Multi-color Optical Monitoring of 10 Blazars from 2005 to 2011

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Abstract
We carried out multi-color optical monitoring of a sample of 10 blazars from 2005 to 2011. The sample contains 3 LBLs, 2 IBLs, 4 HBLs, and 1 FSRQ. Our monitoring focused on the long-term variability and the sample included nine BL Lac objects and one flat-spectrum radio quasar (FSRQ). A total of 14,799 data points were collected. This is one of the largest optical databases for a sample of 10 blazars. All objects showed significant variability except for OT 546. Because of the low sampling on each single night, only BL Lacertae were observed to have intraday variability on 2006 November 6. Most BL Lac objects showed a bluer-when-brighter (BWB) chromatism, while the FSRQ, 3C 454.3, displayed a redder-when-brighter trend. The BWB color behaviors of most BL Lacs can be attributed to the trend of increasing variation amplitude with increasing frequency observed in these objects. The average spectral index of LBLs is around 1.5, as expected from the model dominated by synchrotron self-Compton loss. The optical emission of HBL is probably contaminated by the thermal emission from the host galaxies. Correlation analysis did not reveal any time delay between variations at different wavelengths.

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

Supporting material: machine-readable table

1. Introduction
Blazars are the most violently variable class of active galactic nuclei (AGNs), and their relativistic jets are close to our line of sight. They display strong variability of flux and polarization of non-thermal radiation across the electromagnetic spectrum. Blazars can be divided into flat-spectrum radio quasars (FSRQs) and BL Lac objects. The former show broad emission lines (equivalent width, EW > 5 Å) in their spectra, while the latter have weak (EW < 5 Å) or absent emission lines. The broadband spectral energy distribution (SED) of blazars has two characteristic humps. The low-frequency hump extends from radio to UV or X-rays and is dominated by synchrotron radiation. The high-frequency hump is located from X-rays to γ-rays, and is believed to be due to the inverse Compton scattering emission (e.g., Ulrich et al. 1997; Böttcher 2007). The exact frequency ranges of the two humps may vary from object to object. BL Lac objects can be subdivided into high-, intermediate-, and low-frequency-peaked objects (HBLs, IBLs, and LBLs, respectively), depending on the positions of the peak frequencies of their synchrotron emission (e.g., Padovani & Giommi 1995; Fossati et al. 1998).

The variability of a blazar does not exhibit periodic behavior over a large range of timescales from years down to minutes (e.g., Wagner & Witzel 1995; Dominici et al. 2004; Impey et al. 2011; Dai et al. 2013, 2015; Sorcia et al. 2013; Zeng et al. 2018). Optical variability properties have served as a tool to investigate the emission processes. The variability timescale is important to constrain the size and location of the emitting region. Previous observations at multiple wavelengths revealed complex color behaviors for blazars. Some authors found a bluer-when-brighter (BWB) chromatism (e.g., Vagnetti et al. 2003; Wu et al. 2012), while some others claimed the opposite, the redder-when-brighter (RWB) trend (e.g., Bonning et al. 2012), or no clear tendency (e.g., Böttcher et al. 2009). It appears that BL Lac objects are BWB and FSRQs are RWB (e.g., Gu et al. 2006; Wu et al. 2011; Gaur et al. 2012a; Isler et al. 2017).

2. Observations and Photometry
Our monitoring program was performed with a 60/90 cm Schmidt telescope located at the Xinglong Station of the National Astronomical Observatories, Chinese Academy of Sciences (NAOC). Before 2006, the telescope was equipped with a Ford Aerospace 2048 x 2048 CCD camera. The CCD had a pixel size of 15 μm and a field of view (FOV) of 58’ × 58’, resulting in a spatial resolution of 1"7 pixel⁻¹. After 2006, a new 4096 x 4096 E2V CCD replaced the old one. It has a FOV of 96’ × 96’ and a spatial resolution of 1/3 pixel⁻¹. This telescope is equipped with 15 intermediate-band filters, covering the wavelengths from 300 to 1000 nm (Fan et al. 1996; Yan et al. 2000; Zhou et al. 2003). This photometric system can sample a 15-color SED for the targets. Of the 15 filters, 5, c, e, i, m, and o were adopted for our multi-color quasi-simultaneous observation. Their central wavelengths and bandwidths are listed in Table 1. The central wavelength of the i band is similar to that of the R band. The magnitudes in these two bands can be transformed with a formula of $R = 0.897 \times i + 1.127$ for AGNs (Dai et al. 2013).

In our program, 10 blazars were monitored from 2005 January 29 to 2011 June 13. In order to reduce the readout time and to increase the sampling rate, only the central 512 × 512 pixels are read out as a frame. Each frame has a FOV of about 14.5’ × 14.5’ and 11’ × 11’ for the old and new CCDs, respectively. The observations were mostly made in the c, i, and o bands. Some objects were monitored in the e, i, and m bands at the beginning.
The observation details of our targets are listed in Table 2. The exposure time was determined by the brightness of the source, the moon phase, and weather conditions.

The data reduction procedures include positional calibration, bias subtraction, flat-fielding, extraction of instrumental aperture magnitude, and flux calibration. The comparison and check stars are selected in the finding charts on the website of Landessternwarte Königstuhl.\textsuperscript{3,4} Their $c$, $e$, $i$, $m$, and $o$ magnitudes were obtained by observing them and the standard star HD 19945 on photometric nights. The $c$, $e$, $i$, $m$, and $o$ magnitudes of each blazar were calibrated relative to those magnitudes of comparison stars. Example results are given in Table 3. The full results for all 34 observations of the blazars are available in electronic form online. The columns are the observation date and time in universal date and time, Julian date, exposure time in seconds, magnitude and error, and differential magnitude (its nightly average values were set to zero) of the check star.

3. Data Analyses

The long-term light curves are displayed in Figure 1. Since we had low sampling for a single object on each night, the intrainight magnitude changes for a certain object are all very small (as will be shown later), so we plotted for each object only the median measurements on all single nights in Figure 1. Unless specifically mentioned, the following analyses are all based on the median light curves.

The spectral indices were calculated by assuming a power law for the spectrum of each blazar and using measurements in three passbands. Before calculating the spectral indices, we corrected the Galactic interstellar reddening. Based on the model of Schlafly & Finkbeiner (2011), the extinctions in our passbands were obtained by cubical interpolation from those of 88 passbands provided by NED.\textsuperscript{5} The extinctions of all sources are listed in Table 4. The spectral index curves are also plotted in Figure 1.

The statistical results of the variability behaviors are summarized in Table 5. The columns are the maximum and minimum magnitudes, average magnitudes, and amplitudes of the full observations. The long-term color–magnitude diagrams are presented for all 10 blazars in Figure 2. Based on the original complete data, we searched for the intraday variability (IDV) for each target and used four statistical tests, the $C$, $\chi^2$, $F$, and ANOVA tests (Pica & Smith 1983; Jang & Miller 1997; de Diego et al. 1998; Romero et al. 1999; de Diego 2010) to perform a quantitative assessment of whether there is IDV.

\begin{table}[h]
\centering
\caption{Central Wavelengths and Bandwidths of the Five Filters}
\begin{tabular}{|c|c|c|}
\hline
Filter & Central Wavelength & Bandwidth \\
(Å) & (Å) & \\
\hline
$c$ & 4206 & 289 \\
$e$ & 4885 & 372 \\
i & 6685 & 514 \\
m & 8013 & 287 \\
o & 9173 & 248 \\
\hline
\end{tabular}
\end{table}

The correlation analyses were performed on the variations at different wavelengths for those objects, with relatively intensive monitoring in order to search for the possible interband time lags. The results are listed in Table 6. We now discuss the results of each blazar in detail.

4. Individual Comments on Each Blazar

4.1. 3C 66A

The blazar 3C 66A is classified as an IBL, because its synchrotron peak is located between $10^{15}$ and $10^{16}$ Hz (Perri et al. 2003; Abdou et al. 2010). The redshift was determined to be $z = 0.444$ by independent authors (Miller et al. 1978; Lanzetta et al. 1993). Ever since its optical counterpart was identified by Wills & Wills (1974), 3C 66A was studied over a wide frequency range, from radio to $\gamma$-ray. Very Long Baseline Interferometry (VLBI) images from 2.3 to 43 GHz revealed a typical core-jet structure on parsec scales (e.g., Jorstad et al. 2001; Marscher et al. 2002). It is one of the sources detected in TeV (e.g., Acciari et al. 2009; Aliu et al. 2009).

Its optical variability has been studied on different timescales by many investigators (e.g., Miller & McGimsey 1978; Carini & Miller 1991; Xie et al. 1992; Takalo et al. 1996; Fan & Lin 2000; Hu et al. 2011). The study of Fan & Lin (2000) showed that the variability amplitude increased with increasing frequency. IDV was reported by Carini & Miller (1991), but some observations did not reveal IDV (Miller & McGimsey 1978; Xie et al. 1992; Hu et al. 2011). 3C 66A has been extensively monitored by two Whole Earth Blazar Telescope (WEBT) campaigns (Böttcher et al. 2005, 2009). The first WEBT campaign from 2003 July through 2004 April revealed IDV within a 2 hr timescale (Böttcher et al. 2005). The time lag of shorter wavelengths preceding longer wavelengths was shown by correlation analysis (Hu et al. 2011). The optical spectrum turns bluer/flatter when the source brightens, and this tendency was confirmed by many other authors (e.g., Vagnetti et al. 2003; Gù et al. 2006; Rani et al. 2010; Hu et al. 2011).

Our optical observations of 3C 66A in the $c$, $i$, and $o$ bands were carried out for 237, 248, and 235 nights, respectively, between 2005 January and 2011 February (Table 2). Part of these data have already been published in Böttcher et al. (2009) and Hu et al. (2011). Böttcher et al. (2009) included our data from 2007 September to December. Hu et al. (2011) covered the period from 2005 January 26 to 2008 October 16.

3C 66A remained active throughout the whole period and there are significant correlations between the light curves in different passbands. One can see from Figure 1 that the overall brightness of 3C 66A showed a wave pattern with two peaks around JDs 2454400 and 2455200 and three troughs at around JDs 2454100, 2454800, and 2455600. A number of short-term oscillations overlapped on the overall wave pattern. On the other hand, we did not detect any IDV because of the low sampling on each night. The variation amplitude tends to decrease with decreasing frequency (see Table 5). This is consistent with the results of Fan & Lin (2000). The correlation analysis did not find any interband time lag at long and short timescales (see Table 6).

No systematic spectral variability was detected in the second WEBT campaign that covered the autumn and winter of 2007–2008 (Böttcher et al. 2009). It can be seen from Figure 1 that the spectral index became smaller (the spectrum became flatter) when the brightness of the source increased. One can

\footnotesize
\textsuperscript{3} https://www.lsw.uni-heidelberg.de/projects/extragalactic/charts/
\textsuperscript{5} The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.
Table 2
Observation Details of the 10 Objects

| Name                | R.A.    | Decl.  | z      | Type | Band | Start Date    | End Date    | $N_{\text{day}}$ | $N_{\text{datas}}$ |
|---------------------|---------|--------|--------|------|------|---------------|--------------|-----------------|-----------------|
| 3C 66A              | 02 22 39.61 | +43 02 07.8 | 0.444 | IBL  | c    | 2006 Nov 26  | 2011 Feb 27 | 237             | 1623            |
|                     |         |        |        |      | i    | 2005 Jan 29  | 2011 Feb 27 | 248             | 1790            |
|                     |         |        |        |      | o    | 2006 Nov 26  | 2011 Feb 27 | 235             | 1649            |
| PKS 0735+178        | 07 38 07.39 | +17 42 19.0 | 0.424 | LBL  | c    | 2009 Dec 18  | 2010 Nov 30 | 13              | 29              |
|                     |         |        |        |      | i    | 2009 Dec 18  | 2010 Nov 30 | 15              | 37              |
|                     |         |        |        |      | o    | 2009 Dec 18  | 2010 Nov 30 | 10              | 23              |
| OI 090.4            | 07 57 06.64 | +09 56 34.8 | 0.266 | LBL  | c    | 2007 Jan 20  | 2011 Mar 30 | 19              | 81              |
|                     |         |        |        |      | i    | 2006 Mar 14  | 2011 Mar 30 | 21              | 99              |
|                     |         |        |        |      | o    | 2007 Jan 20  | 2011 Mar 30 | 18              | 78              |
| Mrk 421             | 11 04 27.20 | +38 12 32.0 | 0.030 | HBL  | c    | 2007 Apr 05  | 2008 May 05 | 15              | 108             |
|                     |         |        |        |      | m    | 2005 Jan 30  | 2006 Mar 30 | 5               | 39              |
|                     |         |        |        |      | o    | 2007 Apr 05  | 2008 May 05 | 16              | 128             |
| ON 231              | 12 21 31.69 | +28 13 58.5 | 0.102 | IBL  | c    | 2009 May 23  | 2011 Jun 04 | 76              | 338             |
|                     |         |        |        |      | i    | 2009 May 23  | 2011 Jun 04 | 80              | 380             |
|                     |         |        |        |      | o    | 2009 May 23  | 2011 May 15 | 78              | 360             |
| PG 1553+113         | 15 55 43.04 | +11 11 24.4 | 0.360 | HBL  | c    | 2009 May 26  | 2010 Mar 28 | 28              | 135             |
|                     |         |        |        |      | i    | 2009 May 26  | 2010 Mar 28 | 28              | 134             |
|                     |         |        |        |      | o    | 2009 May 26  | 2010 Mar 28 | 28              | 131             |
| OT 546 (phase 1)    | 17 28 18.62 | +50 13 10.5 | 0.055 | HBL  | c    | 2005 Mar 14  | 2006 Jul 02 | 55              | 577             |
|                     |         |        |        |      | i    | 2005 Mar 14  | 2006 Jul 02 | 54              | 566             |
|                     |         |        |        |      | m    | 2005 Mar 14  | 2006 Jul 02 | 52              | 564             |
| OT 546 (phase 2)    | 17 28 18.62 | +50 13 10.5 | 0.055 | HBL  | c    | 2007 Feb 03  | 2011 May 31 | 113             | 456             |
|                     |         |        |        |      | i    | 2007 Feb 02  | 2011 May 31 | 121             | 549             |
|                     |         |        |        |      | o    | 2007 Feb 03  | 2011 Mar 23 | 110             | 466             |
| 1ES 1959+650        | 19 59 59.85 | +65 08 54.7 | 0.047 | HBL  | c    | 2009 Jul 03  | 2011 Jun 13 | 81              | 336             |
|                     |         |        |        |      | i    | 2009 Jul 03  | 2011 Jun 13 | 81              | 349             |
|                     |         |        |        |      | o    | 2009 Jul 03  | 2011 May 14 | 71              | 256             |
| BL Lacertae (phase 1) | 22 02 43.29 | +42 16 39.9 | 0.069 | LBL  | c    | 2006 Jul 01  | 2006 Nov 16 | 10              | 135             |
|                     |         |        |        |      | i    | 2006 Jul 01  | 2006 Nov 23 | 11              | 158             |
|                     |         |        |        |      | m    | 2006 Jul 01  | 2006 Nov 16 | 10              | 142             |
| BL Lacertae (phase 2) | 22 02 43.29 | +42 16 39.9 | 0.069 | LBL  | c    | 2006 Dec 04  | 2010 Dec 29 | 155             | 791             |
|                     |         |        |        |      | i    | 2006 Dec 04  | 2010 Dec 29 | 162             | 877             |
|                     |         |        |        |      | o    | 2006 Dec 04  | 2010 Dec 29 | 161             | 853             |
| 3C 454.3            | 22 53 57.74 | +16 08 53.5 | 0.859 | FSRQ | c    | 2007 Aug 17  | 2010 Dec 14 | 39              | 179             |
|                     |         |        |        |      | i    | 2007 Jul 19  | 2010 Dec 14 | 42              | 196             |
|                     |         |        |        |      | o    | 2007 Aug 17  | 2010 Dec 14 | 40              | 187             |

see from Figure 2 that 3C 66A shows significant BWB trends ($p \leq 0.05$) in all three colors (see Table 7), which is in accord with the previous results mentioned above.

4.2. PKS 0735+178

PKS 0735+178 was first classified as a BL Lac object by Carswell et al. (1974). The broadband spectrum suggested that it is a LBL (Urry et al. 1996). Nilsson et al. (2012) derived a redshift of 0.45 ± 0.06 for this object using the host galaxy as a standard candle.

Historical optical data over a century show its violent long-term variations, with an amplitude of 3–4 mag (Pollock et al. 1979; Fan et al. 1997). It probably has periods of 4.89 and 14.2 years (Webb et al. 1988; Fan et al. 1997). Ciprini et al. (2007) found 3 characteristic timescales of about 4.5, 8.5, and 11–13 years. For short timescales, some IDV and interday variations were reported in its optical history. However, Goyal et al. (2009) reported an unusual quiescence of IDV between 1998 and 2008. Optical variations of this source often show larger amplitudes than those in the infrared (Fan & Lin 2000), which indicates a BWB trend.

We observed this source on 13, 15, and 10 nights in the c, i, and o bands, respectively, between 2009 December 18 and 2010 November 30. The recorded maximum brightness of 15.819 mag in the i band occurred on 2010 January 10 (JD 2455207). The brightness dropped by 0.58 mag at the end. The variation amplitude decreases in the wavelength sequence of c, i, and o (see Table 5). No IDV was detected because of the low sampling.

As can be seen in Figure 1, the spectral index varied slightly between 1.1 and 1.8. One can see from Figure 2 that PKS 0735+178 exhibits different levels of positive correlations for all its observed colors. Significant BWB trends were found for the $c - i$ and $c - o$ colors, while the $i - o$ color had a significance of less than 95%. These BWB behaviors are consistent with the
The light curves for all 34 observations of the blazars are available in their entirety in machine-readable form in the online journal. A portion is shown for 2006 Nov 26 15:10:47.0 2454066.13249 240 15.284 0.022 0.007

Note. The light curves for all 34 observations of the blazars are available in their entirety in machine-readable form in the online journal. A portion is shown for guidance regarding its form and content.

(This table is available in its entirety in machine-readable form.)

decreasing amplitude at decreasing frequency observed in this object, as mentioned above, Fan & Lin (2000) reported similar color trends. On the other hand, this type of correlation appears to be weak (Gu et al. 2006) or opposite (Ghosh et al. 2000) compared to other observations.

4.3. OI 090.4

OI 090.4 was first identified as a BL Lac object by Tapia et al. (1977). Cross-identification of optical and radio sources was accomplished by Condon et al. (1977). A tentative redshift $z = 0.66$ was proposed by Persic & Salucci (1986) and was then questioned by Abraham et al. (1991). Falomo (1996) suggested $z \approx 0.3$, on the basis of the host galaxy properties. Carangelo et al. (2003) identified [OII] 3727 and [OIII] 5007, indicating redshift $z = 0.266 \pm 0.001$. Ghosh & Soundararajaperumal (1995) suggested it was a LBL by its multi-frequency spectrum. Pushkarev et al. (2009) reported its jet viewing angle at about 6.9 degs.

Its optical variability was studied by a number of authors (e.g., Baumert 1980; Zekl et al. 1981; Pica et al. 1988; Sillanpää et al. 1991; Xie et al. 1991, 1994; Katajainen et al. 2000). Zekl et al. (1981) reported 2 mag fluctuations in the B band. Pica et al. (1988) observed 0.8 mag changes in the B band on a 2 year timescale. Sillanpää et al. (1991) detected 0.9 mag variations in the V band from 1984 to 1989. Xie et al. (1994) claimed 1.04 mag variations both in the V and B bands from 1985 to 1991, and a rapid optical flare of 0.56 mag in the B band within 80 minutes on 1988 December 11 was also reported by Xie et al. (1991). There were no systematic color changes with brightness in the results of Noble et al. (1997); they argued that the underlying emission mechanism of this source was of a non-thermal nature.

We observed this source on 19, 21, and 18 nights in the c, i, and o bands, respectively, between 2006 March 14 and 2011 March 30 (Table 2). Due to the few data points, brief statistical results are listed for this source. No IDV was found because of the low sampling. The amplitude of the variations is systematically larger at higher frequencies (see Table 5).

As can be seen in Figure 1, the average spectral index was 1.46. One can see from Figure 2 that OI 090.4 shows a stronger BWB trend with $i - o$ color than with the $c - i$ and $c - o$ colors. The low confidence levels ($p > 0.1$) for the $c - i$ and $c - o$ colors may be related to the few data points and big errors. The observed BWB trend is inconsistent with the results from Noble et al. (1997).

4.4. Mrk 421

Mrk 421 is one of the nearest blazars and it has a redshift of $z = 0.03$ (Sbarufatti et al. 2005). It was first reported as an elliptical galaxy with a highly condensed nucleus emitting non-thermal continuum radiation but no emission lines in the optical regime (Ulrich et al. 1975). It is classified as an HBL due to its synchrotron peak higher than 0.1 keV (Gaur et al. 2012c).

In optical region, Miller (1975) found variations of $\geq 4.7$ mag from 1899 to 1975. Observations on 17 nights between 2009 November 15 and 2011 May 2 were made by Gaur et al. (2012a), which showed a maximum brightness of $\approx 12.46$ in the V band on JD 2455684. Fan & Lin (1999) found that the variations in the J, H, and K bands were much smaller than those in the optical. Gupta et al. (2004) reported typical brightness variations of $\approx 0.4$ mag and a maximum variation of 0.89 mag in the J band from 2003 February to March. A BWB behavior was claimed for this source (Sillanpää et al. 1988; Fiorucci et al. 1997; Tosti et al. 1998b; Chen et al. 2014). Fiorucci et al. (1997) and Tosti et al. (1998b) claimed that this BWB chromatism may be due to the thermal contribution of the host galaxy. But Chen et al. (2014) argued that only a host galaxy contribution was not sufficient, and some intrinsic mechanism was also needed.

We observed this source on 15, 5, and 16 nights in the c, m, and o bands, respectively, between 2005 January 30 and 2008 May 05. The observed maximum brightness of 13.159 mag in the c band occurred on 2008 March 2 (JD = 2454528). As can be seen from Table 5, the amplitude in this band was larger than that in the o band for the same period.

We only observed Mrk 421 simultaneously in the c and o bands for several days. So we did not calculate its spectral index. One can see from Figure 2 that the positive correlation derives that Mrk 421 exhibits a strong BWB trend with the $c - o$ color, which is in accordance with the previous results mentioned above.

4.5. ON 231

ON 231 was discovered as a variable star by Wolf (1916), and was reported as a new quasar by Browne (1971). The detection of a few weak emission lines in its spectrum made it possible to determine a redshift of $z = 0.102$ (Weistrop et al. 1985). The synchrotron peak frequency log $\nu_{\text{peak}} = 14.84$ was calculated by Nieppola et al. (2006) and it is classified as an IBL.

In the optical regime, the optical outbursts in 1940, 1953, and 1968 were observed by Tosti et al. (1998a). A series of 2 mag outbursts were claimed in 1975–1976, and this type of...
rapid activity continued through 1986 and early 1987 (Webb et al. 1988). A variation with a timescale of 6 days was detected in 1983 (Xie et al. 1987). Xie et al. (1991) reported three outbursts with similar profiles from 1987 to 1989. Massaro et al. (1999) observed an extraordinary outburst from 1988 April to May, and the magnitude in the $R$ band reached a maximum brightness of 12.2. In 1997, the $R$ magnitude showed an oscillating behavior between 14 and 14.5 for about two months (Tosti et al. 2002). Cheng et al. (2013) claimed the larger variation amplitude at a higher frequency and the BWB chromatism. They also found that the variability at the $R$ band lagged behind that at the $B$ band by $\sim 1200$ s on March 17.

Our optical $c$, $i$, and $o$ band observations of ON 231 were carried out for 76, 80, and 78 nights, respectively, between 2009 May 23 and 2011 May 15. At the beginning, the object was at a relatively high state. Then it got fainter and showed some oscillations at the second and third stages. At the last stage, the brightness dropped gradually from JDs 2455572 to...
and rose again after that. One can see from Table 5 that the variation amplitude decreases toward longer wavelengths, which is in accord with Cheng et al. (2013). We did not find any IDV because of the low sampling on each single night. No interband time lags were found at long and short timescales for this source (see Table 6).

One can see from Figure 1 that the spectral indices decreased with increasing luminosity. However, Hu et al. (2006b) reported the spectral index $\alpha$ decreased with increasing luminosity. ON 231 shows strong BWB behavior in all three color–magnitude diagrams (Figure 2). This is in agreement with the results of Tosti et al. (1998a) and Sandrinelli et al. (2014).

Located in the Serpens Caput constellation, PG 1553+113 was classified as a BL Lac object based on its featureless spectrum (Falomo & Treves 1990) and was classified as a HBL blazar (Falomo et al. 1994; Giommi et al. 1995; Beckmann et al. 2002). Evidence of very-high-energy (VHE) $\gamma$-ray emission from this source was first reported by H.E.S.S. in 2005 (Aharonian et al. 2006) and was later confirmed by observations above 200 GeV with the MAGIC telescope at a significance level of 8.8$\sigma$ (Albert et al. 2007). Due to its featureless optical spectrum, the redshift of PG 1553+113 remains highly uncertain. Measurements using the Hubble Space Telescope (HST) Cosmic Origins Spectrograph (COS) yielded a lower limit of 0.395 (Danforth et al. 2010). The small statistical uncertainties of the VERITAS energy spectrum provided a robust upper limit of 0.62 (Aliu et al. 2015). Gopal-Krishna et al. (2011) claimed the detection of its IDV in the optical region. A general BWB trend was found in the optical observations by a WEBT campaign from 2013 April to August (Raiteri et al. 2015). However, Wierzcholska et al. (2015) did not find a definite long-term trend when analyzing the color behavior in 2007–2012.

We observed this source on 28 nights in the $c$, $i$, and $o$ bands between 2009 May 26 and 2010 March 28. One can see from Figure 1 that there is an outburst of about 0.2 mag on a timescale of 23 days (from JD 2454988 to JD 2455011). The

![Figure 1. (Continued.)](image_url)

Table 4
Galactic Extinction Values of Each Source in the Passbands

| Name            | $A_c$ (mag) | $A_o$ (mag) | $A_i$ (mag) | $A_m$ (mag) | $A_w$ (mag) |
|-----------------|-------------|-------------|-------------|-------------|-------------|
| 3C 66A          | 0.314       | 0.261       | 0.172       | 0.127       | 0.101       |
| PKS 0735+178    | 0.127       | 0.105       | 0.070       | 0.052       | 0.041       |
| OI 090.4        | 0.082       | 0.069       | 0.045       | 0.033       | 0.027       |
| ON 231          | 0.087       | 0.072       | 0.048       | 0.035       | 0.028       |
| OT 546          | 0.109       | 0.091       | 0.060       | 0.045       | 0.035       |
| 1ES 1959+650    | 0.642       | 0.535       | 0.353       | 0.261       | 0.207       |
| BL Lacertae     | 1.223       | 1.017       | 0.671       | 0.495       | 0.394       |
| 3C 454.3        | 0.392       | 0.326       | 0.215       | 0.159       | 0.126       |

2455680 and rose again after that. One can see from Table 5 that the variation amplitude decreases toward longer wavelengths, which is in accord with Cheng et al. (2013). We did not find any IDV because of the low sampling on each single night. No interband time lags were found at long and short timescales for this source (see Table 6).
source got fainter at the second stage and changed into a relatively high state at the last. Since we only got the differential magnitudes, we did not calculate the spectral indices. The overall variation amplitudes were $\Delta c = 0^{m}475$, $\Delta i = 0^{m}47$, and $\Delta o = 0^{m}462$, which showed a decreasing trend with decreasing frequency. No IDV was observed on each single night. Although we did not collect much data for this object, it showed a complete outburst at the beginning, so we made a correlation analysis for it. As can be seen from Table 6, however, no interband time lags were found for this source.

4.7. OT 546

OT 546 was first noticed by Zwicky (1966) and was classified as a BL Lac object by Angel & Stockman (1980). The redshift of $z = 0.0554 \pm 0.0003$ was measured by Oke (1978). It was a nearby HBL (Archambault et al. 2015) and was discovered as a VHE source by MAGIC (Aleksic et al. 2014). OT 546 was also found to have a massive black hole (BH) $\sim5.4 \times 10^{8} M_{\odot}$ at its center (Fan 1995).

Its optical variations were discovered by Sandage (1967). From 1975 to 1987, the light curves from Rosemary Hill Observatory observations showed variations with an overall amplitude of 0.8 mag and an average magnitude of $\sim16.7$ in the $B$ band (Pica et al. 1988). The monitoring from 1996 to 1997 in Tuorla Observatory showed that the brightness in the $V$ band varied between 15.76 and 16.12 (Katajainen et al. 2000).

The monitoring of OT 546 can be divided into two phases. Phase 1 is from JDs 2453444 to 2453919. The object was observed on 55, 54, and 52 nights in the $e$, $i$, and $m$ bands, respectively. Phase 2 is from JDs 2454134 to 2455713. The object was observed on 113, 121, and 110 nights, respectively, in the $c$, $i$, and $o$ bands. The brightness of this object was quite stable during our monitoring period. There are four flares at around JDs 2453650, 2454800, 2454960, and 2455330. The last flare has an amplitude of about 0.2 mag in the $i$ band. As can be seen from Table 5, the variation amplitude decreases toward longer wavelengths in both phases. The overall amplitudes are less than 1 mag and this is in agreement with the results of Pica et al. (1988) and Katajainen et al. (2000). We

| Name            | Band | Maximum (mag) | Minimum (mag) | Average (mag) | Amplitude (mag) |
|-----------------|------|---------------|---------------|---------------|-----------------|
| 3C 66A          | $c$  | 15.548 ± 0.014| 14.047 ± 0.029| 14.798        | 1.501           |
|                 | $i$  | 14.882 ± 0.012| 13.409 ± 0.012| 14.146        | 1.473           |
|                 | $o$  | 14.465 ± 0.019| 12.900 ± 0.016| 13.728        | 1.475           |
| PKS 0735+178    | $c$  | 17.489 ± 0.136| 16.554 ± 0.022| 17.022        | 0.935           |
|                 | $i$  | 16.675 ± 0.044| 15.819 ± 0.030| 16.247        | 0.856           |
|                 | $o$  | 16.191 ± 0.063| 15.434 ± 0.037| 15.813        | 0.757           |
| OI 090.4        | $c$  | 17.712 ± 0.065| 16.575 ± 0.020| 17.144        | 1.137           |
|                 | $i$  | 16.933 ± 0.041| 15.613 ± 0.086| 16.273        | 1.320           |
|                 | $o$  | 16.362 ± 0.066| 15.347 ± 0.026| 15.855        | 1.015           |
| Mrk 421         | $c$  | 13.616 ± 0.057| 13.159 ± 0.016| 13.388        | 0.457           |
|                 | $m$  | 13.250 ± 0.030| 12.962 ± 0.027| 13.106        | 0.288           |
|                 | $o$  | 12.906 ± 0.102| 12.569 ± 0.026| 12.738        | 0.337           |
| ON 231          | $c$  | 16.661 ± 0.033| 15.105 ± 0.038| 15.883        | 1.556           |
|                 | $i$  | 15.976 ± 0.027| 14.493 ± 0.021| 15.235        | 1.483           |
|                 | $o$  | 15.510 ± 0.047| 14.064 ± 0.018| 14.787        | 1.446           |
| OT 546 (phase 1)| $e$  | 16.791 ± 0.170| 16.344 ± 0.060| 16.568        | 0.447           |
|                 | $i$  | 15.858 ± 0.032| 15.607 ± 0.021| 15.751        | 0.241           |
|                 | $m$  | 15.502 ± 0.039| 15.287 ± 0.026| 15.395        | 0.215           |
| OT 546 (phase 2)| $c$  | 16.925 ± 0.072| 16.162 ± 0.028| 16.544        | 0.763           |
|                 | $i$  | 16.016 ± 0.042| 15.493 ± 0.025| 15.806        | 0.523           |
|                 | $o$  | 15.322 ± 0.042| 14.898 ± 0.039| 15.110        | 0.424           |
| IES 1959+650    | $c$  | 16.275 ± 0.026| 14.900 ± 0.017| 15.588        | 1.375           |
|                 | $i$  | 15.205 ± 0.016| 14.159 ± 0.016| 14.682        | 1.046           |
|                 | $o$  | 14.663 ± 0.031| 13.737 ± 0.024| 14.200        | 0.926           |
| BL Lacertae (phase 1)| $e$ | 16.067 ± 0.020| 15.247 ± 0.070| 15.657        | 0.820           |
|                 | $i$  | 14.880 ± 0.028| 14.119 ± 0.092| 14.387        | 0.761           |
|                 | $m$  | 14.337 ± 0.034| 13.572 ± 0.034| 13.955        | 0.765           |
| BL Lacertae (phase 2)| $c$ | 16.701 ± 0.055| 15.039 ± 0.041| 15.870        | 1.662           |
|                 | $i$  | 15.108 ± 0.012| 13.704 ± 0.017| 14.449        | 1.404           |
|                 | $o$  | 14.181 ± 0.015| 12.854 ± 0.014| 13.518        | 1.327           |
| 3C 454.3        | $c$  | 16.840 ± 0.034| 14.346 ± 0.013| 15.593        | 2.494           |
|                 | $i$  | 16.096 ± 0.033| 13.166 ± 0.021| 14.631        | 2.930           |
|                 | $o$  | 15.494 ± 0.044| 12.758 ± 0.016| 14.126        | 2.736           |
Figure 2. Color–magnitude diagrams. The solid lines are the best linear fit.
did not find any IDV on each single night because of the low sampling.

One can see from Figure 1 that the spectral indices fluctuated slightly around 1.8. From the results in Figure 2 and Table 7, strong BWB chromatisms were found for the $c - i$, $c - o$, $e - i$, and $e - m$ color behaviors, at $\geq 99.99\%$ confidence. Meanwhile, BWB trends with the $i - o$ and $i - m$ colors were detected at a relatively low confidence level. This may be because of the closely separated frequencies and the differences between the variation amplitudes at different wavelengths. On the other side, Fan & Lin (1999) claimed a RWB trend from their observations.

### 4.8. 1ES 1959+650

1ES 1959+650, with a redshift of $z = 0.047$ (Schachter et al. 1993), was classified as an HBL because its synchrotron bump peaked at UV–X-ray frequencies (Bottacini et al. 2010). Holder et al. (2003) found it to be a TeV emission source. The mass of its BH was estimated to be $\sim 1.5 \times 10^9 M_\odot$ (Falomo et al. 2002).

Previous studies suggested that 1ES 1959+650 was highly variable in the optical wavelengths (e.g., Villata et al. 2000b; Krawczynski et al. 2004; Kurtanidze et al. 2009; Sorcia et al. 2013). Villata et al. (2000b) obtained a decrease of 0.28 mag within 4 days. Kurtanidze et al. (2009) reported a maximum variability of $\Delta R = 1.07$ mag within 358 nights. Sorcia et al. (2013) found that the maximum and minimum $R$ magnitudes were 14.08 and 15.20, respectively, from 2009 to 2010. Gaur et al. (2012b) did not detect the genuine IDV, whereas IDV was observed on two nights in 2009 and no quasi-periodicity was found in the long-term light curves of Yuan et al. (2015). Zhang & Li (2017) also claimed no detection of IDV for 38 intraday light curves and they argued that the larger variation amplitude in the higher frequency can be demonstrated by the BWB trend.

We observed this source in the $c$, $i$, and $o$ bands on 81, 81, and 71 nights, respectively, between 2009 July 03 and 2011 June 13. There was one outburst at the first stage. After that, the light curves were characterized by a continuous increase in brightness and the $i$ magnitude ran up to 14.760 on 2010 September 13 (JD 2455453). Several data points were recorded during the last stage of our observation and the object turned faint. For the entire monitoring period, the light curves were quite “clean” and no fast flares overlapped with the long-term variability. The variation amplitude tends to decrease with decreasing frequency (see Table 5). No IDV was claimed because of the low sampling for this source, which actually agrees with no appearance of fast flares for our observations. We did not detect any interband time lags (see Table 6).

As can be seen from Figure 1, the spectral indices become smaller when the brightness of the source increases. One can see from Figure 2 that this source shows very strong BWB chromatisms in all three color–magnitude diagrams, at $\geq 99.99\%$ confidence. This is in agreement with the results obtained by Yuan et al. (2015) and Zhang & Li (2017). The BWB color behaviors can be at least partly attributed to the trend of increasing variation amplitude with increasing frequency, in agreement with Zhang & Li (2017).

### 4.9. BL Lacertae

BL Lacertae, with a redshift of $z = 0.069$ (Miller & Hawley 1977), is a prototype BL Lac object. The first bump of its SED peaks at optical/IR bands and it was classified as a LBL object (Fossati et al. 1998). Woo & Urry (2002) found that the BH mass is $1.7 \times 10^8 M_\odot$. It is highly variable at all wavelengths, ranging from radio to $\gamma$-rays. Raiteri et al. (2013) suggested that the optical and $\gamma$-ray emitting regions were located upstream from the zone producing the millimeter radiation in the jet.

Within the optical bands, numerous investigations have been carried out to search for its flux variability and spectral behaviors (e.g., Carini et al. 1992; Villata et al. 2002; Hu et al. 2006a; Gaur et al. 2012a; Agarwal & Gupta 2015; Wierzcholska et al. 2015; Meng et al. 2017). Most observations detected its IDV and revealed larger IDV amplitudes at higher frequencies. They also confirmed the presence of a BWB trend, but yielded no evidence of periodicities. Nesci et al. (1998) did not find any significant time lags between different optical bands during a single night. However, a possible time lag between the $e$ and $m$ bands was reported as $\sim 11.6$ minutes by Hu et al. (2006a). Meng et al. (2017) revealed a possible time delay of $\sim 10$ minutes between the variations in the $V$ and $R$ bands. Wierzcholska et al. (2015) observed a positive correlation for their entire data set, albeit with a large scatter, and they argued the observed BWB behavior was intrinsic to the jet emission regions.

The observation period of BL Lacertae can be divided into two phases. In phase 1, the object was monitored on 10, 11, and 10 nights in the $e$, $i$, and $m$ bands, respectively, from JDs 2453918 to 2454063. In phase 2, the object was observed on 155, 162, and 161 nights, respectively, in the $c$, $i$, and $o$ bands from JDs 2454074 to 2455559. The object kept fluctuating throughout the period. It showed two overall brightening trends in phase 1 and in the first stage of phase 2 and an overall darkening behavior in the last stage of phase 2. The light curves demonstrated several fluctuations before JD 2455200. Afterward, this object dropped its brightness to a minimum of
15.042 in the $i$ band on 2010 November 12 (JD 2455513). With a turnover, the object brightened again. As can be seen from Table 5, the variation amplitude decreases toward longer wavelengths in phase 2.

We detected the IDV of BL Lacertae in the $e$, $i$, and $m$ bands on 2006 November 6 by visual inspection and using C, $\chi^2$, and F statistical tests. The presence of IDV in the $i$ and $m$ bands is confirmed by the ANOVA test. Previous work also claimed significant IDVs (e.g., Nesci et al. 1998; Webb et al. 1998; Meng et al. 2017). The IDV light curves are displayed in Figure 3. The correlation analyses were performed for both the overall and IDV light curves and no time lags were found for both long- and short-term variability (see Table 6).

As can be seen from Figure 1, the spectral indices fluctuated slightly around 1.8. On the color–magnitude diagram, BL Lacertae exhibits strong BWB trends with $c - i$, $c - o$, and $i - o$ colors at a high confidence level, while no clear correlations were claimed between the $e - i$, $e - m$, and $i - m$ colors and their corresponding magnitudes due to very low confidence. The observed BWB trends are in agreement with the previous results (Villata et al. 2002, 2004; Gu et al. 2006; Ikejiri et al. 2011; Gaur et al. 2015; Wierzcholska et al. 2015).

### Table 7: Color–Magnitude Correlation Fitting Results

| Source (1) | Color (2) | Mag. (3) | Slope (4) | Intercept (5) | $r$ (6) | Prob. (7) |
|------------|-----------|----------|-----------|---------------|--------|----------|
| 3C 66A     | $c - i$   | $c$      | 0.04      | 0.16          | 0.24   | $7.56 \times 10^{-4}$ |
|            | $c - o$   | $c$      | 0.07      | 0.06          | 0.35   | $2.61 \times 10^{-7}$ |
|            | $i - o$   | $i$      | 0.02      | 0.09          | 0.25   | $5.37 \times 10^{-4}$ |
| PKS 0735+178 | $c - i$ | $c$      | 0.15      | $-1.89$      | 0.76   | $6.39 \times 10^{-3}$ |
|            | $c - o$   | $c$      | 0.28      | $-3.60$      | 0.77   | $1.43 \times 10^{-2}$ |
|            | $i - o$   | $i$      | 0.11      | $-1.34$      | 0.58   | $7.62 \times 10^{-2}$ |
| OI 090.4   | $c - i$   | $c$      | 0.02      | 0.32          | 0.10   | $7.65 \times 10^{-1}$ |
|            | $c - o$   | $c$      | 0.11      | $-0.59$      | 0.40   | $1.16 \times 10^{-1}$ |
|            | $i - o$   | $i$      | 0.11      | $-1.27$      | 0.70   | $1.54 \times 10^{-2}$ |
| Mrk 421    | $c - o$   | $c$      | 0.37      | $-4.29$      | 0.86   | $7.56 \times 10^{-4}$ |
| ON 231     | $c - i$   | $c$      | 0.16      | $-1.84$      | 0.78   | $9.95 \times 10^{-16}$ |
|            | $c - o$   | $c$      | 0.24      | $-2.55$      | 0.78   | $4.08 \times 10^{-15}$ |
|            | $i - o$   | $i$      | 0.09      | $-0.84$      | 0.59   | $4.42 \times 10^{-8}$ |
| OT 546 (phase 1) | $e - i$ | $e$      | 0.51      | $-7.56$      | 0.67   | $8.19 \times 10^{-8}$ |
|            | $e - m$   | $e$      | 0.56      | $-8.14$      | 0.67   | $1.38 \times 10^{-7}$ |
|            | $i - m$   | $i$      | 0.15      | $-2.04$      | 0.34   | $1.51 \times 10^{-2}$ |
| OT 546 (phase 2) | $c - i$ | $c$      | 0.42      | $-6.18$      | 0.85   | $3.12 \times 10^{-31}$ |
|            | $c - o$   | $c$      | 0.49      | $-6.76$      | 0.86   | $3.36 \times 10^{-30}$ |
|            | $i - o$   | $i$      | 0.16      | $-1.97$      | 0.36   | $2.37 \times 10^{-4}$ |
| 1ES 1959+650 | $c - i$ | $c$      | 0.27      | $-3.37$      | 0.95   | $3.85 \times 10^{-38}$ |
|            | $c - o$   | $c$      | 0.37      | $-4.46$      | 0.98   | $2.12 \times 10^{-47}$ |
|            | $i - o$   | $i$      | 0.16      | $-1.88$      | 0.89   | $1.62 \times 10^{-23}$ |
| BL Lacertae (phase 1) | $e - i$ | $e$      | 0.07      | $-0.03$      | 0.60   | $8.64 \times 10^{-2}$ |
|            | $e - m$   | $e$      | 0.11      | 0.02         | 0.68   | $4.18 \times 10^{-2}$ |
|            | $i - m$   | $i$      | 0.03      | 0.03         | 0.40   | $2.89 \times 10^{-1}$ |
| BL Lacertae (phase 2) | $c - i$ | $c$      | 0.15      | $-1.00$      | 0.43   | $4.16 \times 10^{-4}$ |
|            | $c - o$   | $c$      | 0.18      | $-0.54$      | 0.71   | $2.99 \times 10^{-19}$ |
|            | $i - o$   | $i$      | 0.10      | $-0.50$      | 0.46   | $3.87 \times 10^{-6}$ |
| 3C 454.3   | $c - i$   | $c$      | $-0.13$   | 3.02          | 0.71   | $9.80 \times 10^{-6}$ |
|            | $c - o$   | $c$      | $-0.10$   | 3.26          | 0.49   | $3.10 \times 10^{-3}$ |
|            | $i - o$   | $i$      | $-0.03$   | 1.10          | 0.31   | $8.02 \times 10^{-2}$ |

Note. (1) Source name; (2) color; (3) magnitude; (4) slope; (5) intercept; (6) correlation coefficient; (7) null hypothesis probability.

### 4.10. 3C 454.3

3C 454.3 is a highly variable blazar with a redshift of 0.859 and was classified as a FSRQ. Its BH mass was $4.4 \times 10^9 M_\odot$ (Gu et al. 2001). It is one of the best studied blazars at all wavelengths. In 2005 May, a dramatic outburst was recorded from the radio to X-ray energy (Vercellone et al. 2010).

In the optical region, its variability has been studied on different timescales by a lot of authors (e.g., Villata et al. 2006; Raiteri et al. 2007; Vercellone et al. 2008; Zhai et al. 2011; Agarwal et al. 2015). In 2005 May, it reached a historical maximum with $R = 12.0$ and then decayed to $R = 15.8$ (Villata et al. 2006). Based on the continuous monitoring of the object with the WEBT, a quiescent state from spring of 2006 to 2007 was reported by Raiteri et al. (2007). After this quiescent state, the object again underwent multi-frequency flaring activity in 2007 July (Vercellone et al. 2008). Zhai et al. (2011) claimed it reached a brightness of $R = 12.69$. 

Agarwal et al. (2015) detected IDV for this target only in the $B$ and $R$ bands, and not in both $V$ and $I$ bands.

We observed this source on 39, 42, and 40 nights, respectively, in the $c$, $i$, and $o$ bands between 2007 July 19 and 2010 December 14. The object was first at a high state and then dropped dramatically to 15.3 mag in the $i$ band. At the second stage, the object kept getting faint and reached a minimum of 16.096 mag, which corresponds to $R \sim 15.565$. A dramatic 1.17 mag decline was detected from the second half of 2008 to early 2009 (around JD 2454800). And then it brightened again and showed a strong flare with an amplitude of about 2 mag at the end. One more data point at the beginning was obtained in the $i$ band when compared with the other two wavelength observations. The overall variation amplitude was $\Delta i = 2^{56}688$ after removing that point. The variation amplitude tends to increase with decreasing frequency. On the other hand, we did not detect any IDV because of the low sampling on each single night.

One can see from Figure 1 that the spectral indices became smaller when the brightness decreased. In the color–magnitude diagram, as the only FSRQ in our sample, 3C 454.3 showed different from those of other objects. Significant RWB trends were found for the $c - i$ and $c - o$ colors, while the $i - o$ color had the same chromatism at $<95\%$ confidence. Zhai et al. (2011) found an RWB chromatism in its faint states.

It has been suggested that a few components in the spectrum of 3C 454.3 may be responsible for the RWB phenomenon (Raiteri et al. 2008). These components are the blue bumps between $\sim$2000 and 4000Å in the rest-frame. It is a combination of many emission features produced in the broad-line region (BLR), in particular a forest of the Fe II emission lines, the Mg II lines, and the Balmer continuum. In the case of 3C 454.3, which is at a redshift of $0.859$, its $c$-band flux is enhanced by the fluxes of the Fe II lines. The Fe II lines are evident when the synchrotron radiation from the jet is faint. When 3C 454.3 is in the low state, these less variable emission components dominate the fluxes and dilute the variability at high frequencies. Thus, the variation amplitudes at higher frequencies are smaller than those at lower frequencies, as can be seen in Table 5 for this object, which leads to the RWB behaviors (Raiteri et al. 2007, 2008, 2011; Sasada et al. 2010; Bonnoli et al. 2011; Wu et al. 2011).

5. Conclusions and Discussions

We performed long-term multi-color observations of 10 blazars in the $c$, $e$, $i$, $m$, and $o$ bands from 2005 January 29 to 2011 June 13 using the 60/90 cm Schmidt Telescope located at the Xinglong Station of the NAOC. We collected 14,799 data points. This is one of the largest optical databases for a sample of blazars. They cannot only be used to study long-term flux and spectral variabilities, but also can be correlated with data in radio, X-ray, or gamma-ray wavelengths to investigate the broadband behaviors.

Nine of our targets are BL Lac objects. Only 3C 454.3 belong to FSRQs. Most of them were active and displayed small amplitude oscillating behaviors superposed on the long-term variability, with the exception of OT 546. A total range of 0.5 mag in the $i$ band were attained in our 6 year time span for OT 546. In contrast, 3C 454.3 demonstrated a total amplitude of 2.93 mag in the $i$ band.

This project focused on the long-term variability of blazars. We collected only several data points within a short period for individual target on each night, so we did not detect IDV for most objects. Only BL Lacertae was captured to show IDV on 2006 November 6. We adopt the $z$-transformed discrete correlation functions (ZDCF; in autocorrelation mode) method to get a quantitative calculation IDV timescale (Alexander 1997). We choose the minimum zero-crossing time of the DCF as the correlation timescale and find a timescale of variability of $2.13$ hr in the $i$ band (see Figure 4).

The minimum timescale $\Delta t_{\text{obs}}$ will provide an upper limit to the mass of the supermassive BH. According to Gupta et al. (2012), the mass of a BH can be estimated by

$$M_{\text{BH}} = \frac{c^3 \Delta t_{\text{obs}}}{10 G (1+z)}.$$  \hspace{1cm} (1)

The $M_{\text{BH}}$ of BL Lacertae is calculated to be $1.47 \times 10^8 M_\odot$. This result is consistent with the BH mass of $0.1-6 \times 10^8 M_\odot$ obtained by Fan et al. (1999), Woo & Urry (2002), Ghisellini et al. (2010), Capetti et al. (2010), Gupta et al. (2012), and Meng et al. (2017).

In our observations, most BL Lac objects showed strong BWB trends except for PKS 0735+178, 01 090.4, and BL Lacertae in phase 1. PKS 0735+178 displayed BWB, RWB, or weak trends in the literature (Fan & Lin 2000;
Our result for its color behavior was hindered by the small number of data points and relatively large measurement errors (see Figure 2). OI 090.4 may be intrinsically achromatic when varying its brightness (Noble et al. 1997). Our few data points and relatively large measurement errors can hardly give any new results for this object. BL Lacertae demonstrated a strong BWB chromatism in phase 2 of our observations and in the literature (e.g., Gu et al. 2006; Ikekiri et al. 2011). The weak BWB in phase 1 probably resulted from the limited amount of data points. The BWB color behaviors of most BL Lacgs can be at least partly attributed to the trend of increasing variation amplitude with increasing frequency observed in these objects. A possible physical explanation for the observed BWB chromatism is that more than one mechanism is at work, as proposed by Villata et al. (2004). The optical variability can be interpreted in terms of two components: “strong-chromatic” fast flares and “mild-chromatic” long-term variations. The former are likely due to the intrinsic shock-in-jet model (e.g., Mastichiadis & Kirk 2002). The flattening of the spectrum can be caused by increasing luminosity due to injection of instantaneous renewed electrons with an energy distribution harder than that of the previously cooled ones. As the shock propagates down the jet, it strikes a region where the local plasma density is enhanced. The radiation at different frequencies is then produced at different distances behind the shock. Higher-frequency radiation emerges sooner and closer to the shock front than the lower-frequency radiation, thus causing color variations. Papadakis et al. (2007) claimed the BWB “mild-chromatic” long-term variations could be explained in terms of a variable Doppler factor $\delta$ due to changes in the view angle of a curved and inhomogeneous jet. Most objects in our sample showed fast flares that overlapped in long-term variability (see Figure 1), which is consistent with the suggestions of Villata et al. (2004) and Papadakis et al. (2007). On the other hand, the FSRQ, 3C 454.3, displayed clear RWB behavior. Several less variable components, such as the Fe II lines and Balmer continuum at short wavelengths, may be responsible for this kind of color behavior, as discussed by many authors (Raiteri et al. 2007, 2008, 2011; Sasada et al. 2010; Bonnoli et al. 2011; Wu et al. 2011). When 3C 454.3 is in the low state, these less variable components dominate the fluxes and dilute the variability at short wavelengths. Thus, the variation amplitudes at short wavelengths are smaller than those at long wavelengths, leading to RWR behavior.

Our sample contains three LBLs, two IBLs, four HBLs, and one FSRQ. For the two HBLs (Mrk 421 and PG 1553+113), we did not find their spectral indices. In Figure 5 we plot the spectral index against the synchrotron peak frequency for eight objects, excluding Mrk 421 and PG 1553+113. The synchrotron peak frequencies of these eight objects are taken from Fan et al. (2016) and Abdo et al. (2010). Abdo et al. (2010) took three new acronyms (low synchrotron peaked blazars or LSP, intermediate synchrotron peaked blazars or ISP, and high synchrotron peaked blazars or HSP) to redefine all types of non-thermal-dominated AGNs, depending on their synchrotron hump frequency, $v_{\text{peak}}$. They suggested the following classification: LSP with $v_{\text{peak}} \leq 10^{14}$ Hz; ISP with $10^{14} < v_{\text{peak}} < 10^{15}$ Hz; and HSP with $v_{\text{peak}} \geq 10^{15}$ Hz. The large majority of FSRQs are of the LSP type.

As we can see from Figure 5, our three LBLs and one FSRQ, 3C 454.3, are LSPs. Thus, we expect their optical spectral index to be greater than 1 due to the fact that they are on the descending part of the synchrotron peak. Except for BL Lacertae, the other two LBLs have spectral indices around 1.5. In the case of radiative losses dominated by synchrotron self-Compton (SSC) emission, the time-averaged synchrotron spectrum should be $J_\nu \propto \nu^{-(2+\alpha)/4}$. For a particle distribution in the power-law form $N(E) = N_0 E^{-\alpha}$, the synchrotron emission above the break energy $(Be^{\delta^2_{\text{max}}}/(mc^3))$ will have a spectral shape $F_\nu \propto \nu^{-3/2}$. Chiang & Böttcher (2002) further demonstrated that the SSC-loss-dominated synchrotron emission exhibits a distribution of spectral indices around 1.5 in the optical regime as the particle injection index varies. Thus, the fact that the two LBLs have spectral indices of about 1.5 can be interpreted with the SSC model. For 3C 454.3, even though its optical emission at short wavelengths is contaminated by the blue bumps as mentioned above, the average spectral index is 1.486. This indicates that the optical continuum of 3C 454.3 is likely dominated by the synchrotron component. This interpretation is also supported by the fact that 3C 454.3 shows strong variability in our observations.

Our two IBLs show intermediate synchrotron hump frequencies that belong to ISP. Their average spectral indices are 1.058 and 1.384, respectively, which are in agreement with the expected value of $\alpha \geq 1$. This also indicates that the synchrotron process dominates their optical emission.

For HSP, the predicted spectral index under simple synchrotron emission model should be less than or equal to 0.80, corresponding to the optically thin synchrotron emission (Urry & Padovani 1995). However, the spectral indices of our two HBLs, OT 546 and 1ES 1959+650, are about 1.816 and 1.08, respectively. This indicates that the optical emission of these two HSPs is contaminated by other components such as the thermal contribution from the host galaxies. For the nearby blazars, the host galaxy contribution is relatively important (Pian et al. 1994; Falomo 1996). For example, Gaur et al. (2012a) determined the spectral index of 1ES 1959+650 to be 0.67 after the subtraction of the host galaxy contribution. In addition, the Galactic absorption had a great influence on 1ES 1959+650. Before the dereddening, the average spectral index was 1.59. It is necessary for this target to correct the Galactic absorption.

It will be interesting to check the changes of the SEDs in response to the brightness variations for these blazars. In Figure 6, the SEDs at the highest, intermediate, and lowest

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**Figure 5.** Average spectral index vs. synchrotron peak frequency. Mrk 421 and PG 1553+113 are excluded because their spectral indices were not calculated.
states are displayed for those eight objects with spectral index calculations in Figure 1. The SEDs are compiled using the fluxes at the c, i, and o wavelengths. The observations in the e and m bands were made only for OT 546 and BL Lacertae. Those observations have either much fewer data points (for BL Lacertae) or much larger measurement errors (for OT 546) than the observations in the c and o bands, so we did not use them in the SEDs. The slopes of the SEDs changed clearly between different states in all eight objects. This is consistent with the color behavior demonstrated in Figure 2. More than half the SEDs can be well fitted with a power law, especially for 3C 66A, ON 231, and BL Lacertae, whose SEDs at three states are all power laws. The lowest SED of PKS 0735+178 and OT 546 and the intermediate SED of OI 090.4, show concave shapes. However, because of the relatively large errors in the fluxes, the concave shapes are at a relatively low confidence level and the precise shapes are unknown. The highest SED of OT 546, has a significant concave shape. This is quite unexpected, as even the fluxes may be polluted by the contribution of its host galaxy. We then plotted its second highest SED, which is clearly a power law. Given the small variation amplitudes of OT 546 in all five passbands, such a significant change in its SED is unexpected and spurious measurement might occur in one or more passbands at the highest state. The lowest SED of 3C 454.3 also has a concave shape. The excess in the c band should be the result of the contribution of the less variable blue bump. The three SEDs of 1ES 1959+650 all have convex shapes. As a low redshift object, its host galaxy is expected to contribute more flux in the i band than in the c and o bands, which leads to the observed convex SEDs. Böttcher et al. (2009) compiled six convex SEDs for 3C 66A in the optical-near-IR domain. This is not confirmed in our work, due partly to our minimal sampling in frequency. Sandrinelli et al. (2014) presented the optical–IR SEDs for seven blazars. Their SEDs of PKS 0735+178 and ON 231 are basically power laws and are consistent with our
results. The SEDs with complete coverage in the UV–optical–IR will help reveal the possible shift of the synchrotron peak with varying flux for at least the LBL/IBL objects (e.g., Villata et al. 2000a; Foschini et al. 2007). However, this is beyond the scope of this work.

Depending on the injection and acceleration of relativistic electrons and subsequent radiative cooling and escape processes, the observed interband time lags are expected (e.g., Kirk et al. 1998; Sokolov et al. 2004). In the optical regime, a few lags have been reported in several blazars (Qian et al. 2000; Romero et al. 2000; Papadakis et al. 2003; Stalin et al. 2006; Poon et al. 2009; Wu et al. 2012; Meng et al. 2017). For example, Poon et al. (2009) found a possible lag of about 11 minutes between B and I band variations. Villata et al. (2000a) presented an upper limit to the possible 10 minute delay between B and I variations. Wu et al. (2012) reported that the variability at the B' and V' bands leads that at the R' band by 30 minutes. Meng et al. (2017) derived a ~10 minute lag between variations in the V and R bands. We performed the interband correlation analysis for 3C 66A, ON 231, PG 1553 +113, 1ES 1959+650, and BL Lacertae. No time delay was identified for these targets at long and short timescales. The previous lags are mainly found for short periods. Actually, most authors claimed no detection of interband delays in the optical regime, especially for long-term variability (e.g., Hao et al. 2010; D’Ammando et al. 2013; Dai et al. 2015). Only a few data points were collected for our observations for individual target on each night and there were not enough of them to detect time lags.

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