Multicolor Optical Monitoring of the BL Lacertae Object S5 0716+714 during the 2012 Outburst

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Abstract

We monitored the BL Lacertae object S5 0716+714 in the optical bands during 2012 January and February with long time spans on intraday timescales (>5 hr) and high time resolutions. During this monitoring period, the object shows violent flaring activity in both short and intraday timescales. The object has a high duty cycle. The light curves detected as intraday variability show variability of various shapes. The variability amplitude is from 12.81% to 33.22%, and the average value is 19.92% ± 5.87%. The overall magnitude variabilities are \( \Delta B = 1^m 24, \Delta V = 1^m 42, \Delta R = 1^m 3, \) and \( \Delta I = 1^m 23. \) During the observations, the average change rate is \( \langle CR \rangle = 0.035 \pm 0.009 \text{ Mag/h} \) during the ascent and \( \langle CR \rangle = 0.035 \pm 0.014 \text{ Mag/h} \) during the descent. However, different cases are found on certain nights. There are good interband correlations but no significant time lags for intrady and short timescales. The results of the autocorrelation function show that the variability timescales range from 0.054 to 0.134 day. Most nights show a bluer-when-brighter (BWB) chromatic trend, a weak redder-when-brighter (RWB) trend is found, and a few nights show no correlation between magnitude and color index. The BWB trend appears in short timescales. During the flare, the spectral index exhibits a clockwise loop for internights. A shock-in-jet model and the shock wave propagating along a helical path are likely to explain the variability and color index variability.

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

Supporting material: machine-readable tables

1. Introduction

BL Lacertae (BL Lac) objects are the most extreme subclass of active galactic nuclei (AGNs), hosted in massive elliptical galaxies, the emission of which is dominated by a relativistic jet closely aligned with the line of sight. This implies the existence of a parent population of sources with a misaligned jet that has been identified with low-power Fanaroff–Riley type I radio galaxies. The most distinctive characteristic of the class is the weakness or absence of spectral lines that historically hindered the identification of their nature and thereafter proved to be a hurdle in the determination of their distance (Angel & Stockman 1980; Urry & Padovani 1995; Falomo et al. 2014). The spectrum of BL Lac objects, dominated by nonthermal emission over the whole electromagnetic range, together with bright compact radio cores, high luminosity, rapid and large amplitude flux variability at all frequencies, and strong polarization, make these sources become an optimal laboratory for high-energy astrophysics. The broadband spectral energy distributions of BL Lac objects have a double-peaked structure. The low-energy peak at the IR-optical-UV band is explained with the synchrotron emission of relativistic electrons, and the high-energy peak at the GeV–TeV gamma-ray band is due to the inverse Compton scattering (e.g., Dermer 1995; Dermer & Schlickeiser 2002; Bottcher 2007). The hadronic model is an alternative explanation for the high-energy emission from BL Lac objects (e.g., Dermer et al. 2012). According to their differences in synchrotron peak frequency, BL Lac objects can be divided into three categories (Abdo et al. 2010): low-synchrotron-peaked \( (\nu^s_{\text{peak}} < 10^{14} \text{ Hz}) \), intermediate-synchrotron-peaked (ISP; \( 10^{14} \text{ Hz} < \nu^s_{\text{peak}} < 10^{15} \text{ Hz} \)), and high-synchrotron-peaked \( (10^{15} \text{ Hz} < \nu^s_{\text{peak}}) \).

The variabilities of BL Lac objects at frequencies ranging from radio to TeV bands have been detected (e.g., Rani et al. 2013; Liao et al. 2014; Bartoli et al. 2016). The timescales of variabilities are from years to minutes (e.g., Fan 2005; Zhang et al. 2008a; Fan et al. 2009a, 2014; Poon et al. 2009). Brightness changes of a few tenths or hundredths of a magnitude during hours or less are often observed as intrady variability (IDV) or microvariability (Wagner & Witzel 1995). Short-term variability (STV) has timescales of days to weeks, even months, and long-term variability ranges from months to years (Gupta et al. 2008a; Dai et al. 2015). IDV has been confirmed as the intrinsic nature of the BL Lac objects and has become a subject of intense activity, as its physical mechanisms are not understood well (e.g., Bai et al. 1998; Zhang et al. 2008b; Fan et al. 2009b; Chandra et al. 2011; Dai et al. 2015; Xiong et al. 2016). The shortest variability (microvariability) timescales are important for understanding the geometry of jets, the magnetic field, and black hole mass, because they provide a possible minimum size of variation sources (e.g., Zhang et al. 2008b; Fan et al. 2009b, 2014; Gupta et al. 2009; Rani et al. 2010; Dai et al. 2015; Xiong et al. 2016). The spectral index (or color behavior) is an important but simple factor to explore the variability mechanism (e.g., Wu et al. 2007; Zheng et al. 2008; Gu & Ai 2011).

The object S5 0716+714 (R.A. = 07\(^{h}\)21\(^{m}\)53\(^{s}\).4, decl. = 71°20′36″, J2000) is classified as an ISP BL Lac object.
It was discovered in the Bonn-NRAO radio survey of flat-spectrum radio sources with a 4.9 GHz flux greater than 1 Jy (Kuehr et al. 1981). Radio maps detected a compact core-jet structure and an extended emission resembling that of an FR II object (Antonucci et al. 1986; Gabuzda et al. 1998). The source has a featureless optical continuum with a redshift of 0.31 ± 0.08 derived by using the host galaxy as a standard candle (Nilsson et al. 2008). Danforth et al. (2013) used intervening absorption systems to set the redshift range 0.2315 < z < 0.3407. It is one of the brightest BL Lac objects that is highly variable from radio to gamma-ray bands with a very high duty cycle (DC; Wagner & Witzel 1995). Because of its high power and lack of signs of ongoing accretion or surrounding gas, the source is an ideal candidate to explore multiwavelength nonthermal emission. The flux and spectral variations of S5 0716+714 have been extensively studied over the entire electromagnetic spectrum (Wagner & Witzel 1995; Heidt & Wagner 1996; Wagner et al. 1996; Ghisellini et al. 1997; Sagar et al. 1999; Villata et al. 2000, 2008; Qian et al. 2002; Raiteri et al. 2003; Nesci et al. 2005; Wu et al. 2000, 2005, 2007; Forschini et al. 2006; Gu et al. 2006; Montagni et al. 2006; Ostorero et al. 2006; Stalin et al. 2006, 2009; Gupta et al. 2008b, 2009, 2012; Zhang et al. 2008b; Anderhub et al. 2009; Vittorini et al. 2009; Rani et al. 2010, 2014; Carini et al. 2011; Chandra et al. 2011, 2015; Zhang et al. 2012; Dai et al. 2013; Larionov et al. 2013; Hu et al. 2014; Liao et al. 2014; Bhattacharyya et al. 2015, 2016; Dai et al. 2015; Wierzcholska & Siejkowski 2015, 2016; Agarwal et al. 2016; Man et al. 2016; Li et al. 2017). In the observations of Poon et al. (2009), the object showed four fast flares with amplitudes ranging from 0.3 to 0.75 mag. Typical timescales of microvariability ranged from 2 to 8 hr. Strong bluer-when-brighter (BWB) chromatism was found on internight timescales. However, a different spectral behavior was found on intranight timescales. A possible time lag of ∼1.5 minutes between the R and I bands was observed on internight timescales. But, from the results of Carini et al. (2011), there are no significant lags between the B- and I-band flux variations. During nearly continuous multiband observations, Bhattacharyya et al. (2016) found that the source displayed pronounced variability and BWB spectral evolution. The results from Hu et al. (2014) showed a strong BWB trend on internight timescales and a mild BWB trend on internight timescales for the source. Dai et al. (2013, 2015) found that BWB chromatism was observed in long, intermediate, and short timescales. Stalin et al. (2006) and Agarwal et al. (2016) found no evidence of spectral changes with source brightness on either internight or intranight timescales for S5 0716+714, even when the target was in a flaring state.

In order to further explore the characteristics of IDV and STV timescales and spectral properties on both intranight and internight timescales, we monitored the source in multicolor optical bands during the 2012 outburst. Due to the high temporal resolution and long time spans on intraday timescales, more accurate results can be obtained. This paper is organized as follows. The observations and data analysis are described in Section 2. Section 3 presents the results. Discussion and conclusions are reported in Section 4.

### 2. Observations and Data Analysis

Our optical observations were carried out using the 60 cm BOOTES-4 auto-telescope that is located at the Lijiang Observatory of the Yunnan Observatories of the Chinese Academy of Sciences, where the longitude is 100°01′51″E and the latitude is 26°42′32″N, with an altitude of 3193 m. The telescope’s main objective is to observe gamma-ray bursts and blazars. Further details about it are given in Table 1. During our observations, the telescope was equipped with standard Johnson UBV and Cousins RI filters. The optical observations in the B, V, R, and I bands were in a corresponding cyclic mode. Time resolutions for most of the nights are less than 6 minutes, and time spans on a night are more than 5 hr (Table 2). The time intervals between the V and R bands range from 30 to 131 s, and most of the nights have time intervals less than 50 s. The typical exposure times in the V, R, and I bands are 60, 40, 40, and 40 s, respectively. Thus, our observations with high temporal resolution (few minutes) can be considered quasi-simultaneous measurements. All images have been prereduced with the CCDRED package, and observing data were processed using the photometric tool DAOPHOT in the IRAF software package. The flat-field images were taken at dusk and dawn when possible. The bias images were taken at the beginning and end of the observation. In order to determine aperture radius, we used different aperture radii (1.5 × FWHM, 1.7 × FWHM, 2 × FWHM, 2.5 × FWHM, and 3 × FWHM) to carry out aperture photometry for all observations per night. We found that the low-aperture radius had a better mean signal-to-noise ratio (S/N) on a night, i.e., 1.5 × FWHM had the best mean S/N on a night. Moreover, we plotted the aperture radii (from 1 × FWHM to 4 × FWHM) versus magnitudes for different frames on a night. The results showed that the change rate of increasing brightness was rapid from 1 × FWHM to 1.7 × FWHM and quickly slowed after 1.7 × FWHM. When the aperture radius was near 3 × FWHM, the brightness stayed almost constant. So, considering the best S/N and constant brightness, we made a compromise, i.e., the aperture radius of
1.7 × FWHM was selected. In order to obtain pure skylight background, the target and other objects should be excluded from the sky annulus. The inner radius and width of the sky annulus were 5 × FWHM and 2 × FWHM, respectively. After correcting the flat field and bias, aperture photometry was performed, and instrumental aperture magnitudes were obtained. The finding chart of S5 0716+714 was taken from the website. From the above finding chart, we chose the marked 3 and 5 stars as comparison stars, because their magnitudes were similar to that of the blazar and the differential magnitude between the 3 and 5 stars was the smallest variation among the comparison stars. Following Zhang et al. (2004, 2008a), Fan et al. (2014), and Bai et al. (1998), the source magnitude was given as the average of the values derived with respect to the two comparison stars. The magnitudes of the comparison stars in the field of S5 0716+714 were taken from Villata et al. (1998) and Ghisellini et al. (1997). The observing uncertainty on each night was the rms error of the differential magnitude between the two comparison stars. The rms errors of the photometry on a certain night were

| Date (UT) | Band | Number of Observations | Time Span (hr) | Time Resolution (minutes) |
|-----------|------|------------------------|----------------|--------------------------|
| 2012 Jan 27 | I    | 126                    | 6.9            | 3.2                      |
| 2012 Jan 27 | R    | 126                    | 6.9            | 3.2                      |
| 2012 Jan 27 | V    | 126                    | 6.9            | 3.2                      |
| 2012 Jan 27 | B    | 126                    | 6.9            | 3.2                      |
| 2012 Jan 28 | I    | 74                     | 7.2            | 5.9                      |
| 2012 Jan 28 | R    | 74                     | 7.2            | 5.9                      |
| 2012 Jan 28 | V    | 74                     | 7.2            | 5.6                      |
| 2012 Jan 29 | I    | 72                     | 7.2            | 5.9                      |
| 2012 Jan 29 | R    | 71                     | 7.2            | 5.9                      |
| 2012 Jan 29 | V    | 73                     | 7.2            | 5.9                      |
| 2012 Jan 29 | B    | 73                     | 7.2            | 5.9                      |
| 2012 Jan 30 | I    | 71                     | 6.9            | 5.9                      |
| 2012 Jan 30 | R    | 71                     | 6.9            | 5.9                      |
| 2012 Jan 30 | V    | 71                     | 6.9            | 5.9                      |
| 2012 Jan 30 | B    | 71                     | 6.9            | 5.9                      |
| 2012 Jan 31 | I    | 66                     | 6.8            | 5.9                      |
| 2012 Jan 31 | R    | 66                     | 6.8            | 5.9                      |
| 2012 Jan 31 | V    | 66                     | 6.8            | 5.9                      |
| 2012 Jan 31 | B    | 67                     | 6.8            | 5.9                      |
| 2012 Feb 01 | I    | 58                     | 5.6            | 5.9                      |
| 2012 Feb 01 | R    | 59                     | 5.7            | 5.9                      |
| 2012 Feb 01 | V    | 59                     | 5.7            | 5.9                      |
| 2012 Feb 01 | B    | 59                     | 5.7            | 5.9                      |
| 2012 Feb 02 | I    | 58                     | 6.8            | 5.9                      |
| 2012 Feb 02 | R    | 58                     | 6.8            | 5.9                      |
| 2012 Feb 02 | V    | 57                     | 6.6            | 5.9                      |
| 2012 Feb 02 | B    | 59                     | 6.8            | 5.9                      |
| 2012 Feb 03 | I    | 30                     | 5.1            | 3.7                      |
| 2012 Feb 03 | R    | 30                     | 5.1            | 3.7                      |
| 2012 Feb 03 | V    | 30                     | 5.1            | 3.7                      |
| 2012 Feb 03 | B    | 28                     | 5.0            | 3.7                      |
| 2012 Feb 04 | I    | 78                     | 6.2            | 4.7                      |
| 2012 Feb 04 | R    | 78                     | 6.2            | 4.7                      |
| 2012 Feb 04 | V    | 78                     | 6.2            | 4.7                      |
| 2012 Feb 04 | B    | 78                     | 6.2            | 4.7                      |
| 2012 Feb 05 | I    | 51                     | 7.2            | 4.7                      |
| 2012 Feb 05 | R    | 51                     | 7.2            | 4.7                      |
| 2012 Feb 05 | V    | 51                     | 7.1            | 4.7                      |
| 2012 Feb 05 | B    | 53                     | 7.0            | 4.7                      |
| 2012 Feb 06 | I    | 35                     | 6.4            | 11.4                     |
| 2012 Feb 06 | R    | 35                     | 6.4            | 11.4                     |
| 2012 Feb 06 | V    | 35                     | 6.4            | 11.4                     |
| 2012 Feb 07 | I    | 66                     | 6.9            | 4.5                      |
| 2012 Feb 07 | R    | 67                     | 6.9            | 4.5                      |
| 2012 Feb 07 | V    | 65                     | 6.7            | 4.5                      |
| 2012 Feb 08 | I    | 94                     | 7.0            | 4.5                      |
| 2012 Feb 08 | R    | 94                     | 7.0            | 4.5                      |
| 2012 Feb 08 | V    | 93                     | 7.0            | 4.5                      |
Table 3

| Date (UT)    | MJD        | Magnitude | σ   |
|--------------|------------|-----------|-----|
| 2012 Jan 27  | 55953.6895 | 14.7430   | 0.0225 |
| 2012 Jan 27  | 55953.6920 | 14.7385   | 0.0225 |
| 2012 Jan 27  | 55953.6943 | 14.6920   | 0.0225 |
| 2012 Jan 27  | 55953.6966 | 14.7290   | 0.0225 |
| 2012 Jan 27  | 55953.6988 | 14.7315   | 0.0225 |

Note. Column (1) is the universal time (UT) of observation, column (2) is the corresponding modified Julian day (MJD), column (3) is the magnitude, and column (4) is the rms error.

Table 4

| Date (UT)    | MJD        | Magnitude | σ   |
|--------------|------------|-----------|-----|
| 2012 Jan 27  | 55953.6901 | 14.2280   | 0.0133 |
| 2012 Jan 27  | 55953.6924 | 14.2300   | 0.0133 |
| 2012 Jan 27  | 55953.6946 | 14.2095   | 0.0133 |
| 2012 Jan 27  | 55953.6969 | 14.2405   | 0.0133 |
| 2012 Jan 27  | 55953.6992 | 14.2090   | 0.0133 |

Note. The meaning of each column is the same as in Table 3.

Table 5

| Date (UT)    | MJD        | Magnitude | σ   |
|--------------|------------|-----------|-----|
| 2012 Jan 27  | 55953.6904 | 13.8020   | 0.0112 |
| 2012 Jan 27  | 55953.6927 | 13.8100   | 0.0112 |
| 2012 Jan 27  | 55953.6950 | 13.8215   | 0.0112 |
| 2012 Jan 27  | 55953.6973 | 13.8045   | 0.0112 |
| 2012 Jan 27  | 55953.6996 | 13.8015   | 0.0112 |

Note. The meaning of each column is the same as in Table 3.

Table 6

| Date (UT)    | MJD        | Magnitude | σ   |
|--------------|------------|-----------|-----|
| 2012 Jan 27  | 55953.6908 | 13.2665   | 0.0117 |
| 2012 Jan 27  | 55953.6931 | 13.2760   | 0.0117 |
| 2012 Jan 27  | 55953.6954 | 13.2750   | 0.0117 |
| 2012 Jan 27  | 55953.6976 | 13.2590   | 0.0117 |
| 2012 Jan 27  | 55953.6999 | 13.2750   | 0.0117 |

Note. The meaning of each column is the same as in Table 3.

In order to quantify the IDV of the object, we have employed three statistical analysis techniques: the C-test, F-test, and one-way analysis of variance (ANOVA) (e.g., de Diego 2010; Goyal et al. 2012; Hu et al. 2014; Agarwal & Gupta 2015; Dai et al. 2015; Xiong et al. 2016). The blazar is considered variable (V) if the light curve satisfies the criteria of the C-test, F-test, and ANOVA. The blazar is considered probably variable (PV) if only one of the above three criteria is satisfied. The blazar is considered nonvariable (N) if none of the criteria are met. Romero et al. (1999) introduced the variability parameter, C, as the average value between C1 and C2,

\[
C_i = \frac{\sigma_{(BL-StarA)}}{\sigma_{(StarA-StarB)}}, \quad C_2 = \frac{\sigma_{(BL-StarB)}}{\sigma_{(StarA-StarB)}},
\]

where (BL-StarA), (BL-StarB), and (StarA-StarB) are the differential instrumental magnitudes of the blazar and comparison stars A, the blazar and comparison star B, and comparison stars A and B, respectively. Here σ is the standard deviation of the differential instrumental magnitudes. The adopted variability criterion requires \( C \geq 2.576 \), which corresponds to a 99% confidence level. Despite the very common use of C-statistics, de Diego (2010) pointed out that it has severe problems. The F-test is considered to be a proper statistic to quantify the IDV (e.g., de Diego 2010; Joshi et al. 2011; Goyal et al. 2012; Hu et al. 2014; Agarwal & Gupta 2015; Xiong et al. 2016). The value of F is calculated as

\[
F_1 = \frac{\text{Var}(BL-StarA)}{\text{Var}(StarA-StarB)}, \quad F_2 = \frac{\text{Var}(BL-StarB)}{\text{Var}(StarA-StarB)},
\]

where Var(BL-StarA), Var(BL-StarB), and Var(StarA-StarB) are the variances of the differential instrumental magnitudes. The F-value from the average of \( F_1 \) and \( F_2 \) is compared with the critical F-value, \( F_{\nu_h, \nu_b}^{\alpha} \), where \( \nu_h \) and \( \nu_b \) are the number of degrees of freedom for the blazar and comparison star, respectively (\( \nu = N - 1 \)), and \( \alpha \) is the significance level set as 0.01 (2.6\( \sigma \)). If the average F-value is larger than the critical value, the blazar is variable at a confidence level of 99%. De Diego (2010) reported that the ANOVA is a powerful and robust estimator for micromotions. It does not rely on error measurement but derives the expected variance from subsamples of the data. The one-way ANOVA test divides the data into many groups. Then, it compares the variances between intergroups and intragroups. From Appendix A3 of de Diego (2010), the statistics

\[
F = \frac{\sum_{j=1}^{k} \sum_{i=1}^{\eta_j} (y_{ij} - \bar{y})^2 / (k - 1)}{\sum_{j=1}^{k} \sum_{i=1}^{\eta_j} (\bar{y}_{ij} - \bar{y})^2 / (N - k)} = \frac{\text{SS}_G / (k - 1)}{\text{SS}_R / (N - k)},
\]

where \( y_{ij} \) represents the \( i \)th observation (with \( i = 1, 2, ..., \eta_j \) ) on the \( j \)th group (with \( j = 1, 2, ..., k \) ), \( \bar{y} \) is the mean of the whole data set, \( \bar{y}_{ij} \) is the mean on the \( j \)th group, \( k \) is the number of groups, and \( N \) is the number of the whole data set. The \( \text{SS}_G \) and \( \text{SS}_R \) are the between-groups and within-groups sum of squares, respectively. Considering the time of exposure, we bin the data in a group of five observations (see de Diego 2010 and Xiong et al. 2016).
2016 for details). If the measurements in the last group are less than 5, then it is merged with the previous group. The critical value of ANOVA can be obtained by \( F_{\nu_1,\nu_2} \) in the F-statistics, where \( \nu_1 = k - 1, \nu_2 = N - k \), and \( \alpha \) is the significance level set at 0.01. If the F-value from Equation (4) exceeds the critical value \( F_{\nu_1,\nu_2} \), the blazar is variable at a confidence level of 99%. In order to further quantify the reliability of variability, the value of \( S_{\gamma} \) can be calculated as (e.g., Hu et al. 2014)

\[
S_{\gamma} = m_i - m, \quad x = V, R, I,
\]

where \( m_i \) and \( m \) are same as in Equation (1). The variability amplitude (Amp) can be calculated by (Heidt & Wagner 1996)

\[
\text{Amp} = 100 \times \sqrt{(A_{\text{max}} - A_{\text{min}})^2 - 2 \sigma^2 \%},
\]

where \( A_{\text{max}} \) and \( A_{\text{min}} \) are the maximum and minimum magnitude, respectively, of the light curve for the night being considered, and \( \sigma \) is the rms error. When estimating the variability amplitude, we only consider the nights detected as variability.

The DC is calculated as (Romero et al. 1999; Stalin et al. 2009; Hu et al. 2014)

\[
\text{DC} = 100 \sum_{i=1}^{n} N_i (1/\Delta T_i) \%,
\]

where \( \Delta T_i = \Delta T_{\text{obs}}(1+z)^{-1}, z \) is the redshift of the object, and \( \Delta T_{\text{obs}} \) is the duration of the monitoring session of the \( i \)th night. Note that since the monitoring durations on different nights for a given source were not always equal, the computation of DC has been weighted by the actual monitoring duration \( \Delta T_i \) on the \( i \)th night. The value of \( N_i \) will be set to 1 if IDV is detected, otherwise \( N_i = 0 \) (Goyal et al. 2013).

3. Results

3.1. Variability

The analysis results on IDV are shown in Table 7. From Table 7, it can be seen that IDV is found on seven nights with at least two bands detected as IDV on a night. The light curves detected as IDV are given in Figure 1, which shows the variability of various shapes. For the seven nights, we also check the color variations on intraday timescales. However, the results from three statistical tests do not show significant color variations on intraday timescales. The rest of the nights are considered PV, except for the I band on 6 February. On 27 January, the brightness first increases and then decreases along the arc. On 28 January, the brightness first increases and then decreases, and finally increases. On 29 January, the brightness first decreases and then increases along the symmetrical arc. On 30 January, the brightness changes are similar to those of 29 January but not along the symmetrical arc. On 1 and 8 February, the brightness continues to increase, while on 4 February, the brightness continues to decrease. The corresponding changes of magnitude and change rate are seen in Table 8. When calculating the change rate, we first determine increasing or decreasing time points and then use the slope from error-weighted linear regression analysis as the change rate. The results from Table 8 show that the average change rate is \( \langle CR \rangle = 0.035 \pm 0.009 \text{ Mag/h} \) during the ascent and \( \langle CR \rangle = 0.035 \pm 0.014 \text{ Mag/h} \) during the descent. The average change rates between the ascent and descent are equal.

However, different cases are found on certain nights. The corresponding times of variation range from 47 to 274 minutes. On 29 January, the increasing and decreasing change rates are close. The correlations between variability amplitude and source average brightness are shown in Figure 2. Although Figure 2 shows trends/tendencies of larger amplitude with brighter magnitude for the I and R bands, the analysis of the nonparametric Spearman rank indicates that there are no significant correlations between variability amplitude and source average brightness for different wavebands (significance level \( P_1 = 0.1, P_2 = 0.1, P_3 = 0.8, \) and \( P_4 = 0.7 \)). The variability amplitude is from 12.81% to 33.22%, and the average value is 19.92% \pm 5.87% (Table 7 and Figure 2). Making use of Equation (7), we calculate the DC of the IDV. The DC is 44% for S5 (0716+714) (98%, if PV cases are also included).

Short-term light curves and the color index are given in Figure 3. From Figure 3, we can see that, on the whole, the BL Lac object continues to brighten with a remarkable first brightening and then darkening peak during the short term, and the average color index on each night remains approximately constant during this period. The overall magnitude variabilities are \( \Delta B = 1^n 24, \Delta V = 1^n 42, \Delta R = 1^n 53, \) and \( \Delta I = 1^n 23 \). The magnitude distributions in the \( B, V, R, \) and \( I \) bands are 14\text{th} 89 < \( B < 13\text{th} 65, 14\text{th} 45 < V < 13\text{th} 03, 13\text{th} 94 < R < 12\text{th} 64, \) and \( 13\text{th} 39 < I < 12\text{th} 16 \), respectively. The average values of the magnitudes and color index are \( \langle B \rangle = 14\text{th} 35 \pm 0^n 31, \langle V \rangle = 13\text{th} 73 \pm 0^n 36, \langle R \rangle = 13\text{th} 33 \pm 0^n 34, \langle I \rangle = 12\text{th} 81 \pm 0^n 33, \) and \( \langle V - R \rangle = 0^n 39 \pm 0^n 04 \).

3.2. Cross-Correlation Analysis and Variability Timescales

Following Giveon et al. (1999), Wu et al. (2007), Liu et al. (2008), Liao et al. (2014), and Xiong et al. (2016), we use the \( z \)-transformed discrete correlation function (ZDCF; Alexander 1997) to perform the interband correlation analysis and search for the possible interband time delay. The ZDCF code of Alexander (1997) can automatically set how many bins are given and be used to calculate the interband correlation and autocorrelation function (ACF). In order to achieve statistical significance, the minimal number of points per bin is 10. The results of the ZDCF for all data are given in Figure 4. As an illustration, the results of the ZDCF on four nights are given in Figure 4. They show that there are good interband correlations but no significant time lags.

The zero-crossing time of the ACF is a well-defined quantity and used as a characteristic variability timescale (e.g., Netzer et al. 1996; Alexander 1997; Giveon et al. 1999; Liu et al. 2008). The zero-crossing time is the shortest time it takes the ACF to fall to zero (Alexander 1997). If there is an underlying signal in the light curve with a typical timescale, then the width of the ACF peak near zero time lag will be proportional to this timescale (Giveon et al. 1999; Liu et al. 2008). The width of the ACF may be related to the characteristic size scale of the corresponding emission region (Chatterjee et al. 2012). Another function used in variability studies to estimate the variability timescales is the first-order structure function (SF; e.g., Trevese et al. 1994). There is a simple relation between the ACF and the SF (Giveon et al. 1999). We therefore perform only an ACF analysis on our light curves. The ACF was estimated by the ZDCF. We only analyze the nights detected as IDV. The results of the ACF analysis are given in Figure 5. The results of the ACF analysis on 4 and 8 February are not
shown in Figure 5 because all of the ACF values of the two nights are more than zero. Following Givens et al. (1999), we then use a least-squares procedure to fit a fifth-order polynomial to the ACF, with the constraint that ACF \( \tau = 0 \) = 1. From the fitting results, it is seen that the variability timescales range from 0.054 to 0.134 day.

### 3.3. Correlation between Magnitude and Color Index

For the color index, we use the correction factors from Schlafly & Finkbeiner (2011) to correct the Galactic extinction. In order to minimize the bias introduced by the dependence of the color index on the magnitudes, brightness was calculated by averaging the magnitudes of the two bands used to calculate the

### Table 7

Results of IDV Observations of S5 0716+714

| Date       | Band | C   | F   | F1(99) | F2(99) | Ave (mag) |
|------------|------|-----|-----|--------|--------|-----------|
| 2012 Jan 27| I    | 3.69| 13.60| 1.53   | 52.89  | 17.12     |
| 2012 Jan 27| R    | 4.25| 18.08| 1.51   | 58.32  | 18.23     |
| 2012 Jan 27| V    | 3.66| 13.78| 1.53   | 36.13  | 18.10     |
| 2012 Jan 27| B    | 2.78| 7.75 | 1.53   | 8.02   | 17.92     |
| 2012 Jan 28| I    | 4.00| 15.99| 1.73   | 27.60  | 15.61     |
| 2012 Jan 28| R    | 3.93| 15.46| 1.73   | 48.93  | 12.85     |
| 2012 Jan 28| V    | 2.93| 8.60 | 1.73   | 31.00  | 25.09     |
| 2012 Jan 28| B    | 2.73| 7.44 | 1.74   | 28.37  | 17.13     |
| 2012 Jan 29| I    | 1.81| 3.33 | 1.75   | 5.09   | 24.65     |
| 2012 Jan 29| R    | 2.60| 6.76 | 1.75   | 24.43  | 17.13     |
| 2012 Jan 29| V    | 3.06| 9.37 | 1.74   | 26.68  | 19.09     |
| 2012 Jan 30| I    | 2.26| 5.12 | 1.74   | 14.55  | 24.54     |
| 2012 Jan 30| R    | 3.79| 14.33| 1.75   | 42.76  | 24.66     |
| 2012 Jan 30| V    | 2.75| 7.56 | 1.75   | 40.27  | 18.20     |
| 2012 Jan 31| I    | 1.86| 3.46 | 1.79   | 6.01   | 14.19     |
| 2012 Jan 31| R    | 1.69| 2.85 | 1.79   | 6.41   | 15.99     |
| 2012 Jan 31| V    | 2.31| 5.33 | 1.79   | 5.78   | 18.24     |
| 2012 Feb 01| I    | 1.82| 3.31 | 1.78   | 4.85   | 24.53     |
| 2012 Feb 01| R    | 1.69| 2.85 | 1.79   | 6.41   | 15.99     |
| 2012 Feb 01| V    | 2.31| 5.33 | 1.79   | 5.78   | 18.24     |

Note. Column (1) is the date of observation, column (2) is the observed band, column (3) is the value of the C-test, column (4) is the average F-value, column (5) is the critical F-value with 99% confidence level, column (6) is the F-value of ANOVA, column (7) is the critical F-value of ANOVA with 99% confidence level, column (8) is the variability status (V: variable; PV: probable variable; N: nonvariable), and columns (9) and (10) are the variability amplitude and daily average magnitudes, respectively.
We concentrate on the $V - R$ index and $VR^2$ magnitude because the $V - R$ index is frequently studied. Figure 6 shows the correlations between the $V - R$ index and $VR^2$ magnitude on intraday and short timescales. The results of the analysis of Spearman rank are given in Table 9. The table shows that eight nights have significant correlations between the $V - R$ index and $(V + R)/2$ magnitude, and one night has a significant anticorrelation between the $V - R$ index and $(V + R)/2$ magnitude (significance level $P < 0.05$ confidence level). Moreover, four nights have no significant correlations between the $V - R$ index and $(V + R)/2$ magnitude ($P > 0.05$). For short timescales, the significant correlation
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Table 8
Results of Change Rate

| Date (UT)  | Band | MJD*  | Magnitude* | CR (Mag/h) |
|------------|------|-------|------------|------------|
| 2012 Jan 27 | B    | 55953.6895 | 14.743     | 0.037      |
|            |      | 55953.8845 | 14.517     | −0.075     |
|            |      | 55953.9619 | 14.782     | −0.032     |
|            | V    | 55953.7152 | 14.248     | 0.039      |
|            |      | 55953.8573 | 14.066     | −0.026     |
|            |      | 55953.9668 | 14.188     | −0.032     |
|            | R    | 55953.7064 | 13.825     | 0.038      |
|            |      | 55953.8714 | 13.642     | −0.04      |
|            |      | 55953.9671 | 13.763     | −0.03     |
|            | I    | 55953.7091 | 13.291     | 0.03      |
|            |      | 55953.8879 | 13.119     | −0.031     |
|            |      | 55953.9744 | 13.225     | −0.025     |
| 2012 Jan 28 | B    | 55954.6851 | 14.889     | 0.034      |
|            |      | 55954.8249 | 14.749     | −0.032     |
|            | V    | 55954.6898 | 14.828     | −0.032     |
|            |      | 55954.8659 | 14.380     | 0.032      |
|            |      | 55954.8052 | 14.255     | −0.032     |
|            | R    | 55954.6886 | 14.322     | −0.032     |
|            |      | 55954.8685 | 13.942     | 0.031      |
|            |      | 55954.8346 | 13.821     | −0.054     |
|            |      | 55954.8674 | 13.882     | −0.032     |
|            | I    | 55954.6871 | 13.380     | 0.029      |
|            |      | 55954.8352 | 13.281     | −0.032     |
|            |      | 55954.9049 | 13.328     | −0.032     |
| 2012 Jan 29 | V    | 55955.6805 | 13.831     | −0.026     |
|            |      | 55955.8317 | 13.960     | 0.027      |
|            |      | 55955.9753 | 13.842     | −0.032     |
|            | R    | 55955.6811 | 13.429     | −0.02      |
|            |      | 55955.8405 | 13.534     | 0.03       |
|            |      | 55955.9718 | 13.434     | −0.032     |
|            | I    | 55955.6898 | 12.975     | −0.032     |
|            |      | 55956.8345 | 13.111     | 0.024      |
|            |      | 55956.9745 | 13.013     | −0.025     |
| 2012 Feb 01 | V    | 55958.8348 | 13.694     | 0.054      |
|            |      | 55958.9539 | 13.522     | 0.052      |
|            | R    | 55958.8313 | 13.285     | 0.052      |
|            |      | 55958.9586 | 13.136     | −0.032     |
|            | I    | 55958.8319 | 12.773     | 0.043      |
|            |      | 55959.9798 | 12.607     | −0.032     |
| 2012 Feb 04 | V    | 55961.7198 | 13.616     | −0.019     |
|            |      | 55961.9772 | 13.399     | −0.032     |
|            | R    | 55961.7205 | 13.185     | −0.024     |
|            |      | 55961.9778 | 13.451     | −0.032     |
|            | I    | 55961.7211 | 12.636     | −0.027     |
|            |      | 55961.9718 | 12.868     | −0.032     |
| 2012 Feb 08 | R    | 55965.6871 | 12.979     | 0.039      |
|            |      | 55965.9327 | 12.654     | 0.038      |
|            | I    | 55965.6911 | 12.457     | 0.034      |
|            |      | 55965.9430 | 12.162     | −0.032     |

Note. The star symbol stands for increasing/decreasing time points and corresponding magnitudes. When calculating the change rate, we consider the coefficients of correlation ≥0.7; for CR, the positive and negative signs are increasing brightness and decreasing brightness, respectively.

4. Discussion and Conclusions

4.1. Variability

We have observed the BL Lac object S5 0716+714 with long time spans on intraday timescales (>5 hr) and high time resolutions. During this monitoring period, the object shows violent flaring activity on both short-term and intraday timescales. The DC is 44% for S5 0716+714 (98%, if PV cases are also included). If we only consider the F-test and ANOVA, the DC is 74%. So, similar to the previous results (e.g., Stalin et al. 2009; Chandra et al. 2011; Hu et al. 2014; Agarwal et al. 2016), the object has a high DC value. The light curves detected as IDV show variability of various shapes. The variability amplitude is from 12.81% to 33.22%, and the average value is 19.92% ± 5.87%. The overall magnitude variabilities are 

\[ \Delta V = 1.2 \pm 0.4 \]

\[ \Delta R = 1.2 \pm 0.3 \]

\[ \Delta I = 1.2 \pm 0.3 \]

During the observations, the average change rate is (CR) = 0.035 ± 0.009 Mag/h during the ascent and (CR) = 0.035 ± 0.014 Mag/h during the descent, i.e., the average change rates between the ascent and descent are equal. However, different cases are found on certain nights. On 29 January, the brightness first decreases and then increases along the symmetrical arc. Also, the increasing and decreasing change
rates are close on the night. Previous observations (Wu et al. 2007; Sasada et al. 2008; Zhang et al. 2008b; Poon et al. 2009; Stalin et al. 2009; Chandra et al. 2011, Wu et al. 2012; Hu et al. 2014; Dai et al. 2015; Agarwal et al. 2016; Man et al. 2016) found that many of the common cases of variability in the object are as follows: (i) the brightness continues to increase/decrease; (ii) the brightness first decreases and then increases, or vice versa, but not along the symmetrical arc; (iii) the brightness first increases and then decreases, and finally increases; and (iv) the brightness first increases and then decreases along the arc. These cases of variability are shown in Figure 1. Compared with these cases of variability, the type of variability on 29 January is rarely found on intraday timescales. From Figure 3, we can see that the brightness is likely to increase from 28 to 29 January and then decrease from 29 to 30 January. In addition, the color index on 29 January has a BWB trend. Therefore, the variability on the night is likely related to relativistic jet activities (see the following discussions).

For a blazar, these components (jet, accretion disk, and host galaxy) could contribute to the emission of optical band. The

**Figure 3.** Short-term light curves of S5 0716+714 in the B, V, R, and I bands and color index V − R.
host galaxy is more than 4 mag fainter than the brightness of S5 0716+714 (Nilsson et al. 2008). During the outburst period, the accretion disk radiation is always overwhelmed by the Doppler boosting flux from the relativistic jet. Then, the variability of S5 0716+714 in the outburst state is likely to have an association with jet activities. The shock-in-jet model

Figure 4. ZDCF plots. The first row of panels give the results of the ZDCF for all data. The rest of the panels are the results of the ZDCF for intraday timescales.
Figure 5. Results of the ACF analysis. The red dashed line is a fifth-order polynomial least-squares fit.
is often used to explain the IDV/STV. The shocks propagate down relativistic jets, sweeping the emitting regions. If the emitting regions have intrinsic variations (magnetic field, particle velocity/distribution, a large number of new particles injected), then we can see the IDV/STV (Marscher & Gear 1985; Xiong et al. 2017). In addition to intrinsic variations, geometrical variations could also bring in flux variations. Rani et al. (2015) presented a high-frequency, very long baseline interferometry kinematical study of S5 0716 +714. They found repetitive optical/gamma-ray flares and the curved trajectories of the associated components and suggested that the shock front propagates along a bent trajectory or helical path. In order to explain the multifrequency behavior of an optical/gamma-ray outburst in 2011, Larionov et al. (2013)

Figure 6. Correlations between $V - R$ index and $(V + R)/2$ magnitude on intraday and short timescales.
also suggested a shock wave propagating along a helical path in the blazar jet. The helical jet structure may cause the Doppler factor to change on a very short variability timescale (Gopal-Krishna & Wiita 1992). The variability may also be explained by turbulence behind an outgoing shock along the jet or the magnetic reconnections (Chandra et al. 2015; Agarwal et al. 2016). The symmetric/asymmetric light curves can be interpreted as arising from the light travel time effect (Chiaberge & Ghisellini 1999; Chatterjee et al. 2012). Chiaberge & Ghisellini (1999) found that the symmetric shapes of the light curves strongly constrain the injection and cooling timescales. When the cooling time of the electrons is much shorter than the light crossing time, the light curves are symmetric. When the cooling time of the electrons is much larger than the light crossing time, the light curves are asymmetric.

The results of the ACF show that the variability timescales range from 0.054 to 0.134 day. If we consider the variability timescales as the light crossing time of the emitting blob, the range of the emission region in the jet is from $R \leq 2.14 \times 10^{15}$ to $R \leq 5.3 \times 10^{15}$ cm ($R \leq c\delta \Delta t_{\text{min}}/(1 + z)$, where $\delta = 20$ from Nesci et al. 2005 and the redshift $z = 0.31$). In addition, there are good interband correlations but no significant time lags for intraday and short timescales or correlations between variability amplitude and source average brightness at individual bands. However, we still need more data to further confirm the correlations between variability amplitude and source average brightness at individual bands due to the small sample size at individual bands in this work.

### 4.2. Spectral Properties

Generally, the BWB chromatic trend is dominant for most of the blazars, while the RWB trend is also found, especially for flat spectrum radio quasar (e.g., Gu et al. 2006; Guo & Gu 2016). The BWB behavior is most likely explained by the shock-in-jet model. According to the shock-in-jet model, as the shock propagating down the jet strikes a region with a large electron population, radiation at different visible colors is produced at different distances behind the shocks. High-energy photons from the synchrotron mechanism typically emerge sooner and closer to the shock front than the lower-frequency radiation, thus causing color variations (Agarwal & Gupta 2015; Xiong et al. 2017). The BWB trend could be explained by two different jet components, i.e., the flare component has a higher synchrotron peak frequency than the underlying component (Ikejiri et al. 2011). Assuming that the optical/UV variability is triggered by fluctuations, Guo & Gu (2016) found that the RWB trend can likely be explained if the fluctuations occur first in the outer disk region and the inner disk region has not yet fully responded when the fluctuations are being propagated inward. In contrast, the common BWB trend implies that the fluctuations likely more often happen first in the inner disk region. Gu et al. (2006) suggested that the different relative contributions of the thermal versus nonthermal radiation to the optical emission may be responsible for the different trends of the color index with brightness in FSRQs and BL Lac objects. Moreover, the achromatic trend could be due to a Doppler factor variation on a spectrum slightly deviating from a power law (Villata et al. 2004). For our results, the average color index on each night remains approximately constant during this period. Most of nights show a BWB chromatic trend, a weak RWB trend is found, and a few nights show no correlation between magnitude and color index. The BWB trend appears in the short timescales. As discussed above, the variability and color index of S5 0716+714 in the outburst state are likely to have an association with jet activities. The shock-in-jet model can explain the BWB chromatic trend. The BWB or flatter-when-brighter could be due to the injection of fresh electrons, with an energy distribution harder than that of the previous cooled ones (e.g., Kirk et al. 1998; Mastichiadis & Kirk 2002). However, if the injection of fresh electrons has an energy distribution softer than that of the previous cooled ones, the weak RWB may be seen. When a shock wave propagates along a helical path, the achromatic trend could be found. Therefore, a shock-in-jet

![Figure 7. Spectral index vs. flux in the flare event. The flare extended from 28 January to 4 February.](image-url)

**Table 9**

| Date (UT) | $N$  | $r$   | $P$      |
|----------|-----|-------|---------|
| 2012 Jan 27 | 126 | 0.036 | 0.69    |
| 2012 Jan 28 | 70  | 0.38  | 0.001   |
| 2012 Jan 29 | 69  | 0.38  | 0.001   |
| 2012 Jan 30 | 71  | 0.43  | 0.0002  |
| 2012 Jan 31 | 66  | 0.25  | 0.04    |
| 2012 Feb 01 | 57  | 0.14  | 0.32    |
| 2012 Feb 02 | 56  | −0.05 | 0.73    |
| 2012 Feb 03 | 30  | 0.53  | 0.002   |
| 2012 Feb 04 | 77  | −0.27 | 0.02    |
| 2012 Feb 05 | 51  | 0.25  | 0.07    |
| 2012 Feb 06 | 35  | 0.41  | 0.01    |
| 2012 Feb 07 | 65  | 0.36  | 0.003   |
| 2012 Feb 08 | 92  | 0.29  | 0.006   |
| 2012 Jan 28–Feb 08 | 866 | 0.56 | $1 \times 10^{-6}$ |

**Note.** Here $N$ is the number of data, $r$ is the coefficient of correlation, and $P$ is the significance level.
model and the shock wave propagating along a helical path are likely to explain the variability and color index variability.

Finally, during the flare, the spectral index exhibits a clockwise loop for internathms. This type of variability pattern represents a sort of hysteresis cycle in the scatter plot between the energy index and the flux. It may arise whenever the spectral slope is controlled by cooling processes (Fiorucci et al. 2004). The clockwise direction is due to changes in the injection of accelerated particles propagating from high to low energies (Kirk et al. 1998).

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References

Abdo, A. A., Ackermann, M., Aguado, I., et al. 2010, ApJ, 716, 30
Agarwal, A., & Gupta, A. C. 2015, MNRAS, 450, 541
Agarwal, A., Gupta, A. C., Bachev, R., et al. 2016, MNRAS, 455, 680
Alexander, T. 1997, in Astronomical Time Series, ed. D. Maoz, Aeronautics and Space Administration.

Institute of Technology, under contract with the National

References

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