescopes, one in India and four in Bulgaria. We detected short-term flux variations in 11 of these blazars and colour variability in eight of them. Our data indicate that six blazars (3C 66A, AO 0235+164, S5 0716+714, PKS 0735+178, OJ 287 and 3C 454.3) were observed in pre- or post-outburst states, five (PKS 0420−014, 4C 29.45, 3C 279, PKS 1510−089 and BL Lac) were in a low state, while one (3C 273) was in an essentially steady state. The duty cycles for flux and colour variations on short time-scales in these LBLs are ∼92 and ∼33 per cent, respectively. The colour versus magnitude correlations seen here support the hypothesis that BL Lac objects tend to become bluer with increase in brightness; however, FSRQs may show the opposite trend, and there are exceptions to these trends in both categories of blazar. We briefly discuss emission models for active galactic nuclei that might explain our results.

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

1 INTRODUCTION

BL Lacertae objects (BL Lacs) and flat-spectrum radio quasars (FSRQs) are now usually clubbed together and called blazars; they represent a small subset of radio-loud active galactic nuclei (AGNs) characterized by strong and rapid flux variability across the entire electromagnetic (EM) spectrum. Blazars exhibit strong polarization from radio to optical wavelengths and usually have core-dominated radio structures. These extreme AGNs provide a natural laboratory to study the mechanisms of energy extraction from the central supermassive black holes and the physical properties of jets and perhaps accretion discs. According to the orientation based unified model of radio-loud AGNs, blazar jets usually make an angle $\leq 10^{\circ}$ to our line of sight (e.g. Urry & Padovani 1995).

The EM radiation from blazars is predominantly non-thermal. At lower frequencies (through the UV or X-ray bands), the mechanism is almost certainly synchrotron emission while at higher frequencies the emission mechanism is probably due to inverse Compton (IC) emission (e.g. Sikora & Madejski 2001; Krawczynski 2004). The spectral energy distributions (SEDs) of blazars have a double-peaked structure (e.g. Giommi, Ansari & Micol 1995; Ghisellini et al. 1997; Fossati et al. 1998). Based on the location of the first peak of their SEDs, $\nu_{\rm peak}$, blazars are often sub-classified into low-energy peaked blazars (LBLs) and high-energy peaked blazars (HBLs) (Padovani & Giommi 1995); however, it should be noted that the SED peaks can be located at intermediate frequencies as well, giving rise to the intermediate peaked blazar (IBL) classification (e.g. Sambruna, Maraschi & Urry 1996). The first component peaks in the near-infrared (NIR)/optical in case of LBLs and at UV/X-rays in HBLs, while the second component usually peaks at GeV energies in LBLs and at TeV energies in HBLs. More specifically, Nieppola, Tornikoski & Valtaoja (2006) classify over 300 BL Lacs and suggest that blazars with $\nu_{\rm peak} \approx 10^{13-14}$ Hz are LBLs, those with $\nu_{\rm peak} \approx 10^{15-16}$ Hz are IBLs and those with $\nu_{\rm peak} \approx 10^{17-18}$ Hz are HBLs.

Observations of blazars reveal that they are variable at all accessible time-scales, from a few tens of minutes to years and even

⋆E-mail: bindu@aries.res.in

Table 1. Details of telescopes and instruments used.

Site:	ARIES Nainital	NAO Rozhen	NAO Rozhen	NAO Rozhen	AO Belogradchik
Telescope	1.04-m RC Cassegrain	2-m Ritchey-Chrétien	50/70-cm Schmidt	60-cm Cassegrain	60-cm Cassegrain
CCD model	Wright 2K CCD	PI VersArray:1300B	SBIG STL-11000M	FLI PL09000	FLI PL09000
Chip size (pixels)	2048 × 2048	1340 × 1300	4008 × 2672	3056 × 3056	3056 × 3056
Pixel size (μm^2)	24 × 24	20 × 20	9 × 9	12 × 12	12 × 12
Scale (arcsec pixel^{-1})	0.37	0.258	1.079	0.330[a]	0.330[a]
Field (arcmin^2)	13 × 13	5.76 × 5.59	72.10 × 48.06	16.8 × 16.8	16.8 × 16.8
Gain	10 e^- ADU^{-1}	1.0 e^- ADU^{-1}	0.84 e^- ADU^{-1}	1.0 e^- ADU^{-1}	1.0 e^- ADU^{-1}
Read out noise	5.3 e^- rms	2.0 e^- rms	13.0 e^- rms	8.5 e^- rms	8.5 e^- rms
Binning used	2 × 2	1 × 1	1 × 1	2 × 2	3 × 3
Typical seeing (arcsec)	1 to 2.8	1.5 to 3.5	1.5 to 3.5	1.5 to 3.5	1.5 to 3.5

[a]With a binning factor of 1 × 1.

decades at many frequencies (e.g. Aller, Aller & Hughes 1992; Carini & Miller 1992; Carini et al. 1992; Wagner & Witzel 1995; Gupta et al. 2004; Teräsranta et al. 2004; Ostorero et al. 2006; Villata et al. 2007; D'Ammando et al. 2009). Based on these different time-scales, the variability of blazars can be broadly divided into three classes, e.g. intraday variability (IDV), short-term variability (STV) and long-term variability (LTV). Variations in the flux of a source of a couple of hundredths of a magnitude 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. Flux changes over days to a few months are often considered to be STV, while those taking from several months to many years are usually called LTV (e.g. Gupta et al. 2004); both of these classes of variations typically exceed ∼1 mag and can exceed even 5 mag.

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. Over the last two decades, the optical/NIR variability of blazars has been extensively studied on diverse time-scales (e.g. Miller, Carini & Goodrich 1989; Carini et al. 1992; Courvoisier et al. 1995; Heidt & Wagner 1996, Takalo et al. 1996; Sillanpää et al. 1996a,b; Bai et al. 1998, 1999; Fan et al. 1998; Xie et al. 2002a; Gupta et al. 2004, 2008a,b,c,d; Gupta, Srivastava & Wiita 2009; Stalin et al. 2005, 2006; also Teräsranta et al. 1992, 2004; Ciprini et al. 2003, 2007; Rani, Wiita & Gupta 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 based upon shocks propagating down relativistic jets (e.g. Marscher & Gear 1985; Hughes, Aller & Aller 1991; Qian et al. 1991; Marscher, Gear & Travis 1992; Wagner & Witzel 1995; Marscher 1996). Some of the variability may arise 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 (e.g. Rickett et al. 2001). Hot spots or 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 the a blazar jet and then Doppler amplified.

In this work, we aimed to search for STV in the multiband fluxes and colours of a sample of 12 LBLs that consists of six BL Lacs and six FSRQs and to thereby cast more light on the emission mechanisms responsible for these variations. Our work is mainly focused on day to day variations in the magnitudes as well as the colours of these dozen sources which were the brightest blazars visible from India and Bulgaria. Throughout this paper, when we use the term colour variation, we mean a change in the colour of a blazar with time. Optical flux variations in blazars are often associated with changes in their spectral shapes. These can be quantified by studying the properties of the colour indices of each source. So we have also investigated the spectral variabilities in the observed visible wavebands of LBLs and have investigated if there are differences between spectral variability trends in those classified as BL Lacs and those called FSRQs. We have also studied the spectral variability of these LBLs with changes in the brightness of the sources.

The paper is structured as follows. In Section 2, we present the observations and data reduction procedure. Section 3 provides our results, which are discussed in Section 4. We present our conclusions in Section 5.

2 OBSERVATIONS AND DATA REDUCTION

Our observations of 12 LBLs were performed using five optical telescopes, one in India and four in Bulgaria. All of these telescopes are equipped with CCD detectors and Johnson UBV and Cousins RI filters. Details about the telescopes, detectors and other parameters related to the observations are given in Table 1. A complete log of observations of these LBLs from these five telescopes is given in Table 2.

We carried out optical photometric observations during the period 2008 September to 2009 June. The raw photometric data were processed by standard methods which are briefly described here. For image processing or pre-processing, we generated a master bias frame for each observing night by taking the median of all bias frames. The master bias frame for the night 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 all flat frames in each passband. Next, the normalized master flat for each passband was generated. Each source image frame was flat-fielded by dividing by the normalized master flat in the respective band to remove pixel-to-pixel inhomogeneities. Finally, cosmic ray removal was done from all source image frames. Data pre-processing used the standard routines in Image Reduction and Analysis Facility[1] (IRAF) and European Southern observatory (ESO) MIDAS software.

[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.

Table 2. Observation log of optical photometric observations.

Source (z)	$\alpha_{2000.0}$ (hh mm ss)	$\delta_{2000.0}$ (hh mm ss)	Date of observation (yyyy mm dd)	Telescope	Filters	Data points
3C 66A	02 22 39.61	+43 02 07.80	2008 10 20	A	B,V,R,I	1,1,1,1
(0.444)			2008 10 22	A	B,V,R,I	1,1,1,1
			2008 10 23	A	B,V,R,I	1,1,1,1
			2008 10 24	A	B,V,R,I	1,1,1,1
			2008 10 25	A	B,V,R,I	1,1,1,1
			2008 10 26	A	B,V,R,I	1,1,1,1
			2008 10 27	A	B,V,R,I	1,1,1,1
			2008 10 28	A	B,V,R,I	1,1,1,1
			2008 10 30	A	B,V,R,I	1,1,1,1
			2009 01 20	A	B,V,R,I	1,1,1,1
			2009 01 22	A	B,V,R,I	1,1,1,1
			2009 02 02	A	B,V,R,I	1,1,1,1
AO 0235+164	02 38 39.93	+16 36 59.27	2008 09 04	A	B,V,R,I	1,1,1,1
(0.94)			2008 10 20	A	B,V,R,I	1,1,1,1
			2008 10 22	A	B,V,R,I	1,1,1,1
			2008 10 23	A	B,V,R,I	1,1,1,1
			2008 10 24	A	B,V,R,I	1,1,1,1
			2008 10 25	A	B,V,R,I	1,1,1,1
			2008 10 26	A	B,V,R,I	1,1,1,1
			2008 10 27	A	B,V,R,I	1,1,1,1
			2008 10 28	A	B,V,R,I	1,1,1,1
			2008 10 30	A	B,V,I	1,1,1
			2009 01 20	A	B,V,R,I	1,1,1,1
			2009 01 22	A	B,V,R,I	1,1,1,1
PKS 0420−014	04 23 15.73	−01 20 32.70	2008 10 23	A	B,V,R,I	1,1,1,1
(0.915)			2008 10 24	A	B,V,R,I	1,1,1,1
			2008 10 26	A	B,V,R,I	1,1,1,1
			2009 01 20	A	B,V,R,I	1,1,1,1
			2009 01 22	A	B,V,R,I	1,1,1,1
			2009 02 02	A	B,V,R,I	1,1,1,1
S5 0716+714	07 21 53.45	+71 20 36.35	2008 10 24	A	B,V,R,I	1,1,1,1
(0.31 ± 0.08)			2008 10 26	A	B,V,R,I	1,1,1,1
			2009 02 25	A	B,V,R,I	1,1,1,1
			2009 03 26	C	B,V,R,I	2,2,2,2
			2009 04 16	C	B,V,R,I	2,2,2,2
			2009 04 17	B	U,B,V,R,I	2,2,2,2,2
			2009 05 19	C	B,V,R,I	2,2,2,2
			2009 05 20	C	B,V,R,I	2,2,2,2
			2009 05 21	C	B,V,R,I	2,2,2,2
PKS 0735+178	07 38 07.39	+17 42 18.99	2009 01 20	A	B,V,R,I	1,1,1,1
(0.424)			2009 01 22	A	B,V,R,I	1,1,1,1
			2009 03 25	D	V,R,I	2,2,2
			2009 03 26	D	V,R	1,1
			2009 04 16	D	R,I	2,1
OJ 287	08 54 48.87	+20 06 30.64	2008 10 24	A	B,V,R,I	1,1,1,1
(0.306)			2008 10 26	A	B,V,R,I	1,1,1,1
			2009 01 20	A	B,V,R,I	1,1,1,1
			2009 01 22	A	B,V,R,I	1,1,1,1
			2009 03 24	C	B,V,R,I	1,2,2,2
			2009 03 25	C	B,V,R,I	1,2,2,2
			2009 03 26	D, C	B,V,R,I	3,4,4,4
			2009 04 01	A	B,V,R,I	1,1,1,1
			2009 04 15	D, C	B,V,R,I	2,2,2,2
			2009 04 16	C	B,V,R,I	4,4,4,4
			2009 04 17	A	B,V,R,I	1,1,1,1
			2009 04 18	A	B,V,R,I	1,1,1,1
			2009 04 19	A	B,V,R,I	1,1,1,1
			2009 05 17	C	B,V,R,I	2,2,2,7
			2009 05 20	C	V,R,I	1,1,1
			2009 05 21	C	B,V,R,I	2,2,2,2
			2009 05 25	A	B,V,R,I	1,1,1,1
			2009 05 26	A	B,V,R,I	1,1,1,1

Table 2 – *continued*

Source (z)	$\alpha_{2000.0}$ (hh mm ss)	$\delta_{2000.0}$ (hh mm ss)	Date of observation (yyyy mm dd)	Telescope	Filters	Data points
4C 29.45 (0.729)	11 59 32.07	+29 14 42.00	2009 03 25	D	V,R,I	2,2,2
			2009 03 26	D	B,V,R,I	2,2,2,2
			2009 04 15	D	V,R,I	2,3,4
			2009 04 16	D	V,R,I	2,2,2
			2009 04 17	A	B,V,R,I	1,1,1,1
			2009 04 18	A	B,V,R,I	1,1,1,1
			2009 04 23	B	B,V,R,I	2,2,2,2
			2009 04 24	B	B,V,R,I	2,2,2,2
			2009 05 15	C	B,V,R,I	2,2,2,2
			2009 05 17	C	V,R,I	1,1,1
			2009 05 21	C, D	V,R,I	2,2,2
			2009 05 22	C	V,R,I	1,1,1
			2009 05 23	C, A, D	B,V,R,I	1,3,3,3
			2009 05 25	C, A	B,V,R,I	1,2,2,2
			2009 05 26	C	V,R,I	1,1,1
			2009 05 27	A	B,V,R,I	1,1,1,1
			2009 06 14	E	V,R,I	2,2,2
3C 273 (0.1575)	12 29 06.69	+02 03 08.58	2009 20 01	A	B,V,R,I	1,1,1,1
			2009 22 01	A	B,V,R,I	1,1,1,1
			2009 25 02	A	B,V,R,I	1,1,1,1
			2009 24 03	A	B,V,R,I	1,1,1,1
			2009 25 03	D	U,B,V,R,I	2,2,2,2,2
			2009 26 03	D	U,B,V,R,I	2,2,2,2,2
			2009 04 01	A	B,V,R,I	1,1,1,1
			2009 04 15	D	U,B,V,R,I	2,2,2,2,2
			2009 04 16	D	U,B,V,R,I	2,2,2,2,2
			2009 04 17	B	U,B,V,R,I	2,2,2,2,2
			2009 04 18	A	B,V,R,I	1,1,1,1
			2009 04 19	A	B,V,R,I	1,1,1,1
			2009 04 27	A	B,V,R,I	1,1,1,1
			2009 05 15	D	B,V,R,I	3,2,2,2
			2009 05 21	D, C	B,V,R,I	3,3,3,3
			2009 05 23	A	B,V,R,I	1,1,1,1
			2009 05 25	A, D	B,V,R,I	3,3,3,3
			2009 05 26	A, D	U,B,V,R,I	1,2,3,3,3
			2009 05 27	A	B,V,R,I	1,1,1,1
			2009 06 03	E	B,V,R,I	2,2,2,2
			2009 06 14	E	B,V,R,I	6,4,4,4
			2009 06 15	E	B,V,R,I	6,6,4,6
			2009 06 16	E	B,V,R,I	8,4,6,6
3C 279 (0.5362)	12 56 11.17	−05 47 21.52	2009 03 25	D	V,R,I	2,1,2
			2009 03 26	D	V,R,I	2,3,2
			2009 04 15	D	V,R,I	2,2,2
			2009 04 16	D	V,R,I	2,2,2
			2009 05 15	D	V,R,I	1,1,1
			2009 05 19	D	V,R,I	1,1,1
			2009 05 21	C	V,R,I	1,2,2
			2009 05 25	D	V,R,I	1,1,1
			2009 05 26	D	V,R,I	1,1,1
			2009 06 14	E	V,R,I	4,4,4
			2009 06 15	E	V,R	4,2
PKS 1510−089 (0.36)	15 12 50.53	−09 05 58.99	2009 04 17	A	B,V,R,I	1,1,1,1
			2009 04 19	A	B,V,R,I	1,1,1,2
			2009 04 27	A	B,V,R,I	1,1,1,1
			2009 05 25	A	B,V,R,I	1,1,1,1
			2009 05 27	A	B,V,R,I	1,1,1,1
			2009 06 14	A	B,V,R,I	1,1,1,1
			2009 06 21	A	V,R,I	1,1,1
			2009 06 24	A	B,V,R,I	1,1,1,1

Table 2 – *continued*

Source (z)	$\alpha_{2000.0}$ (hh mm ss)	$\delta_{2000.0}$ (hh mm ss)	Date of observation (yyyy mm dd)	Telescope	Filters	Data points
BL Lac (0.069)	22 02 42.29	+42 16 39.98	2008 09 04	A	B,V,R,I	1,1,1,1
			2008 09 07	A	B,V,R,I	1,1,1,1
			2008 09 08	A	R	1
			2008 09 10	A	B,V,R,I	1,1,1,1
			2008 10 23	A	B,V,R,I	1,1,1,1
			2008 10 24	A	B,V,R,I	1,1,1,1
			2008 10 25	A	B,V,R,I	1,1,1,1
			2008 10 26	A	B,V,R,I	1,1,1,1
			2008 10 27	A	B,V,R,I	1,1,1,1
			2008 10 30	A	B,V,R,I	1,1,1,1
			2009 04 17	B	U,B,V,R,I	2,2,2,5,2
3C 454.3 (0.8590)	22 53 57.75	+16 08 53.56	2008 09 06	A	R	1
			2008 09 07	A	B,V,R,I	1,1,1,1
			2008 09 09	A	B,V,R,I	1,1,1,1
			2008 10 20	A	B,V,R,I	1,1,1,1
			2008 10 22	A	B,V,R,I	1,1,1,1
			2008 10 23	A	B,V,R,I	1,1,1,1
			2008 10 24	A	B,V,R,I	1,1,1,1
			2008 10 25	A	B,V,R,I	1,1,1,1
			2008 10 26	A	B,V,R,I	1,1,1,1
			2008 10 27	A	B,V,R,I	1,1,1,1
			2008 10 28	A	B,V,R,I	1,1,1,1
			2008 10 29	A	B,V,R,I	1,1,1,1
			2008 10 30	A	B,V,R,I	1,1,1,1

Note. A, 1.04-m Sampuranand Telescope, ARIES, Nainital, India; B, 2-m Ritchey-Chretien Telescope at National Astronomical Observatory Rozhen, Bulgaria; C, 50/70-cm Schmidt Telescope at National Astronomical Observatory, Rozhen, Bulgaria; D, 60-cm Cassegrain Telescope at Astronomical Observatory Belogradchik, Bulgaria; E, 60-cm Cassegrain Telescope at National Astronomical Observatory Rozhen, Bulgaria.

We processed the data using the Dominion Astronomical Observatory Photometry (DAOPHOT II) software to perform the circular concentric aperture photometric technique (Stetson 1987, 1992). For each night we carried out aperture photometry with four different aperture radii, i.e. 1×FWHM, 2×FWHM, 3×FWHM and 4×FWHM. On comparing the photometric results, we found that aperture radii of 2×FWHM almost always provided the best S/N, so we adopted that aperture for our final results.

For each of the 12 blazars, we observed more than three local standard stars on the same field. The magnitudes of the standard stars that we measured in the fields of our target sources are given in Table 3. Having multiple standard stars was required to confirm that the final standard stars were truly non-variable. We employed two non-varying standard stars from each blazar field with magnitudes similar to those of the target and plotted their differential instrumental magnitudes so as to obtain an indication of the noise in the measurements. Finally, to calibrate the photometry of the blazars, we used the one standard star which had a colour closer to that of the blazar. The calibrated light curves (LCs) of these blazars are plotted in the same panel with the differential instrumental magnitudes of those two standard stars in the Figs 1–12. We used R[2] to write additional programs for data processing.

[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.

3 RESULTS

3.1 Variability parameters

To search for and describe blazar variability, we have employed two quantities commonly used in the literature, the variability detection parameter, C, and the variability amplitude, A. The former was introduced by Romero, Cellone & Combi (1999), and is defined as the average of $C1$ and $C2$ where

$$C1 = \frac{\sigma(\mathrm{BL}-\mathrm{starA})}{\sigma(\mathrm{starA}-\mathrm{starB})} \quad \text{and} \quad C2 = \frac{\sigma(\mathrm{BL}-\mathrm{starB})}{\sigma(\mathrm{starA}-\mathrm{starB})}. \tag{1}$$

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), σ(BL-starB) and σ(starA-starB) are the observational scatter of the differential instrumental magnitudes of the blazar and star A, the blazar and star B and star A and star B, respectively. If $C \geq 2.57$, the confidence level of a variability detection is >99 per cent, and we consider this to be a positive detection of a variation. For a few sources, the (starA – starB) LCs show isolated apparently discrepant points, that we conservatively retain in our analysis. These points increase the σ(starA – starB) values relatively more than the BL star scatter, thereby slightly reducing the C values and the confidence with which variability claims are made.

Heidt & Wagner (1996) introduced the variability amplitude, defined as

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

where $A_{\max}$ and $A_{\min}$ are the maximum and minimum magnitudes in the calibrated LCs of the blazar and the average measurement error of the blazar LC is σ.

Table 3. Standard stars in the blazar fields.

Source name	Standard star	*B* magnitude (error)	*V* magnitude (error)	*R* magnitude (error)	*I* magnitude (error)	References[a]
3C 66A	1	14.13 (0.02)	13.65 (0.02)	13.36 (0.01)	13.05 (0.02)	5
	2	15.82 (0.03)	14.82 (0.03)	14.28 (0.04)	13.75 (0.03)	5
	3	16.36 (0.13)	15.89 (0.04)	15.46 (0.12)	15.05 (0.13)	5
	4		12.79 (0.04)	12.70 (0.04)	12.59 (0.04)	6
	5		14.18 (0.05)	13.62 (0.05)	13.10 (0.05)	6
	6	16.77 (0.08)	16.10 (0.08)			7
AO 0235+164	1	13.59 (0.04)	13.03 (0.03)	12.69 (0.02)	12.35 (0.03)	1
	2	13.55 (0.02)	12.71 (0.02)	12.23 (0.02)	11.79 (0.02)	1
	3	13.68 (0.02)	12.92 (0.02)	12.48 (0.03)	12.08 (0.03)	1
	6		14.02 (0.05)	13.64 (0.04)	13.30 (0.07)	6
	8	18.22 (0.14)	16.58 (0.12)	15.79 (0.10)	14.94 (0.15)	1
	C1		14.78 (0.05)	14.23 (0.05)	13.76 (0.08)	6
PKS 0420−014	1	13.02 (0.03)	12.45 (0.02)	12.09 (0.03)		4
	2	13.60 (0.01)	13.10 (0.02)	12.80 (0.02)	12.44 (0.03)	5
	3	13.97 (0.03)	13.28 (0.01)	12.89 (0.01)	12.50 (0.04)	5
	4	15.72 (0.02)	14.91 (0.03)	14.47 (0.01)	14.01 (0.05)	5
	5		14.96 (0.03)	14.37 (0.03)		4
	6	16.03 (0.03)	15.18 (0.03)	14.70 (0.03)		4
	7		15.31 (0.03)	14.91 (0.03)		4
	8		15.99 (0.03)	15.46 (0.03)		4
	9		16.29 (0.03)	15.58 (0.04)		4
S5 0716+714	1	11.54 (0.01)	10.99 (0.02)	10.63 (0.01)		2
	2	12.02 (0.01)	11.46 (0.01)	11.12 (0.01)	10.92 (0.04)	2, 3
	3	13.04 (0.01)	12.43 (0.02)	12.06 (0.01)	11.79 (0.05)	2, 3
	4	13.66 (0.01)	13.19 (0.02)	12.89 (0.01)		2
	5	14.15 (0.01)	13.55 (0.02)	13.18 (0.01)	12.85 (0.05)	2, 3
	6	14.24 (0.01)	13.63 (0.02)	13.26 (0.01)	12.97 (0.04)	2, 3
	7	14.55 (0.01)	13.74 (0.02)	13.32 (0.01)		2
	8	14.70 (0.01)	14.10 (0.02)	13.79 (0.02)		2
PKS 0735+178	A	13.87 (0.04)	13.40 (0.04)	13.14 (0.05)	12.85 (0.06)	1
	C	15.48 (0.05)	14.40 (0.05)	13.87 (0.06)	13.33 (0.07)	1
	D	16.48 (0.10)	15.80 (0.07)	15.45 (0.06)	15.16 (0.08)	1
OJ 287	2	13.45 (0.04)	12.80 (0.04)	12.46 (0.05)	12.06 (0.07)	1
	4	15.01 (0.06)	14.14 (0.05)	13.72 (0.06)	13.23 (0.07)	1
	10	15.01 (0.05)	14.56 (0.04)	14.26 (0.06)	13.94 (0.09)	1
	11	15.47 (0.07)	14.96 (0.05)	14.67 (0.07)	14.29 (0.09)	1
4C 29.45	1	14.01 (0.06)	13.39 (0.05)	13.01 (0.02)		4
	13	16.02 (0.04)	15.36 (0.04)	14.97 (0.04)	14.62 (0.07)	1
	14	16.41 (0.05)	15.89 (0.09)	15.53 (0.08)	15.16 (0.18)	1
	15	17.14 (0.05)	16.60 (0.05)	16.30 (0.04)	15.88 (0.30)	1
3C 273	C	12.85 (0.05)	11.87 (0.04)	11.30 (0.04)	10.74 (0.04)	1
	D	13.17 (0.05)	12.68 (0.04)	12.31 (0.04)	11.99 (0.06)	1
	E	13.33 (0.07)	12.69 (0.04)	12.27 (0.05)	11.84 (0.04)	1
	G	14.12 (0.05)	13.56 (0.05)	13.16 (0.05)	12.83 (0.05)	1
3C 279	1	16.81 (0.05)	15.94 (0.03)	15.45 (0.03)	14.99 (0.04)	8
	2	13.02 (0.02)	12.42 (0.02)	12.05 (0.02)	11.69 (0.02)	8
	3	15.45 (0.07)	14.90 (0.03)	14.53 (0.05)	14.18 (0.09)	8
	4	13.75 (0.01)	13.00 (0.01)	12.57 (0.03)	12.17 (0.01)	8
	6	13.43 (0.01)	12.81 (0.01)	12.45 (0.03)	12.12 (0.01)	8
	7	16.53 (0.05)	15.66 (0.03)	15.13 (0.02)		4
PKS 1510−089	1	12.23 (0.02)	11.60 (0.03)	11.23 (0.03)	10.87 (0.02)	5
	2	13.74 (0.02)	13.26 (0.03)	12.95 (0.03)	12.60 (0.06)	5
	3	15.16 (0.04)	14.44 (0.06)	13.98 (0.09)	13.54 (0.05)	5
	4	15.36 (0.06)	14.72 (0.06)	14.34 (0.05)	13.87 (0.05)	5
	5	15.43 (0.05)	14.70 (0.05)	14.35 (0.05)		4
	6	16.09 (0.04)	15.16 (0.02)	14.61 (0.02)		4
BL Lac	B	14.52 (0.04)	12.78 (0.04)	11.93 (0.05)	11.09 (0.06)	1
	C	15.09 (0.03)	14.19 (0.03)	13.69 (0.03)	13.23 (0.04)	1
	H	15.68 (0.03)	14.31 (0.05)	13.60 (0.03)	12.93 (0.04)	1
	K	16.26 (0.05)	15.44 (0.03)	14.88 (0.05)	14.34 (0.10)	1

Table 3 – *continued*

Source name	Standard star	*B* magnitude (error)	*V* magnitude (error)	*R* magnitude (error)	*I* magnitude (error)	References[a]
3C 454.3	A	16.85 (0.05)	15.86 (0.09)	15.32 (0.09)	14.80 (0.06)	6, 9, 10
	B	15.87 (0.02)	15.21 (0.06)	14.73 (0.05)	14.31 (0.05)	6, 9, 10
	C	15.18 (0.02)	14.43 (0.02)	13.98 (0.02)	13.51 (0.02)	9, 10, 11
	D	14.94 (0.02)	13.85 (0.02)	13.22 (0.01)	12.63 (0.01)	9, 10, 11
	E	17.10 (0.14)	15.76 (0.09)	14.92 (0.08)	14.26 (0.08)	6, 9, 10
	F	16.06 (0.11)	15.21 (0.11)	14.83 (0.03)		4, 9, 10
	G	16.28 (0.08)	15.42 (0.08)	14.83 (0.02)		4, 9, 10
	H	14.62 (0.02)	13.65 (0.04)	13.10 (0.04)	12.58 (0.04)	6, 9, 10
	C1		15.67 (0.06)	15.27 (0.06)	14.71 (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, Johnson & Tapia (1975); 8. http://quasar.colgate.edu/~tbalonek/optical/3C279compstars.gif; 9. Craine (1977); 10. Angione (1971); 11. http://www.lsw.uni-heidelberg.de/projects/extragalactic/charts/2251+158.html

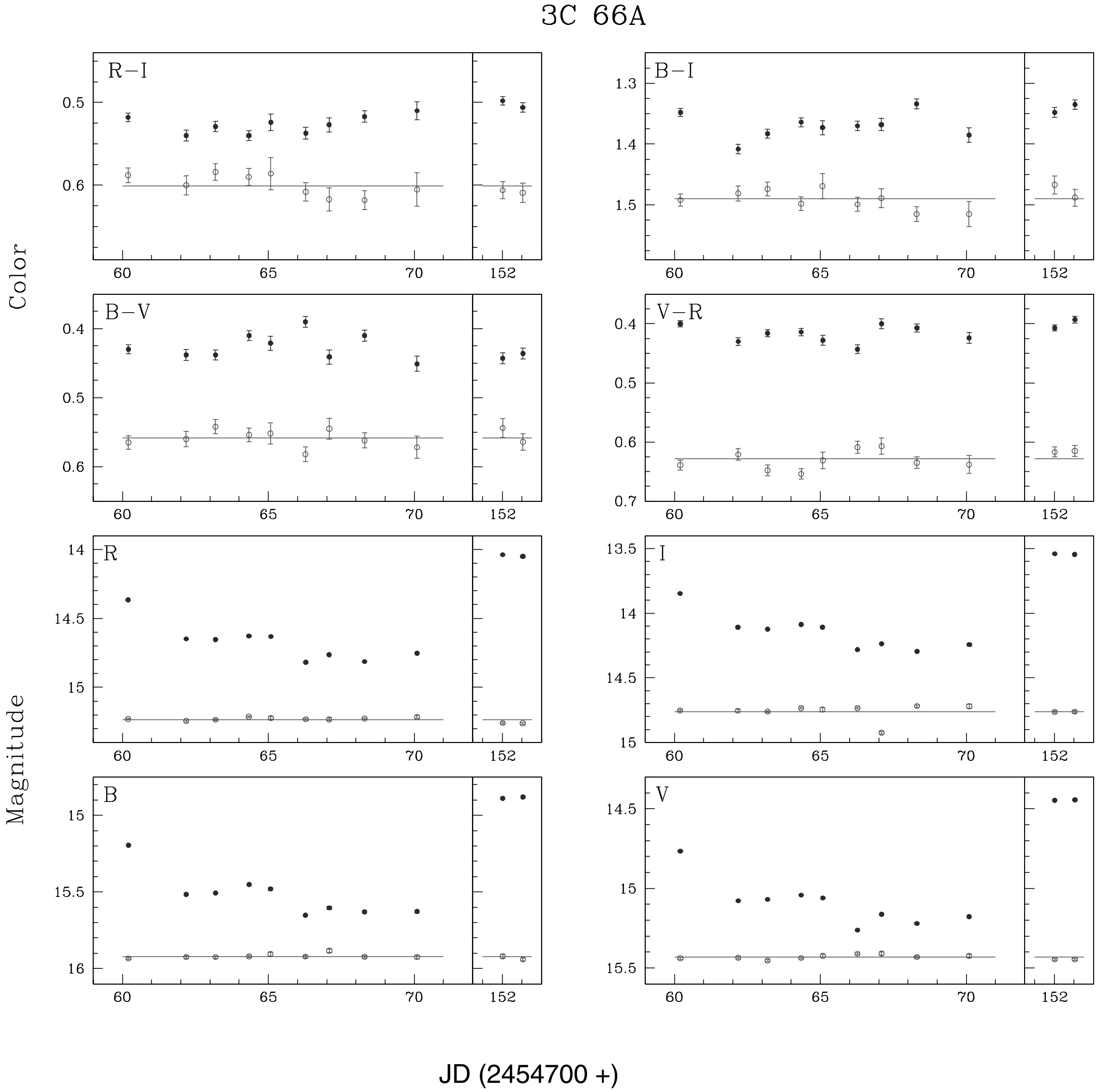

Figure 1. Calibrated LCs of 3C 66A (w.r.t. star 2) are in the lower four panels, plotted with the differential instrumental magnitudes of stars 2 and 3 with arbitrary offsets. The colour LCs in the upper four panels are plotted with the corresponding colours of star 2. Empty circles are the standard stars' LCs with arbitrary offsets and the straight line represents the mean of the standard stars' LCs.

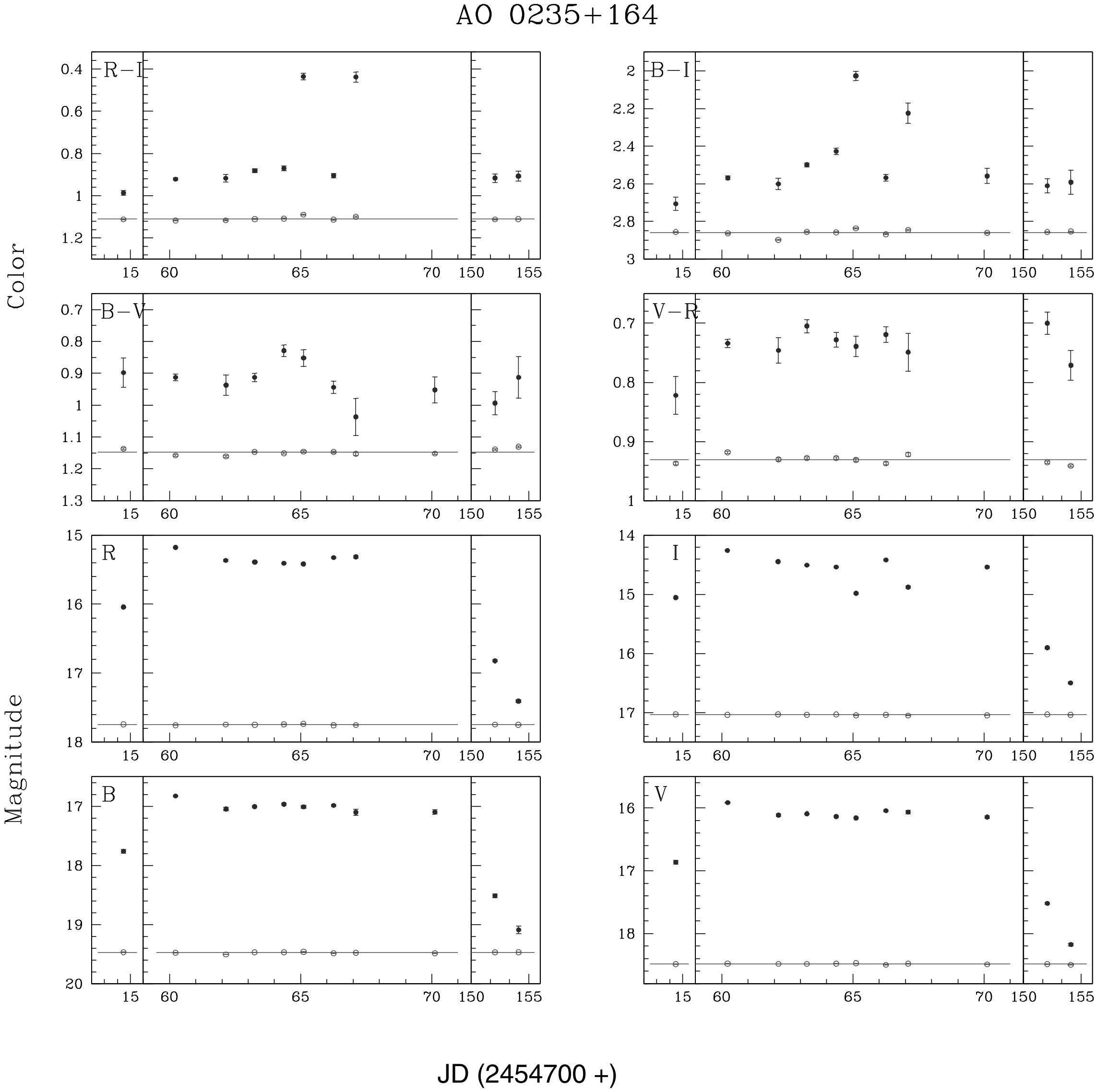

Figure 2. As in Fig. 1 for AO 0235+164. The comparison stars are 2 and 3; 2 is the calibrator.

3.2 Short-term flux and colour variability of individual blazars

The LCs in the BVRI filters and the time curves of the $B-V$, $V-R$, $R-I$ and $B-I$ colours are displayed in Figs 1–12, one figure for each source, plotted along with the corresponding curves of the standard stars used for comparison. The complete observing log for the blazars is given in Table 2. Table 3 contains the standard stars observed in the fields of the blazars. The estimated A and C values of the individual blazars are listed in Table 4. We now report some key individual results for each of our sources, placed in the context of earlier work.

3.2.1 3C 66A

This BL Lac object is an LBL; although its redshift is usually taken as $z = 0.444$ (Lanzetta, Turnshek & Sandoval 1993), that value is actually quite uncertain (e.g. Bramel et al. 2005). Since its optical identification (Wills & Wills 1974), the source has been regularly monitored at optical frequencies, and somewhat less regularly at radio frequencies (Aller et al. 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 $\lesssim$1.5 mag at time-scales of $\sim$1 week to several years at those two frequencies. Böttcher et al. (2005) reported a rapid microvariability of $\sim$0.2 mag within 6 h and they also reported several major outbursts in the source separated by $\sim$50 d and argued that the outbursts seem to have quasi-periodic behaviour. Towards the end of 2007, 3C 66A 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).

The source 3C 66A showed large flux, but no significant colour, variations during our observing run (Fig. 1). The source first faded by $\sim$0.6 mag within 10 d and then it brightened by $\sim$0.9 mag within 80 d in all four of the observed bands. During the observing run, the maximum brightness detected in the R band was 14.0 mag, which is only $\sim$0.6 mag fainter than the brightest ($R \simeq 13.4$) reported in the source by Böttcher et al. (2009). We may have observed the source in a pre-outburst state since the LC showed an overall brightening trend.

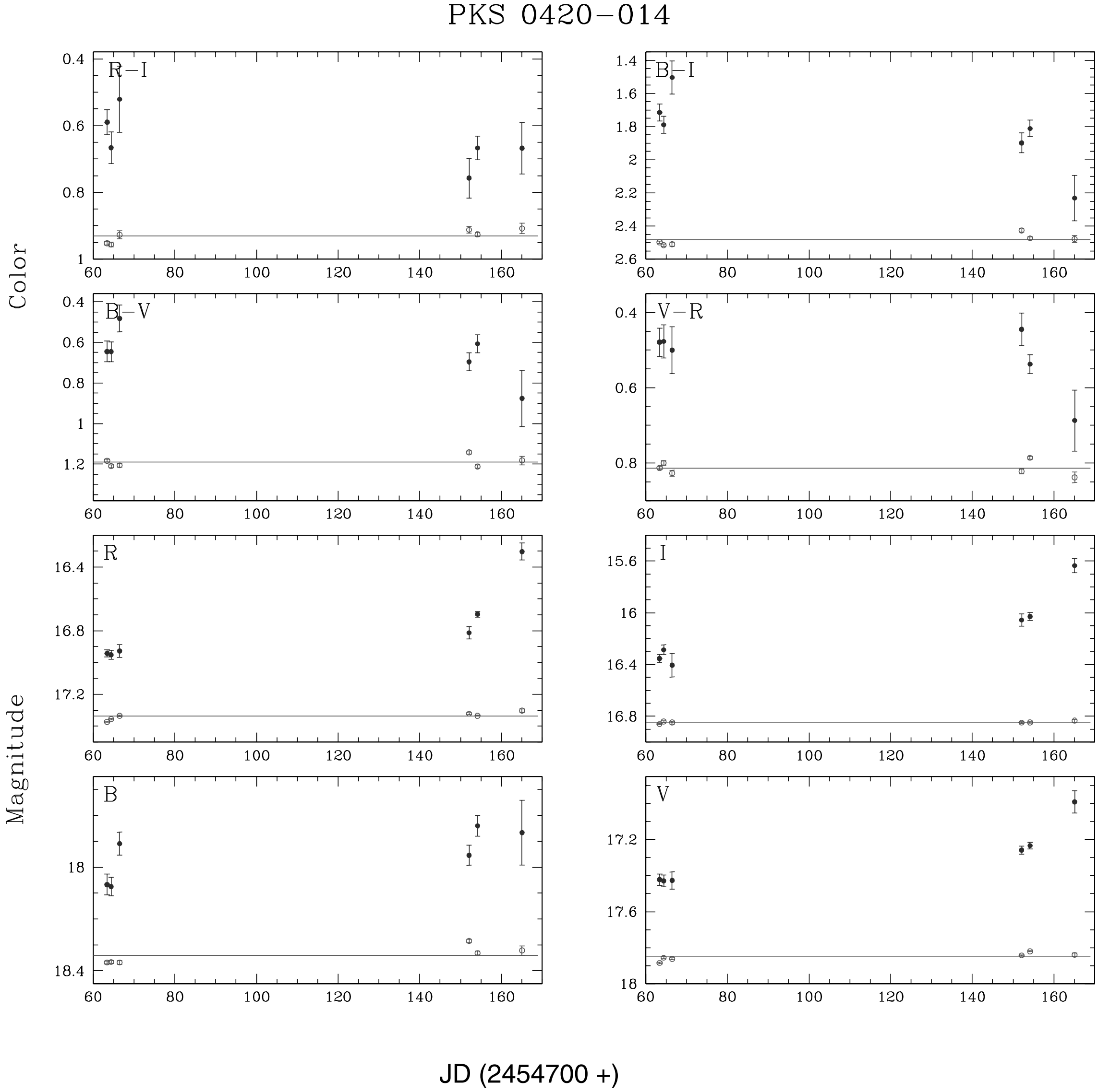

Figure 3. As in Fig. 1 for PKS 0420−014. The comparison stars are 4 and 2; 4 is the calibrator.

3.2.2 AO 0235+164

This blazar was classified as a BL Lac object by Spinrad & Smith (1975). AO 0235+164 has been seen to be highly variable over all time-scales and at all frequencies (e.g. 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 (e.g. 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. 2006a). A more detailed long-term optical data analysis suggested a possible outburst period of ∼8 yr in this source (Raiteri et al. 2006b) and this period was supported by observations of Gupta et al. (2008c). Strong IDV flux variations of 9.5 and 13.7 per cent during two nights were observed by Gupta et al. (2008c). Rani et al. (2009) recently reported a high probability of the presence of nearly periodic fluctuations with a time-scale of ∼17.8 d in a 12 yr long X-ray LC obtained by the *Rossi X-ray Timing Explorer* satellite's All Sky Monitor instrument.

During our observations AO 0235+164 showed significant flux as well as colour variations (Fig. 2). The source first brightened by ∼0.9 mag within an interval of 46 d and then it faded by >2 mag within 94 d in all four bands. An outburst state in 2007 January was reported by Gupta et al. (2008c) with $R_{\rm mag} \sim 14.98$ being the peak during their observing run. In our observation span, the source reaches a maximum brightness of $R = 15.18$ mag and then fades to $R = 17.4$ mag, so it seems likely that we have caught this BL Lac in a post-outburst phase.

3.2.3 PKS 0420−014

The blazar PKS 0420−014 is classified as a FSRQ. It has been observed in optical bands for four decades. Several papers have reported multiple optically active and bright phases of the source

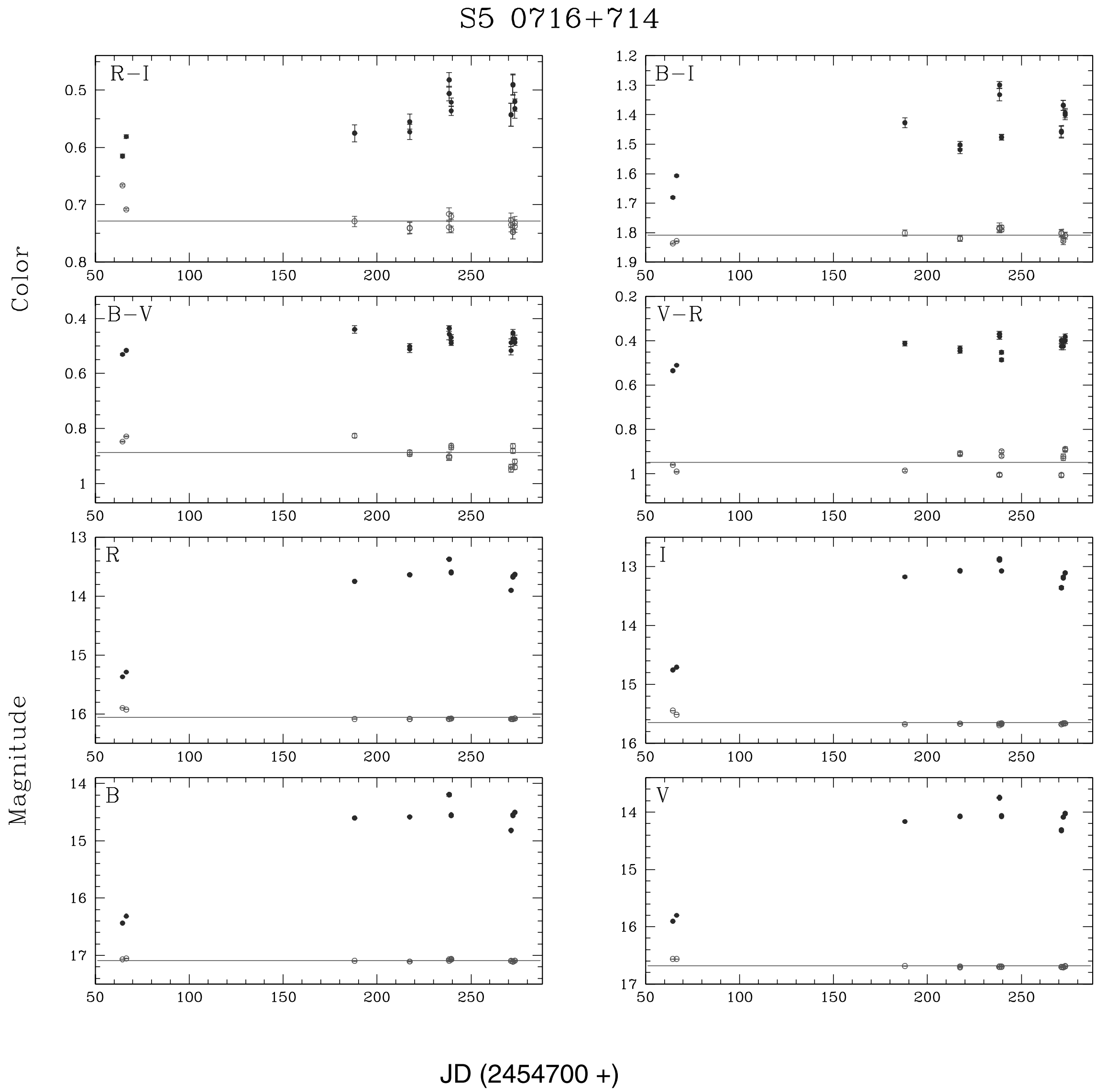

Figure 4. As in Fig. 1 for S5 0716+714. The comparison stars are 5 and 3; 5 is the calibrator.

and perhaps regular major flaring cycles (e.g. Villata et al. 1997; Webb et al. 1998; Raiteri et al. 1998, and references therein). An increase of ∼2–3 mag during the active phases of this blazar was reported by Webb et al. (1998) during observations that stretched from 1969 December to 1986 January. Variations of 2.8 mag with a time-scale of ∼22 yr have been reported (Clements et al. 1995). Two modes of variability at radio wavelengths superimposed on a ∼13 months nearly regular cycle were suggested through 5 yr of radio monitoring in the Hamburg Quasar Monitoring Program (Britzen et al. 2000).

During our observations PKS 0420−014 exhibited significant flux and colour variations (Fig. 3). Raiteri et al. (1998) reported that the historical peak in the LC of this source reached $R =$ 14.15 mag after which it decayed to 16.9 mag. The LC of the source during our observing run varies from 16.9 to 16.3 mag in R with an average of ∼16.6 mag, which is ∼2.5 mag fainter than the brightest reported value for this source. Since our values are close to the faintest reported for this source, we conclude that PKS 0420−014 was probably in a low state in the period we observed it.

3.2.4 S5 0716+714

This blazar is classified as a BL Lac object. It is important to note that this source has been classified as an IBL by Giommi et al. (1999) since the frequency of the first SED peak varies between 10^{14} and 10^{15} Hz, and thus does not fall into the wavebands specified by the usual definitions of LBLs and HBLs. More recently, however, Nieppola et al. (2006) studied the SED distribution of a large sample of BL Lac objects and categorized 0716+714 as a LBL; we adopt that classification in this paper. The optical continuum of the source is so featureless that it was hard to estimate its redshift, but there is a very recent claim of $z = 0.31 \pm 0.08$ by Nilsson et al. (2008). This source has been extensively studied at all observable wavelengths from radio to γ-rays on diverse time-scales (e.g. Wagner et al. 1990; Heidt & Wagner 1996; Giommi et al. 1999; Villata et al. 2000; Raiteri et al. 2003; Foschini et al. 2006; Montagni et al. 2006; Ostorero et al. 2006; Gupta et al. 2008a,c, and references therein). This source is one of the brightest BL Lacs in optical bands and has an IDV duty cycle (DC) of nearly 1. Unsurprisingly, S5 0716+714 has been the subject of several optical monitoring

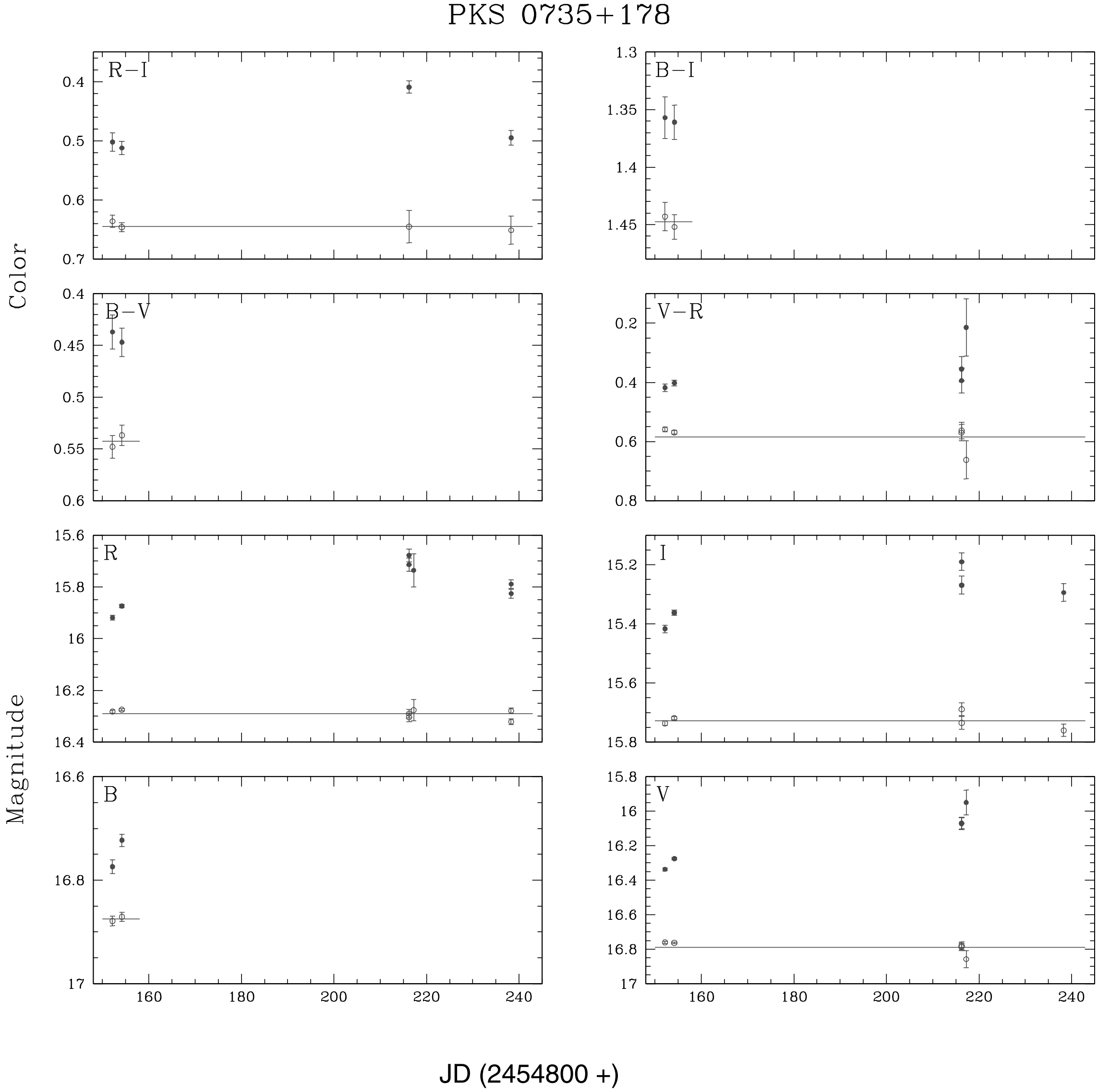

Figure 5. As in Fig. 1 for PKS 0735+178. The comparison stars are D and C; D is the calibrator.

campaigns on IDV time-scales (e.g. Wagner et al. 1996; Sagar et al. 1999; Montagni et al. 2006; Gupta et al. 2008c, and references therein). This source has shown five major optical outbursts (Gupta et al. 2008c) separated by $\sim 3.0 \pm 0.3$ yr. High optical polarizations of ∼20–29 per cent have also been observed in the source (Takalo, Sillanpää & Nilsson 1994; Fan et al. 1997). Recently, Gupta & Yuan (2009) analysed the excellent intraday optical LCs of the source obtained by Montagni et al. (2006) and reported good evidence for nearly periodic oscillations ranging between 25 and 73 min on several different nights.

Our LCs of S5 0716+714 showed very significant variations of ∼2 mag in each of the observed bands; however, no significant colour variation is observed in the source except for $B - I$ (Fig. 4). A large increase in the brightness of the source occurred between the two early observations and the seven later ones: over 230 d the source brightened by 2.2 mag (15.4 to 13.2) in R, becoming only ∼0.65 mag fainter than the brightest magnitude ($R = 12.55$ mag) reported for the source (Gupta et al. 2008c). Assuming that the source continued its brightening following a linear trend, it should have reached $R = 12.55$ mag in 2009 September. The calculated time difference between the last known outburst in 2007 January and this possible outburst is ∼2.7 yr. This temporal gap is consistent with the optical outburst time 3.0 ± 0.3 yr in the long-term optical period that was earlier reported for this source (Gupta et al. 2008c). Therefore, we organized a radio-optical observing campaign for 5 d in 2009 December to ascertain the source behaviour and state; the analysis of these data is underway.

3.2.5 PKS 0735+178

This blazar has been classified as a BL Lac object (Carswell et al. 1974). There have been several papers concerning its redshift determination (e.g. Carswell et al. 1974; Falomo & Ulrich 2000, and references therein) with the most recent result of $z = 0.424$ for PKS 0735+718 found using a *Hubble Space Telescope* (*HST*) snapshot image (Sbarufatti, Treves & Falomo 2005). Since it was optically identified, this source has been extensively observed across the whole EM spectrum (Fan & Lin 2000; Teräsranta et al. 2004; Gu

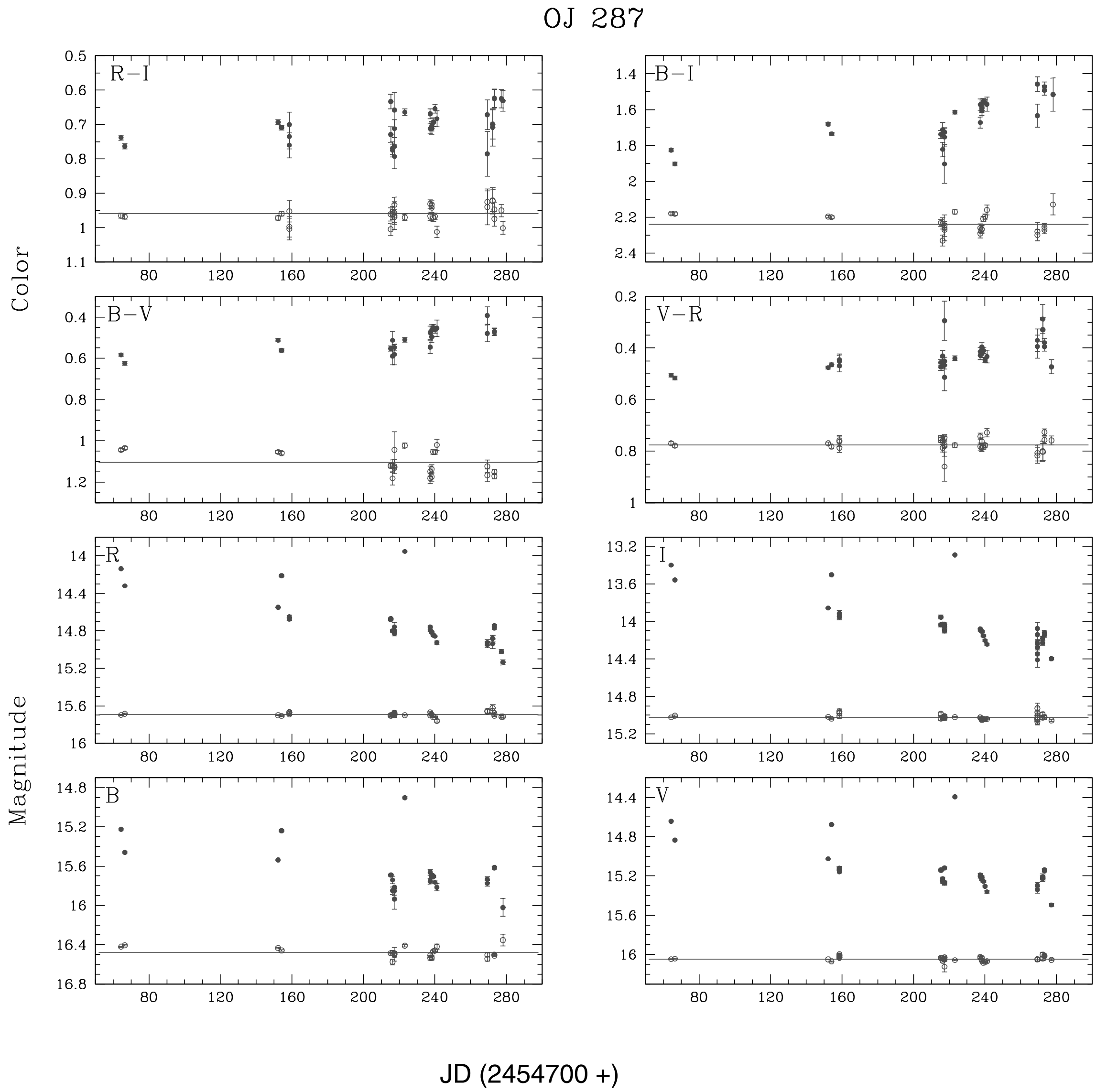

Figure 6. As in Fig. 1 for OJ 287. The comparison stars are 11 and 4; star 11 is the calibrator.

et al. 2006; Gupta et al. 2008c; Ciprini et al. 2007, and references therein). Radio frequency observations show slow variability with some outbursts (Teräsranta et al. 1992, 2004), but hardly any correlation has been found between the radio and optical flares (Clements et al. 1995; Hanski, Takalo & Valtaoja 2002; Ciaramella et al. 2004). A periodicity of ∼14 yr has been suggested to be present in the source using a century long optical LC (Fan et al. 1997). Optical variability on IDV and STV time-scales has naturally 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. 2008c). Significant fractional polarizations (∼1 to 30 per cent) have been observed both at optical and IR bands (Mead et al. 1990; Takalo 1991; Takalo et al. 1992b; Valtaoja et al. 1991a, 1993; Tommasi et al. 2001).

We found strong flux variations in all the well observed passbands for PKS 0735+178 (Fig. 5); however, as there are only two data points in the *B* band LC, we cannot discuss the nature of its variation. Except for $R - I$, no significant colour variation was seen in the source. The average $R_{\rm mag}$ of PKS 0735+178 during our observing run was 15.80 which is ∼1.8 mag fainter than the brightest (R ∼ 14.0 mag) and ∼1.2 mag brighter than the faintest magnitude ($R_{\rm mag}$ ∼ 17.0) reported in the source (Ciprini et al. 2007). Thus, we have probably observed the source in either a pre- or post-outburst state as long as there have been no long-term changes in the underlying LC.

3.2.6 OJ 287

This BL Lac object is one of the most extensively observed for variability; it is also among the very few AGNs whose substantial brightness means that more than a century of optical observations are available (e.g. Carini et al. 1992; Sillanpää et al. 1996a,b; Abraham 2000; Fan & Lin 2000, 2009; Gupta et al. 2008c). 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). On re-analysing the optical data from OJ-94 project, Wu et al. (2006) reported another possible time-scale, suggesting a periodicity of ∼40 d. Very high optical polarization that is variable in both degree and angle has been reported in the

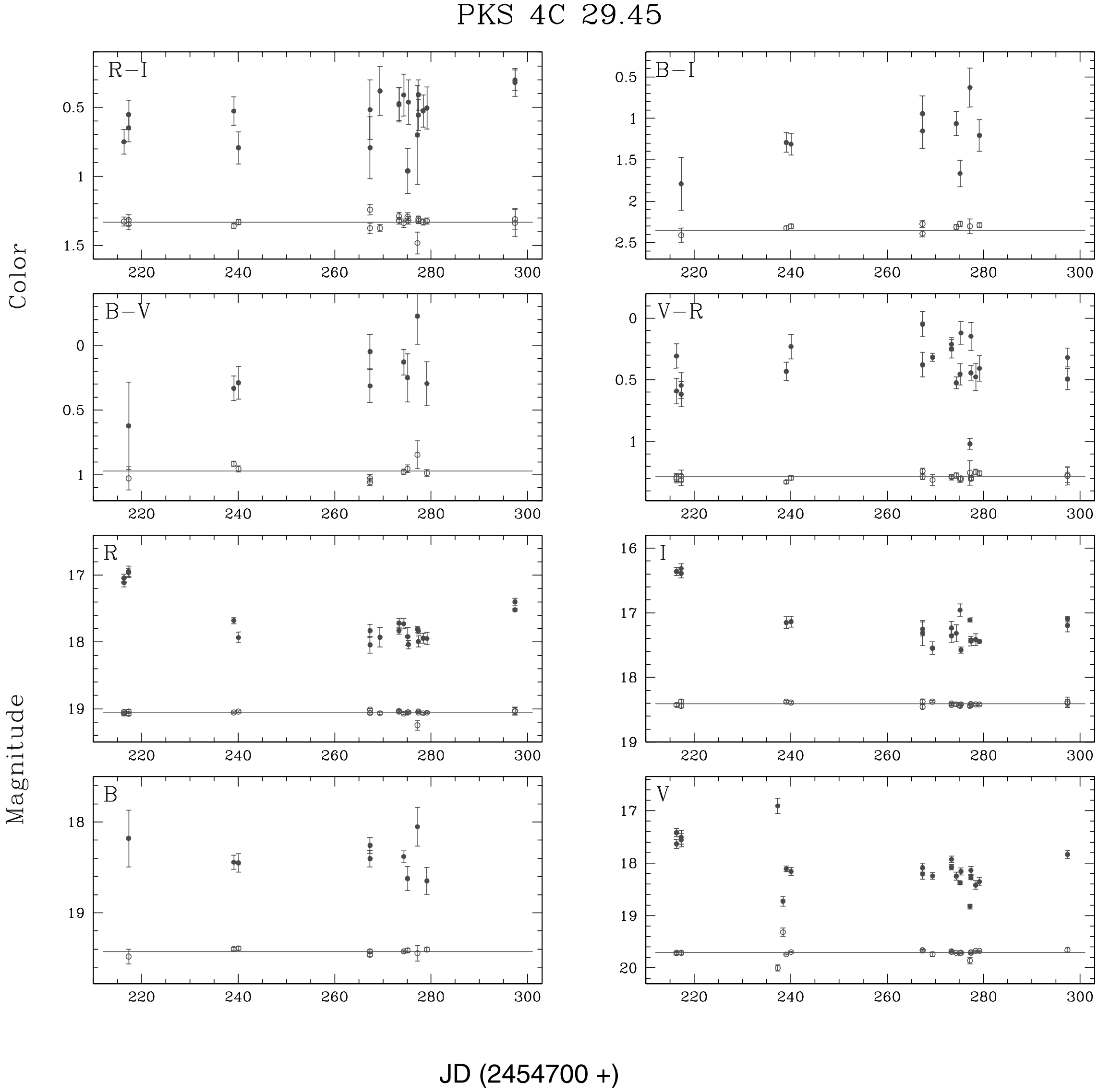

Figure 7. As in Fig. 1 for 4C 29.45. The comparison stars are 14 and 13; 14 is the calibrator.

source (Efimov et al. 2002). The observational properties of OJ 287 from radio to X-ray energy bands have been reviewed by Takalo et al. (1994). During their observations spanning 2002 to 2007 Fan et al. (2009), reported large variations in the source of $\Delta V = 1.96$ mag, $\Delta R = 2.36$ mag and $\Delta I = 1.95$ mag.

We found OJ 287 to have significant flux variations in all the observed passbands but no significant colour variation was found (Fig. 6). A flare in the LCs of the blazar OJ 287 of ∼1 mag was observed in all bands over an interval of 36 d, but we had only one night of data near the flare's peak, so it is quite likely that the maximum of the flare was even stronger. It is interesting that this result is consistent with a ∼37 d period of rotation of the plane of polarization seen of OJ 287 (Efimov et al. 2002) and close to a 40 d periodicity reported in source by Wu et al. (2006). The average R-band magnitude ($R \sim 14.7$ mag) of the source during our observing run is ∼2.5 mag fainter than the brightest ($R = 12.09$ mag) and ∼2.3 mag brighter than the faintest magnitude ($R = 16.47$ mag) reported in the source by Fan & Lin (2000). So it seems that we observed OJ 287 in an intermediate state.

3.2.7 4C 29.45

This optically violent variable quasar belongs to the class of FSRQs. At both optical and IR bands STV and LTV have been observed in this source (Branly et al. 1996; Noble & Miller 1996; Ghosh et al. 2000). A very large variation ($\Delta V > 5$ mag) has been reported in the source during the optical outburst of 1981 (Wills et al. 1983). Large fractional polarizations, up to ∼28 per cent, have been observed in 4C 29.45 both at optical and IR frequencies (Holmes et al. 1984; Mead et al. 1990). Its optical flux and colour variations have been recently studied by Fan et al. (2006). They have reported amplitude variations of ∼4.5–6 mag in all passbands (U, B, V, R, I) and also found that there were possible periods of 3.55 or 1.58 yr in the long-term optical LC of the source.

Our LCs of 4C 29.45 indicate that it is variable in all the observed bands but the percentage of variation differs substantially among them, leading to the significant colour variations (Fig. 7). During our observing run, 4C 29.45 varied from 16.30 to 17.57 mag in the I band. The faintest magnitude we observed in the source is thus

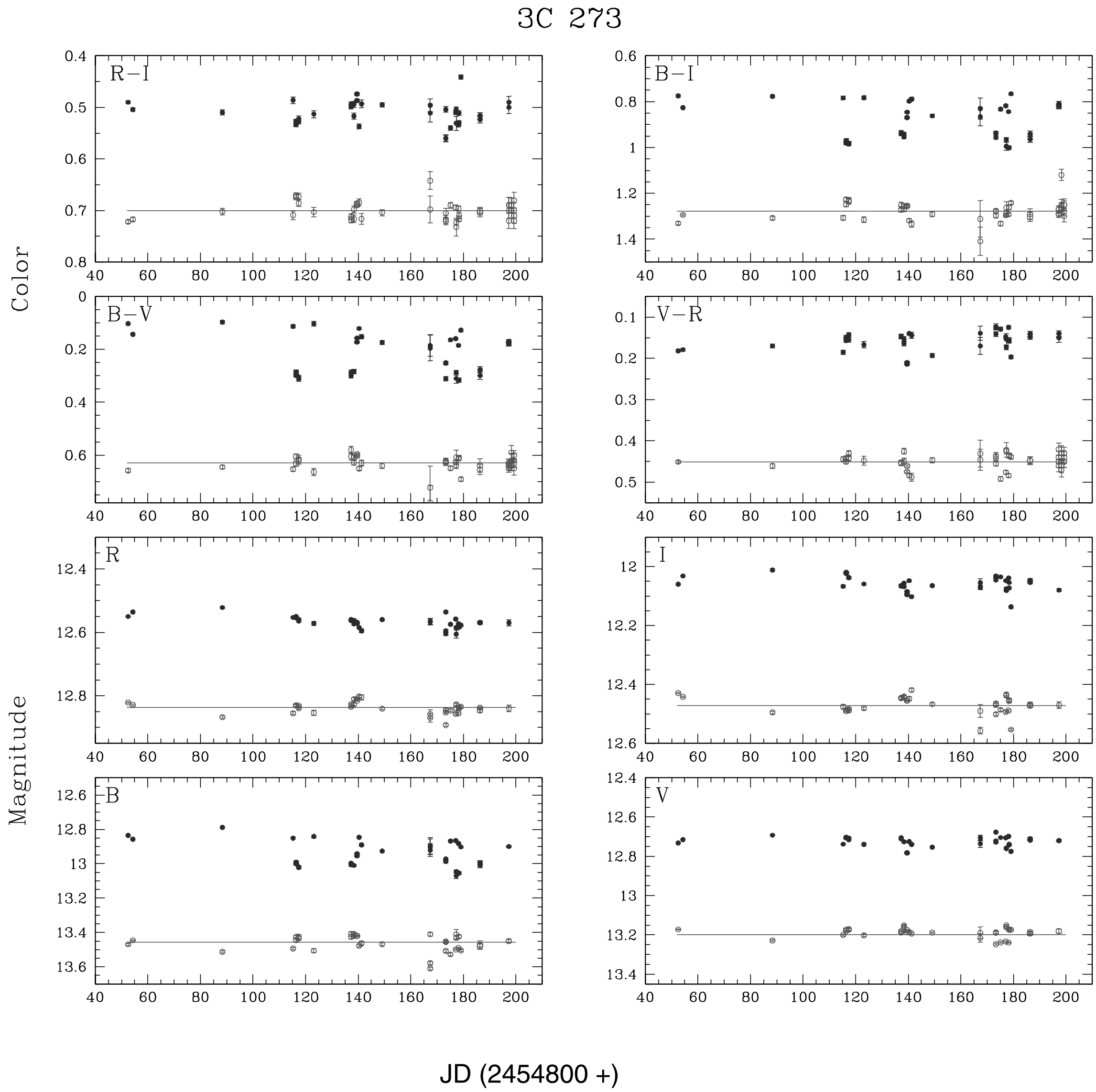

Figure 8. As in Fig. 1 for 3C 273. The comparison stars are E and G; E is the calibrator.

0.12 mag fainter than the faintest level, $I = 17.45 \pm 0.05$ mag, reported for this source by Fan et al. (2006), so we clearly observed the source in a faint phase. The faintest state of the source was on 2009 May 23, but it had brightened by ~0.2 mag by the next day.

3.2.8 3C 273

The FSRQ 3C 273 was the first quasar discovered (Schmidt 1963). Categorized as an LBL (Nieppola et al. 2006), its SED, correlations among flares in different energy bands and the approaching jet's orientation have been extensively studied at all EM bands (e.g. Valtaoja et al. 1991b; Takalo et al. 1992a,b). Many papers cover 3C 273's observational properties of the source in the visible band (Angione et al. 1981; 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. 1992a,b; Elvis et al. 1994; Lichti et al. 1995; Ghosh et al. 2000; Dai et al. 2009). Analyses of the optical LC of 3C 273 spanning over 100 yr suggests a LTV time-scale of ~13.5 yr (Fan, Qian & Tao 2001). Recently, the STV and colour index properties of the source were studied by Dai et al. (2009). They found a strong correlation between the colour index and brightness of the source in the sense that the spectrum becomes flatter, or bluer, when the source brightens and steeper, or redder, when it fades.

The blazar 3C 273 was essentially in a steady state during our observing run, with no significant variation greater than ~0.03 mag in any of the observed LCs (Fig. 8). Nor were any significant variations found in the colour LCs of the source. Very recently Dai et al. (2009) reported that the source also was essentially steady during their observations, which ran from 2003 January to 2005 April, with an average R-band magnitude $\simeq$12.44 which was only 0.12 mag brighter than that of our observing run ($R = 12.56$ mag). Thus, it is very possible that the same dull state continued in 3C 273 from 2003 through our observations in 2009.

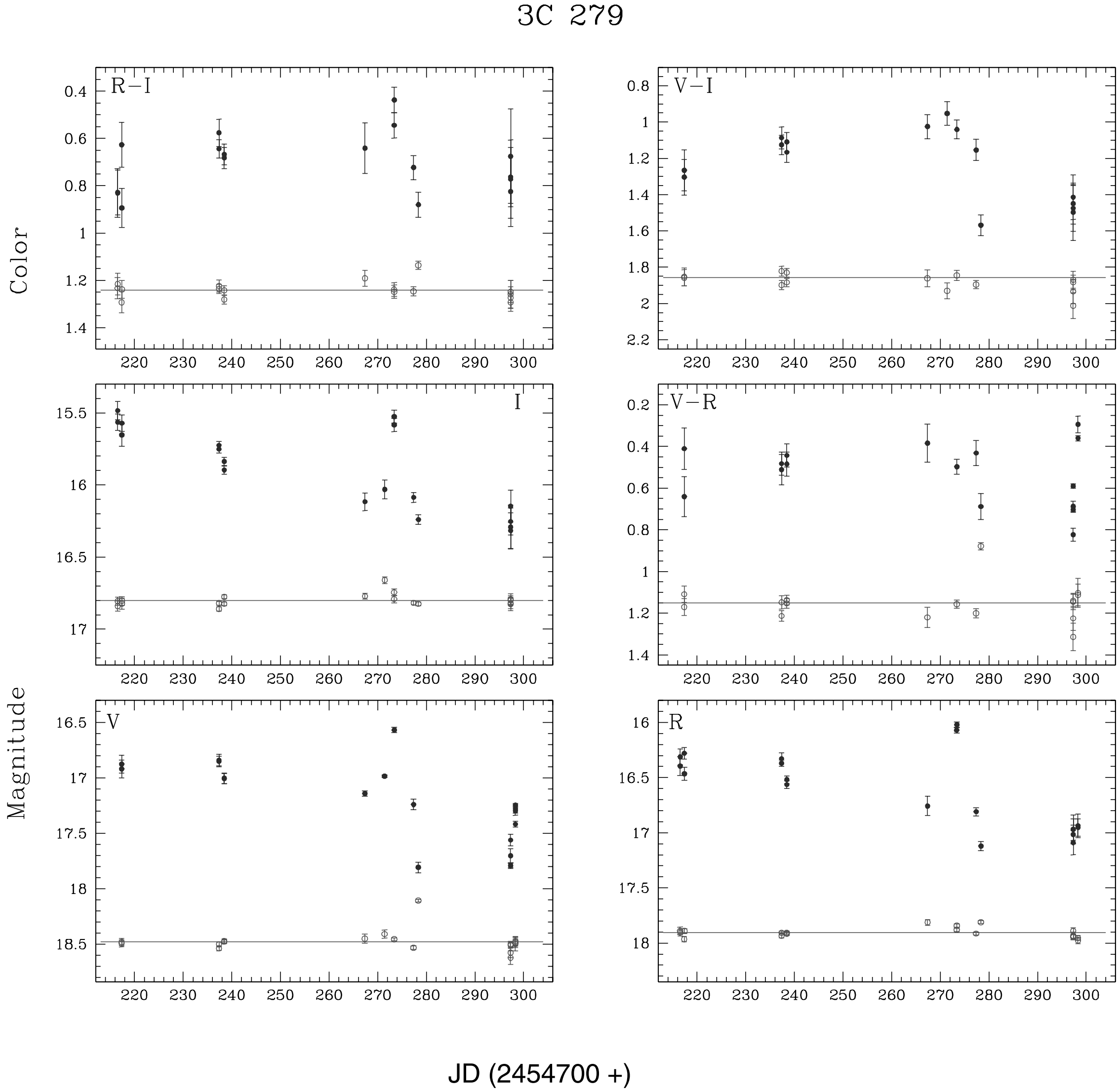

Figure 9. As in Fig. 1 for 3C 279. The comparison stars are 1 and 4; 1 is the calibrator.

3.2.9 3C 279

This FSRQ shows strong optical polarization and flux variabilities at all frequencies. A very large amplitude variation of $\Delta B \geq 6.7$ in the optical flux of 3C 279 was reported long ago by Eachus & Liller (1975). A rapid variation of 1.17 mag within 40 min was seen in the V band (Xie et al. 1999) and a STV of 0.91 mag in the R band was seen over 49 d (Xie et al. 2002b). Recently, Gupta et al. (2008c) reported a 1.5 mag variation in the R band of 3C 279 over 42 d but Webb et al. (1990) reported rapid fluctuations of $\sim$2 mag within 24 h at visible wavelengths. Not surprisingly, this source also has been intensively studied through multiwavelength campaigns (Hartman et al. 1996; Wehrle et al. 1998). The most recent WEBT campaign on 3C 279 reported that the source was in the high optical state and the LCs show quasi-exponential decays of flux of $\sim$1 mag on a time-scale of $\sim$12.8 d (Böttcher et al. 2007) which was explained by Böttcher & Principe (2009) as a signature of deceleration of a synchrotron emitting jet component.

It is clear from our LCs that the source is highly variable in all the observed passbands (Fig. 9). However, except for $R - I$, the colours of the source are not significantly variable. 3C 279's LC shows a rapid decay in brightness, i.e. within 5 d $\Delta V = 1.24$ mag, $\Delta R = 1.10$ mag and $\Delta I = 0.8$ mag which is faster than most earlier STVs reported in the source (e.g. Xie et al. 1999, 2002b; Böttcher et al. 2007; Gupta et al. 2008c). The source was reported to be in outburst in 2007 January by Gupta et al. (2008c) reaching a brightness of $R \sim 12.6$ mag. The faintest level we observed for 3C 279 was $R = 17.1$ mag which is $\sim$4.5 mag fainter than the outburst brightness seen about 2.4 yr earlier, indicating that we caught 3C 279 in a low state.

3.2.10 PKS 1510−089

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

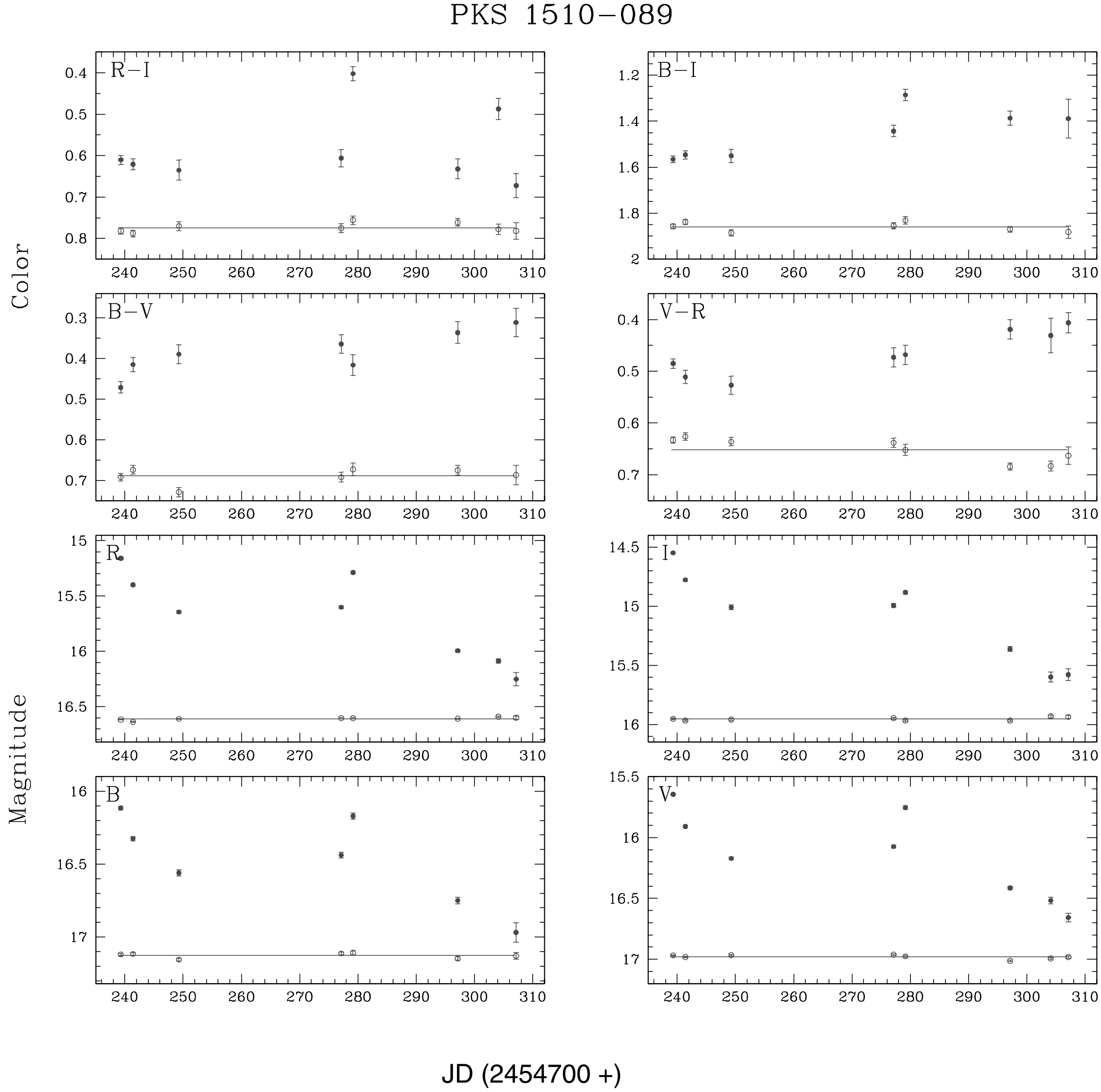

Figure 10. As in Fig. 1 for PKS 1510−089. The comparison stars are 3 and 4; 3 is the calibrator.

60 min (Xie et al. 2002a). In the optical LCs of this source, deep minima have been observed on different days (e.g. Dai et al. 2001; Xie et al. 2001, 2002b) that nominally correspond to a time-scale of ∼42 min, though no more than three such dips were ever seen in a single night so the evidence for a real periodicity is slight. None the less, an eclipsing binary black hole model was proposed to explain the occurrence of these minima (Wu et al. 2005). This group has also claimed another possible time-scale between minima of ∼89 min (Xie et al. 2004). Very recently, while it was being monitored by WEBT, D'Ammando et al. (2009) reported detecting a rapid γ-ray flare from PKS 1510−089 in 2008 March using the *AGILE* satellite.

We found significant variations in the brightness of PKS 1510−089 over a 3 month period of observations (Fig. 10). Even though there is not much difference in the percentage variation in the magnitude of the source (see Table 4) in different bands, the colour variations are still significant (except for $V - R$). PKS 1510−089 decayed from 16.1 to 17 mag in the B band during our observations, which is only ∼0.8 mag brighter than the faintest magnitude ($B_{\rm mag} = 17.8$) reported in the historic LC of Liller & Liller (1975); hence, we observed the source in a faint phase.

3.2.11 BL Lac

The object BL Lac 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 (e.g. Sitko, Schmidt & Stein 1985). BL Lac 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 $\Delta B = 5.3$ 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 a shock model that can explain it.

We found that BL Lac was variable in all the observed passbands during our observations (Fig. 11). As the percentage variation is nearly equal in all the four passbands (although a little higher in

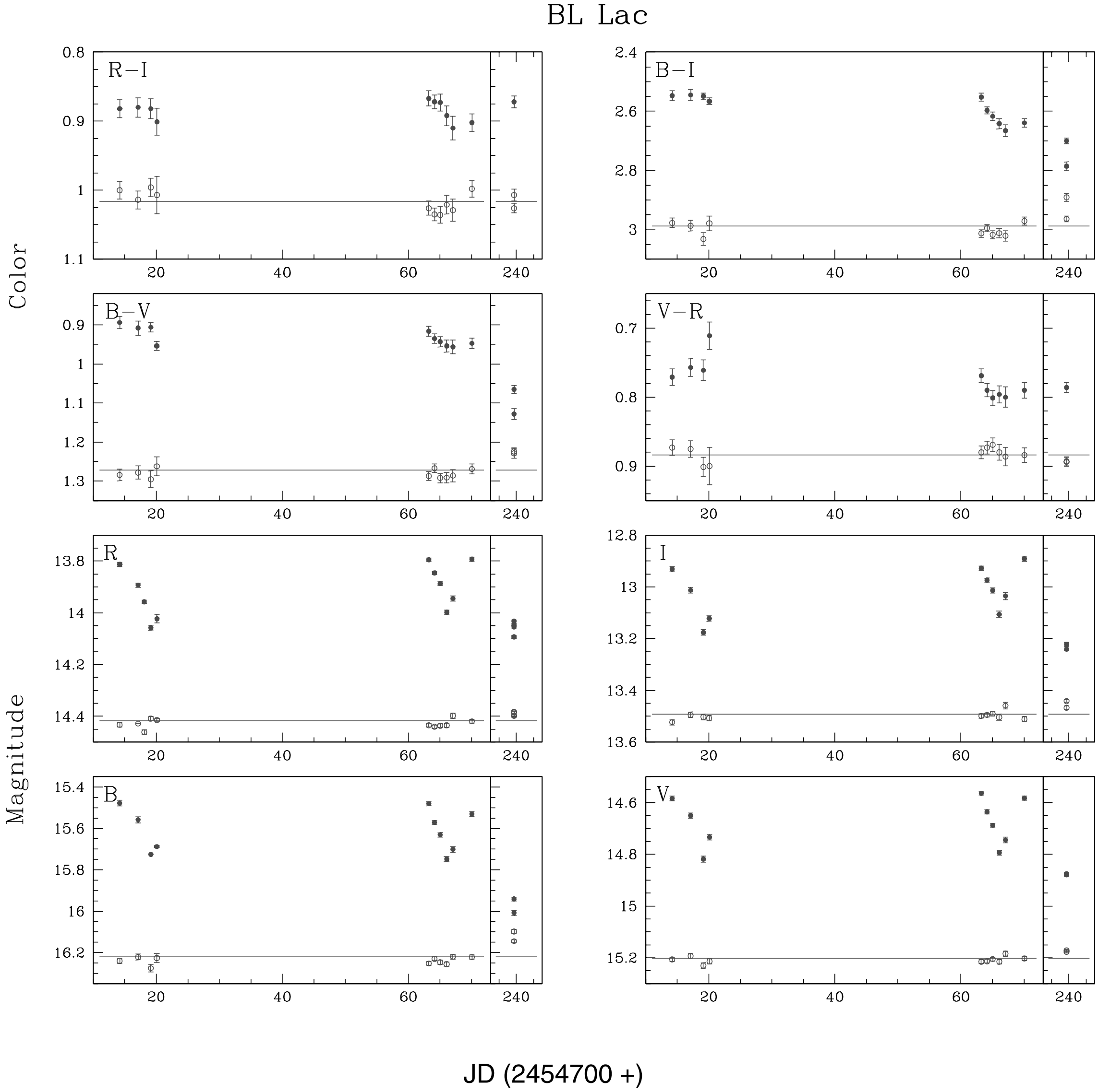

Figure 11. As in Fig. 1 for BL Lac. The comparison stars are K and C; K is the calibrator.

B band), we find no significant colour variations (except perhaps $B - V$). The average R-band magnitude of the source during our observing run is 13.95 (13.8–14.1) which is ∼1.0 mag brighter than the faintest magnitude reported for the source by Fan & Lin (2000).

3.2.12 3C 454.3

This FSRQ is among the most intense and variable sources. The source has been detected in the flaring state in 2007 July 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 3C 454.3 at optical and radio frequencies have been well studied through multiwavelength campaigns (e.g. Villata et al. 2006, 2007). The IDV of the source has been recently studied by Gupta et al. (2008c) who reported that the amplitude varied by ∼5–17 per cent during their observations.

The source 3C 454.3 showed large flux variations in all the passbands during our observations and the percentage variation differs significantly, which leads to significant variations in the colour of source (Fig. 12). The source decayed significantly from $R = 14.5$ to 15.5, i.e. $\Delta R = 1$ mag during our observing run of 50 d; this is ∼3.5 mag fainter than the brightest magnitude ($R_{\rm mag} = 12$) but ∼1.5 mag brighter than the faintest magnitude ($R_{\rm mag} = 17$) reported in the source by Villata et al. (2006). It is very likely that we have observed this FSRQ in a post-outburst state.

3.3 Correlated variations between colour and magnitude

Any relationships between the variations in brightness of each of these 12 blazars and the corresponding variations in their $B - V$, $V - R$, $R - I$ and $B - I$ colour indices are worth examining. Such colour–magnitude plots of the individual sources are displayed in Figs 13–15. We display colour indices that are calculated by only considering data taken by the same instrument within a time interval of no more than 20 min; still, the possibility of a rapid variation in overall flux within that interval sufficient to confound our measurements must be noted. The individual panels show the $B - V$, $V - R$, $R - I$ and $B - I$ colours plotted (in sequence from bottom to top with arbitrary offsets) with respect to V magnitude.

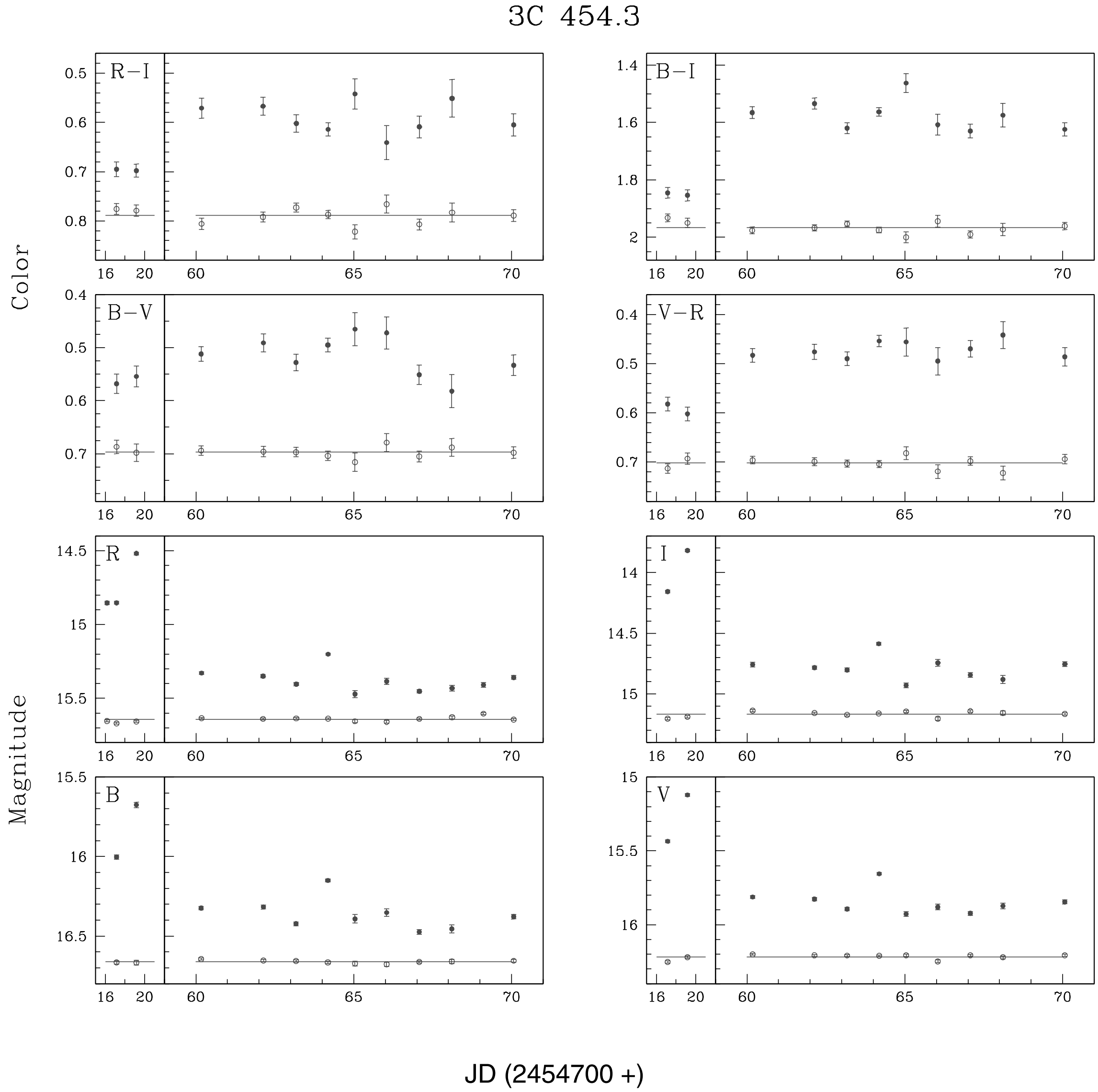

Figure 12. As in Fig. 1 for 3C 454.3. The comparison stars are B and C; B is the calibrator.

The straight lines shown are the best linear fit for each of the colour indices, *CI*, against magnitude, *V*, for each of the sources: $CI = mV + c$. Those fitted values for the slopes of the curves, *m*, and the constants, *c*, are listed in Table 5. Table 5 also gives the linear Pearson correlation coefficients, *r*, and the corresponding null hypothesis probability values, *p*.

Here, a positive slope means a positive correlation between the colour index and apparent magnitude of the blazar, which physically means that the source tends to be bluer when it brightens or redder when it dims. A negative slope implies the opposite correlation between brightness and colour, so that the source exhibits a redder when brighter behaviour. We found significant negative correlations ($p \leq 0.05$) between the V magnitudes and at least some colour indices for the following blazars: PKS 0420−014 ($B - V$, $V - R$ and $R - I$); OJ 287 ($B - V$); 4C 29.45 ($B - V$); 3C 273 ($B - V$ and $R - I$); PKS 1510−089 ($B - V$ and $V - R$) and 3C 454.3 ($V - R$, $R - I$ and $B - I$). Significant positive correlations ($p \leq 0.05$) are found for: 3C 66A ($V - R$ and $R - I$); S5 0716+714 ($B - V$, $V - R$, $R - I$ and $B - I$); 3C 273 ($V - R$); 3C 279 ($V - R$ and $R - I$) and BL Lac ($B - V$ and $B - I$) while the correlations among the rest have significance less than 95 per cent. The two sources lacking any such correlations were AO 0235+164 and PKS 0735+178. The only blazar in our sample to show both positive and negative correlations, depending upon the bands considered, was 3C 273.

3.4 Variability duty cycles on STV time-scales

The DC for variability of a class of objects can be roughly taken to be the fraction of them showing significant variations on particular time-scales. If N denotes the total number of sources observed in a search for STV and n denotes the number of sources that are found to be variable, then the DC, as a percentage (Gupta & Yuan 2009), is defined as

$$DC = \frac{n}{N} \times 100. \quad (3)$$

We detected STV in 11 out of 12 LBLs, so the DC of flux variation on STV time-scales is ∼92 per cent.

We searched for variations in all of the $B - V$, $V - R$, $R - I$ and $B - I$ colour indices of each source. In our sample of a dozen

Table 4. Results of short-term variability observations.

Source name	Duration of observation (yyyy mm dd) to (yyyy mm dd)	Band	N	$\sigma(\mathrm{BL}-\mathrm{S_A})$	$\sigma(\mathrm{BL}-\mathrm{S_B})$	$\sigma(\mathrm{S_A}-\mathrm{S_B})$	C	A	Variable
3C 66A	2008 10 20 to 2009 02 02	B	12	0.286	0.279	0.015	19.05	77.2	V
		V	12	0.292	0.283	0.014	19.91	81.8	V
		R	12	0.284	0.272	0.016	17.59	78.0	V
		I	12	0.274	0.281	0.057	4.89	75.5	V
		$B-V^a$	12				1.46	6.1	NV
		$V-R$	12				0.96	4.9	NV
		$R-I$	12				1.14	4.2	NV
		$B-I$	12				1.37	7.4	NV
AO 0235+164	2008 09 04 to 2009 01 22	B	12	0.744	0.739	0.012	60.00	226.4	V
		V	12	0.736	0.740	0.008	92.63	226.3	V
		R	11	0.758	0.758	0.006	133.64	222.7	V
		I	12	0.697	0.697	0.007	102.98	224.1	V
		$B-V$	12				6.49	20.8	V
		$V-R$	11				4.96	12.2	V
		$R-I$	11				24.21	55.1	V
		$B-I$	12				12.94	68.0	V
PKS 0420−014	2008 10 23 to 2009 02 02	B	6	0.119	0.100	0.034	3.26	23.5	V
		V	6	0.188	0.173	0.022	8.15	43.9	V
		R	6	0.271	0.250	0.025	10.49	64.9	V
		I	6	0.293	0.287	0.009	32.73	77.1	V
		$B-V$	6				4.83	39.4	V
		$V-R$	6				4.59	24.2	V
		$R-I$	6				4.03	23.6	V
		$B-I$	6				7.30	72.8	V
S5 0716+714	2008 10 24 to 2009 04 17	B	9	0.648	0.201	0.018	23.24	224.6	V
		V	9	0.649	0.184	0.048	8.73	216.2	V
		R	9	0.592	0.178	0.059	6.48	199.7	V
		I	9	0.584	0.179	0.069	5.55	188.7	V
		$B-V$	9				0.52	9.5	NV
		$V-R$	9				0.65	16.6	NV
		$R-I$	9				2.03	13.3	NV
		$B-I$	9				4.10	38.2	V
PKS 0735+178	2009 01 20 to 2009 04 16	B	2	0.036	0.042	0.005	6.87	5.1	PV
		V	5	0.161	0.129	0.039	3.67	38.7	V
		R	7	0.087	0.083	0.017	4.97	24.1	V
		I	5	0.087	0.093	0.026	3.44	22.7	V
		$B-V$	2				0.90	1.0	NV
		$V-R$	5				1.91	20.4	NV
		$R-I$	5				7.61	10.3	V
		$B-I$	2				0.44	0.4	NV
OJ 287	2008 10 24 to 2009 05 26	B	22	0.250	0.269	0.053	4.89	111.7	V
		V	24	0.241	0.240	0.025	9.62	110.2	V
		R	24	0.268	0.267	0.026	10.28	118.2	V
		I	24	0.274	0.272	0.027	10.21	121.5	V
		$B-V$	22				1.51	42.3	NV
		$V-R$	24				2.09	22.3	NV
		$R-I$	24				2.19	16.9	NV
		$B-I$	22				2.56	44.5	NV
4C 29.45	2009 03 25 to 2009 06 14	B	11	0.195	0.178	0.030	6.15	59.7	V
		V	19	0.431	0.391	0.111	3.69	192.2	V
		R	25	0.365	0.370	0.045	8.11	109.9	V
		I	21	0.377	0.376	0.026	14.45	125.9	V
		$B-V$	11				3.58	84.7	V
		$V-R$	19				9.22	97.2	V
		$R-I$	21				3.68	65.8	V
		$B-I$	11				7.13	116.3	V
3C 273	2009 01 20 to 2009 06 16	B	44	0.061	0.057	0.041	1.43	28.1	NV
		V	38	0.022	1.456	1.458	0.51	10.6	NV
		R	38	0.018	0.019	0.017	1.09	8.4	NV
		I	40	0.024	0.038	0.031	0.99	12.5	NV

Table 4 – *continued*

Source Name	Duration of observation (yyyy mm dd) to (yyyy mm dd)	Band	N	σ(BL – S_A)	σ(BL – S_B)	σ(S_A – S_B)	C	A	Variable
		$B-V$	38				0.04	21.9	NV
		$V-R$	38				0.01	9.1	NV
		$R-I$	38				1.27	11.9	NV
		$B-I$	38				1.76	23.5	NV
3C 279	2009 03 25 to 2009 06 15	V	16	0.370	0.376	0.101	3.68	124.1	V
		R	14	0.353	0.362	0.046	7.70	110.0	V
		I	16	0.295	0.294	0.044	6.69	83.3	V
		$V-R$	14				1.62	52.9	NV
		$R-I$	14				3.29	45.7	V
PKS 1510−089	2009 04 17 to 2009 06 24	B	7	0.308	0.319	0.018	17.56	85.2	V
		V	8	0.366	0.375	0.017	22.01	101.2	V
		R	8	0.397	0.389	0.014	29.02	109.1	V
		I	8	0.382	0.373	0.014	26.38	104.9	V
		$B-V$	7				2.76	15.9	V
		$V-R$	8				1.91	12.1	NV
		$R-I$	8				8.24	26.9	V
		$B-I$	7				5.13	27.9	V
BL Lac	2008 09 04 to 2009 04 17	B	15	0.169	0.137	0.049	3.08	53.0	V
		V	15	0.113	0.107	0.017	6.25	31.6	V
		R	19	0.107	0.091	0.029	3.42	30.1	V
		I	15	0.118	0.105	0.024	4.72	35.0	V
		$B-V$	15				2.99	23.4	NV
		$V-R$	15				2.42	8.9	NV
		$R-I$	15				0.99	4.3	NV
		$B-I$	15				1.97	24.1	NV
3C 454.3	2008 09 06 to 2008 10 30	B	11	0.240	0.238	0.009	25.67	79.9	V
		V	11	0.252	0.247	0.017	14.47	80.6	V
		R	13	0.298	0.289	0.016	17.84	95.2	V
		I	11	0.343	0.329	0.023	14.53	110.8	V
		$B-V$	11				3.93	11.7	V
		$V-R$	11				4.29	15.9	V
		$R-I$	11				3.13	15.6	V
		$B-I$	11				5.99	39.1	V

Note. V, variable; NV, non-variable; PV, partially variable.
[a]Colour variability is investigated using only one comparison star, as its non-variability was established while searching for flux variations.

blazars, we found strong short-term colour variability (STCV) in most of them, using a >0.99 probability definition for the presence of such variations ($C > 2.57$). Based on our results here, we can categorize the colour variations into three classes: strong STCV; partial STCV; and non-STCV, or no variation of colour with time. The sources that we find to have strong STCV are AO 0235+164, PKS 0420−014, 4C 29.45 and 3C 454.3, as they show significant variations in all the four colour indices. The formally non-STCV sources during our observations were 3C 66A, OJ 287, 3C 273 and BL Lac. The remainder of the blazars showed one to three nominally significant colour variations and thus could be fairly said to have exhibited partial STCV. If we are conservative and only consider the four blazars with strong STCV, then the DC of colour variation on STV time-scales is ∼33 per cent.

4 DISCUSSION

4.1 Flux variations

During the period 2008 September to 2009 June, we carried out multiband photometric observations of 12 LBLs. Comparisons of our observations with earlier measurements of the same sources indicated that the blazars, PKS 0420−014, 4C 29.45 and PKS 1510−089, were in relatively faint states; AO 0235+164, BL Lac and 3C 454.3 were possibly in post-outburst states; S5 0716+714 and 3C 66A were more likely to be in pre-outburst states; while the two sources PKS 0735+178 and OJ 287 were in some intermediate state during our observing run, and none of them appeared to be in outburst. We cannot even attempt to classify 3C 273 in this fashion because it has never shown a large amount of optical activity: the observed total ΔB is a modest ∼2 mag between 1887 and 2000 (Courvoisier 1998). We observed large flux variations in all the sources except 3C 273 during our observing span.

The substantial flux variations we and others have observed in these LBLs can be reasonably explained by models that involve relativistic shocks propagating outwards (e.g. Marscher & Gear 1985; Wagner & Witzel 1995; Marscher 1996). The larger flares are expected to be produced by the emergence and motion of a new shock triggered by some strong variation in a physical quantity such as velocity, electron density or magnetic field moving into and through the relativistic jet. Smaller variations may be nicely explained by turbulence behind a shock propagating down the jet (Marscher et al. 1992). In a minority of blazars, gravitational microlensing (e.g. Gopal-Krishna & Subramanian 1991) might be important. The one such case among our sample where microlensing may play a role is AO 0235+164 which is known to have two galaxies (at $z = 0.524$ and 0.851) along our line of sight to it.

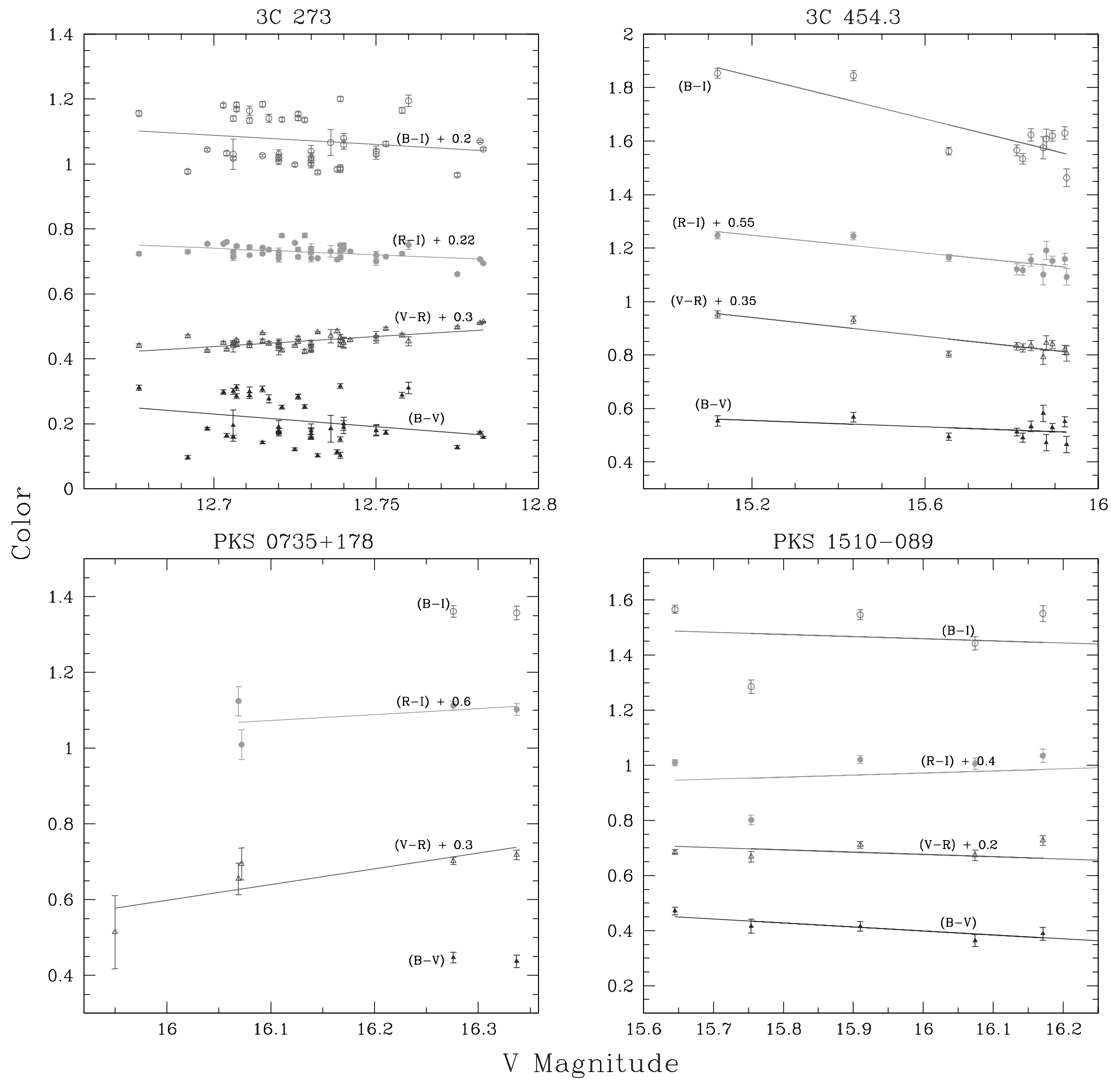

Figure 13. Colour–magnitude plots of the blazars 3C 273, 3C 454.3, PKS 0735+178 and PKS 1510-089.

4.2 Colour variations

The variability of blazars has been extensively studied over the past two decades. Still, to the best of our knowledge, we are reporting the most extensive search for optical STCV, i.e. variations in colour with time for time periods corresponding to STV, in a sample of LBLs. Gu et al. (2006) presented monitoring of eight LBLs, seven of which are also in our sample of 12, for about 6 months during 2003 and 2004; their observations were only in the *V, R* and *I* bands for six of their sources, though they did also have *B* band coverage for two of them.

Three phenomena that could lead to colour variations with time were discussed by Hawkins (2002): the effect of the underlying host galaxy; colour changes in accretion discs; and colour changes from microlensing, and we now consider each of these. The effect of the underlying host galaxy on colour variations of the source is usually seen in the case of low-luminosity AGNs such as Seyfert galaxies ($M_B > -22$) where variable seeing would include more or less of the galaxy's light along with that of the Seyfert. Since the FSRQs are among the most luminous AGNs ($M_B < -23$), any colour variation in these sources is most unlikely to arise from the underlying host galaxy. This is true for BL Lacs as well, in that the Doppler boosted jet emission almost invariably swamps the light from the host galaxy, thereby often making the determination of redshifts very difficult, as noted above.

The STCV observed in blazar LCs might conceivably come from colour changes arising in the accretion disc itself, particularly for the FSRQ class, where accretion disc emission may be significant (e.g. Malkan 1983; Pian et al. 1999), although the BL Lacs seem to have much weaker disc emission. The standard model of a geometrically and optically thick accretion disc (e.g. Shakura & Sunyaev 1973) yields a negative temperature gradient, i.e. the disc is cooler and redder with increasing radial distance from the central black hole. Hence, any non-linear oscillations of such a disc lead to temperature, and hence colour, changes (Hawkins 2002). Microlensing of radiation from an accretion disc having the expected radial temperature gradient can also produce variations in colour. Yonehara et al. (1999) carried out numerical simulations of the microlensing of accretion discs by a compact body and showed that for an optically thick accretion disc with a radial temperature gradient colour variations are seen, while for optically thin accretion discs such induced colour variations are unlikely to be observable. The blazar AO 0235+164 showed strong STCV during our observing run and is known to have two foreground galaxies at $z = 0.524$ and 0.851

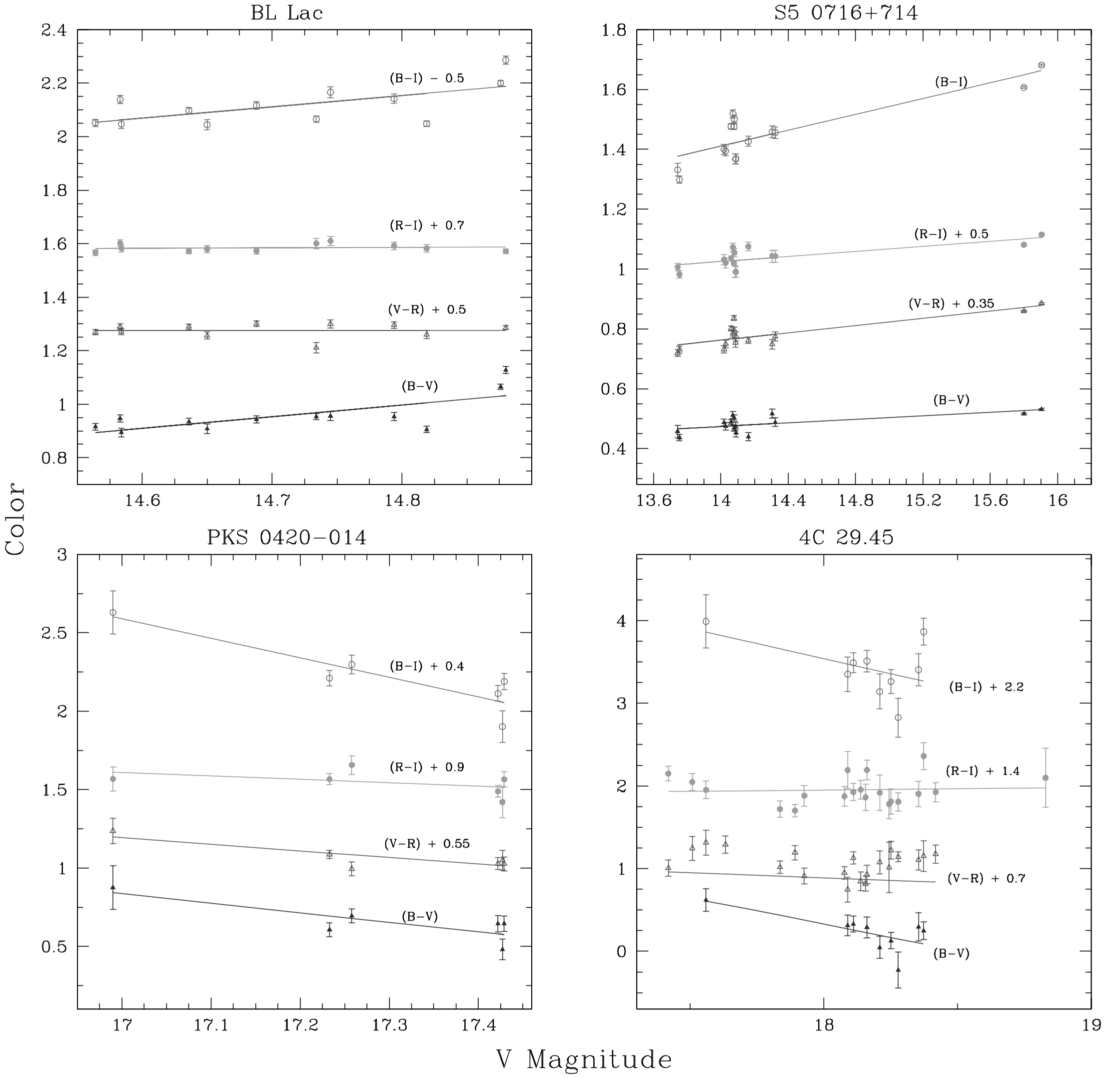

Figure 14. Colour–magnitude plots of the blazars BL Lac, S5 0716+714, PKS 0420-014 and 4C 29.45.

(Nilsson et al. 1996). So, at least some of the strong variations seen in this source could arise from microlensing of different regions within a relativistic jet (e.g. Gopal-Krishna & Subramanian 1991). Since there are no microlenses known to be in front of the FSRQs PKS 0420−014, 4C 29.45 and 3C 454.3, it is possible that the STCV observed in these sources arise from of colour changes in the accretion disc itself.

The usual models for BL Lacs attribute the vast bulk of their emission to Doppler boosted fluxes from the relativistic jet (e.g. Blandford & Königl 1979; Scheuer & Readhead 1979). Under these circumstances, any accretion disc radiation is always likely to be overwhelmed by that from the jet, just as the galaxy's light also only comprises a small fraction of that observed. Therefore, jet models that can produce different fluctuations at different colours are most likely to be able to explain the STV and colour variations we have detected. In the usual boosted synchrotron models involving shocks propagating down the jets (e.g. Marscher & Gear 1985; Marscher et al. 2008), radiation at different frequencies is produced (or at least emerges when the jet becomes optically thin to it) at different distances behind the shocks. Typically, higher frequency photons emerge sooner (e.g. Valtaoja et al. 1992). Therefore, as we see a blazar brighten or fade, we expect to see some differences in the times and rates at which radiation observed at different visible colours rise and fall.

4.3 Relation between colour index and flux variation

Correlated trends in variability between an optical colour index and brightness have been studied by quite a few authors for a number of blazars, although usually just two colours were monitored as opposed to the four we usually could obtain. The historical optical observations seem to show that the correlation between colour index and magnitude for BL Lac objects is such that their spectra become steeper (redder) when their fluxes decrease and flatter (bluer) when they increase. In this context, the blazar BL Lac is one of the most extensively studied objects (Carini et al. 1992; Massaro et al. 1998; Nesci et al. 1998; Webb et al. 1998; Clements & Carini 2001; Villata et al. 2002, 2004; Gu et al. 2006). These extensive data show that this source usually follows a bluer-when-brighter trend, both in flaring and nearly steady states. A similar trend was also observed in S5 0716+714 (Ghisellini et al. 1997; Raiteri et al. 2003; Gu et al. 2006), 3C 66A (Ghosh et al. 2000; Gu et al. 2006) and OJ 287 (Carini et al. 1992; Gu et al. 2006). Apart from the apparently general trend in BL Lac objects, a redder-when-brighter correlation

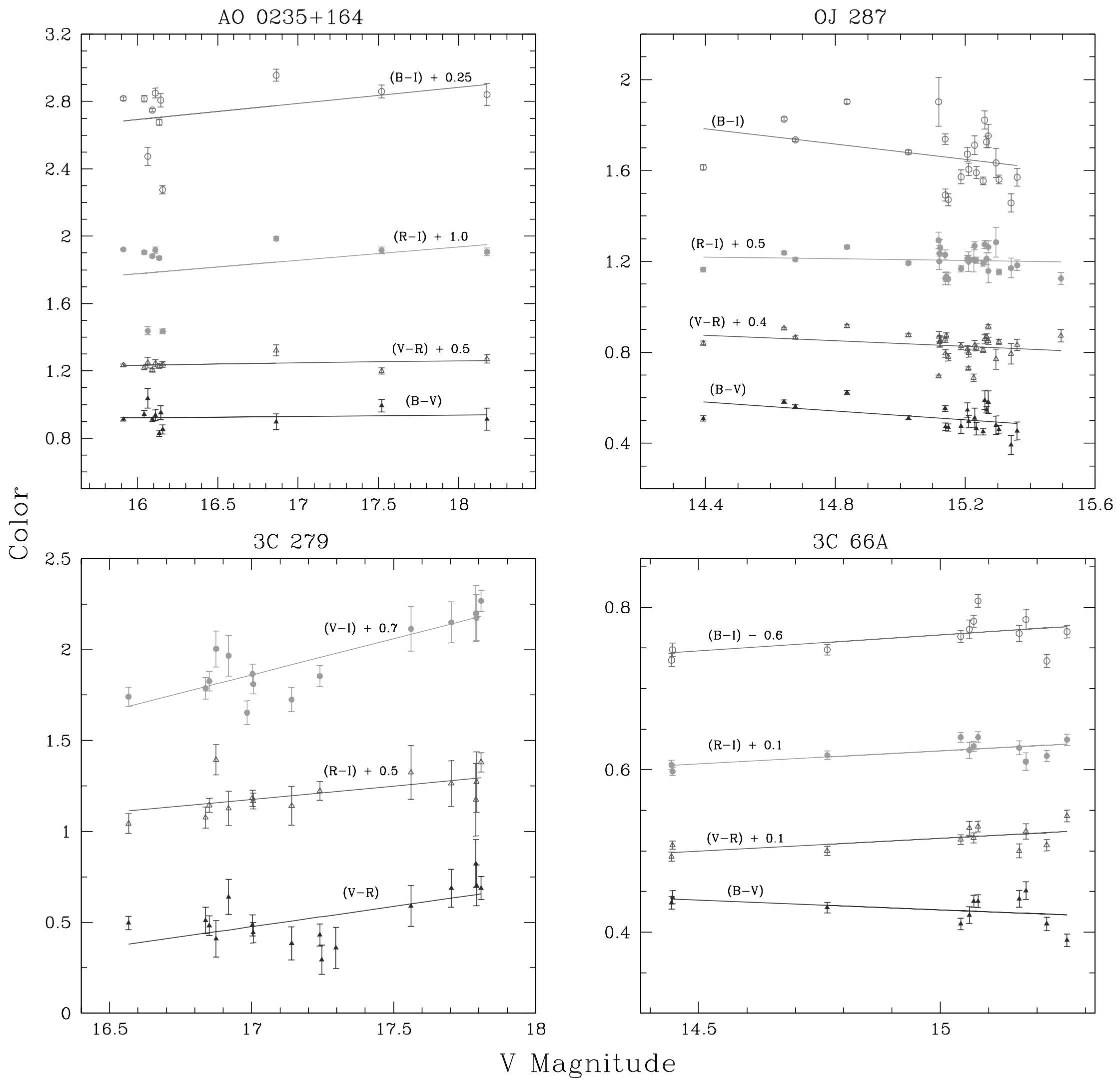

Figure 15. Colour–magnitude plots of the blazars AO 0235+164, OJ 287, 3C 279, & 3C 66A.

has sometimes been observed in the BL Lacs PKS 0735+178, 3C 66A and AO 0235+164 (Ghosh et al. 2000). This overall trend is easily explained if there is a shift to higher peak frequencies during a flare (e.g. Giommi et al. 1999, and references therein), but there is as yet no clear understanding as to why such a shift should occur. The FSRQs have been much less well studied in this regard, but a general redder-when-brighter trend seems to be present in at least two of them, 3C 454.3 and PKS 0420−014 (Gu et al. 2006, and references therein), as well as another, CTA 102 (Osterman Meyer et al. 2009).

Our data do support the general bluer-when-brighter trend for BL Lacs since three of the six BL Lacs we examined showed this trend: 3C 66A, S5 0716+714 and BL Lac itself. In our observations AO 0235+164 and PKS 0735+178 showed no significant trend either way, and only OJ 287 showed a weak redder-when-brighter correlation. More importantly, our results add quite a bit of evidence in favour of the hint of a redder-when-brighter trend for FSRQs (Gu et al. 2006; Osterman Meyer et al. 2009). Four of the six FSRQs in our sample, PKS 0420−014, 4C 29.45, PKS 1510−089 and 3C 454.3, show that trend. The special object 3C 273 had similar negative correlations for two colour indices but a positive one for the other; only 3C 279 among the FSRQs showed a clear bluer-when-brighter trend, and it was one of the two objects for which we lacked *B* band data.

This possibility that the colour index variations with brightness typically follow different trends in FSRQs and BL Lacs is intriguing. If a general result, it would indicate that the physical conditions are different in the two types of blazars in some important way. This perhaps would not be too surprising, in that most BL Lacs are believed to be beamed, but intrinsically weak, FR I radio galaxies (e.g. Padovani & Urry 1992), while the parent population of the FSRQs are the more powerful FR II radio galaxies (e.g. Maraschi & Rovetti 1994). On the other hand, the hypothesis that FR II and FR I radio galaxies have fundamentally similar engines and that the difference between them arises merely from difference in their jet powers and the gases through which they flow on the kpc-scale (e.g. Bicknell 1994; Maraschi & Rovetti 1994) is well supported, particularly by the existence of HYbrid MOrphology Radio Sources (HYMORS), in which one side of the source has an FR I morphology, while the other shows a clear FR II structure (e.g. Gopal-Krishna & Wiita 2000). Still, there do seem to be some differences in the nuclear UV properties of the two classes (e.g. Chiaberge, Capetti & Celotti 2002), so this dichotomy is not completely clear.

Table 5. Fits to colour–magnitude dependences and colour–magnitude correlation coefficients.

Source name	$B-V$ versus V		$V-R$ versus V		$R-I$ versus V		$B-I$ versus V	
	m^a	c^a	m	c	m	c	m	c
	r^a	p^a	r	p	r	p	r	p
3C 66A	−0.02	0.79	0.03	−0.05	0.03	0.04	0.04	0.78
	−0.386	0.2397	0.601	0.050	0.670	0.02385	0.509	0.1098
AO 0235+164	0.007	0.80	0.01	0.53	0.08	−0.50	0.09	0.92
	0.094	0.7814	0.273	0.4438	0.302	0.3955	0.355	0.2836
PKS 0420−014	−0.61	11.19	−0.42	7.77	−0.22	4.46	−1.25	23.43
	−0.818	0.0462	−0.835	0.0383	−0.474	0.3414	−0.901	0.0141
S5 0716+714	0.03	0.06	0.06	−0.44	0.04	−0.07	0.13	−0.44
	0.655	0.0079	0.814	0.0002	0.729	0.0020	0.850	5.9e-05
PKS 0735+178	*	*	0.42	−6.37	0.16	−2.06	*	*
	*	*	0.805	0.0999	0.415	0.5846	*	*
OJ 287	−0.09	4.21	−0.06	1.34	−0.02	0.98	−0.17	4.21
	−0.437	0.0475	−0.249	0.1840	−0.091	0.6309	−0.329	0.1342
4C 29.45	−0.63	11.71	−0.13	2.47	0.03	−0.002	−0.73	14.45
	−0.665	0.050	−0.235	0.3175	0.059	0.803	−0.504	0.1665
3C 273	−0.78	10.16	0.62	−7.76	−0.41	5.68	−5.67	8.08
	−0.258	0.0905	0.650	1.3e-06	−0.413	0.0048	−0.176	0.2523
3C 279	*	*	0.22	−3.32	0.15	−1.82	*	*
	*	*	0.603	0.0134	0.585	0.0277	*	*
PKS 1510−089	−0.14	2.69	−0.08	1.78	0.07	−0.64	−0.08	2.71
	−0.952	0.0009	−0.685	0.0606	0.305	0.4613	−0.264	0.5662
BL Lac	0.44	−5.46	0.003	0.722	0.01	0.66	0.42	−3.58
	0.713	0.0091	0.014	0.9661	0.109	0.7485	0.639	0.0253
3C 454.3	−0.06	1.44	−0.18	3.27	−0.17	3.22	−0.40	7.94
	−0.378	0.2516	−0.869	0.0005	−0.79	0.0033	−0.837	0.0013

[a] m = slope and c = intercept of *CI* against V; r = Pearson coefficient, p = null hypothesis probability.
*Missing entry is due to lack of data.

So it is very important to investigate whether the claim that the BL Lacs and FSRQs follow different trends for colour index against brightness is correct. While the preponderance of data, both in BL Lacs and FSRQs, is with these opposite trends, the numbers are small and exceptions are present in both groups. All the optical observations of the source BL Lac shows that it follows a bluer-when-brighter trend and our observations also revealed the same trend. A similar trend has also been commonly observed in S5 0716+714 and OJ 287. Our literature search shows the general steepening trend with increase in brightness of FSRQs in 3C 454.3 and PKS 0420−014 which we have also found in our analysis results. In PKS 0735+178 and 3C 66A, Ghosh et al. (2000) report the steepening trend with increases in brightness while Gu et al. (2006) report the opposite trend. During our observations, both of them show a bluing trend with increase in flux although the correlation is weak in the case of PKS 0735+178. We stress that the amount of data for FSRQs is quite limited and additional observations could easily erase the nominal trend we find for redder-when-brighter behaviour among them.

We suggest that both of these behaviours can be accommodated within shock-in-jet models. When an outgoing shock strikes a region with larger electron populations, stronger magnetic fields or a turbulent cell within the underlying flow, the emissivity from that region will rise. The radiation emitted at higher frequencies will typically emerge sooner while the maximum flux at somewhat lower frequencies will be seen later (e.g. Valtaoja et al. 2002). Therefore, during the early phase of a rise in flux, one is more likely to see a bluer colour. However, an observation later during the same flare might show a more enhanced redder band as the bluer one might have stopped rising as fast or may even have passed its peak. The former situation should be more likely to be seen than the latter, yielding a predominance of bluer-when-brighter situations, particularly when the jet is completely dominating the flux, as is the case for BL Lacs. Whereas, for FSRQs, there can be a significant disc component to the optical emission and this contribution is stronger towards the UV where the disc temperature peaks. Then, an increase in synchrotron emission from the jet, which usually peaks in the IR for LBLs, would naturally yield a redder-when-brighter trend (e.g. Gu et al. 2006). Our one counterexample among the FSRQs, 3C 279, can sometimes have quite weak lines; since we seem to have observed it in a low state, it may well have been in that circumstance. Then, it could easily have been disc dominated, and thus shown a bluer-when-brighter trend, though it might behave in the opposite manner in a phase when its jet component is stronger (e.g. Pian et al. 1999).

5 CONCLUSIONS

We have carried out multiband optical photometry of a sample of 12 LBLs during 2008 September through 2009 June. The results of our study can be summarized as follows:

(i) All sources except 3C 273 showed strong flux variations on time-scales of months, as expected. The amplitude of variation was ~0.3 mag in PKS 0420−014, BL Lac and PKS 0735+178, while for AO 0235+164 and S5 0716+714, the variability amplitude we saw exceeded 2 mag. For the remaining six blazars, the amplitude of variability exceeded 0.9 mag.

(ii) We found strong STCV in at least one colour index for eight of the 12 sources, with 3C 66A, OJ 287, 3C 273 and BL Lac as the exceptions, but only four showed it in all four bands.

(iii) The DCs for flux and colour variations on STV time-scales in LBLs are ∼92 and ∼33 per cent, respectively.

(iv) Three out of six BL Lacs followed the bluer-when-brighter trend that had been rather well established in earlier studies; AO 0235+164 was achromatic; however, both OJ 287 and PKS 0735+178 were redder-when-brighter.

(v) Four of the six FSRQs showed the opposite, redder-when-brighter, trend, which had been suggested earlier. Two colour indices went in this direction for 3C 273 but one went the other way; the only clear violator of this trend was 3C 279. Our new data substantially increases the evidence in favour of this proposition, but by no means establish it. Substantial additional multicolour observations of this class of blazars would be needed to do so and they are on our agenda.

ACKNOWLEDGMENTS

We thank the anonymous referee for numerous suggestions that led to an improved presentation. BR is thankful to Mr Tarun Chhikara for help while finalizing the text. PJW is grateful for hospitality at ARIES. This research was partially supported by Scientific Research Fund of the Bulgarian Ministry of Education and Sciences (BIn-13/09, DO02-340/08 and DO 02-85) and by Indo–Bulgaria bilateral scientific exchange project INT/Bulgaria/B-5/08 funded by DST, India.

REFERENCES

Abraham Z., 2000, A&A, 355, 915
Aller M. F., Aller H. D., Hughes P. A., 1992, ApJ, 399, 16
Angione R. J., 1971, AJ, 76, 412
Angione R. J., Roosen R. G., Sievers J., Moore E. P., 1981, AJ, 86, 653
Bai J. M., Xie G. Z., Li K. H., Zhang X., Liu W. W., 1998, A&AS, 132, 83
Bai J. M., Xie G. Z., Li K. H., Zhang X., Liu W. W., 1999, A&AS, 136, 455
Bicknell G. V., 1994, ApJ, 422, 542
Blandford R. D., Königl A., 1979, ApJ, 232, 34
Bramel D. A. et al., 2005, ApJ, 629, 108
Branly R., Kilgard R., Sadun A., Shcherbanovsky A., Webb J., 1996, in Miller H. R., Webb J. R., Noble J. C., eds, ASP Conf. Ser. Vol. 110, Blazar Continuum Variability. Astron. Soc. Pac., San Francisco, p. 170
Britzen S., Witzel A., Krichbaum T. P., Campbell R. M., Wagner S. J., Qian S. J., 2000, A&A, 360, 65
Böttcher M., Principe D., 2009, ApJ, 692, 1374
Böttcher M. et al., 2005, ApJ, 631, 169
Böttcher M. et al., 2007, ApJ, 670, 968
Böttcher M. et al., 2009, ApJ, 694, 174
Camenzind M., Krockenberger M., 1992, A&A, 255, 59
Carswell R. F., Strittmatter P. A., Williams R. E., Kinman T. D., Serkowski K., 1974, ApJ, 190, L101
Carini M. T., Miller H. R., 1992, ApJ, 385, 146
Carini M. T., Miller H. R., Noble J. C., Goodrich B. D., 1992, AJ, 104, 15
Chakrabarti S. K., Wiita P. J., 1993, ApJ, 411, 602
Chiaberge M., Capetti A., Celotti A., 2002, A&A, 394, 791
Ciaramella A. et al., 2004, A&A, 419, 485
Ciprini S., Tosti G., Raiteri C. M., Villata M., Ibrahimov M. A., Nucciarelli G., Lanteri L., 2003, A&A, 400, 487
Ciprini S. et al., 2007, A&A, 467, 465
Clements S. D., Carini M. T., 2001, AJ, 121, 90
Clements S. D., Smith A. G., Aller H. D., Aller M. F., 1995, AJ, 110, 529
Corso G. J., Schultz J., Purcell B., Garino G., Dey A., 1985, PASP, 97, 118
Corso G. J., Schultz J., Dey A., 1986, PASP, 98, 1287
Craine E. R., 1977, Handbook of Quasistellar and BL Lacertae Objects. Pachart, Tucson
Craine E. R., Johnson K., Tapia S., 1975, PASP, 87, 123
Courvoisier T. J.-L., 1998, A&AR, 9, 1
Courvoisier T. J.-L. et al., 1995, ApJ, 438, 108
Dai B. Z., Xie G. Z., Li K. H., Zhou S. B., Liu W. W., Jiang Z. J., 2001, AJ, 122, 2901
Dai B. Z. et al., 2009, MNRAS, 392, 1181
D'Ammando F. et al., 2009, A&A, 508, 181
Eachus L. J., Liller W., 1975, ApJ, 200, L61
Efimov Y. S., Shakhovskoy N. M., Takalo L. O., Sillanpää A., 2002, A&A, 381, 408
Elvis M. et al., 1994, ApJS, 95, 1
Falomo R., Ulrich M.-H., 2000, A&A, 357, 91
Fan J. H., Lin R. G., 1999, ApJS, 121, 131
Fan J. H., Lin R. G., 2000, ApJ, 537, 101
Fan J. H., Cheng K. S., Zhang L., Liu C. H., 1997, A&A, 327, 947
Fan J. H., Xie G. Z., Pecontal E., Pecontal A., Copin Y., 1998, ApJ, 507, 173
Fan J. H., Qian B. C., Tao J., 2001, A&A, 369, 758
Fan J.-H. et al., 2006, PASJ, 58, 945
Fan J. H., Zhang Y. W., Qian B. C., Tao J., Liu Y., Hua T. X., 2009, ApJS, 181, 466
Fiorucci M., Tosti G., 1996, A&AS, 116, 403
Fossati G., Maraschi L., Celotti A., Comastri A., Ghisellini G., 1998, MNRAS, 299, 433
Foschini L. et al., 2006, A&A, 455, 871
Ghisellini G. et al., 1997, A&A, 327, 61
Ghisellini G., Foschini L., Tavecchio F., Pian E., 2007, MNRAS, 382, L82
Ghosh K. K., Soundararajaperumal S., 1995, ApJS, 100, 37
Ghosh K. K., Ramsey B. D., Sadun A. C., Soundararajaperumal S., 2000, ApJS, 127, 11
Giommi P., Ansari S. G., Micol A., 1995, A&AS, 109, 267
Giommi P. et al., 1999, A&A, 351, 59
Gopal-Krishna, Subramanian K., 1991, Nat, 349, 766
Gopal-Krishna, Wiita P. J., 1992, A&A, 259, 109
Gopal-Krishna, Wiita P. J., 2000, A&A, 363, 507
Gu M. F., Lee C.-U., Pak S., Yim H. S., Fletcher A. B., 2006, A&A, 450, 39
Gupta A. C., Yuan W., 2009, New Astron., 14, 88
Gupta A. C., Banerjee D. P. K., Ashok N. M., Joshi U. C., 2004, A&A, 422, 505
Gupta A. C. et al., 2008a, AJ, 136, 2359
Gupta A. C., Deng W. G., Joshi U. C., Bai J. M., Lee M. G., 2008b, New Astron., 13, 375
Gupta A. C., Fan J. H., Bai J. M., Wagner S. J., 2008c, AJ, 135, 1384
Gupta A. C. et al., 2008d, AJ, 136, 2359
Gupta A. C., Srivastava A. K., Wiita P. J., 2009, ApJ, 690, 216
Hamuy M., Maza J., 1987, A&AS, 68, 383
Hanski M. T., Takalo L. O., Valtaoja E., 2002, A&A, 394, 17
Hartman R. C. et al., 1996, ApJ, 461, 698
Hawkins M. R. S., 2002, MNRAS, 329, 76
Heidt J., Wagner S. J., 1996, A&A, 305, 42
Holmes P. A., Brand P. W. J. L., Impey C. D., Williams P. M., 1984, MNRAS, 210, 961
Hughes P. A., Aller H. D., Aller M. F., 1991, ApJ, 374, 57
Impey C. D., Brand P. W. J. L., Tapia S., 1982, MNRAS, 198, 1
Krawczynski H., 2004, New Astron. Rev., 48, 367
Lanzetta K. M., Turnshek D. A., Sandoval J., 1993, ApJS, 84, 109
Lichti G. G. et al., 1995, A&A, 298, 711
Liller M. H., Liller W., 1975, ApJ, 199, L133
Lü P. K., 1972, AJ, 77, 829
Malkan M. A., 1983, ApJ, 268, 582
Mangalam A. V., Wiita P. J., 1993, ApJ, 406, 420
Maraschi L., Rovetti F., 1994, ApJ, 436, 79
Marscher A. P., 1996, in Miller H. R., Webb J. R., Noble J. C., eds, ASP Conf. Ser. Vol. 110, Blazar Continuum Variability. Astron. Soc. Pac., San Francisco, p. 248
Marscher A. P., Gear W. K., 1985, ApJ, 298, 114
Marscher A. P., Gear W. K., Travis J. P., 1992, in Valtaoja E., Valtonen M., eds, Variability of Blazars. Cambridge Univ. Press, Cambridge, p. 85
Marscher A. P. et al., 2008, Nat, 452, 966

Massaro E., Nesci R., Perola G. C., Lorenzetti D., Spinoglio L., 1995, A&A, 299, 339
Massaro E., Nesci R., Maesano M., Montagni F., D'Alessio F., 1998, MNRAS, 299, 47
Mead A. R. G., Ballard K. R., Brand P. W. J. L., Hough J. H., Brindle C., Bailey J. A., 1990, A&AS, 83, 183
Miller H. R., Carini M. T., Goodrich B. D., 1989, Nat, 337, 627
Moles M., Garcia-Pelayo J. M., Masegosa J., Garrido R., 1986, AJ, 92, 1030
Montagni F., Maselli A., Massaro E., Nesci R., Sclavi S., Maesano M., 2006, A&A, 451, 435
Nesci R., Maesano M., Massaro E., Montagni F., Tosti G., Fiorucci M., 1998, A&A, 332, L1
Nilsson K., Charles P. A., Pursimo T., Takalo L. O., Sillanpää A., Teerikorpi P., 1996, A&A, 314, 754
Nilsson K., Pursimo T., Sillanpää A., Takalo L. O., Lindfors E., 2008, A&A, 487, L29
Nieppola E., Tornikoski M., Valtaoja E., 2006, A&A, 445, 441
Nieppola E., Hovatta T., Tornikoski M., Valtaoja E., Aller M. F., Aller H. D., 2009, AJ, 137, 5022
Noble J. C., Miller H. R., 1996, in Miller H. R., Webb J. R., Noble J. C., eds, ASP Conf. Ser., Vol. 110, Blazar Continuum Variability. Astron. Soc. Pac., San Francisco, p. 30
Ostorero L. et al., 2006, A&A, 451, 797
Osterman Meyer A., Miller H. R., Marshall K., Ryle W. T., Aller H., Aller M., Balonek T., 2009, AJ, 138, 1902
Padovani P., Urry C. M., 1992, ApJ, 387, 449
Padovani P., Giommi P., 1995, ApJ, 444, 567
Pian E. et al., 1999, ApJ, 521, 112
Qian S. J., Quirrenbach A., Witzel A., Krichbaum T. P., Hummel C. A., Zensus J. A., 1991, A&A, 241, 15
Raiteri C. M., Ghisellini G., Villata M., de Francesco G., Lanteri L., Chiaberge M., Peila A., Antico G., 1998, A&AS, 127, 445
Raiteri C. M. et al., 2001, A&A, 377, 396
Raiteri C. M. et al., 2003, A&A, 402, 151
Raiteri C. M., Villata M., Kadler M., Krichbaum T. P., Böttcher M., Fuhrmann L., Orio M., 2006a, A&A, 452, 845
Raiteri C. M. et al., 2006b, A&A, 459, 731
Raiteri C. M. et al., 2008, A&A, 491, 755
Rani B., Wiita P. J., Gupta A. C., 2009, ApJ, 696, 2170
Rickett B. J., Witzel A., Kraus A., Krichbaum T. P., Qian S. J., 2001, ApJ, 550, L11
Romero G. E., Cellone S. A., Combi J. A., 1999, A&AS, 135, 477
Sagar R., Gopal-Krishna, Mohan V., Pandey A. K., Bhatt B. C., Wagner S. J., 1999, A&AS, 134, 453
Sambruna R. M., Maraschi L., Urry C. M., 1996, ApJ, 463, 444
Sbarufatti B., Treves A., Falomo R., 2005, ApJ, 635, 173
Scheuer P. A. G., Readhead A. C. S., 1979, Nat, 277, 182
Schmidt M., 1963, Nat, 197, 1040
Shakura N. I., Sunyaev R. A., 1973, A&A, 24, 337
Shen B. S. P., 1970, Nat, 228, 1070
Sillanpää A., Haarala S., Valtonen M. J., Sundelius B., Byrd G. G., 1988, ApJ, 325, 628
Sillanpää A., Mikkola S., Valtaoja L., 1991, A&AS, 88, 225
Sillanpää A. et al., 1996a, A&A, 305, L17
Sillanpää A. et al., 1996b, A&A, 315, L13
Sikora M., Madejski G., 2001, AIP Conf., 558, 275
Sitko M. L., Stein W. A., Zhang Y.-X., Wisniewski W. Z., 1982, ApJ, 259, 486
Sitko M. L., Schmidt G. D., Stein W. A., 1985, ApJS, 59, 323
Smith P. S., Balonek T. J., 1998, PASP, 110, 1164
Smith P. S., Balonek T. J., Heckert P. A., Elston R., Schmidt G. D., 1985, AJ, 90, 1184
Spinrad H., Smith H. E., 1975, ApJ, 201, 275
Stalin C. S., Gupta A. C., Gopal-Krishna, Wiita P. J., Sagar R., 2005, MNRAS, 356, 607
Stalin C. S., Gopal-Krishna, Sagar R., Wiita P. J., Mohan V., Pandey A. K., 2006, MNRAS, 366, 1337
Stetson P. B., 1987, PASP, 99, 191
Stetson P. B., 1992, J. R. Astron. Soc. Canada, 86, 71
Takalo L. O., 1991, A&AS, 90, 161
Takalo L. O., Kidger M. R., de Diego J. A., Sillanpää A., 1992a, A&A, 261, 415
Takalo L. O., Sillanpää A., Nilsson K., Kidger M., de Diego J. A., Piirola V., 1992b, A&AS, 94, 37
Takalo L. O., Sillanpää A., Nilsson K., 1994, A&AS, 107, 497
Takalo L. O. et al., 1996, A&AS, 120, 313
Teräsranta H. et al., 1992, A&AS, 94, 121
Teräsranta H. et al., 2004, A&A, 427, 769
Tommasi L. et al., 2001, A&A, 376, 51
Urry C. M., Padovani P., 1995, PASP, 107, 803
Valtaoja L., Sillanpää A., Valtaoja E., Shakhovskoi N. M., Efimov I. S., 1991a, AJ, 101, 78
Valtaoja L. et al., 1991b, AJ, 102, 1946
Valtaoja E., Terasranta H., Urpo S., Nesterov N. S., Lainela M., Valtonen M., 1992, A&A, 254, 80
Valtaoja L., Karttunen H., Efimov Y., Shakhovskoy N. M., 1993, A&A, 278, 371
Valtaoja E., Savolainen T., Wiik K., Lähteenmäki A., 2002, Publ. Astron. Soc. Aust., 19, 117
Valtonen M., Kidger M., Lehto H., Poyner G., 2008, A&A, 477, 407
Villata M. et al., 1997, A&AS, 121, 119
Villata M., Raiteri C. M., Lanteri L., Sobrito G., Cavallone M., 1998, A&AS, 130, 305
Villata M. et al., 2000, A&A, 363, 108
Villata M. et al., 2002, A&A, 390, 407
Villata M. et al., 2004, A&A, 421, 103
Villata M. et al., 2006, A&A, 453, 817
Villata M. et al., 2007, A&A, 464, L5
Wagner S. J., Witzel A., 1995, ARA&A, 33, 163
Wagner S., Sanchez-Pons F., Quirrenbach A., Witzel A., 1990, A&A, 235, L1
Wagner S. J. et al., 1996, AJ, 111, 2187
Webb J. R., Smith A. G., Leacock R. J., Fitzgibbons G. L., Gombola P. P., Shepherd D. W., 1988, AJ, 95, 374
Webb J. R., Carini M. T., Clements S., Fajardo S., Gombola P. P., Leacock R. J., Sadun A. C., Smith A. G., 1990, AJ, 100, 1452
Webb J. R. et al., 1998, AJ, 115, 2244
Wills B. J., Wills D., 1974, ApJ, 190, L97
Wills B. J. et al., 1983, ApJ, 274, 62
Wehrle A. E. et al., 1998, ApJ, 497, 178
Wu J., Zhou X., Peng B., Ma J., Jiang Z., Chen J., 2005, MNRAS, 361, 155
Wu J. et al., 2006, AJ, 132, 1256
Xie G. Z., Li K. H., Liu F. K., Lu R. W., Wu J. X., Fan J. H., Zhu Y. Y., Cheng F. Z., 1992, ApJS, 80, 683
Xie G. Z., Li K. H., Zhang X., Bai J. M., Liu W. W., 1999, ApJ, 522, 846
Xie G. Z., Li K. H., Bai J. M., Dai B. Z., Liu W. W., Zhang X., Xing S. Y., 2001, ApJ, 548, 200
Xie G. Z., Zhou S. B., Dai B. Z., Liang E. W., Li K. H., Bai J. M., Xing S. Y., Liu W. W., 2002a, MNRAS, 329, 689
Xie G. Z., Liang E. W., Zhou S. B., Li K. H., Dai B. Z., Ma L., 2002b, MNRAS, 334, 459
Xie G. Z., Zhou S. B., Li K. H., Dai H., Chen L. E., Ma L., 2004, MNRAS, 348, 831
Yonehara A., Mineshige S., Fukue J., Umemura M., Turner E. L., 1999, A&A, 343, 41
Zhang X., Zhang L., Zhao G., Xie Z.-H., Wu L., Zheng Y.-G., 2004, AJ, 128, 1929

This paper has been typeset from a TEX/LATEX file prepared by the author.