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Optical observations of BL Lacertae in 2004–2005

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ABSTRACT

We present optical observations of BL Lacertae (BL Lac) in the standard *BVRI* bands with the 80 cm Tsinghua Centre for Astrophysics–National Astronomical Observatories of China telescope. In 2004, BL Lac was monitored for 25 nights, between September and November, to study its long-term optical variability behaviour. The source initially faded by $\Delta R \sim 1$ mag in ∼30 d and then brightened by $\Delta R \sim 0.8$ mag in ∼20 d. It was further monitored for six consecutive nights on 2005 September 3–8, focusing on its intranight variability characteristics. The source continuously brightened by $\Delta R \sim 0.7$ mag during the six nights, with some visible fluctuations superimposed on to the brightness-increasing trend. The amplitudes of intranight variations tend to increase from *I* to *B* wavelengths. BL Lac exhibited strong bluer-when-brighter behaviour for the internight variations, which is less pronounced for some of the intranight variations. The intranight variations between different bands are correlated without measurable time lags in most time, but the flare on 2005 September 6 showed that the *R*-band variations lagged the *B* band ones by 1052^{+859}_{-759} s. Our results indicate that the optical variability properties of BL Lac (the prototype of low-energy-peaked BL Lac objects, LBLs) remarkably resemble the X-ray variability properties of high-energy-peaked BL Lac objects (HBLs). The similarities imply common origin of the variations, plausibly the most energetic tails of the synchrotron emission produced by the relativistic electrons in the jets, for both the optical emission of LBLs and the X-ray emission of HBLs.

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

1 INTRODUCTION

Blazars, an assembly of BL Lacertae (BL Lac) objects and flat spectrum radio quasars (FSRQs), usually exhibit rapid and large-amplitude variations on different time-scales across the whole accessible electromagnetic spectrum (e.g. see Ulrich, Maraschi & Urry 1997 for a review). Such flux variations frequently accompany changes of spectral shapes. The spectral energy distributions (SEDs) of blazars show two remarkably smooth components in the $\nu - \nu F_\nu$ representation. The SED shapes, characterized by the peak energies of the two components, are most likely luminosity related: the higher the luminosity, the lower the peak energy (e.g. Fossati et al. 1998). The low-luminosity BL Lac objects, including the well-studied Mrk 421, Mrk 501 and PKS 2155−304, are referred to as high-energy-peaked BL Lac objects (HBLs) since their low-energy component typically peaks at UV–X-ray bands. However, the low-energy component of the high-luminosity BL Lac objects, e.g. BL Lac and S5 0716+714, usually peaks at optical bands, they are thus referred to as low-energy-peaked BL Lac objects (LBLs). The peak of the low-energy component of FSRQs, such as 3C 279, can be at lower frequency.

The general consensus is that the non-thermal continuum emission from blazars almost certainly comes from relativistic jets roughly aligned along the line of sight (e.g. Urry & Padovani 1995). Synchrotron emission from relativistic electrons gyrating around magnetic field in relativistic jets is thought to be responsible for the low-energy component, and the inverse Compton scattering of soft photons by the same relativistic electrons may account for the high-energy component.

The luminosity-related SEDs indicate that the emission of blazars at the same energy band may be dominated by different radiation components and/or by different energy portions of the same component. The variability characteristics at the same energy band are thus expected to be significantly different among HBLs, LBLs and FSRQs. In the X-ray band, HBLs are highly variable while LBLs and FSRQs do not show rapid and large-amplitude variations (see e.g. Pian 2002 for a review). In optical band, however, LBLs are more variable than HBLs are. These differences are expected because the X-ray emission of HBLs and the optical emission of

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LBLs are both dominated by the highly variable high-energy tail of the low-energy synchrotron component. In particular, the simultaneous optical and X-ray observations showed that BL Lac was more variable in the optical and the soft X-ray bands than in the hard X-ray band (e.g. Ravasio et al. 2002, 2003). Such energy-dependent variability in individual sources can be interpreted by the fact that the hard X-ray emission of BL Lac is controlled by less-variable low-energy part of the high-energy inverse Compton component while the optical to soft X-ray emission is dominated by the strongly variable high-energy tail of the low-energy synchrotron component.

BL Lac, the prototype of a class of extragalactic objects referred to as BL Lac objects, has been observed in the optical band on different time-scales for more than one century (e.g. Fan et al. 1998; Villata et al. 2002 and references therein). Rapid and large-amplitude changes in fluxes over time-scales of less than one day were first detected by Racine (1970). Miller, Carini & Goodrich (1989) found a 0.12 mag variation within 1.5 h. Carini et al. (1992) and Maesano et al. (1997) noted that the optical spectrum of BL Lac became harder with increasing fluxes. In 1997, BL Lac showed a prominent optical outburst, characterized by long duration and large amplitude (e.g. Nesci et al. 1998; Speziali & Natali 1998; Webb et al. 1998; Ghosh et al. 2000; Clements & Carini 2001). During this outburst, the source also showed a number of rapid and large-amplitude variations, e.g. a rapid brightening of ∼0.6 mag within 40 min (Matsumoto et al. 1999). Using intensive multiband optical observations of 5 d in 1999 and 2001 July, Papadakis et al. (2003) studied in detail the optical microvariability of BL Lac; they found that BL Lac was highly variable and the optical spectrum became harder with increasing fluxes. The light curves in different bands were strongly correlated with no measurable time lags except for one case in which *I*-band variations were possibly delayed by an amount of ∼0.2 h in reference to *B*-band variations. Stalin et al. (2006) found that the optical spectra of BL Lac hardened with increasing brightness on intranight time-scales rather than on internight time-scales, and there might exist a delay between the *V*- and *R*-band variations as well. Zhai & Wei (2012) also claimed complicated spectral changes from observations done during 2011 May–August, with no measurable interband lags.

BL Lac is also an interesting target to perform simultaneous multiwavelength observations from radio to γ-ray bands (e.g. Ghosh et al. 2000; Villata et al. 2002, 2004b; Böttcher et al. 2003), in collaboration with the Whole Earth Blazar Telescope (WEBT[1]) (e.g. Villata et al. 2002, 2004a,b; Raiteri et al. 2009, 2010). In particular, the WEBT collaboration provides an opportunity to monitor and study the long-term optical flux and spectral variations of blazars. For example, with the long (1997–2002) and well-sampled *B*- and *R*-band light curves of the WEBT data, Papadakis, Villata & Raiteri (2007) confirmed the ‘bluer-when-brighter’ long-term optical variations of BL Lac, and found that its spectral variations lead the flux ones by about 4 d.

The X-ray variability characteristics of HBLs (mainly the TeV sources) have been intensively studied on short time-scales with various X-ray telescopes (e.g. Tanihata et al. 2001; Zhang et al. 2002, 2006a,b; Brinkmann et al. 2005). The X-ray variability of HBLs is also remarkably complicated (see Pian 2002; Zhang 2003 for reviews). In order to study the optical variability of different subtypes of blazars on intranight time-scale, we started a campaign to intensively monitor a small sample of bright blazars. The main purpose of this project is to study in detail the optical variability of LBLs and FSRQs on intranight time-scale. Very high energy (VHE) gamma-ray emission was detected for LBLs and FSRQs, e.g. BL Lac (Albert et al. 2007) and 3C 279 (Teshima et al. 2008). Possible correlations between their VHE and optical emission strengthened optical observations and studies of LBLs and FSRQs. This is analogous to the simultaneous X-ray and VHE observations that have been frequently carried out for HBLs, e.g. Gliozzi et al. (2006) for Mrk 501 and Aharonian et al. (2005) for PKS 2155−304. Our optical observations will be compared with the short-term X-ray variability of HBLs. We present here the first results from the observations of BL Lac.

The observations and data reduction are described in Section 2. Section 3 presents analysis of the light curves, colour indices and cross correlation. In Section 4, we discuss our results and compare them with the X-ray variability of HBLs. Conclusions are given in Section 5.

2 OBSERVATIONS AND DATA REDUCTION

BL Lac was observed with the 0.8 m, *f*/10, THCA[2]–NAOC[3] telescope (TNT) at Xinglong Station of NAOC. In 2004, the source was monitored in 25 nights from September to November. Further intensive observations were performed in six consecutive nights one year later from 2005 September 3 to 8. The charge coupled device installed on TNT was a 1024 × 1024 chip with a field of view (FOV) of ∼5.7 × 5.7 arcmin^2 in 2004 and was later upgraded to a 1340 × 1300 chip with an FOV of ∼11.2 × 11.2 arcmin^2 in 2005. We used the standard Johnson *B* and *V* and Cousin *R* and *I* filters. The exposure times, ranging from 60 to 360 s, were adjusted for different filters, weather conditions and air masses. In total, we obtained 501, 520, 536 and 528 image frames in the *B*, *V*, *R* and *I* bands, respectively.

The images were reduced using the APPHOT package of Image Reduction and Analysis Facility (IRAF) software. All images were corrected by the biases taken at the beginning or at the end of observation and by the flat-fields obtained at dusk or dawn every night. We performed aperture photometry and obtained the instrumental magnitudes for both BL Lac and the comparison stars for each frame. According to the seeing (∼2.5 arcsec on average) conditions, different aperture radii (5–11 arcsec) were used for the photometry. The four comparison stars B, C, H and K in the BL Lac frame (Fig. 1) are taken from Smith et al. (1985). By averaging the differences between the standard magnitudes and the instrumental magnitudes of the four comparison stars, we converted the instrumental magnitudes of BL Lac to the standard magnitudes. Errors in magnitude determination are typically 0.01–0.02 mag by checking the standard uncertainties of the differences of the instrumental magnitudes between any pair of comparison stars. Table 1 tabulates the apparent magnitudes and the standard uncertainties of BL Lac averaged per night.

In order to calculate fractional variability amplitude (Section 3.3) and cross-correlation function (CCF, Section 3.5), we performed the Galactic extinction corrections for the apparent magnitudes of BL Lac and then converted them into flux densities. We adopt the latest extinction values for BL Lac from NED,[4] i.e. $A_B = 1.193$ mag,

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[1] See http://www.oato.inaf.it/blazars/webt/ for details.

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[4] http://ned.ipac.caltech.edu/

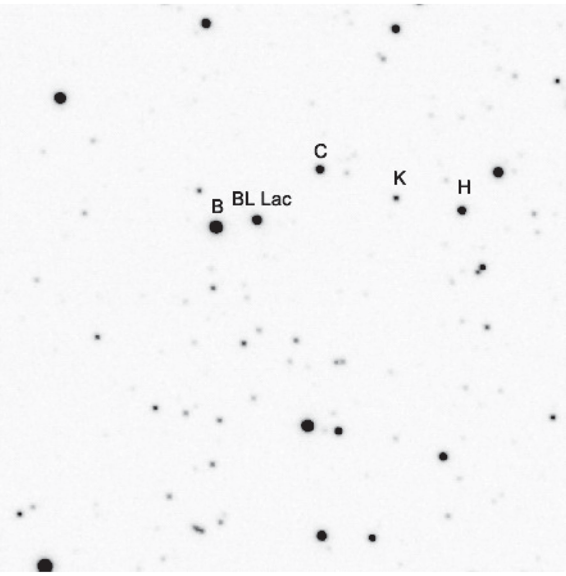

Figure 1. An R-band image of BL Lac field (5.7 arcsec × 5.7 arcsec) obtained with TNT on 2004 September 18. Up is North and left is East. The four comparison stars B, C, H and K are taken from Smith et al. (1985).

$A_V = 0.902$ mag, $A_R = 0.714$ mag and $A_I = 0.495$ mag, which were based on the recent work of Schlafly & Finkbeiner (2011). Corrected magnitudes are then transformed to flux densities by using the absolute irradiance of zero magnitude tabulated in Zombeck (2007).

3 RESULTS

3.1 Long-term variability

Fig. 2 plots the R-band light curve of BL Lac obtained with TNT, showing the long-term optical variations on time-scale of about one year from 2004 September to 2005 September. The source was strongly variable, characterized by changes of more than 1.7 mag in the R band over about one year interval.

During the 2004 observational run, BL Lac decayed about 1 mag in the first ∼30 d, then it brightened ∼0.8 mag in the subsequent ∼20 d. The source was less variable towards the end (∼30 d interval) of the 2004 observations. It is worth referring to the similar variability pattern, with similar variability amplitude and time-scale, already detected in LBL S5 0716+714 (Stalin et al. 2006) and FSRQ 3C 279 (Böttcher 2007).

During the observations of six consecutive nights on 2005 September 3–8, BL Lac continuously brightened ∼0.7 mag. Our observations showed that BL Lac was fainter in 2005 than in 2004

Table 1. The nightly averaged apparent magnitudes of BL Lac observed with TNT[a].

Date (UT)	B (mag)	V (mag)	R (mag)	I (mag)
2004-09-09	14.829 ± 0.039(31)	13.808 ± 0.034(32)	13.176 ± 0.027(29)	12.363 ± 0.025(32)
2004-09-10	14.714 ± 0.038(22)	13.485 ± 0.036(23)	13.016 ± 0.038(23)	12.413 ± 0.036(22)
2004-09-11	14.665 ± 0.009(15)	13.661 ± 0.009(15)	13.030 ± 0.006(15)	12.225 ± 0.013(15)
2004-09-12	14.889 ± 0.043(17)	13.872 ± 0.043(17)	13.230 ± 0.036(17)	12.403 ± 0.035(17)
2004-09-17	15.009 ± 0.024(10)	13.984 ± 0.019(10)	13.339 ± 0.012(10)	12.518 ± 0.017(10)
2004-09-18	14.894 ± 0.010(37)	13.861 ± 0.013(37)	13.208 ± 0.017(37)	12.373 ± 0.009(36)
2004-09-20	14.874 ± 0.011(28)	13.880 ± 0.016(27)	13.227 ± 0.011(28)	12.414 ± 0.013(29)
2004-09-21	14.991 ± 0.011(25)	13.982 ± 0.015(24)	13.331 ± 0.010(25)	12.511 ± 0.012(24)
2004-09-21	–	14.148 ± 0.033(19)	13.514 ± 0.032(20)	12.706 ± 0.042(20)
2004-10-07	15.471 ± 0.017(7)	14.414 ± 0.018(9)	13.755 ± 0.011(9)	12.895 ± 0.017(6)
2004-10-08	15.413 ± 0.091(23)	14.402 ± 0.100(22)	13.746 ± 0.072(25)	12.919 ± 0.070(24)
2004-10-09	15.595 ± 0.023(24)	14.560 ± 0.023(26)	13.901 ± 0.025(27)	13.056 ± 0.029(25)
2004-10-11	15.081 ± 0.073(22)	14.085 ± 0.067(18)	13.457 ± 0.066(19)	12.659 ± 0.061(21)
2004-10-25	–	13.912 ± 0.022(4)	13.249 ± 0.018(4)	12.458 ± 0.018(4)
2004-10-28	14.790 ± 0.036(14)	13.765 ± 0.020(15)	13.120 ± 0.018(18)	12.301 ± 0.014(18)
2004-10-29	14.757 ± 0.030(9)	13.728 ± 0.013(9)	13.088 ± 0.014(9)	12.215 ± 0.012(9)
2004-11-01	14.999 ± 0.010(12)	13.962 ± 0.009(12)	13.314 ± 0.009(11)	12.485 ± 0.007(12)
2004-11-02	14.944 ± 0.028(17)	13.925 ± 0.029(18)	13.275 ± 0.023(19)	12.446 ± 0.021(19)
2004-11-03	14.923 ± 0.020(12)	13.897 ± 0.013(11)	13.251 ± 0.015(10)	12.423 ± 0.013(11)
2004-11-10	14.787(1)	13.735 ± 0.015(3)	13.114 ± 0.018(2)	12.271 ± 0.002(2)
2004-11-11	14.794 ± 0.035(6)	13.755 ± 0.036(9)	13.109 ± 0.044(6)	12.257 ± 0.052(7)
2004-11-14	14.971 ± 0.007(5)	13.947 ± 0.003(5)	13.307 ± 0.005(5)	12.470 ± 0.008(5)
2004-11-15	14.806 ± 0.015(2)	13.791 ± 0.002(2)	13.166 ± 0.009(2)	12.340 ± 0.004(2)
2004-11-26	14.928 ± 0.020(7)	13.898 ± 0.019(15)	13.268 ± 0.018(14)	12.446 ± 0.013(14)
2004-11-28	15.134 ± 0.032(9)	14.104 ± 0.016(10)	13.460 ± 0.010(10)	12.628 ± 0.010(10)
2005-09-03	16.360 ± 0.044(27)	15.278 ± 0.041(29)	14.591 ± 0.038(29)	13.719 ± 0.035(28)
2005-09-04	16.150 ± 0.032(29)	15.110 ± 0.023(29)	14.427 ± 0.023(29)	13.558 ± 0.022(29)
2005-09-05	16.169 ± 0.056(36)	15.097 ± 0.056(35)	14.422 ± 0.058(36)	13.566 ± 0.053(36)
2005-09-06	16.037 ± 0.037(19)	–	14.281 ± 0.031(14)	13.434 ± 0.034(12)
2005-09-07	15.821 ± 0.021(14)	14.756 ± 0.016(14)	14.087 ± 0.012(14)	13.234 ± 0.018(13)
2005-09-08	15.683 ± 0.041(21)	14.645 ± 0.031(21)	13.977 ± 0.025(20)	13.130 ± 0.018(16)

[a] The errors are the standard uncertainties of the apparent magnitudes obtained each night. The numbers in the parentheses are the number of exposures per night. All magnitudes are available upon request.

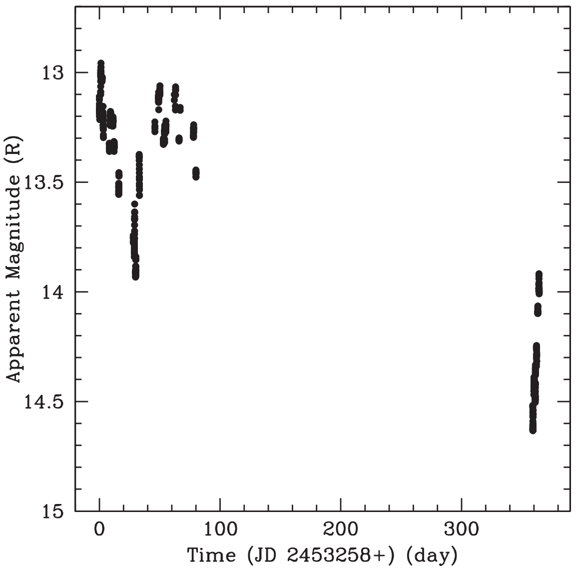

Figure 2. The *R*-band light curve of BL Lac obtained with TNT in 2004 September–November and on 2005 September 3–8. Errors are not shown for clarity.

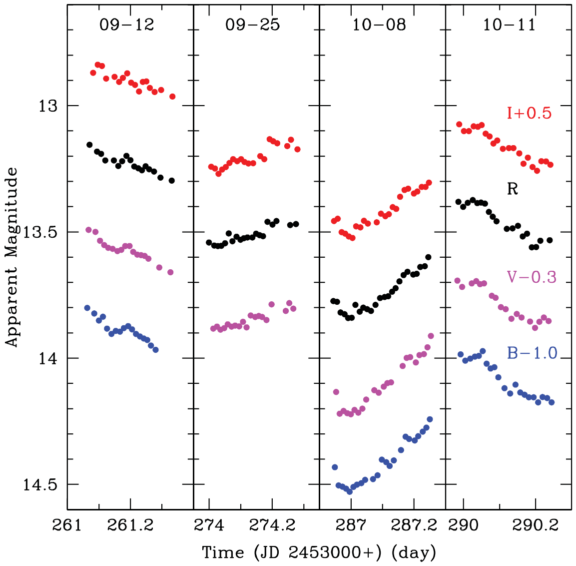

Figure 3. The intranight B, V, R and I light curves of BL Lac are shown for the nights of 2004 September 12 and 25, October 8 and 11. For easy comparison of the variations between different bands, the $B-$, $V-$ and I-band data are shifted with respect to the R-band data, respectively. The errors are not shown for clarity. Note that the time axis is not continuous between nights. The B-band data were not obtained for September 25.

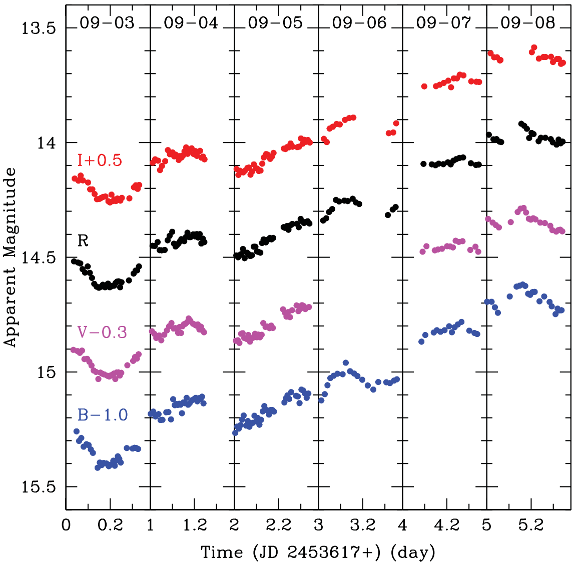

Figure 4. Same as for Fig. 3, but for 2005 September 3–8. The V-band data were not obtained for September 6.

by about 1 mag in the R band, implying that pronounced variations do not depend on the source's brightness levels.

3.2 Intranight variability

Fig. 3 shows the intranight light curves for four nights selected from the observations in 2004. Other intranight light curves are not shown because they are either not variable or have few data points only. BL Lac showed a decaying trend on September 12 and October 11, while it exhibited a brightening trend on September 25 and October 8. Some flickers with smaller variability amplitude are superimposed on to the intranight variability trend. The variations in the different bands appear to track with each other.

Fig. 4 presents the intranight light curves of BL Lac acquired on 2005 September 3–8. On September 3, the source decayed in the first ∼2.5 h and then brightened within the subsequent ∼2.5 h. It exhibited a slower trend of brightening on September 4. It brightened within the ∼8 h observations on September 5 as well. A flare might be completely sampled in the B band on September 6: BL Lac brightened in the first ∼1.5 h and then faded. It is worth noting that the peak of the R-band flare appears to be delayed with respect to that of the B-band flare. On September 7, the source was characterized by a slowly brightening trend, while a decaying trend may describe the variations on September 8. The intranight variations in the different bands appear to follow each other as well.

It is worth noting that the intranight variability of BL Lac, as viewed by our observations, only showed a rising or decaying trend in most of time. This phenomenon might be caused by an insufficient observational length (duration of typical ∼6–8 h or even less) in each night performed with a single telescope. The observed rising or decaying trends should be a portion of 'full flares' on longer time-scales of about 1 d.

3.3 Variability amplitude

We quantified the intranight variability of BL Lac with the fractional variability amplitude ($F_{\rm var}$; e.g. Zhang et al. 2005). Table 2 lists the values of $F_{\rm var}$ for the eight nights from the intranight light curves

Table 2. Intranight fractional variability amplitude ($F_{\rm var}$, per cent).

Date (UT)	B(per cent)	V(per cent)	R(per cent)	I(per cent)
2004-09-12	3.60 ± 0.38	3.25 ± 0.52	2.16 ± 0.77	2.12 ± 0.72
2004-09-25	–	2.53 ± 0.41	2.15 ± 0.52	3.43 ± 0.41
2004-10-08	8.17 ± 0.29	8.91 ± 0.45	6.66 ± 0.27	6.21 ± 0.30
2004-10-11	6.58 ± 0.27	5.76 ± 0.44	5.52 ± 0.50	5.10 ± 0.47
2005-09-03	3.78 ± 0.26	3.55 ± 0.19	3.13 ± 0.23	0.22 ± 0.02
2005-09-05	4.78 ± 0.36	4.94 ± 0.23	5.11 ± 0.26	4.59 ± 0.28
2005-09-06	3.50 ± 0.27	–	2.57 ± 0.27	2.92 ± 0.22
2005-09-08	2.10 ± 1.03	2.38 ± 0.38	1.99 ± 0.27	1.09 ± 0.38

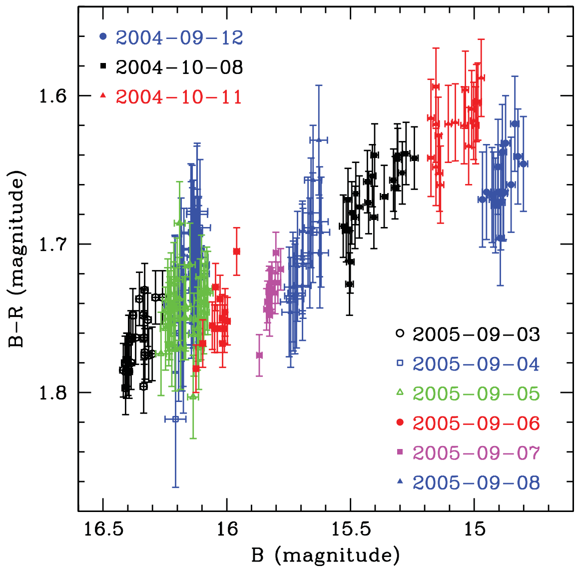

Figure 5. The correlations between the $B - R$ colour indices and B magnitudes. The errors on $B - R$ colour indices are propagated from the errors on both B and R magnitudes. The bluer-when-brighter trends are evident for most of intranight variability and internight variability. However, the correlation is much flatter for the internight variability than for the intranight variability.

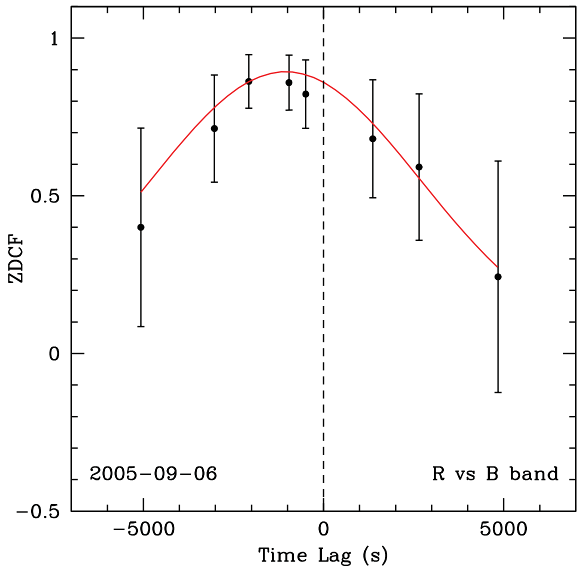

Figure 6. The central part of the ZDCF between the R- and B-band light curves for 2005 September 6. The negative lags indicate that the R-band variations lag the B band ones. The red solid line represents the best fit to the ZDCF with a Gaussian function plus a constant. The peaks of both the ZDCF and the Gaussian function suggest the existence of a soft lag.

shown in Figs 3 and 4, whose values of F_{var} are larger than 2 per cent in most of the observed bands. The intranight variability amplitude tends to increase with decreasing wavelengths for most of the nights.

3.4 Spectral variability

Fig. 5 plots the correlation between the $B - R$ colour indices and B magnitudes for the intranight variations presented in Figs 3 and 4. The $B - R$ colour indices were not available for 2004 September 25 because the B magnitudes were not obtained in that night. We calculated the $B - R$ colour indices by using the adjacent B and R exposures in time order, and the errors on $B - R$ colour indices are propagated from the errors on B and R magnitudes. The bluer-when-brighter trend is evident for most of the intranight variations. This trend is more pronounced if viewing the nine intranight variations together (designated as the internight variations). Fig. 5 shows two more interesting features. One is that the correlation is steeper for several intranight variations than for the internight variations and another is that for the internight variations the $B - R$ colour indices (the spectra) do not decrease (harden) monotonically with the increasing brightness of the source. BL Lac may show similar phenomenon in 2011 May–August as well (Zhai & Wei 2012, see their fig. 14).

3.5 Cross-correlation analysis

We used the z-transformed discrete cross-correlation function (ZDCF) technique (Alexander 1997) to calculate CCF and to search for possible time lags between the intranight R- and B-band variations. We binned the lags by collecting the data pairs with small time differences between the R- and B-band light curves. The ZDCF and its error at each lag were estimated by randomizing the flux densities on the basis of Gaussian distribution for the observational errors. We calculated the ZDCFs for the intranight variations shown in Figs 3 and 4. Except for 2005 September 6, we found that the time lags between the B- and R-band variations are consistent with zero lags for other nights. Fig. 6 plots the ZDCF for 2005 September 6. The negative time lag indicates that the variations in the R band lag those in the B band. The maximum correlation coefficient is ∼0.86, indicating that the two band variations are correlated (this is also true for other nights). The ZDCF peaks at lag of ∼− 2000 or ∼− 1000 s (both ZDCF values are statistically indistinguishable), implying that the R-band variations lag the B band ones (i.e. the so-called soft lag). We fitted the ZDCF with a Gaussian function plus a constant. The time lag to which the peak of Gaussian function corresponds gives a more reliable estimation of lag. The best-fitting Gaussian function is plotted in Fig. 6 to guide the most possible position of the ZDCF peak. The best fit suggests a soft lag of 1052^{+859}_{-759} s. As we mentioned in Section 3.2, this soft lag might be already perceived in the light curves themselves (see Fig. 4).

Our CCF results are similar to those obtained by Papadakis et al. (2003) for BL Lac. Among their five nights of observations, they also detected a significant soft lag of ∼0.2 h in one night, and the lags are also consistent with zero for the other four nights. However, the four intranight variations of BL Lac presented by Zhai & Wei (2012) did not show time lags.

4 DISCUSSION

On intranight time-scales, our results state clearly that the optical variability properties of BL Lac resemble the X-ray variability properties of the well-studied HBLs such as Mrk 421 and PKS 2155−304.

Both Mrk 421 and PKS 2155−304 show 'characteristic' X-ray variability time-scale of about 1 d (e.g. Takahashi et al. 2000; Zhang et al. 2002). The optical variability of BL Lac also exhibits similar time-scale as shown by our observations (see also Papadakis et al. 2003; Zhai & Wei 2012). The X-ray fractional variability amplitude of Mrk 421 and PKS 2155−304 is of the order of a few per cent (e.g. Sembay et al. 2002; Zhang et al. 2005), which is comparable to the optical fractional variability amplitude of BL Lac that we obtained (see also Papadakis et al. 2003). The variability amplitude becomes larger with higher energies for both the X-ray variations of Mrk 421 and PKS 2155−304 and for the optical variations of BL Lac. The optical power spectral density (PSD) of BL Lac (Papadakis et al. 2003) is similar to the X-ray PSDs of Mrk 421 and PKS 2155−304 (Kataoka et al. 2001; Zhang et al. 2002), both are characterized by the red noise shape with a slope of ∼2–3. More interestingly, visual examination of the light curves on 2005 September 3–8 (Fig. 4) suggests that the intranight fluctuations are superimposed on to the brightening trend on longer time-scale. A very similar phenomenon was already detected in the X-ray variability of Mrk 421 (Takahashi et al. 2000).

The X-ray spectra of Mrk 421 and PKS 2155−304 become harder with increasing brightness (e.g. Fossati et al. 2000; Zhang et al. 2002). Papadakis et al. (2003) and our results also show that the optical spectra of BL Lac harden when the source brightens. However, the relationship between spectral indices and fluxes is not trivial. For the well-sampled individual ‘flares’, the relationship for the rising and decaying phases does not follow the same trend, i.e. the spectral variations with respect to the flux variations usually show a clockwise or an anticlockwise ‘loop-like’ pattern. This empirical pattern has been detected in individual X-ray flares of Mrk 421 and PKS 2155−304 (e.g. Fossati et al. 2000; Zhang et al. 2002). Papadakis et al. (2003) also claimed a similar phenomenon for an ‘optical flare’ of BL Lac obtained on 2001 July 6.

The interband X-ray variations are correlated for Mrk 421 and PKS 2155−304 and the interband X-ray time lags change with time (e.g. Brinkmann et al. 2003, 2005; Zhang et al. 2006a). The optical variations of BL Lac are correlated between different energy bands and the interband optical time lags change with time as well (Papadakis et al. 2003; Zhai & Wei 2012; this work). The flare on 2005 September 6 showed a pronounced soft lag of ∼0.3 h in the sense that the *R*-band variations lag the *B* band ones. Papadakis et al. (2003) also claimed that the *R*-band variations lag the *I* band ones by ∼0.2 h. However, the optical variations of BL Lac did not show clear lags in most of time.

We note that the optical variability of other classical LBLs, such as S5 0716+714 (e.g. Wu et al. 2012) and ON 231 (e.g. Cheng, Zhang & Xu 2013), also exhibit similar properties to those of BL Lac.

If the soft lag represents the difference of the energy-dependent synchrotron cooling times of the emitting relativistic electrons in the relevant *R* and *B* bands, i.e. $\tau_{\rm soft} = t_{\rm cool}(R) - t_{\rm cool}(B)$, the physical parameters of the emitting region could be constrained by using the following relation (e.g. Zhang 2002):

$$\mathcal{B}\delta^{1/3} = 209.91 \left(\frac{1+z}{E_R}\right)^{1/3} \left[\frac{1-(E_R/E_B)^{1/2}}{\tau_{\rm soft}}\right]^{2/3} \ {\rm G}, \qquad (1)$$

where $\mathcal{B}$ is the magnetic field strength, δ the Doppler factor of the emitting region, z the source’s redshift, and E_R and E_B are the *R* and *B* band photon energies (in keV), respectively. For the soft lag of ∼1052 s we obtained for the 2005 September 6 flare, we derived $\mathcal{B}\delta^{1/3} \sim 5.3$ G, or $\mathcal{B} \sim 1.7$–2.5 G for $\delta \sim 10$–30 generally adopted for BL Lac objects. Such a magnetic field strength of the optical emitting region in BL Lac is thus about 10 times that in the X-ray emitting region in Mrk 421 and PKS 2155−304, derived with the same method (e.g. Fossati et al. 2000; Zhang et al. 2002).

Similar properties of intraday variations in the X-ray bands of HBLs Mrk 421 and PKS 2155−304 and in the optical bands of LBL BL Lac may hint at similar physical origin for their variability. This inference seems to be supported by the luminosity-related SED sequence of blazars. Simultaneous multiwavelength observations show that both the optical emission of BL Lac and the X-ray emission of Mrk 421 and PKS 2155−304 are most likely the high-energy tail of synchrotron emission, as the synchrotron emission peaks in the optical and X-ray range for LBLs and HBLs, respectively. Rapid variability with similar characteristics is therefore expected in the optical band of LBLs and in the X-ray band of HBLs. Lower synchrotron peak energies of LBLs with respect to those of HBLs may relate to the higher value of magnetic field for LBLs than for HBLs in their emitting region (Ghisellini et al. 1998), which is in agreement with the observational inferences derived from the time lags.

5 CONCLUSIONS

We present multicolour optical observations of BL Lac with TNT in 2004 and 2005. Our main results are summarized as follows.

(i) The observations in 2004 September–November provided long-term optical variability of BL Lac over time-scale of months, which is characterized by a decaying and then a brightening phase, lasting ∼20–30 d, respectively.

(ii) During the consecutive six nights of observations on 2005 September 3–8, BL Lac exhibited intranight variations superimposed on to a brightening trend on longer time-scale.

(iii) The bluer-when-brighter trend of spectral variability is significant for the internight variations, which is less pronounced for some intranight variations.

(iv) The intranight light curves in different bands are correlated. A pronounced soft lag of ∼0.3 h is found for the flare obtained on 2005 September 6, but the time lags are consistent with zero within the uncertainties for other intranight variations.

The optical variability properties of LBL BL Lac are very similar to the X-ray variability properties of HBLs Mrk 421 and PKS 2155−304. The similarities are expected within the current blazar SED sequence scenario: both the optical emission of LBLs and the X-ray emission of HBLs are the high-energy tail of synchrotron emission produced by relativistic electrons in the jets. Therefore, not only the rapid X-ray variations of Mrk 421 and PKS 2155−304 but also the rapid optical variations of BL Lac can provide valuable clues on the acceleration and cooling of relativistic particles. However, due to different peak energies of synchrotron emission, the detailed physical parameters of emitting regions are not expected to be identical for the two classes of objects. With the significant soft lags detected occasionally, we estimated magnetic field strength of the optical emission region in BL Lac as $\mathcal{B} \sim 2$ G, which is about one order of magnitude larger than those of the X-ray emitting region of Mrk 421 and PKS 2155−304.

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