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Multiband optical monitoring of the blazars S5 0716+714 and BL Lacertae

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ABSTRACT

We report the results of multiband optical photometric monitoring of two well-known blazars, S5 0716+714 and BL Lacertae, carried out during 1996 and 2000–01 with an aim to study optical variations on time-scales ranging from minutes to hours and longer. The light curves were derived relative to comparison stars present on the CCD frames. Night-to-night intensity variations of $\geqslant$0.1 mag were observed in S5 0716+714 during a campaign of about 2 weeks in 1996. A good correlation between the light curves in different optical bands was found for both inter-night and intra-night observations. In all, two prominent events of intra-night optical variability were detected in S5 0716+714. Each of these rapidly varying segments of the light curves can be well fitted with an exponential intensity profile whose rate of variation is essentially the same in both the cases. Our long-term monitoring data of S5 0716+714 showed a distinct flare around JD 245 1875, which can be identified in the *BVRI* bands. This flare coincides with the brightest phase recorded during 1994–2001 in the long-term light curves reported by Raiteri et al. No evidence for the object to become bluer when brighter was noted on either inter-night or intra-night time-scales. On the other hand, our essentially simultaneous multiband optical observations of BL Lacertae in 2001 October showed flux variations that were not achromatic. This blazar was definitely found to become bluer when brighter on intra-night time-scales, and there is a less significant trend of the same type on inter-night time-scales. Based on five nights of observations during a week, BL Lacertae showed a peak night-to-night variability of ~0.6 *B* mag. Thus, we found that the present optical observations of the two prominent blazars, made with similarly high sensitivity, reveal a contrasting behaviour in terms of the dependence of spectral hardening with increasing brightness, at least on intra-night, and possibly also on inter-night, time-scales.

Key words: galaxies: active – BL Lacertae objects: individual: S5 0716+714 – galaxies: photometry.

1 INTRODUCTION

Active galactic nuclei (AGNs) are known to be variable on different time-scales across the electromagnetic spectrum. Photometric studies of intensity variations in AGNs provide a uniquely powerful tool for investigating the processes occurring in the vicinity of their central engine. In particular, studies of very rapid intensity variations, or intra-night optical variability (INOV), where the variations have amplitudes of a few hundredths of a magnitude on hour-like or shorter time-scales, enable us to probe their innermost nuclear cores, on the scales of microarcseconds. Blazars define a class of AGNs made up of optically violent variable quasars, high-polarization quasars and BL Lacertae objects. They show high polarization and violent variability at optical wavelengths, and in the radio band, contain compact flat spectrum sources which often exhibit apparent superluminal motion and a high polarization level. These characteristics are generally attributed to synchrotron emission from a relativistic jet with the jet axis oriented at small angles to the observer's line of sight.

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Theoretical explanations for the origin of INOV can be broadly divided into intrinsic and extrinsic categories. One such extrinsic mechanism is refractive interstellar scintillation (e.g. Kedziora-Chudczer et al. 1997), though this is relevant only in the radio band. Another proposed extrinsic mechanism is superluminal microlensing (Gopal-Krishna & Subramanian 1991), which can explain the rapidity of variations, though it is unlikely to apply to a large fraction of blazars. The dominant basic model for intrinsic variability invokes shocks propagating through the jet (e.g. Blandford & Königl 1979; Marscher & Gear 1985). Models designed to explain INOV based on jets involve turbulence behind the jet (Marscher, Gear & Travis 1992), light echo effects (Qian et al. 1991), helical filaments (Rosen 1990) or changing directions of the shocks in the jet (Gopal-Krishna & Wiita 1992; Nesci et al. 2005). The effectiveness of all these models is enhanced by relativistic effects in the jet, especially when the viewing angle is small. Another family of intrinsic explanations invokes numerous flares or hot spots on the surface of (or in the corona above) the accretion disc (e.g. Mangalam & Wiita 1993). Similar models have been proposed to explain the X-ray variations of AGN (e.g. Abramowicz et al. 1992). While such disc perturbations are unlikely to dominate blazar variability, they may propagate into or otherwise affect jet-dominated emission (e.g. Wiita 2005).

1.1 S5 0716 +714

S5 0716+714, classified as a BL Lac object, was discovered in the Bonn-National Radio Astronomy Observatories (NRAO) Radio Survey (Kühr et al. 1981) of flat spectrum radio sources with a 5-GHz flux greater than 1 Jy. It is believed to be at a redshift $z > 0.3$ (Wagner et al. 1996) due to the lack of the detection of its host galaxy; however, a lower value of $z \sim 0.1$ has also been suggested recently (Kadler et al. 2004). This source, an intra-day variable at radio and optical wavelengths as well as a γ-ray emitter (Wagner et al. 1996), is a favourite target for variability studies. In a 4-week long monitoring campaign in 1990 February, this blazar showed an abrupt transition in its variability pattern from a higher flux level with roughly 1-d time-scale during the first week to a lower flux level with approximately 7-d time-scale for the remainder of the campaign, both at optical and at centimetre wavelengths (Quirrenbach et al. 1991). Another interesting result is that the radio spectral index of this blazar was found to correlate with intra-night optical variations such that a flattening of the radio spectrum near the optical maxima was found for several quasi-cycles (Qian et al. 1996; Wagner et al. 1996). The intriguing evidence for correlated variability in the radio and optical ranges (Quirrenbach et al. 1991; Wagner et al. 1996) certainly points to an intrinsic origin of the variations in this blazar. These authors further inferred that the *R*-band light curves evinced a significant signature of flickering on time-scales as short as 15 min, much faster than the apparent quasi-periodic time-scales.

Raiteri et al. (2003) present results on multiband optical observations ranging from 1994 to 2001, and radio observations spanning more than 20 yr. They report that the long-term optical brightness variations of this source appear to have a characteristic time-scale of ~3.3 yr. Ghisellini et al. (1997) and Sagar et al. (1999) too have reported results of monitoring of this blazar in *BVRI* colours during 1994 February to April. Their campaigns recorded a few events of INOV with an amplitude of about 5 per cent within a few hours, superposed on slower variations.

In order to further investigate the INOV behaviour of this blazar, we carried out a 2-week long optical monitoring campaign during 1996 April. These observations covered a total baseline of 16 days and provided a fairly dense temporal coverage on most of the nights. These data, in conjunction with our additional observations during 2000–01, are used here to investigate both short-term and long-term variability of this prominent blazar.

1.2 BL Lac

BL Lac (2200+420), the prototype of this class of AGNs, was identified by Schmitt (1968) with the radio source VRO 42.22.01, and its spectrum was found to be featureless by Viswanathan (1969). However, a broad $H\,\alpha$ line with equivalent width (EW) > 5 Å was later detected by Vermeulen et al. (1995). It is found to be embedded in an elliptical host galaxy (Wurtz, Stocke & Yee 1996) with $z = 0.069$. Though large amplitude variations on time-scales ranging from days to decades (Webb et al. 1988) and rapid variations of 0.1 $\mathrm{mag\,h^{-1}}$ (Racine 1970) were already known, the advent of CCDs used as N-star photometers conclusively demonstrated INOV in BL Lac (Miller, Carini & Goodrich 1989). These authors report rapid changes in the *V*-band flux on time-scales as short as 1.5 h. It brightens almost every year and was reported to be in the active state in 2001 by Mattei et al. (2001). We carried out intra-night *BVR* monitoring of this blazar for five nights in 2001 October.

1.3 Spectral variability in blazars

Although optical variability on hour-like time-scales is now a well-established phenomenon for blazars, its relationship to the long-term variability remains unclear. Possible clues could come from monitoring the optical spectrum for correlations with brightness. S5 0716+714 has been intensively studied for variability across the electromagnetic spectrum on various time-scales (see Nesci et al. 2005; Wu et al. 2005 and references therein). On inter-night time-scales, a bluer when brighter correlation was found when the object was in an active or flaring state, but this trend was absent during its relatively quiescent state (Wu et al. 2005). Also, during one night's monitoring, Wu et al. (2005) noted no spectral hardening with brightness.

During an 11-d long intra-night monitoring campaign of BL Lac during a major outburst in 1997 July, clear evidence for the object to become bluer when brighter was noted by Clements & Carini (2001). However, they interpreted this as an artefact of an increased contribution from the host galaxy when the blazar was fainter. In contrast, based on their *BRI* photometry of BL Lac on five nights during 1999 and 2001, Papadakis et al. (2003) argued that spectral hardening with increasing brightness is evident even after the contribution from the host galaxy is subtracted, hinting that the effect is intrinsic to the blazar. The same significant trend was independently reported by Villata et al. (2004) from the intra-night monitoring of BL Lac in *UBVRI* bands. They also noted that this colour–brightness correlation is much weaker for the long-term brightness variations, which were nearly achromatic on a few day-like time-scale. The results of long-term *BVRI* monitoring between 1995 and 1999 of eight BL Lac objects, including BL Lac and S5 0716+714, by D'Amicis et al. (2002) were further analysed by Vagnetti, Trevese & Nesci (2003) who found a tendency for bluer colour at higher luminosity for all of them; however, for their data set, BL Lac showed a fairly strong correlation while 0716+714 showed a weaker one.

If the trend of spectral hardening with increasing brightness is confirmed to be (nearly) universal, at least for the variations on hour-like time-scales, one interesting explanation posits short-term fluctuations of only the electron injection spectral index (e.g. Mastichiadis

Table 1. Log of intra-night observations.

Date	Object	Duration UT (h)	Filter(s)
1996 Apr. 04	S5 0716+716	15.5–17.1	V
1996 Apr. 05	S5 0716+714	16.1–17.1	*R*
1996 Apr. 07	S5 0716+714	15.0–16.4	*V,R*
1996 Apr. 10	S5 0716+714	15.3–16.5	*V,R*
1996 Apr. 11	S5 0716+714	14.0–16.0	*V,R*
1996 Apr. 12	S5 0716+714	14.9–16.4	*V,R*
1996 Apr. 13	S5 0716+714	14.1–15.9	*V,R*
1996 Apr. 14	S5 0716+714	14.8–16.8	*V,R*
1996 Apr. 18	S5 0716+714	14.7–16.3	*V,R*
1996 Apr. 19	S5 0716+714	15.7–16.7	*V,R*
1996 Apr. 20	S5 0716+714	14.7–15.5	*V,R*
2001 Oct. 19	BL Lacertae	18.4–20.4	*B,V,R*
2001 Oct. 20	BL Lacertae	18.8–20.5	*B,V,R*
2001 Oct. 21	BL Lacertae	18.8–20.7	*B,V,R*
2001 Oct. 22	BL Lacertae	18.4–20.4	*B,V,R*
2001 Oct. 25	BL Lacertae	19.8–21.1	*B,V,R*

& Kirk 2002; Böttcher & Reimer 2004). However, some blazars are found to show anomalous spectral behaviour (see Ramírez et al. 2004 and references therein). For example, PKS 0736+017 showed a tendency for its spectrum to become redder when brighter (Ramírez et al. 2004), both on inter-night and on intra-night time-scales. The multiband optical observations of the prominent blazars S5 0716+714 and BL Lac reported here were carried out to shed more light on the possible dependence of optical spectrum on the brightness state of blazars. In the following section, we describe the observations and data reduction. Section 3 presents the analysis of the light curves, and the results are summarized in Section 4.

2 OBSERVATIONS AND REDUCTIONS

The observations were carried out at the f/13 Cassegrian focus of the 104-cm reflector of the Aryabhatta Research Institute of Observational Sciences (ARIES), Nainital, India. Observations during 1996 were performed using a 1024 × 1024 pixel^2 CCD whereas the 2000–01 observations used a 2048 × 2048 pixel^2 chip. The pixel size of 24 × 24 μm^2 of both the CCD systems corresponds to 0.37 × 0.37 arcsec^2 on the sky. Observations were done in 2 × 2 binned mode to improve signal-to-noise ratio. Exposure times varied between 60 and 600 s, depending on the brightness of the object and sky conditions. Several bias frames were taken intermittently during observations, and twilight sky flats were taken to correct for pixel-to-pixel variations on the chip.

Initial processing of the images, including bias subtraction and flat fielding, was done using IRAF[1] whereas cosmic ray removal was carried out using MIDAS.[2] Photometry of the flat fielded frames was carried out using DAOPHOT (Stetson 1987). Typical seeing during the observations was around 2.0 arcsec. The log of observations for INOV is given in Table 1. In order to detect weak fluctuations, we have performed differential photometry, generally ensuring that the locations of the blazar and the comparison stars on the CCD frame do not change by more than a few pixels from exposure to exposure during a night. In all, S5 0716+714 was monitored on 11 nights between 1996 April 4 to 20, and BL Lac was observed on five nights between 2001 October 19 and 25.

3 LIGHT-CURVE ANALYSIS

The instrumental magnitudes resulting from DAOPHOT were used to construct the differential light curves (DLCs). These represent the instrumental magnitudes of the blazar relative to two comparison stars on the CCD frame. The standard deviation (σ) of the DLC for the comparison stars gives a measurement of the observational errors (e.g. Jang & Miller 1995). The comparison stars used for the differential photometry of S5 0716+714 are the stars 5 and 6 identified by Villata et al. (1998). For BL Lac, stars B and C of Smith et al. (1985) are used for the differential photometry. The comparison stars are chosen so as to minimize differences between their instrumental brightnesses and colours and those of the corresponding blazars.

In claiming that a source is variable, we employed the frequently used criterion adopted by Jang & Miller (1997). The confidence level of variability, when observed, is defined as $C = \sigma_T/\sigma$ where σ_T is the standard deviation of the blazar DLC. The adopted variability criterion requires that $C \geqslant 2.576$ for the object to be classified as variable at 99 per cent confidence level (Jang & Miller 1997; Stalin, Gopal-Krishna & Wiita 2004). On a night when three or more filters are employed, the source is called variable only if $C \geqslant 2.576$ in at least two filters.

3.1 S5 0716 +714

The results of the INOV campaign are given in Table 2 where we list the observing date and the filter(s) used, the number of data points in the DLC, the mean and standard deviation of the blazar DLC, the standard deviation of the comparison stars' DLCs, the variability classification for the blazar and the confidence level of any observed variability. The object shows clear evidence for INOV on two nights, 1996 April 7 and 14. The DLCs are shown in Fig. 1.

For some of the densely monitored blazars, the substantial individual optical flares seen on time-scale of ~1 d are characterized by exponential profiles for rise and decay in flux. Examples include the intra-day variable blazars PKS 2155−304 (Urry et al. 1993) and S5 0954+658 (Wagner et al. 1993). For S5 0716+716, too, the individual flares on day-like time-scales recorded in the 1995–96 optical monitoring are well described by an exponential flux change (Sagar et al. 1999).

During our observations (Table 2), S5 0716+714 showed INOV with rates $\geqslant$0.01 mag h^{-1} on two nights. Since the variability on both nights indicates roughly linear trends on the magnitude scale, we have fitted least-squares regression lines to the variable segment of the DLCs. These best-fitting lines are shown in Fig. 2, and their slopes are given in Table 3 together with the regression coefficients (γ). The rate of brightening on 1996 April 7 was faster than the fading rate on 1996 April 14, but on each night, the slopes were essentially the same in both V and R bands. Thus, at least on the two nights, the prominent events of INOV can be described by linear trends on the magnitude scale, which therefore correspond to exponential flux variations.

3.1.1 *Determination of the time lag*

To check for any time lag between V- and R-band DLCs, we have used both the Interpolated Cross-Correlation Function (ICCF)

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

[2] Munich Image Data Analysis System; trademark of the European Southern Observatory.

Table 2. Results of the intra-night monitoring of S5 0716+714 and BL Lac (see Section 3).

Date	Band	N	Diff. mag BL−S1 mag	σ (DLC) S1−S2 mag	Var?	C
0716+714						
1996 Apr. 04	V	14	0.88 ± 0.01	0.008	NV	
1996 Apr. 05	R	35	0.75 ± 0.02	0.008	NV	
1996 Apr. 07	V	12	0.73 ± 0.02	0.007	V	2.9
	R	12	0.68 ± 0.02	0.007	V	2.9
1996 Apr. 10	V	13	0.82 ± 0.01	0.008	NV	
	R	13	0.82 ± 0.01	0.009	NV	
1996 Apr. 11	V	16	0.91 ± 0.01	0.008	NV	
	R	17	0.90 ± 0.01	0.012	NV	
1996 Apr. 12	V	09	0.75 ± 0.01	0.007	NV	
	R	17	0.73 ± 0.01	0.005	NV	
1996 Apr. 13	V	10	0.62 ± 0.01	0.007	NV	
	R	10	0.60 ± 0.01	0.004	NV	
1996 Apr. 14	V	18	0.52 ± 0.02	0.006	V	3.3
	R	18	0.50 ± 0.03	0.011	V	2.7
1996 Apr. 18	V	16	0.64 ± 0.02	0.012	NV	
	R	15	0.60 ± 0.01	0.009	NV	
1996 Apr. 19	V	12	0.81 ± 0.02	0.009	NV	
	R	12	0.76 ± 0.02	0.008	NV	
1996 Apr. 20	V	10	0.93 ± 0.01	0.006	NV	
	R	09	0.88 ± 0.01	0.006	NV	
BL Lac						
2001 Oct. 19	B	10	0.56 ± 0.04	0.004	V	10.0
	V	10	0.55 ± 0.02	0.009	V	2.2
	R	10	0.37 ± 0.04	0.004	V	10.0
2001 Oct. 20	B	8	0.60 ± 0.04	0.008	V	5.0
	V	8	0.60 ± 0.01	0.001	V	10.0
	R	8	0.42 ± 0.02	0.009	V	2.2
2001 Oct. 21	B	10	0.20 ± 0.01	0.008	NV	
	V	10	0.21 ± 0.01	0.004	NV	
	R	10	0.04 ± 0.01	0.015	NV	
2001 Oct. 22	B	10	0.43 ± 0.04	0.003	V	7.5
	V	10	0.43 ± 0.04	0.002	V	6.7
	R	10	0.24 ± 0.04	0.013	V	6.0
2001 Oct. 25	B	8	0.73 ± 0.005	0.003	NV	2.5
	V	7	0.70 ± 0.002	0.001	NV	2.0
	R	7	0.50 ± 0.004	0.002	NV	5.0

method (Gaskell & Peterson 1987) and the Discrete Correlation function (DCF) method (Edelson & Krolik 1988). In the DCF, we first calculated the set of *unbinned DCFs* defined as

$$\mathrm{UDCF}_{ij} = \frac{(a_i - a)(b_j - b)}{\sigma_a * \sigma_b}, \tag{1}$$

where a_i and b_i are the observed differential magnitudes in V and R bands, and a, b, σ_a and σ_b are, respectively, the means and standard deviations of the DLCs in the V and R bands. Binning the result in τ gives the DCF(τ). Averaging over M pairs for which $\tau - \delta\tau/2 \leqslant \delta t_{ij} < \tau + \delta\tau/2$ gives

$$\mathrm{DCF}(\tau) = \mathrm{UDCF}_{ij}/M. \tag{2}$$

The errors in the DCF are calculated using

$$\sigma_{\mathrm{DCF}}(\tau) = \frac{1}{(M-1)} \Sigma[\mathrm{UDCF}_{ij} - \mathrm{DCF}(\tau)]^{1/2}. \tag{3}$$

The computed DCF and ICCF for the two nights when the object showed INOV are displayed in Fig. 3. On both these nights, there are indications that the correlation functions peak at small time lags (about 6 and 13 min, respectively, for 1996 April 7 and 14) with the variation at V leading that at R on both dates. But since the sampling is relatively sparse, with the measurement intervals close to these putative lags, they might not be significant and hence should be treated with caution. A similar lag of ∼6 min between V and I bands was also reported by Qian, Tao & Fan (2000) from observations on a single night, but their data may be best interpreted as providing an upper limit to the lag of that magnitude. Note that Villata et al. (2000) present a strict upper limit of ∼10 min to a possible delay between B- and I-band variations using high-quality data, densely sampled on a single night.

3.1.2 *Colour variations*

The instrumental magnitudes in V and R are converted to the standard system by carrying out differential photometry using star 5 of Villata et al. (1998). To see if the source exhibited any colour variations on inter-night time-scales, we then computed $V - R$ colours by interpolating the R-band magnitudes to the times of the V exposures and computed mean colour, $\langle V - R\rangle$, and the mean magnitude, $\langle V\rangle$, for each night. The colour–magnitude diagram (CMD) thus obtained is shown in Fig. 4. The solid line in the figure shows the unweighted linear least-squares fit to the data points, which has a slope of 0.01 ± 0.04 and a correlation coefficient of 0.15. Thus, no significant evidence for colour variation with brightness is evident. This is also true for the two nights when INOV was observed. Similar colour analyses on time-scales comparable to those of our observations of the optical light curves from 1994 to 2001 of this source by Raiteri et al. (2003) show at most weak correlations between colour index and source brightness, in the sense that the spectrum sometimes steepens as the brightness decreases.

3.1.3 *Inter-night variability*

When compared with the available long-term light curve (Raiteri et al. 2003; Nesci et al. 2005), the blazar was in relatively quiescent state during our 2 weeks of monitoring. Still, the observed variations are often much larger than the rms scatter of the relative magnitudes of the pair of comparison stars, which is found to be ∼0.008 mag for both passbands. There were two prominent variations (around JD 245 0180 and JD 245 0188 with amplitudes of about 0.2 and 0.4 mag, respectively) recorded during the present observations and shown in Fig. 5, in which we plot two data points per night, one from the start and the other from the end of the observation. By comparing our data (filled circles) with those taken from Raiteri et al. (2003; open circles), it is clear that the two data sets are generally consistent and complementary to each other. The combined data set reveals much finer scale structures in the light curves than is evident from either data set.

3.1.4 *Long-term variability*

We made further observations of this blazar on 17 nights between 2000 November and 2001 March (one frame each in *BVRI* filters on each night) to examine its long-term variability. The long-term light curve is shown in Fig. 6. An important feature in this light curve is a major flare seen around JD 245 1875 in all bands. These variations were achromatic to within the errors as a regression analysis gives a linear correlation coefficient of only 0.35. In Fig. 6, we have also plotted with open circles the measurements reported by Raiteri et al. (2003). The combination of our and their data better defines the

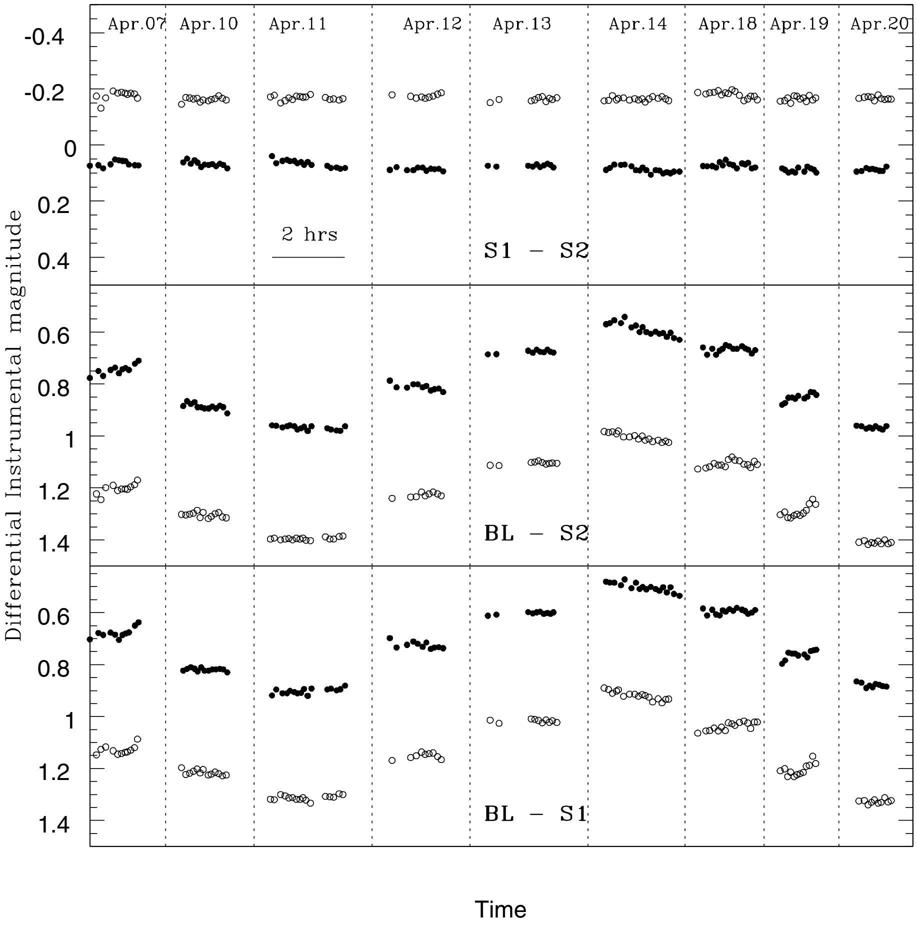

Figure 1. DLCs for S5 0716+714 and the two comparison stars (Section 3). Filled and open circles denote the differential magnitude in *R* and *V* bands, respectively. The *V*-band DLCs have been shifted by +0.4 mag (between blazar and comparison stars) and −0.25 mag (between comparison stars themselves), respectively. The time-scale for all DLCs is indicated by the horizontal bar, with actual times given in Table 1.

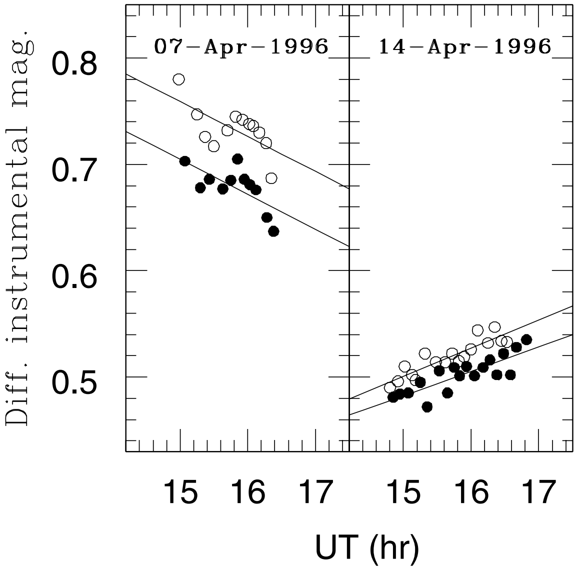

Figure 2. Linear unweighted regression fits to the differential magnitudes of S5 0716+714 for the two nights when the object showed INOV. Filled and open circles denote *R* and *V* bands, respectively.

shape of the flare. Also, it clearly shows a second shallower bump following the flare mentioned above. Note that the variations shown in Fig. 6 coincide with the most active phase seen in the long-term light curve covering the period 1994–2001 (Raiteri et al. 2003). A sample of our observations of S5 0716+714 is shown in Table 4; the complete data are available as an electronic table.

3.2 BL Lac

This blazar showed INOV in at least two bands on three of the five nights it was monitored by us. The summary of the results is given in Table 2, the DLCs are shown in Fig. 7 and the complete data are available electronically (Table 5). Our observations overlap with the long-term photometric measurements reported by Villata et al.

Table 3. Slopes and regression coefficients (γ) of the linear least-squares fit to the intra-night magnitude variations of S5 0716+714.

Date	Band	DLC BL−S1 slope ± σ	γ	DLC BL−S2 slope ± σ	γ
1996 Apr. 07	*V*	-0.033 ± 0.012	0.65	-0.052 ± 0.011	0.84
	R	-0.033 ± 0.012	0.68	-0.039 ± 0.008	0.84
1996 Apr. 14	*V*	0.024 ± 0.003	0.88	0.026 ± 0.003	0.94
	R	0.023 ± 0.004	0.83	0.036 ± 0.004	0.89

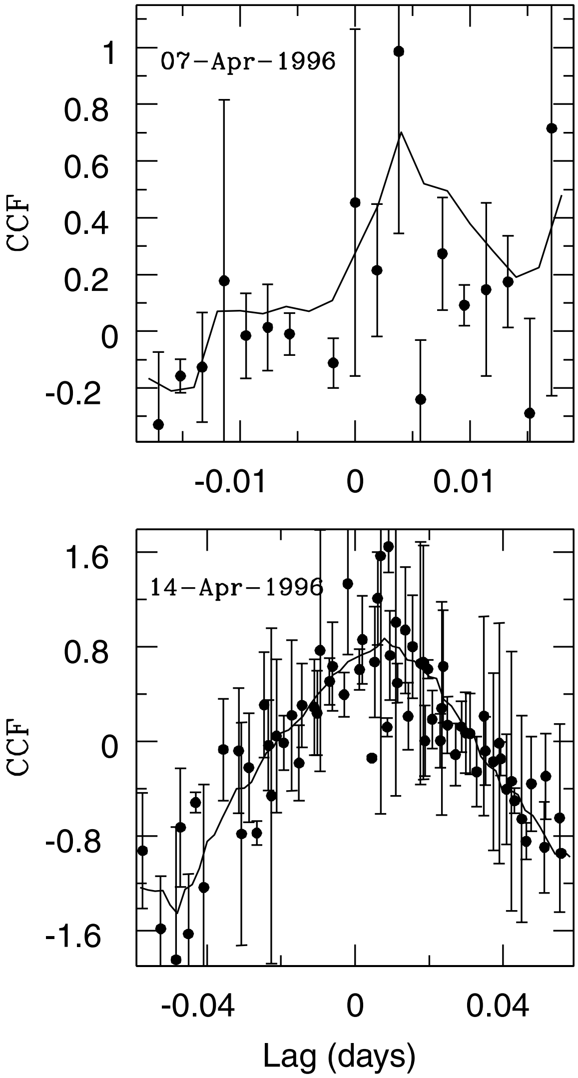

Figure 3. Cross-correlation function for the R- and V-band light curves of S5 0716+714 taken on 1996 April 07 (top panel) and 1996 April 14 (bottom panel). Filled circles with error bars refer to the DCF, whereas the solid line is calculated from the ICCF (see Section 3.1.1).

(2004), and the two data sets are in good agreement. On the first night we observed this source, 2001 October 19, it was found to decline in brightness towards the end of the observations. On the following night, the source increased in brightness by ~0.07 B mag towards the end of the observations. When BL Lac was observed on October 21, it was found to be brighter by ~0.4 B mag than on the previous night. On the following night, the source was found to be about 0.3 mag fainter than at the end of the previous night, but it increased in brightness by ~0.15 B mag within ~1.4 h, with the other bands rising by smaller amounts. On the last night of our observations, October 25, the source had faded by ~0.3 mag compared to its brightness recorded three days earlier.

3.2.1 Colour variations

The object showed hints for colour variations [colours are estimated as described in Section 3.1.2, using stars B and C of Smith et al. (1985)] on inter-night time-scales, as seen from the CMD in Fig. 8.

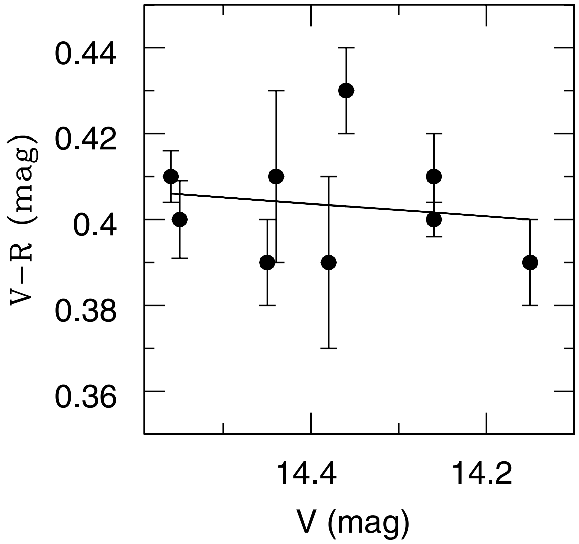

Figure 4. Inter-night CMD for S5 0716+714. The solid line is the linear least-squares fit to the data.

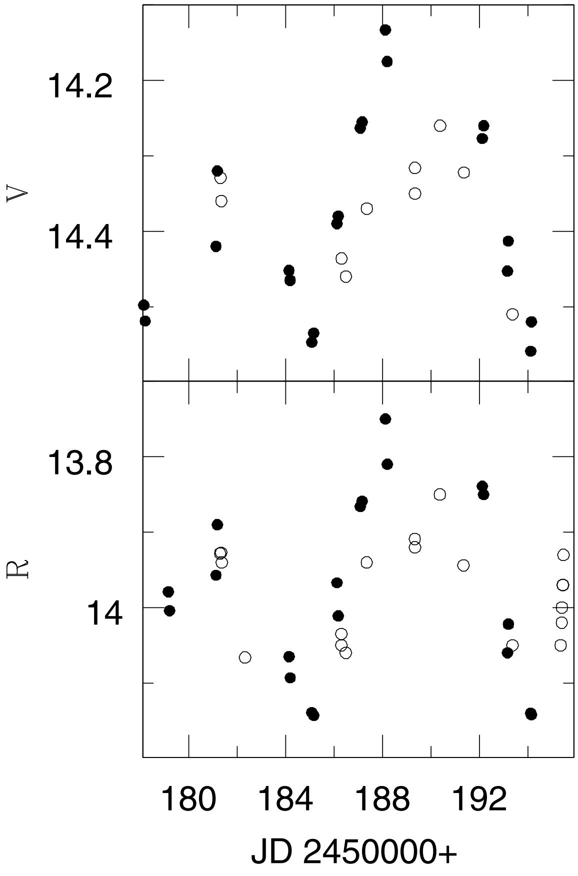

Figure 5. Inter-night variability of S5 0716+714 during our observations (filled circles). For each night, two data points of differential magnitude are plotted (see Section 3.1.3). Note that the first pair of data points in the upper and lower panels refers to two consecutive nights (Table 1) and these are not shown in Fig. 1. The open circles are taken from the long-term monitoring campaign by Raiteri et al. (2003).

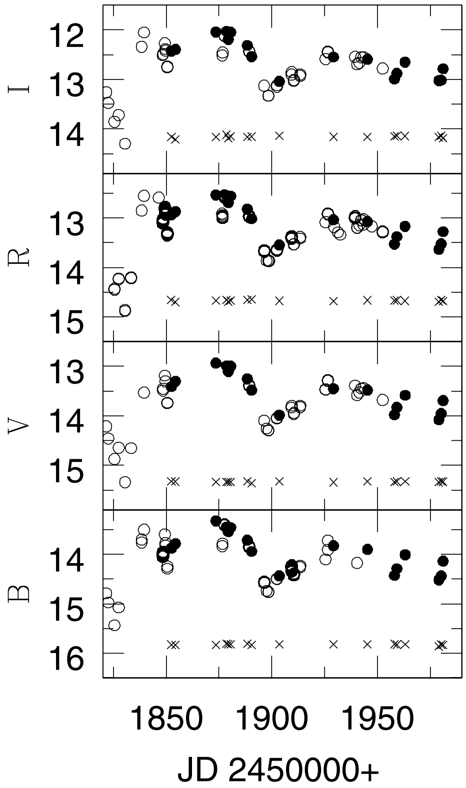

Figure 6. Filled circles show the long-term light curves of S5 0716+714 in the *BVRI* bands from our observations between 2000 November and 2001 March (Section 3.1.4). The crosses refer to our measurements of the standard star 6 defined by Villata et al. (1998) plotted after adding offsets of 1.6, 1.7, 1.4 and 1.2 mag in the *B*, *V*, *R* and *I* filters, respectively. Data taken from the long-term monitoring observations by Raiteri et al. (2003) are shown as open circles.

The solid line is the unweighted linear least-squares fit to the data, giving a slope of 0.05 ± 0.03 and a linear correlation coefficient of 0.67. Thus, our observations on inter-night time-scales suggest a possible bluer when brighter trend for BL Lac. However, removing the first observed point at $V \sim 14.9$ mag, the unweighted linear least-squares fit gives a slope of 0.01 and a linear correlation coefficient of 0.39, which is compatible with a constant $V - R$ colour index with brightness. Fig. 9 shows the CMD on the night of 2001 October 22, when the object showed clear evidence of INOV. Linear least-squares fit to the data gives a slope of 0.26 ± 0.04 with a linear correlation coefficient of 0.91. Thus, on intra-night time-scales, the object showed a clear bluer when brighter correlation. Recently, Villata et al. (2004) have noted that BL Lac shows a stronger CMD on intra-day time-scales, compared to longer (month-like) time-scales.

Table 4. Results of photometric monitoring observations of S5 0716+714. The magnitudes are not corrected for galactic extinction. The table in full is available electronically.

Julian Date	Filter	m (mag)	σ_m (mag)
245 1631.1532	*B*	15.01	0.01
245 1631.1625	*V*	14.51	0.02
245 1631.1667	*R*	14.02	0.01
245 1631.1700	*I*	13.23	0.05
245 1632.1100	*R*	13.92	0.01
245 1632.1166	*B*	14.86	0.01
245 1632.1248	*V*	14.38	0.02
245 1632.1292	*I*	13.35	0.05
245 1633.0966	*R*	13.90	0.01
245 1633.0994	*I*	13.33	0.05

Table 5. Results of photometric monitoring observations of BL Lac. The magnitudes are not corrected for galactic extinction. The table in full is available electronically.

Julian Date	Filter	m (mag)	σ_m (mag)
245 2202.0390	*R*	14.07	0.03
245 2202.0418	*V*	14.76	0.03
245 2202.0449	*B*	15.64	0.03
245 2202.0478	*R*	14.06	0.03
245 2202.0499	*V*	14.74	0.03
245 2202.0529	*B*	15.65	0.03
245 2202.0557	*R*	14.06	0.03
245 2202.0577	*V*	14.74	0.03
245 2202.0611	*B*	15.65	0.03
245 2202.0658	*V*	14.74	0.03

3.2.2 Determination of time lag

A cross-correlation function analysis (see Section 3.1.1) was performed to look for any time lag between the *V*- and *R*-band variations on the one night (22 October 2001) when the object showed INOV in all the three bands. The *V* band was found to lead the *R*-band variations by about 3 min based on both ICCF and DCF analysis. However, given the noise on individual points, this time lag is not significant (Fig. 10).

4 SUMMARY

Based on the published long-term light curves of both these blazars (Raiteri et al. 2003; Villata et al. 2004; Nesci et al. 2005), the present INOV observations are seen to coincide with their relatively faint optical states. None the less, two clear events of INOV, one of brightening and the other of fading, were observed in S5 0716+714. The events are well fitted with an exponential intensity profile with essentially the same rate of variation in the *V* and *R* bands. We note a hint of a possible temporal lag of ~10 min between these two bands with the shorter wavelength leading the longer, as expected in the standard shock-in-jet model; such a lag is not expected in most disc-based variability models (e.g. Wiita 2005). In the present eight nights of our monitoring of S5 0716+714 spanning about a fortnight, two noticeable events of inter-night variability (one around JD 245 0180 and the other around JD 245 0188) of amplitude ⩾0.2 mag were found. Our long-term monitoring of this blazar, on the other hand, coincided with the maximum brightness phase seen in the light curve covering 1994–2001, as reported by Raiteri et al. (2003). By combing their data with the present measurements, a large 1.5-mag flare is detected around JD 245 1875 lasting for about 75 d. This is followed by a weaker variation on a similar time-scale. No clear evidence of colour variation with brightness was found in either our inter-night or our intra-night monitoring of S5 0716+714.

The other blazar, BL Lac, was found to vary strongly in all the three bands (*B*, *V*, *R*) on one of the five nights we monitored it

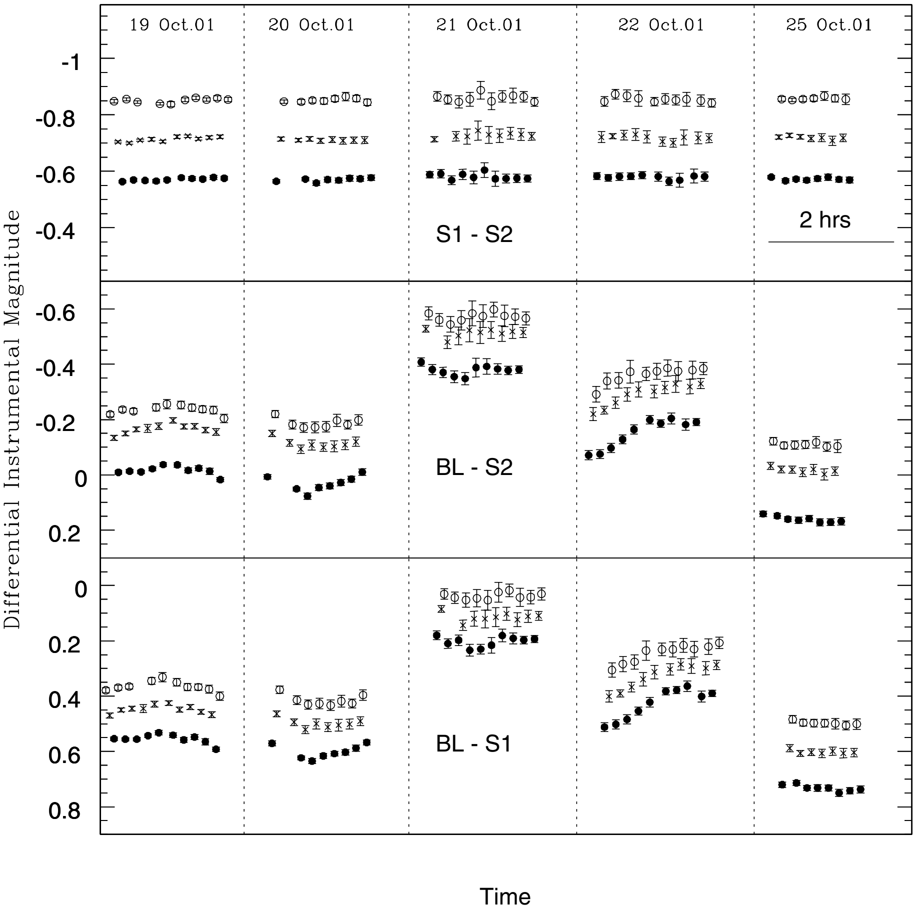

Figure 7. DLCs for BL Lac and comparison stars in the bands *B* (filled circles), *V* (crosses) and *R* (open circles). The *V*- and *R*-band differential magnitudes are shifted by constant amounts for clarity of display. The time-scale of all the DLCs is marked with the horizontal bar of 2-h duration.

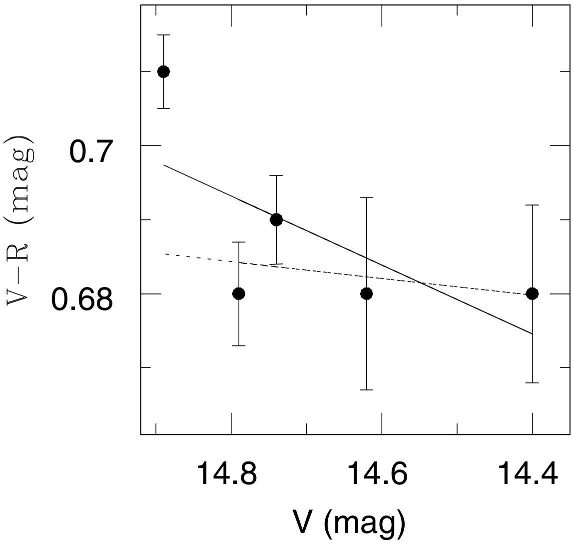

Figure 8. Inter-night CMD for BL Lac based on our observations in 2001. The solid line is the linear least-squares fit to the data points. The dotted line is the linear least-squares fit to the data excluding the first data point at V ∼14.9 mag.

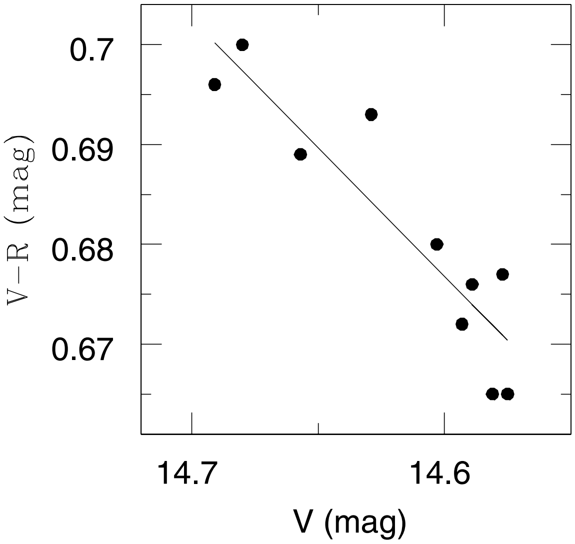

Figure 9. Intra-night CMD for BL Lac on 2001 October 22. The solid line is the linear least-squares fit to the data points.

and in two of the three bands on two other nights. Also, on the night when strong INOV was observed in all the three bands, a temporal lag between the *V*- and *R*-band light curves may be present, with the *V*-band variations apparently leading the *R*-band variations

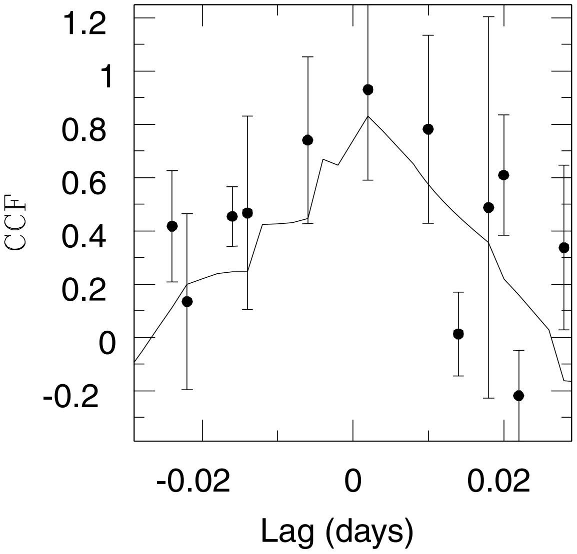

Figure 10. Cross-correlation function for the *V*- and *R*-band light curves of BL Lac on 2001 October 22. Full circles with error bars refer to the DCF, whereas the solid line is calculated from the ICCF (see Section 3.1.1).

by a few minutes. Nesci et al. (1998) also noted that no time lag between different bands could be unambiguously detected during intra-night monitoring observations of BL Lac in 1997. A clear trend was seen in our data for the source to become bluer when brighter on intra-night time-scales. Such a clear trend was not evident on inter-night time-scales, although the data suggest one may be present. The presence (or absence) of this consistency between the colour–magnitude behaviour on intra-night and inter-night time-scales can provide interesting clues about the origin of blazar variability from hour-like to much longer time-sales. In view of this, sustained efforts for multi-colour monitoring of blazars on different time-scales will be fruitful.

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SUPPLEMENTARY MATERIAL

The following supplementary material is available for this article online:

Table 4. Results of photometric monitoring observations of S5 0716+714. The magnitudes are not corrected for galactic extinction.

Table 5. Results of photometric monitoring observations of BL Lacertae. The magnitudes are not corrected for galactic extinction.

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