SIX-YEAR OPTICAL MONITORING OF THE BL LACERTAE OBJECT 1ES 0806+52.4

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Abstract

We present the results of the first systematic long-term multicolor optical monitoring of the BL Lacertae object 1ES 0806+52.4. The monitoring was performed in multiple passbands with a 60/90 cm Schmidt telescope from 2005 December to 2011 February. The overall brightness of this object decreased from 2005 December to 2008 December but was regained after that. A sharp outburst probably occurred around the end of our monitoring program. Overlapping the long-term trend are some short-term small-amplitude oscillations. No intranight variability was found in the object, which is in accordance with the historical observations before 2005. By investigating the color behavior, we found a strong bluer-when-brighter chromatism for the long-term variability of 1ES 0806+52.4. The total amplitudes at the $c$, $i$, and $o$ bands are 1.18, 1.12, and 1.02 mag, respectively. The amplitudes tend to increase toward shorter wavelengths, which may be a major cause of the bluer-when-brighter chromatism. Such bluer-when-brighter chromatisms are also found in other blazars, such as S5 0716+714, OJ 287. The hard-X-ray data collected from the Swift/BAT archive was correlated with our optical data. No positive result was found, the reason for which may be that the hard-X-ray flux is a combination of the synchrotron and inverse Compton emission, but with different timescales and cadences under the leptonic synchrotron self-Compton model.

Key words: BL Lacertae objects: individual (1ES 0806+524) – galaxies: active – galaxies: photometry

Online-only material: machine-readable and VO tables

1. INTRODUCTION

Active galactic nuclei (AGNs) are powered by supermassive black holes surrounded by accretion disks. Blazar, one of the most violently variable classes of AGNs, are distinguished by large and rapid flux variability (Bonning et al. 2012; Sandrinelli et al. 2014), high and variable polarization (Hagen-Thorn et al. 2012). The low energy component is believed to be caused by the synchrotron process of the relativistic particles in the jet. The high energy one, however, is interpreted as either being due to inverse Compton scattering of the low-energy photons by the same ensemble of relativistic electrons responsible for the synchrotron emission named the synchrotron self-Compton model (e.g., Mücke & Protheroe 2001; Levinson 2006). The redshift of its host galaxy is estimated as $z = 0.138$ (Bade et al. 1998). Very-high-energy gamma-ray observations of 1ES 0806+52.4 were reported by the Whipple Collaboration (de la Calle Pérez et al. 2003; Horan et al. 2004), the HEGRA Collaboration (Aharonian et al. 2004) and VERITAS (Weekes et al. 2002).

2. OBSERVATION AND DATA REDUCTION

Our observations were performed using the 60/90 cm Schmidt telescope at the Xinglong Station of the National Astronomical Observatories of China (NAOC). Mounted at the telescope main focus was a Ford Aerospace 2048 × 2048 thick CCD camera, which was then surrogated by a new E2V 4096 × 4096 CCD in 2006 December. The field of view is enlarged from 58′ × 58′ to 96′ × 96′. The resolution is increased from 1.7 pixel⁻¹ to 1.3 pixel⁻¹. The blue quantum efficiency of the new E2V thinned CCD is also higher than the former thick one. The telescope is equipped with 15 color intermediate-band filters, covering a wavelength range from 3000 to 10,000 Å (Fan et al. 1996). Four F sub-dwarfs (Oke & Gunn 1983) are used as standard stars to calibrate the magnitude. For the details of the filter system, such as the definition of the corresponding magnitudes and how to derive flux from the magnitude, one can refer to Yan et al. (2000), Zhou et al. (2001, 2003).
Our monitoring program on 1ES 0806+52.4 started on the night of 2005 December 12 and ended on 2011 February 11. After ruling out the nights with bad weather conditions and those for other targets, the actual number of observation nights is 77. Filters in the \( c, e, i, \) and \( o \) bands were adopted between 2005 and 2006. During most of the nights in this period, more than 10 exposures, sometimes up to 20, were made in each band with a temporal resolution of about 20 minutes. Filters were then surrogated by \( c, i, \) and \( o \) bands from the end of 2006 December to 2011 February, and less than 10 exposures were made on most nights. The exposure time determined by the moon phase, weather conditions, and the filter varies from 60 to 540 s. The overall amplitudes in \( e, i, \) and \( o \) bands are 4210, 4920, 6660, 8020, and 9190 \( \text{A} \), respectively. The \( i \) magnitude can be transformed into the broadband \( R \) magnitude for stars by using the formula given by Zhou et al. (2003) and for AGNs by using the formula given by Dai et al. (2013).

We performed bias subtraction and flat-fielding using the BATC automatic data reduction software PIPELINE I (Fan et al. 1996; Zheng et al. 1999). Four stars, C1, C2, C3, and C4 (see Figure 1), were selected as reference stars (Fiorucci et al. 1998), and we chose star C5 as a check star (for a reasonable selection of reference and check stars, see Howell et al. 1988). We extracted the instrumental aperture magnitudes of the blazar and the five comparison stars from each frame by using the algorithm of Stetson (1987). The radii of the aperture and the sky annuli were adopted as 3, 7, and 10 pixels, respectively, and they may be adjusted slightly according to the seeing. The brightness of the blazar was measured relative to the average magnitude of the four reference stars. The accuracy of our measurement is shown by the check star’s differential magnitude, the difference between the magnitude of C5 and the average magnitude of the four reference stars. We observed stars C1, C2, C3, C4, and C5 on a photometric night, and used the photometric F-type standard stars mentioned above to calibrate their standard magnitudes. The results are listed in Table 1.

3. LIGHT CURVE

The samples of observational log and results are given in Tables 2–6. The columns include observation date and time in universal time, exposure time in seconds, Julian date, magnitude, error, and differential magnitude of star C5 (its nightly averages were set to zero).

We gathered 1399 optical data points in total: numbers of photometric points for \( c, e, i, m, \) and \( o \) bands are 292, 150, 490, 171 and 296, respectively. The light curves of the overall monitoring period in five bands are shown in Figure 2. There are basically two outbursts with a concave shape between them. The peak of the first outburst occurred on 2006 March 15 (JD 2,453,810), and then the brightness of the object started declining until 2008 December 11 (JD 2,454,812). Later on, the curves turned up to the second outburst, which is more powerful than the first one. No details can be known about the strong outburst because our observation ceased on 2011 February 11 (JD 2,455,604). Overlapped on the long-term large-amplitude variations are some short-term small-amplitude oscillations during JD 2,454,000 to JD 2,455,000. We also notice that a double-peak structure of 1ES 0806+52.4 was spotted between 2002 and 2004 (Kapanadze 2009), yet it was not found in our observations.

The overall amplitudes in \( e, i, \) and \( m \) bands from 2005 December 15 to 2006 November 19 are 0.17, 0.12, and 0.09 mag, respectively, the amplitudes in \( c, i, \) and \( o \) bands from 2006 December 4 to 2011 February 11 are 1.18, 1.12, and 1.02 mag. We note that the overall amplitudes tend to decline with the decreasing frequency. We examined the intranight variability of this object by using the methods suggested by de Diego (2010), but found no obvious intranight variability during the whole timespan. It is in accordance with the observation from 2002 to 2004 (Kapanadze 2009), which detected no intranight variability for this source either. Nevertheless, our average

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**Table 1**

| Band | C1 | C2 | C3 | C4 | C5 |
|------|----|----|----|----|----|
| \( c \) | 14.035 | 15.410 | 15.379 | 16.498 | 16.187 |
| \( e \) | 13.291 | 14.859 | 14.938 | 15.901 | 15.809 |
| \( i \) | 12.653 | 14.349 | 14.534 | 15.412 | 15.548 |
| \( m \) | 12.476 | 14.216 | 14.420 | 15.245 | 15.256 |
| \( o \) | 12.387 | 14.164 | 14.402 | 15.170 | 15.399 |

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**Figure 1.** Finding chart of 1ES 0806+52.4 and the five comparison stars taken in \( i \) band with the 60/90 Schmidt telescope on 2007 February 5. The size is 12’ by 12’ (or 512 x 512 in pixels).

**Figure 2.** Nightly average light curves of 1ES 0806+52.4 in the \( c, e, i, m, \) and \( o \) bands.
### Table 2
Observational Log and Results in the $c$ Band

| Observation Date | Observation Time (UT) | Exposure Time (s) | Julian Date JD | $c$ (mag) | $c_{err}$ (mag) | dfmagC5 (mag) |
|------------------|----------------------|------------------|----------------|-----------|-----------------|-------------|
| 2006 Dec 4       | 18:44:51.0           | 480              | 2454074.28115  | 15.886    | 0.034           | 0.064       |
| 2006 Dec 4       | 19:07:27.0           | 480              | 2454074.29684  | 15.806    | 0.035           | −0.011      |
| 2006 Dec 4       | 19:29:52.0           | 480              | 2454074.31241  | 15.809    | 0.031           | 0.008       |
| 2006 Dec 4       | 19:52:18.0           | 480              | 2454074.32799  | 15.832    | 0.032           | 0.012       |
| 2006 Dec 4       | 20:14:53.0           | 480              | 2454074.34367  | 15.850    | 0.037           | −0.006      |

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

### Table 3
Observational Log and Results in the $e$ Band

| Observation Date | Observation Time (UT) | Exposure Time (s) | Julian Date JD | $e$ (mag) | $e_{err}$ (mag) | dfmagC5 (mag) |
|------------------|----------------------|------------------|----------------|-----------|-----------------|-------------|
| 2005 Dec 15      | 15:01:46.0           | 300              | 2453720.12623  | 15.991    | 0.085           | −0.024      |
| 2005 Dec 15      | 15:17:43.0           | 300              | 2453720.13730  | 15.993    | 0.078           | 0.106       |
| 2005 Dec 15      | 15:34:01.0           | 300              | 2453720.14862  | 15.925    | 0.081           | −0.056      |
| 2005 Dec 15      | 15:49:56.0           | 300              | 2453720.15968  | 15.894    | 0.083           | −0.053      |
| 2005 Dec 15      | 16:05:54.0           | 300              | 2453720.17076  | 15.865    | 0.071           | −0.071      |

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

### Table 4
Observational Log and Results in the $i$ Band

| Observation Date | Observation Time (UT) | Exposure Time (s) | Julian Date JD | $i$ (mag) | $i_{err}$ (mag) | dfmagC5 (mag) |
|------------------|----------------------|------------------|----------------|-----------|-----------------|-------------|
| 2005 Dec 12      | 15:44:16.0           | 180              | 2453717.15574  | 15.488    | 0.034           | −0.021      |
| 2005 Dec 12      | 15:55:15.0           | 180              | 2453717.16337  | 15.514    | 0.033           | 0.006       |
| 2005 Dec 12      | 16:05:08.0           | 180              | 2453717.17023  | 15.408    | 0.030           | −0.004      |
| 2005 Dec 12      | 16:15:18.0           | 180              | 2453717.17729  | 15.416    | 0.030           | −0.024      |
| 2005 Dec 12      | 16:25:24.0           | 180              | 2453717.18431  | 15.408    | 0.028           | 0.042       |

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

### Table 5
Observational Log and Results in the $m$ Band

| Observation Date | Observation Time (UT) | Exposure Time (s) | Julian Date JD | $m$ (mag) | $m_{err}$ (mag) | dfmagC5 (mag) |
|------------------|----------------------|------------------|----------------|-----------|-----------------|-------------|
| 2005 Dec 12      | 15:49:15.0           | 300              | 2453717.15920  | 15.248    | 0.044           | 0.014       |
| 2005 Dec 12      | 16:00:10.0           | 300              | 2453717.16678  | 15.238    | 0.041           | −0.057      |
| 2005 Dec 12      | 16:10:21.0           | 300              | 2453717.17385  | 15.189    | 0.040           | 0.053       |
| 2005 Dec 12      | 16:20:26.0           | 300              | 2453717.18086  | 15.236    | 0.045           | −0.019      |
| 2005 Dec 12      | 16:30:24.0           | 300              | 2453717.18778  | 15.264    | 0.051           | −0.006      |

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

### Table 6
Observational Log and Results in the $o$ Band

| Observation Date | Observation Time (UT) | Exposure Time (s) | Julian Date JD | $o$ (mag) | $o_{err}$ (mag) | dfmagC5 (mag) |
|------------------|----------------------|------------------|----------------|-----------|-----------------|-------------|
| 2006 Dec 04      | 18:57:10.0           | 480              | 2454074.28970  | 14.818    | 0.027           | −0.003      |
| 2006 Dec 4       | 19:20:16.0           | 540              | 2454074.30574  | 14.840    | 0.028           | −0.040      |
| 2006 Dec 4       | 19:42:41.0           | 540              | 2454074.32131  | 14.822    | 0.026           | −0.026      |
| 2006 Dec 4       | 20:05:09.0           | 540              | 2454074.33961  | 14.809    | 0.026           | −0.009      |
| 2006 Dec 4       | 20:27:41.0           | 540              | 2454074.35256  | 14.840    | 0.027           | 0.006       |

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observational duration on each night is only 3.6 hr, which may not be long enough to detect the intranight variability, if there are some cases. Some blazars display strong intranight variability. For example, S5 0716+714 was observed to vary by 0.117 mag in 1.1 hr (Dai et al. 2013). PKS 2155-304 was detected to have a very fast variability rate of 0.43 mag/h in the observation session (Sandrinelli et al. 2014).

4. COLOR BEHAVIOR

The long-term color behavior of 1ES 0806+52.4 was investigated based on our data. We adopted the e and m bands to calculate the color in the first stage from 2005 to 2006, and used the c and o bands in the second stage from 2006 to 2011. This is because the differences in wavelength of the two pairs of filters are relatively large, and can thereby denote a better spectral shape. The color–magnitude diagrams are displayed in Figure 3.

The linear least square method with measurement errors taken into consideration was used to fit the points. The points in the left panel for the first stage have a linear regression of $y = 0.537x - 7.847$, and the correlation coefficient is 0.808, which means a significance level of 95%. The points in the right panel for the second stage have a linear regression of $y = 0.176x - 1.791$, and the correlation coefficient is 0.792, which also means a significance level of 95%. Both panels show strong bluer-when-brighter (BWB) chromatisms. The intranight color behavior of 1ES 0806+52.4 was not investigated due to the absence of intranight variability.

A number of BL Lac objects have been reported displaying the BWB phenomenon thus far. Significant BWB correlations were found for both internight and intranight variations in the typical BL Lac object S5 0714+716 (e.g., Wu et al. 2005). Internight BWB was found in BL Lacerate (e.g., Zhai & Wei 2012). In OJ 287, a well-studied BL Lac, BWB is also found on a long time scale (Dai et al. 2011). In fact, such a BWB chromatism is likely to be a general feature of BL Lac objects (e.g., Vagnetti et al. 2003; Rani et al. 2010). For FSRQ, there were once claims of a redder-when-brighter trend (e.g., Gu et al. 2006; Hu et al. 2006). However, Gu & Ai (2011) found evidence of this color behavior for only one object in a sample of 29 FSRQs. The mechanism of BWB was simulated (Dai et al. 2011), and the result shows that BWB is probably due to the difference of the amplitude at different wavelengths. The variation amplitude of 1ES 0806+52.4 was found to decrease with decreasing frequency, which can at least partly explain the BWB behavior observed in this object.

5. CROSS-CORRELATION ANALYSIS AND DISCUSSIONS

In order to research the emission at different wavelengths, our optical data was compared with the timeseries data provided by the Swift/BAT, which has monitored 1ES 0806+52.4 in the hard-X-ray band since 2005. The Swift/BAT hard-X-ray transient monitor provides near-real-time coverage of the X-ray sky in the energy range of 15–50 keV, or $3.63 \times 10^{18}–1.21 \times 10^{19}$ Hz in frequency. The BAT observes 88% of the sky each day with a detection sensitivity of 5.3 mCrab for a full-day observation and a time resolution as fine as 64 s (Krimm et al. 2013). We used the daily average data offered by Swift/BAT. Both sequences were transformed into flux so that we could analyze them together. The light curves of the i band and X-ray band are shown in Figure 4.

We used the $z$-transformed discrete correlation functions (ZDCFs; Alexander 1997) to search for the optical hard-X-ray correlations. The ZDCF differs from the discrete correlation function (DCF; Edelson & Krolik 1988) because it bins the data points into equal population bins and uses Fishers z transform to stabilize the highly skewed distribution of the correlation coefficient. It is much more efficient than the DCF at uncovering correlations involving the variability timescale, and deals with under-sampled light curves better than both the DCF and the interpolated cross-correlation function (Gaskell & Peterson 1987). The results are displayed in Figure 5 for all of the data from JD 2,453,717 to JD 2,455,604.

In Figure 5, no obvious peak of the DCF values can be found, indicating an absence of correlation between the two bands. We try to explain the result as follows.

First, there are daily data for the X-ray band, yet the optical observations have not been performed regularly: 77 daily average points in 1187 days in total. The time resolution of our optical data is not compatible with that of Swift/BAT, which may possibly result in the loss of important fluctuations in the optical light curve, especially at the end of our monitoring program. It is probably difficult to find a strong correlation between two samples with very different sampling rates. Second, as shown
in Figure 4, no significant flare or outburst can be found in both optical and X-ray bands. (There may be a strong flare at the end of the optical data, but the measurements are too few. The X-ray data obviously have no corresponding flare). As a result, it might be hard to find any correlation.

Third, provided that the no-correlation result is not caused by the limited data sampling in the optical band or the lack of significant variability events in both bands, it could be the reflection of a complex radiation mechanism. We notice that the hard-X-ray band from $3.63 \times 10^{18}$ Hz to $1.21 \times 10^{19}$ Hz lies in the transition area of the two peaks in the SED of 1ES 0806+52.4 (Cogan & VERITAS Collaboration 2008). Emission in this regime may be a combination of the synchrotron and inverse Compton mechanisms. Variations of the synchrotron and inverse Compton processes may have different amplitudes and cadences, hence a combination of them may show complicated variability and can hardly be found correlated with the optical variation. A similar explanation was raised to describe why the correlation between X-ray and other bands cannot be found in blazar S5 0716+714 (Rani et al. 2013).

Besides, there are also some other blazars showing no correlation between X-ray and other bands, which might be caused by the different locations of emission regions in different bands. For instance, 3C 279 was observed by Abdo et al. (2010), and its X-ray emission has not been found accompanied quasi-simultaneously by the optical/GeV flares. One argument is that X-ray photons are produced further down to the jet compared to optical–GeV photons. The case in which variations in the X-ray band are not correlated with those of the optical/gamma-ray (the so-called orphan gamma-ray flare) band was also found in other blazars such as Mrk 501 (Neronov et al. 2012), 1ES 1959+650 (Daniel et al. 2005), etc. The TeV flare in Mrk 501 may be produced by an electromagnetic cascade initiated by very-high-energy gamma-rays in the intergalactic medium (Neronov et al. 2012), and a hadronic synchrotron mirror model was employed to explain the orphan TeV flare of 1ES 1959+650 (Daniel et al. 2005). These results, together with ours, can be used to investigate the details of blazar variability, i.e., the radiation mechanism, the location of the emission region, etc.

Our monitoring work, which targeted the BL Lac object 1ES 0806+52.4, was conducted in five intermediate optical wavebands from 2005 December to 2011 February using the 60/90 cm Schmidt telescope located at the Xinglong Station of the NAOC. It was the first systematic multicolor optical monitoring of 1ES 0806+52.4 over a long timescale, and could thereby be effectively used to further study both the long- and short-term flux and spectral variability of this object.

The analysis of the data reveals that its overall brightness declined from 2005 December to 2008 December, and that it turned brighter during 2009–2011. Overlapping the long-term trend are some short-term small-amplitude oscillations. Unfortunately, our data samples are not abundant considering the long period of time that we covered, and there are several interruptions in our observation. No obvious intranight variability was found during the monitoring period, and the historical observation from 2002–2004 revealed the same feature. We did not find the double-peaked structure that the former observation suggested. Color behavior over long timescale was studied, and strong BBW phenomenon was revealed. This is consistent with the color behavior of most blazars. No obvious correlation was found between our optical variations and hard-X-ray variability collected from the Swift/BAT archive. This result can be attributed to the different time resolution of the optical and X-ray bands or the lack of a significant variability event in the observation session; moreover, it may suggest the hard-X-ray emission is a combination of both synchrotron radiation and inverse Compton scattering.

We gathered 1399 data points in total for 1ES 0806+52.4, which is the largest optical multicolor database for the variability of the object to date. Our data can also be correlated with the data aside from the hard-X-ray wavelength, e.g., radio, Gamma-ray, etc. for a more comprehensive investigation of the broadband behavior of 1ES 0806+52.4.

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