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Search for hard lags with intra-night optical observations of BL Lacertae

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It is generally believed that the high energy end of synchrotron emission, generated by the most energetic tail of relativistic electrons in the jets, account for the X-ray emission of high-energy peaked BL Lac objects (HBLs) and the optical emission of intermediate-energy peaked BL Lac objects (IBLs). It is thus expected that both should show similar variability characteristics. One of the important variability parameters is the inter-band time lag which probes the acceleration and cooling of relativistic particles responsible for the emission. The switches between soft and hard lags have been detected in the intra-day X-ray variability of a few HBLs, which is not the case for the intra-day optical variability of IBLs yet. We present the results of our intra-night optical observations for BL Lacertae, aiming at searching for hard lags of its optical variations, performed with the 80 cm telescope in fourteen nights of 2010 September-November. Intra-night changes of ∼0.2 mag were detected in most of nights. The intra-night variability amplitude tends to become larger from red to blue wavelength, and the optical spectrum hardens with increasing brightness. The intra-night variations correlate between different wavebands, but we did not find significant time lags, either soft or hard. Nevertheless, on November 2, the *B* band variations showed a sign of lagging the *R* band ones by 317±214 s. The claim of this hard lag is strongly limited by the photometric precision and time resolution. Therefore, the switches between soft and hard lags of IBLs in the optical bands needs further demonstration with more higher quality observations.

1 Introduction

BL Lacertae (BL Lac) is the prototype of a class of extragalactic objects referred to as BL Lac objects. It is also the archetype of intermediate-energy peaked BL Lac objects (IBLs, e.g, Nieppola, Tornikoski & Valtaoja 2006), a subclass of BL Lac objects characterized by rapid and large amplitude variability in optical wavelengths (e.g., Wu et al. 2005; Zhai & Wei 2012). BL Lac has been monitored in the optical range on various timescales for more than one century (e.g., Fan et al. 1998; Villata et al. 2002). One of the most prominent outcomes is the dense observations and detailed studies of intra-night (nickname for timescales of hours in case of optical observations) optical variations, such as wavelength-dependent variability amplitude, spectral evolution, and inter-band time lags (e.g., Papadakis et al. 2003; Stalin et al. 2006; Zhang et al. 2013).

The intra-night optical variability characteristics of IBLs is in accord with the fact that the low energy bump (i.e., the synchrotron component) of its spectral energy distributions (SED) peaks in the optical range (e.g., Abdo et al. 2010). Therefore, the optical emission of BL Lac corresponds to the high energy part of their synchrotron radiation component, which is thought to be produced by the most energetic electrons that suffers the fastest cooling and thus gives rise to rapid optical variability (Zhang 2010).

Cheng, Zhang & Xu (2013) and Zhang et al. (2013) have shown that the intra-night optical variations of IBLs are remarkably similar to the X-ray variations of high-energy peaked BL Lac objects (HBLs) on similar timescales (see Pian 2002 and Zhang 2003 for reviews). A rational interpretation of such an analogue is that the X-ray emission of HBLs is the high energy tail of synchrotron radiation component of their SEDs as well, even though the synchrotron emission of IBLs and HBLs peaks at different energy.

On timescale of hours, the inter-band time lag is one of the most important properties for the X-ray variability of HBLs and for the optical variability of IBLs. Both soft and hard lags were detected in the X-ray variations of HBLs (e.g., Brinkmann et al. 2005; Tanihata et al. 2001; Ravasio et al. 2004; Zhang et al. 2002, 2006). For the intra-night optical variations of IBLs, however, hard lags have not been detected yet despite soft lags have been already claimed (e.g., Papadakis et al. 2003; Wu et al. 2012; Zhang et al. 2013).

In order to demonstrate whether the intra-night optical variations of IBLs show sign of hard lag, we continually performed intra-night optical monitoring of a few classical and bright IBLs. Obviously, our effort to find out intra-night optical hard lags for IBLs is worthwhile, because it

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Table 1 Apparent magnitudes of BL Lac monitored with TNT in 2010.

Date (UT)	N^a	Bin Size (s)	$B(\sigma_B)^b$	$V(\sigma_V)^b$	$R(\sigma_R)^b$	$I(\sigma_I)^b$
2010-09-27	10	3020	16.469(0.015)	15.493(0.011)	14.774(0.008)	13.889(0.010)
2010-09-28	11	2610	16.495(0.016)	15.488(0.012)	14.751(0.009)	13.875(0.009)
2010-09-29	10	2970	16.522(0.009)	15.527(0.009)	14.790(0.007)	13.908(0.006)
2010-09-30	7	2440	16.680(0.029)	15.591(0.017)	14.837(0.016)	13.961(0.022)
2010-10-05	9	3060	15.967(0.008)	15.037(0.005)	14.345(0.006)	13.511(0.005)
2010-10-06	11	2680	16.024(0.014)	15.113(0.009)	14.426(0.009)	13.565(0.007)
2010-10-07	9	2860	16.139(0.017)	15.184(0.015)	14.459(0.011)	13.609(0.005)
2010-10-08	7	2680	16.067(0.018)	15.109(0.031)	14.390(0.006)	13.544(0.018)
2010-10-11	8	1290	16.278(0.017)	15.335(0.019)	14.617(0.018)	13.762(0.016)
2010-10-25	7	3060	16.227(0.045)	15.307(0.011)	14.584(0.006)	13.725(0.011)
2010-11-02	49	485	16.391(0.015)	15.411(0.009)	14.694(0.007)	13.852(0.010)
2010-11-03	50	485	16.336(0.017)	15.335(0.010)	14.602(0.009)	13.749(0.009)
2010-11-04	3	4660	16.162(0.012)	15.209(0.016)	14.493(0.006)	13.617(0.005)
2010-11-12	6	1430	16.662(0.060)	15.598(0.016)	14.853(0.011)	13.999(0.009)

[a] The number of exposures per filter per night.
[b] The apparent magnitude averaged over one night. The values in the parentheses indicate the photometric errors each night. All magnitudes are available upon request.

will strength the similarities between the optical variations of IBLs and the X-ray variations of HBLs.

In this paper, we present the results of BL Lac observations in 2010 September–November when it was in a relatively low state of brightness.

2 Observations and data reduction

At the Xinglong Observatory of National Astronomical Observatories of the Chinese Academy of Sciences (NAOC), we monitored BL Lac with the 80 cm Tsinghua-NAOC Telescope (TNT). TNT is an equatorial-mounted f/10 Cassegrain telescope, equipped with a Princeton Instrument thin back-illuminated CCD of 1340×1300 pixels. The size of each pixel is ~20 μm, and the whole CCD covers ~11×11 arcmin^2 field of view of the sky. The CCD has read-out noise and gain of 5 electrons and 2.3 electrons per ADU, respectively.

BL Lac was observed in fourteen nights in 2010 September–November. Standard Johnson-Cousin *BVRI* filters were used in turn. Flat-field and bias image frames were routinely taken during dusk and/or dawn at each night. The CCD was sufficiently cooled by liquid-nitrogen, so we did not take dark frames during our observations. The observational journal of BL Lac is shown in Table 1.

We used the MaxIm DL software to carry out aperture photometry for BL Lac and the comparison stars in its field. Before performing aperture photometry, each CCD image was corrected by the bias frames and by the flat-field frames. We took into account the nine comparison stars in the BL Lac field presented by Pace et al. (2013). For these comparison stars, Pace et al. provided an average values of their magnitudes calibrated by different authors in the literature. The apparent magnitudes of BL Lac were derived by averaging the nine apparent magnitudes obtained with the nine comparison stars through the method of different photometry. The photometric errors were estimated as $\sigma^2 = \frac{1}{N}\sum\sigma_i^2$, where N is the number of pairs of comparison stars ($N = 36$ in case of nine comparison stars), and σ_i refers to the standard deviation of the differences of the instrumental magnitudes of a pair of comparison stars during one night. After trying different sizes of photometric aperture, we selected the aperture size of 8 pixels (~4.″13 in the sky), which gives rise to intra-night light curves with the smallest scatters among the aperture sizes we tested. The averaged apparent magnitudes per night and photometric errors are also tabulated in Table 1.

The apparent magnitudes of BL Lac were corrected for the Galactic extinction. We applied the latest extinction values for BL Lac ($A_B = 1.193$ mag, $A_V = 0.902$ mag, $A_R = 0.714$ mag, and $A_I = 0.495$ mag) from NED[1], which were derived from the work of Schlafly & Finkbeiner (2011). Using the absolute irradiance of zero magnitude tabulated in Zombeck (2007), we transformed the extinction-corrected magnitudes into flux densities which will be used in Sect. 3.3.

3 Results

Figure 1 presents the R and B band light curves of BL Lac which we obtained with TNT in 2010 September–November, providing a case to explore the source's variations in the optical band on timescale of a couple of months. It is clear that BL Lac was variable, with changes of about 0.6 and 1 mag in the R and B band over the 46-d time span, respectively. The variations in the blue band is therefore larger than the ones in the red band.

It appears that BL Lac showed an abrupt increase in brightness from September 30 to October 5. During our ob-

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

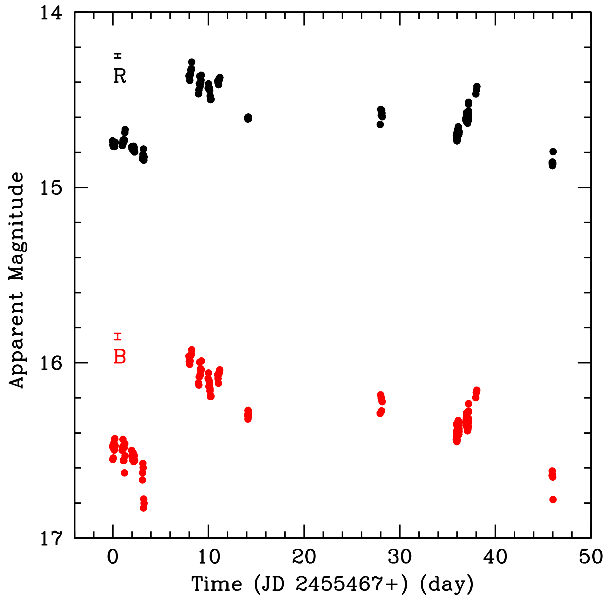

Fig. 1 The *R* and *B* band light curves of BL Lac obtained with TNT in 2010 September–November, showing the optical variability of the source over timescale of about one and half months. Photometric errors are not shown for clarity. The perpendicular lines indicate a typical error bar for each filter.

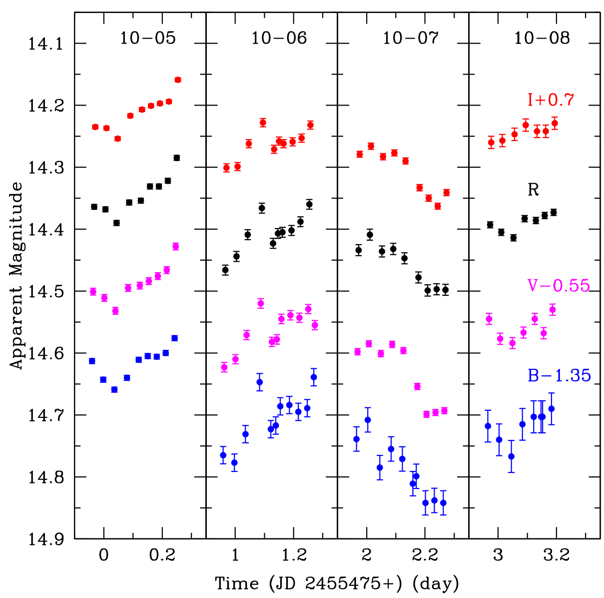

Fig. 2 The intra-night light curves on October 5–8. For easy comparison of the variations between different bands, the *B*, *V*, and *I* band data are shifted with respective to the *R* band data as indicated, respectively. Note that the time axis is not continuous between neighboring nights.

serving period, the source arrived at the minimum and maximum brightness on September 30 and October 5, respectively. However, the variability is more erratic with no clear trend, or at least the sampling is not enough to state this clearly.

3.1 Intra-night variability

Our intra-night observations lasted about 7 hours in most of the nights. Nevertheless, the time resolutions are different between nights mainly due to weather conditions. Here we show in detail the intra-night light curves with relatively high data quality.

Figure 2 plots the four-color light curves obtained in the four successive nights on October 5–8. BL Lac showed intra-night variations of ∼0.1–0.2 mag in the four wavebands. At the same time, one can find that the inter-night variations during the four nights are larger than the individual intra-night variations.

We show in Figs. 3 and 4 the four-color intra-night light curves on November 2 and 3, respectively. On November 2, BL Lac showed a low amplitude flare (changes of ∼0.1 mag) during the central part of the observation. The rising time is significantly longer than the decaying time, implying that the flare slowly brightened and then rapidly darkened. The light curves on November 3 are highlighted by a rapid brightening-trend at the end of the observation, which might be one part of another flare whose feature is unknown due to stop of the observation.

The intra-night light curves show different features from night to night, but they share a common character, that is, the variability amplitudes become stronger from red to blue wavelengths.

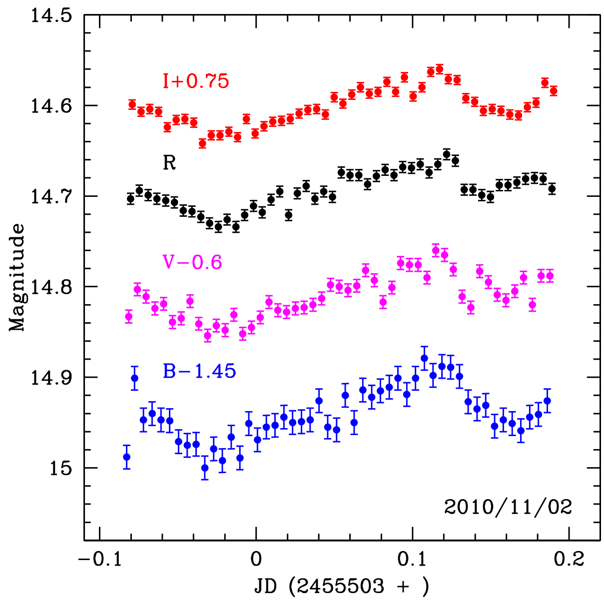

Fig. 3 The intra-night light curves on November 2. For easy comparison of the variations between different bands, the *B*, *V* and *I* band data are shifted with respective to the *R* band data as indicated, respectively.

3.2 Spectral evolution

According to adjacent *B* and *R* exposures in chronological order, we calculated the $B-R$ colour indices. The errors

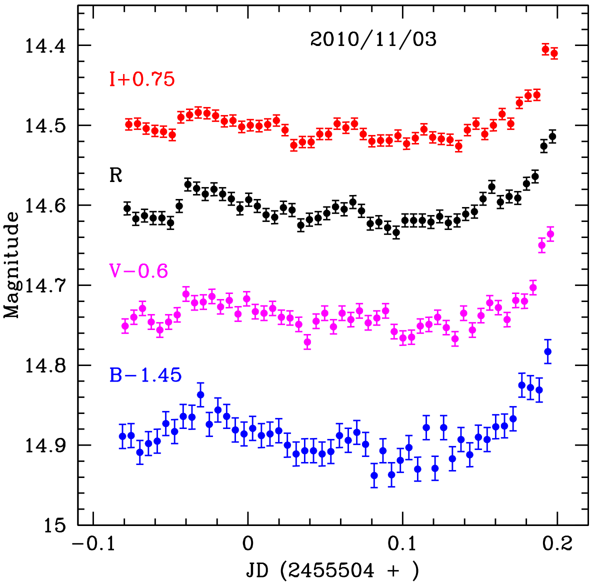

Fig. 4 Same as Fig. 3 but for November 3.

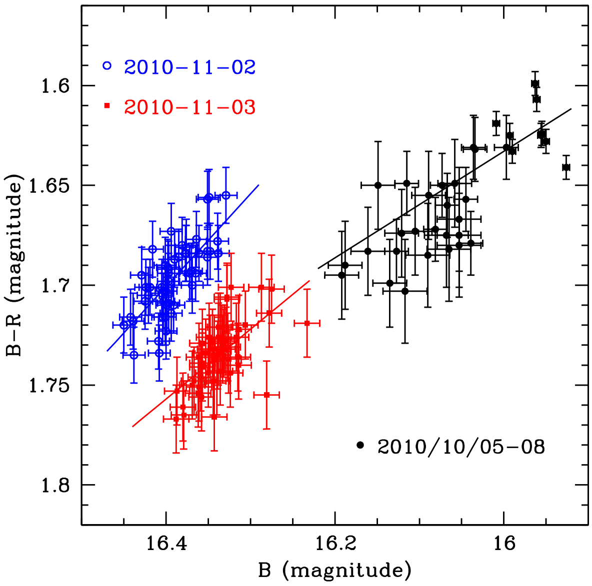

Fig. 5 $B-R$ color indices are plotted against B magnitudes, showing spectral evolution with brightness. The solid line is the best linear fit to the data, done for 2010 October 5–8, November 2 and 3, respectively.

on $B-R$ were propagated from both the errors on B and R magnitudes. Figure 5 plots the correlation between the $B-R$ colour indices and B magnitudes, as a way to reveal spectral variability of BL Lac.

The bluer-when-brighter variability trend is evident for the intra-night variations on November 2 and 3, respectively. The inter-night variations on October 5–8 also show the spectral evolution of bluer-when-brighter pattern. These correlations, however, can not be connected together as a single one. Therefore, our results show that the spectral slopes and the rate of their changes against brightness varied with time.

Table 2 Results of quantitative analysis for the correlation between $B-R$ colour indices and B magnitudes.

Date (UT)	r	p	a	c
2010.10.05–08	0.676	8.46×10^{-6}	0.267±0.051	–2.633±0.810
2010.11.02	0.730	2.67×10^{-9}	0.464±0.063	–5.904±1.038
2010.11.03	0.621	1.51×10^{-6}	0.349±0.064	–3.967±1.039

Notes: r and p is the Pearson correlation coefficient and the null hypothesis probability of the correlation, respectively.
a and c is the slope and intercept of the linear fit to the correlation in the form of $(B-R) = a\cdot B+c$. The error on them is the 1σ level.

We quantified the bluer-when-brighter trends for the data of 2010 October 5–8, November 2 and 3, respectively. In Table 2, we list the Pearson correlation coefficient (r) and the null hypothesis probability (p) of the correlation between $B-R$ colour indices and B magnitudes, indicating that the bluer-when-brighter trends are indeed significant for the three data groups separately. We then fitted the relationship between $B-R$ colour indices and B magnitudes with a linear function of the form $(B-R) = a\cdot B + c$, where a and c is the slope and intercept of the function, respectively. The fits were separately performed on the three data groups as well. The fitting results are also presented in Table 2. The pronounced positive slopes between the colour indices and magnitudes suggest that BL Lac exhibited a bluer-when-brighter trend.

3.3 Time lags

In order to search for inter-band time lags in the intra-night optical variations of BL Lac, we took advantage of the Z-transformed Discrete Cross-Correlation Function (ZDCF) technique (Alexander 1997) to derive cross-correlation functions between the intra-night light curves in different wavelengths. ZDCFs were calculated only for November 2 and 3 observations because the light curves have the highest time resolution. The ZDCF value and its error at each lag were obtained by randomizing the flux densities of light curves on the basis of Gaussian distribution of the photometric errors.

Figures 6 and 7 present the two ZDCFs between the R and B bands for November 2 and 3. A negative time lag indicates that the R band variations lag the B band ones. The maximum correlation coefficient is $\sim$0.74±0.06 and $\sim$0.72±0.07 for November 2 and 3, respectively, indicating that the two band variations are correlated (this is also true for other bands). The ZDCF on November 2 peaks at lag of 224 s, if statistically significant this would imply that the B band variations lag the R band ones (i.e., the so-called hard lag). In contrast, the ZDCF on November 3 may peak at zero lag because the ZDCF values at the two lags closest to zero lag are statistically indistinguishable (The ZDCF value is equal to 0.713 and 0.718 at lag of −261 s and +224 s, respectively), suggesting that there may be no time lag between the two band variations.

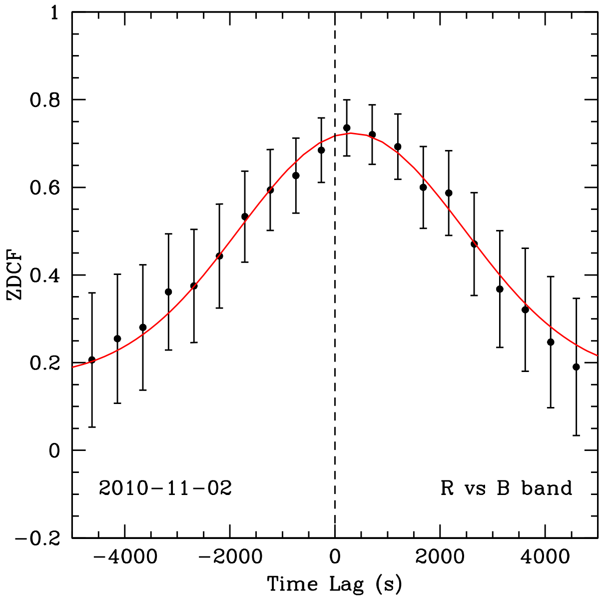

Fig. 6 The central part of the ZDCF between the *R* and *B* band intra-night light curves on November 2. The red solid line is the best fit to the ZDCF with a Gaussian function plus a constant (The negative lags indicate that the *R* band variations lag the *B* band ones).

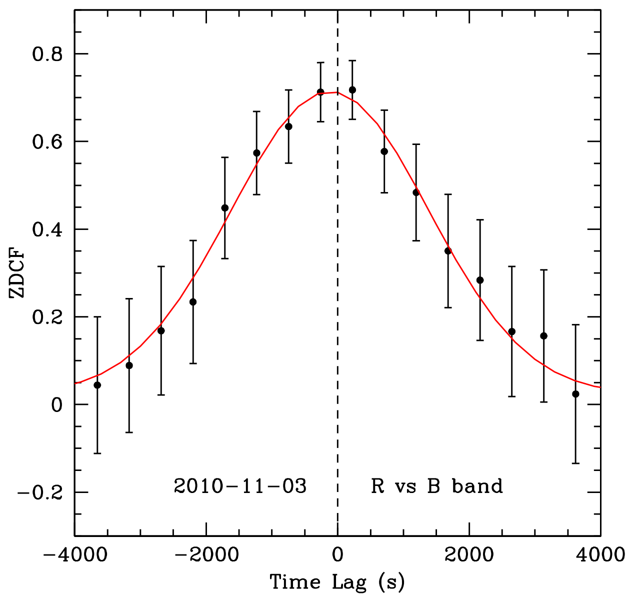

Fig. 7 Same as Fig. 6 but for November 3.

We fitted the ZDCFs 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-fit Gaussian functions are also plotted in Figures 6 and 7 to guide the most possible position of the ZDCF peak on the basis of the global ZDCF shapes. The best fit suggests a hard lag of 317±214 s for November 2. In contrast, the value of lag derived from the best fit is −118±150 s for November 3. The best fits thus suggest that BL Lac showed a hard lag of about 300s on November 2 and zero lag on November 3, respectively. Although the determinations of time lags are constrained by the time resolution of the observations, the ZDCF value may reveal a hard lag for the intra-night variations on November 2.

4 Discussion and conclusions

We observed BL Lac for fourteen nights in 2010 September-November. Compared to its historic optical monitoring data (e.g., the monitoring project led by Tuorla Observatory of Finland[2]), BL Lac was in a relatively low brightness state during our monitoring period. Both Table 1 and Fig. 1 show that the *R* magnitudes range between ∼ 14.9 and ∼ 14.3, in good agreement with those of Tuorla Observatory at the same time interval.

Our new data show that BL Lac exhibited intra-night optical variations of ∼ 0.2 mag in most of nights of our observations. The intra-night variability amplitudes tend to become larger from red to blue optical wavelengths. At the same time, the spectral evolution of intra-night variations shows a bluer-when-brighter trend. Other TNT observations also revealed similar properties for the intra-night optical variations of BL Lac. However, BL Lac was in high states in 2004 September–November (Zhang et al. 2013) and in 2011 May–August (Zhai & Wei 2012), while it was in low states in 2005 September (Zhang et al. 2013) and in 2010 September–November (this work). Therefore, it appears that the intra-night optical variability properties of BL Lac do not obviously depend on its brightness states. Moreover, other IBLs may share common properties of intra-night optical variations (e.g., Cheng et al. 2013 for ON 231; Wu et al. 2012 for S5 0716+714).

Our observations further reveal that the intra-night optical variations of BL Lac between different wavelengths correlate with each other. However, the correlations do not always appear at zero lags. Pronounced inter-band soft lags (i.e., lower energy band variations lag the higher energy band ones) were previously claimed for several intra-night optical variations of BL Lac (e.g., Papadakis et al. 2003; Zhang et al. 2013), although no measurable lags were reported for other more intra-night optical variations of the same source (e.g., Papadakis et al. 2003; Zhai & Wei 2012; Zhang et al. 2013). Our new observations did not reveal significant time lags either. In particular, hard lags have not been significantly detected for BL Lac yet. Obviously, more observations with high time resolution and photometric precision are needed in order to reveal the switches between soft and hard lags for intra-night optical variations of BL Lac.

The optical variability of BL Lac tends to show different characteristics on different timescales, which might be caused by different physical mechanisms. The long-term achromatic (or weak-chromatic) variability may be inter-

[2] http://users.utu.fi/kani/1m/BL_Lac.html

preted by the variations of the Doppler factor of radiation blobs. One way to explain the changes of Doppler factor is the procession of an inhomogeneous helical jet, which results in the viewing angle of emitting blobs with respect to the line of sight to be variable (e.g., Villata et al. 2002). In this paper, we are focusing on the optical flux variability of BL Lac on intra-night timescale. The characteristics of fast variability of BL Lac objects have been interpreted with the shock-in-jet model, where the shock propagates down in a turbulent plasma flow, and causes acceleration of the emitting particles (e.g., Marscher & Gear 1985). The electrons are accelerated at the shock front and then cooled by synchrotron process as they depart from the shock front. Higher frequency radiation is produced in a thinner region behind the shock front as higher energy electrons cool faster. The lower energy electrons cool more slowly, so the lower energy emission produced by them thus is spread out over a larger region behind the shock front. This gives rise to larger amplitude of variability at higher photon frequency, due to smaller emitting volume and faster cooling of higher energy electrons.

As modeled by Kirk & Mastichiadis (1999), the variability pattern of a flare, such as time profile and inter-band time lag, is determined by the interplay between electron acceleration time ($t_{\rm acc}$) and cooling time ($t_{\rm cool}$), and flare duration ($t_{\rm var}$). In case of $t_{\rm cool} \gg t_{\rm acc} \gg t_{\rm var}$, a flare would show a fast rise (because of following $t_{\rm acc}$) and a slow decay (due to following $t_{\rm cool}$), and a soft lag would be observed for the variability since higher energy radiation appear earlier than lower energy one. However, in case of $t_{\rm cool} \sim t_{\rm acc} \sim t_{\rm var}$, which is possible when a source is observed at frequencies close to the maximum frequency of synchrotron radiation, electrons are gathered from lower to higher energy by shock acceleration, in opposite to the above scenario in which lower energy electrons are populated by cooling of higher energy ones progressively. The radiation propagates from lower to higher frequency, resulting in a hard lag variability behavior. Because of longer acceleration time, the flare may slowly brighten and rapidly decline. This case may correspond to the variability pattern of the flare observed on 2010 November 2 by us, which exhibited a slow rise and a fast fall, together with a sign of hard lag. This means that the acceleration process of the energetic electrons may dominate the variability mode of the 2010 November 2 flare of BL Lac.

The variability behavior of a bluer-when-brighter trend is significant for our intra-night optical observations of BL Lac, but the correlation between the $B - R$ color indices and B magnitudes is different from time to time (see Fig. 5 and Table 2). Spectral hardening with increasing intensity is well known for fast optical variability of IBLs and for rapid X-ray variability of HBLs, which can be explained by fresh injection or acceleration of relativistic electrons, followed by subsequent cooling due to synchrotron emission (e.g., Böttcher & Chiang 2002). The different slope and offset of the correlations between color indices and magnitudes at different time hints that the underlying physical conditions of the emitting blobs changed with time when a source flared. A second emission component with different spectral slope at different time, which is stable or variable on a longer timescale, may complicate the observed variability behaviour of flare, including colour indices.

On timescales of hours, as we noted before, the temporal and spectral variations of HBLs in the X-rays are similar to those of IBLs in the optical range (Zhang 2010; Zhang et al. 2013). A number of studies showed that the X-ray variability amplitudes of HBLs increase with increasing photon energies, and that the X-ray spectra harden when sources brighten (e.g., Brinkmann et al. 2005; Zhang et al. 2002, 2005, 2006). More interestingly, the conversions between soft and hard lags were already found in the X-ray variations of HBLs (e.g., Brinkmann et al. 2005; Ravasio et al. 2004; Zhang 2002 for Mrk 421; Zhang et al. 1999, 2002, 2006 for PKS 2155-304; see also Tanihata et al. 2001). In order to strength the similarities between the optical variations of IBLs and the X-ray variations of HBLs, it is necessary to reveal the switching feature between soft and hard lags with more intra-night optical observations of IBLs.

In conclusions, our new optical observations provide more indications in support of our previous claim, i.e., on timescales of a few hours, the optical variability properties of BL Lac (and other IBLs) closely resemble the X-ray variability properties of HBLs in both the temporal and spectral evolution. In particular, future detections of hard lag and of the switches between soft and hard lags for intra-night optical variability of IBLs would provide the most cogent evidence for supporting the similarities, which further pin down a common origin for the radiation and variability of IBLs in the optical wavelengths and HBLs in the X-rays. That is, the similarities can be interpreted by the fact that both the optical emission of IBLs and the X-ray emission of HBLs are the high energy end of the low energy (synchrotron emission) component of their respective SEDs.

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