SEVEN-YEAR MULTI-COLOR OPTICAL MONITORING OF BL LACERTAE OBJECT S5 0716+714

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ABSTRACT

We have monitored the BL Lacertae object S5 0716+714 in five intermediate optical wavebands from 2004 September to 2011 April. Here, we present data that include 8661 measurements representing one of the largest databases obtained for an object in the optical domain. A simple analysis of the data indicates that the object was active most of the time, and intraday variability was frequently observed. In total, the object varied by 2.614 mag in the $i$ band. Strong bluer-when-brighter chromatism was observed on long, intermediate, and short timescales.

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

Online-only material: machine-readable tables

1. INTRODUCTION

Blazars constitute the most variable subclass of active galactic nuclei. Depending on whether or not they show strong emission lines in spectra, blazars are divided into flat-spectrum radio quasars and BL Lacertae (BL Lac) objects. BL Lac objects are characterized by non-thermal continuum emission across the whole electromagnetic spectrum with absent or weak emission lines in spectra, blazars are divided into flat-spectrum radio polarization (Angel & Stockman 1980; Impey & Neugebauer 1988; Gabuzda et al. 1989), large amplitude and rapid variability in a survey of sources with a 5 GHz flux greater than 1 Jy by Biermann et al. (1981). The redshift of S5 0716+714 was determined by the host galaxy as a “standard candle.” Most recently, Nilsson et al. (2008) acquired a deep image of this object and derived a redshift of $0.08$ by using a host galaxy as a “standard candle.” Most recently, Danforth et al. (2012) set an upper bound of $z < 0.304$ with a confidence level of 90% for this object. This source is one of the most studied BL Lac objects because it has high brightness and strong variability. The optical duty cycle of S5 0716+714 is nearly unity, indicating that the source is always in an active state in the visible regime (Wagner & Witzel 1995). Strong bluer-when-brighter correlations were found for both internight and intranight variations (Wu et al. 2005, 2007, 2012; Poon et al. 2009; Hao et al. 2010; Chandra et al. 2011).

This source has been intensively monitored by a number of authors. During a four-week period of continuous monitoring, the source displayed a transition between states of fast and slow variability with a change in the typical variability timescale from about one to about seven days (Quirrenbach et al. 1991) in both the optical and radio regimes. Wagner et al. (1996) investigated the rapid variations of this object in the radio, optical, ultraviolet, and X-ray regimes and found that it always maintained high amplitude change on a timescale of a few days. Sagar et al. (1999) showed the average $V−R$ color of this BL Lac to be $0.4$ mag in their one-month $BVRI$ optical monitoring campaign in 1994. Raiteri et al. (2003) reported that the long-term optical brightness variations of this source appeared to have a characteristic timescale of 3.3 years and four major optical outbursts were observed: at the beginning of 1995, in late 1997, at the end of 2000, and in fall 2001. In particular, an exceptional brightening of 2.3 mag in 9 days was detected in the $R$ band on 2000 October 30. A color analysis of the optical light curves revealed only a weak general correlation between the color index and the source brightness. Recently, Poon et al. (2009) monitored the BL Lac object S5 0716+714 in the optical band during 2008 October and December and 2009 February with a best temporal resolution of about 5 minutes in the $BVRI$ bands. Typical timescales of microvariability range from 2 to 8 hr. The overall $V−R$ color index ranges from $0.37$ to $0.59$. Strong bluer-when-brighter chromatism was found on internight timescales. The overall variability amplitude decreases with decreasing frequency.

We have monitored S5 0716+714 since 2004. Here, we present the data during the period from 2004 to 2011. A simple analysis is performed and the results are described.

This paper is organized as follows. The observations and data analysis are described in Section 2. Section 3 presents the light curves. Section 4 shows the comparison result of data from other authors. The relation of color and magnitude is described in Section 5. The conclusions are given in Section 6.

2. OBSERVATIONS AND DATA ANALYSIS

Our optical monitoring program of S5 0716+714 was carried out with the 60/90 cm Schmidt telescope located at the Xinglong Station of the National Astronomical Observatories of China (NAOC). Prior to 2006, a Ford Aerospace 2048 × 2048 CCD camera was mounted at its main focus. The CCD has a pixel size of 15 μm and its field of view is $58' \times 58'$, resulting in a resolution of 1.7 pixel$^{-1}$. At the beginning of 2006, the 2k CCD was replaced by a new 4096×4096 CCD. The field of view is now $96' \times 96'$, resulting in a resolution of 1.3 pixel$^{-1}$. The telescope is equipped with 15 intermediate-band filters, covering a wavelength range from 3000 to 10000 Å.
The size is 12 with the 60 Figure 1. Finding chart of S5 0716+714 and the four comparison stars taken with the 60/90 Schmidt telescope and filter i on 2011 April 12 (JD 2,455,664). The source remained active during the whole monitoring period in the five bands.

This paper includes data from 2004 September 10 to 2011 April 24. Excluding the nights with bad weather and those devoted to other targets, the actual number of nights of S5 0716+714 observations is 332. We used filters in the e, i, and m bands to observe in 2004–2006 and then changed to the c, i, and o bands from 2006 December onward. The central wavelengths of the c, e, i, m, and o bands were 4210, 4920, 6660, 8020, and 9190 Å, respectively. The central wavelength of the i band is similar to that of the R band. Using results from the observation of stars, the magnitudes in these two bands can be transformed with the formula $R = i + 0.1$ (Zhou et al. 2003). Depending on the weather and seeing conditions, the exposure times of different bands range from 30 s to 480 s and the exposures per night in different bands vary from 2 to 43.

The data reduction procedure includes bias subtraction, flat fielding, extraction of instrumental aperture magnitude, and flux calibration. We used differential photometry. For each frame, the instrumental magnitudes of the blazar and four comparison stars were obtained by observing them and the standard star HD 19945 on a photometric night and are listed in Table 1.

3. LIGHT CURVES

The observational log and results are given in Tables 2–6. The columns are the observation date and time in universal time, Julian date, exposure time in seconds, magnitude and error of S5 0716+714, and differential magnitude of star 6 (its nightly averages were set to zero). Figure 2 shows the light curves of the overall monitoring period in the five bands.

The source remained active during the whole monitoring period. The variation amplitudes of the e, i, and m bands from

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Table 1

| Star | c | e | i | m | o |
|------|---|---|---|---|---|
| 3    | 13.033 | 12.706 | 12.271 | 12.190 | 12.178 |
| 4    | 13.574 | 13.412 | 13.098 | 13.050 | 13.060 |
| 5    | 14.126 | 13.794 | 13.363 | 13.264 | 13.223 |
| 6    | 14.195 | 13.890 | 13.442 | 13.370 | 13.329 |

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Table 2

| Date(UT) | Time | Julian Date | Exp | e | cerr | dfmag |
|----------|------|-------------|-----|---|------|-------|
| 2006 12 06 | 18:43:43.0 | 2454076.28036 | 300 | 14.649 | 0.016 | 0.002 |
| 2006 12 06 | 18:58:33.0 | 2454076.29066 | 300 | 14.636 | 0.020 | -0.018 |
| 2006 12 06 | 19:12:43.0 | 2454076.30050 | 300 | 14.639 | 0.014 | 0.011 |
| 2006 12 06 | 19:27:06.0 | 2454076.31049 | 300 | 14.660 | 0.014 | 0.004 |
| 2006 12 06 | 19:41:42.0 | 2454076.32063 | 300 | 14.612 | 0.014 | -0.003 |

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Table 3

| Date(UT) | Time | Julian Date | Exp | e | cerr | dfmag |
|----------|------|-------------|-----|---|------|-------|
| 2005 01 28 | 15:57:45.0 | 2453399.16510 | 300 | 14.216 | 0.027 | -0.009 |
| 2005 01 28 | 16:07:44.0 | 2453399.17204 | 300 | 14.212 | 0.026 | -0.028 |
| 2005 01 28 | 16:17:43.0 | 2453399.17897 | 300 | 14.186 | 0.023 | 0.015 |
| 2005 01 28 | 16:27:57.0 | 2453399.18608 | 300 | 14.239 | 0.029 | -0.015 |
| 2005 01 28 | 16:37:53.0 | 2453399.19297 | 300 | 14.242 | 0.026 | 0.011 |

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Table 4

| Date(UT) | Time | Julian Date | Exp | i | ierr | dfmag |
|----------|------|-------------|-----|---|------|-------|
| 2004 12 20 | 17:45:00.0 | 2453360.23958 | 240 | 12.739 | 0.011 | -0.012 |
| 2004 12 20 | 17:51:11.0 | 2453360.24388 | 240 | 12.745 | 0.010 | 0.010 |
| 2004 12 20 | 17:55:40.0 | 2453360.24699 | 240 | 12.717 | 0.010 | -0.026 |
| 2004 12 20 | 18:00:06.0 | 2453360.25007 | 240 | 12.748 | 0.011 | 0.032 |
| 2004 12 20 | 18:04:36.0 | 2453360.25319 | 240 | 12.733 | 0.014 | -0.008 |

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Table 5

| Date(UT) | Time | Julian Date | Exp | m | merr | dfmag |
|----------|------|-------------|-----|---|------|-------|
| 2005 12 21 | 18:46:03.0 | 2453726.28198 | 300 | 12.549 | 0.007 | -0.019 |
| 2005 12 21 | 19:02:20.0 | 2453726.29329 | 300 | 12.550 | 0.007 | -0.013 |
| 2005 12 21 | 19:18:14.0 | 2453726.30433 | 300 | 12.551 | 0.007 | 0.012 |
| 2005 12 21 | 19:34:46.0 | 2453726.31581 | 300 | 12.545 | 0.008 | 0.007 |
| 2005 12 21 | 19:50:41.0 | 2453726.32686 | 300 | 12.537 | 0.008 | -0.002 |

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Figure 1. Finding chart of S5 0716+714 and the four comparison stars taken with the 60/90 Schmidt telescope and filter i on 2011 April 12 (JD 2,455,664).
2004 September 10 to 2006 March 29 are 1.200, 1.156, and 1.127 mag, respectively, and the variation amplitudes of the c, i, and o bands from 2006 December 6 to 2011 April 24 are 2.763, 2.614, and 2.522 mag, respectively. The amplitude of variation tends to decrease with decreasing frequency. The light curves continue to fluctuate during the whole monitoring period. The curves reach an extremely bright value on 2004 September 10 (JD 2,453,259), 2007 October 20 (JD 2,454,394), 2008 April 22 (JD 2,454,579), and 2010 September 28 (JD 2,455,468), and reach an extremely dark value on 2005 January 29 (JD 2,453,400), 2007 December 16 (JD 2,454,451), and 2011 April 24 (JD 2,455,676). The faintest optical state was recorded on 2007 December 16 (JD 2,454,451). Nilsson et al. (2008) acquired a deep i-band image of this object at that state and derived a redshift of 0.31 ± 0.08 by using the host galaxy as a "standard candle."

**Figure 2.** Light curves of S5 0716+714 in the c, e, i, m, and o bands.
The BL Lac object S5 0716+714 is one of the brightest BL Lac objects noted for its microvariability. In order to confirm whether or not the object varied within the course of a day, a quantitative assessment was carried out. For each of the 233 nights with an observational duration longer than 2 hr, we used a $\chi^2$ inspection to check whether or not there was any intraday variability (IDV; Penston & Cannon 1970; Kesteven et al. 1976; de Diego 2010). The $\chi^2$ value was compared with the critical value at the 95% confidence level. If the former was greater than the latter, then the null hypothesis that there was no variability was rejected. As a result, 138 nights (62% of 233) with IDV were identified. The fastest variation observed for S5 0716+714 was 0.117 mag within 1.1 hr in the $c$ band.
on 2011 March 5 (JD 2,455,626), as indicated by the bottom line with arrows in Figure 3. Similar work was performed by Villata et al. (2000); they found that the source exhibited strong variability with a similar trend but different amplitudes in all bands, and noted a monotonic brightness increase in the $B$ band for about 130 minutes. The steepest (linear) variation has a rising rate of 0.002 mag per minute and a duration of about 45 minutes.

Figure 4. $i-R$ diagrams between our $i$-band data and the $R$-band data of Villata et al. (top), Poon et al. (middle), and both (bottom).

Figure 5. Color–magnitude diagrams of the $em$ bands (top) and $co$ bands (middle) and the color index and light curves of the $co$ bands (bottom) during the whole monitoring period.
4. COMPARISON WITH OTHER DATA

In Section 2, we mentioned a formula for converting from i to R magnitude. This formula was derived from the observations of stars (Zhou et al. 2003). However, the spectral shape of blazars is quite different from that of stars. Thus, the conversion equation may be different for blazars. Therefore, we made a comparison between our i-band data and the R-band data of other authors in order to find an empirical relation between them. Villata et al. (2000) and Poon et al. (2009) performed intensive monitoring...
Figure 7. Light curves (left) and color–magnitude diagrams (right) of IDV data. The lines in the right panels are the linear fits to the data.

of the same object. Their data were adopted and matched in time with ours with a threshold of less than 0.02 days (or 28.8 minutes). As a result, 24 $R-i$ matches were found between Villata et al.’s data and our data and 97 $R-i$ matches were found between Poon et al.’s data and our data. The average time differences are 0.0038 and 0.0009 days for the 20 and 97 matches, respectively. Two $R-i$ diagrams were plotted in the top and middle panels of Figure 4. Two linear regressions yield the conversion formulae $R = (0.964 \pm 0.015) \times i + (0.279 \pm 0.187)$ and $R = (0.976 \pm 0.009) \times i + (0.059 \pm 0.123)$,
5. RELATION OF COLOR AND MAGNITUDE

The long-term color behavior of S5 0716+714 was studied based on our data. For the 2004–2006 data, the $e−m$ color was calculated and plotted versus $e$ magnitude in the top panel of Figure 5. For the data after 2006 December, the $c−o$ color was calculated and plotted versus $c$ magnitude in the central panel of Figure 5. The bottom panels illustrate how the $c−o$ color and $c$ magnitude changed with time. Despite the discontinuity in the top panel and significant scatter in the central panel, there is an overall bluer-when-brighter chromatism in both panels.

In order to investigate the color behavior of S5 0716+714 on an intermediate timescale, three episodes in our monitoring are isolated. They are from JDs 2,454,101 to 2,454,115, from JDs 2,454,429 to 2,454,463, and from JDs 2,455,597 to 2,455,629. These three episodes lasted from two weeks to more than one month. In these periods, we had relatively continuous monitoring, and the object showed significant variations. The light curves and the corresponding color–magnitude diagrams are plotted in Figure 6 for the three episodes. There are strong color–magnitude correlations. The correlation coefficients are 0.89, 0.78, and 0.82, respectively. A bluer-when-brighter chromatism on an intermediate timescale was also found by other authors (e.g., Villata et al. 2000; Wu et al. 2007). On intraday timescales, the object also displayed strong bluer-when-brighter chromatism. Some examples of this are given in Figure 7.

Depending on the balance between the escape, acceleration, and cooling of electrons with different energy, either soft (low energy) or hard (high energy) lags are expected (Kirk et al. 1998). This will lead to a loop-like path of the blazar’s state in a color–magnitude (or spectral index flux) diagram. The direction of this spectral hysteresis can be either clockwise or counterclockwise. This depends on the relative position between the observing frequency and the peak frequency of the synchrotron component in the spectral energy distribution (SED) of the blazar as well as the relative values of the acceleration, cooling, and escape timescales (Chiaberge & Ghisellini 1999; Dermer 1999).

In our monitoring, we obtained an inconspicuous loop flare on an internight timescale and an obvious loop flare on an intranight timescale, which are shown in Figure 8. The upper-left panel is the light curve of JDs 2,454,390 to 2,454,398, respectively. If all matches are plotted together, as shown in the bottom panel of Figure 4, then the linear regression yields the formula $R = (0.897 \pm 0.004) \times i + (1.127 \pm 0.048)$. 

![Figure 8. Light curves (left) and color–magnitude diagrams (right) for the internight (upper) and intranight (lower) timescales. The numbers in the right panels denote the time sequence.](image-url)
which shows a flare in the \(cio\) bands. The corresponding color–magnitude diagram is displayed in the upper-right panel, in which the numbers denote time sequence. There were no significant variations during these days, so we averaged the data in days to decrease system error. The points spread as a diagonal distribution in the color–magnitude diagram. The loop flare is far less obvious. The result of the intranight timescale, JD 2,455,621, is shown in the bottom of Figure 7. The numbers denote the time sequence. A counterclockwise loop can be seen in the lower-right panel. As Kirk et al. (1998) suggested, if the loop is traced counterclockwise, then there might be a flare propagating from lower to higher energy as suggested, if the loop is traced counterclockwise, then there might be a flare propagating from lower to higher energy as

concerned. A counterclockwise loop can be seen in the lower-right panel. As Kirk et al. (1998) suggested, if the loop is traced counterclockwise, then there might be a flare propagating from lower to higher energy as particles are gradually accelerated into the radiating window. The frequencies of the \(c\) and \(o\) bands are \(7.13 \times 10^{14}\) Hz and \(3.26 \times 10^{14}\) Hz. In 1999, Giommi et al. found that the frequencies are between \(10^{14}\) and \(10^{15}\) Hz. Our counterclockwise loop implies that the peak frequency of the short band in the SED of the blazar should be higher than \(7.13 \times 10^{14}\) Hz.

6. CONCLUSIONS

We monitored the BL Lac object S5 0716+714 in five intermediate optical wavebands from 2004 September to 2011 April using the 60/90 cm Schmidt telescope located at the Xinglong Station of the NAOC. We collected 8661 data points with an error of less than 0.05 mag. The data represent one of the largest databases obtained for an object in the optical domain and can be used to study both the long- and short-term flux and spectral variability of this object. They can also be correlated with data in radio, X-ray, or gamma-ray wavelengths in order to investigate the broadband behavior of this object. A simple analysis of the data indicates that the object was active most of the time. The overall amplitudes of the \(e\), \(i\), and \(m\) bands from 2004 September 10 to 2006 March 29 are 1.200, 1.156, and 1.127 mag, respectively, and the overall amplitudes of the \(c\), \(i\), and \(o\) bands from 2006 December 6 to 2011 April 24 are 2.763, 2.592, and 2.522 mag, respectively. The amplitude of variation tends to decrease with decreasing frequency. The bluer-when-brighter phenomenon was effectively confirmed on long, intermediate, and short timescales. This confirmation provides important support of the shock-in-jet model in which shocks propagate down the relativistic jet, accelerating particles and/or compressing magnetic fields, leading to an observed flux and spectral variability (Marscher & Gear 1985; Qian et al. 1991). There were 138 nights of IDV captured during the whole monitoring period.

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