Quasi-simultaneous Spectroscopic and Multiband Photometric Observations of Blazar S5 0716+714 During 2018–2019

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Abstract

In order to study short timescale optical variability of γ-ray blazar S5 0716+714, quasi-simultaneous spectroscopic and multiband photometric observations were performed from 2018 November to 2019 March with the 2.4m optical telescope located at Lijiang Observatory of Yunnan Observatories. The observed spectra are well fitted with a power law $F_\lambda = A \lambda^{-\alpha}$ (spectral index $\alpha > 0$). Correlations found between $\beta_\alpha$, $A$, $A/A_0$, $F_0$, and $F_0/F_0$ are consistent with the trend of bluer-when-brighter (BWB). It is the same case for colors, magnitudes, color variation rates, and magnitude variation rates of photometric observations. The variations of $\alpha$ lead those of $F_\lambda$. Also, the color variations lead magnitude variations. The observational data are mostly distributed in the I(++,+) and III(−,−) quadrants of the coordinate system. Both spectroscopic and photometric observations show BWB behaviors in S5 0716+714. The observed BWB may be explained by the shock-jet model, and its appearance may depend on the relative position of the observational frequency ranges with respect to the synchrotron peak frequencies, e.g., at the left of the peak frequencies. Fractional variability amplitudes are $F_{var} \sim 40\%$ for both spectroscopic and photometric observations. Variations of $\alpha$ indicate variations of relativistic electron distribution producing the optical spectra.

Unified Astronomy Thesaurus concepts: BL Lacertae objects (158); Active galaxies (17); Blazars (164); Galaxy photometry (611); Spectroscopy (1558)

Supporting material: machine-readable tables

1. Introduction

Blazars are a subclass of active galactic nuclei (AGNs) and usually exhibit extreme variability in the whole electromagnetic spectrum (e.g., Ulrich et al. 1997). Depending on the rest-frame equivalent widths (EWs), blazars can be divided into BL Lacertae objects (BL Lacs) and flat-spectrum radio quasars (FSRQs). The EWs of BL Lacs and FSRQs are <5Å and >5Å, respectively (e.g., Ghisellini et al. 2011; Ghisellini & Tavecchio 2015). Generally, the continuum radiation of BL Lacs is believed to be relativistically boosted along the line of sight by relativistic jets with small viewing angles (e.g., Urry & Padovani 1995; Ulrich et al. 1997) and shows observational characteristics, such as featureless optical spectra, strong nonthermal emission, and high polarization. There are two peaks in broadband spectral energy distributions (SEDs) of blazars (e.g., Ulrich et al. 1997; Ghisellini et al. 1998). Their low and high energy peaks are located around from infrared-optical-ultraviolet (UV) to X-ray bands and around MeV-GeV-TeV γ-ray bands, respectively. The low energy peak is the synchrotron radiation from relativistic electrons in the relativistic jets and the high energy peak, the γ-ray emission, is generally interpreted as the inverse-Compton (IC) scattering of the synchrotron soft photons for blazars and the external soft photons for FSRQs by the same electron distribution that radiates the synchrotron photons (e.g., Ulrich et al. 1997; Ghisellini et al. 1998; Celotti & Ghisellini 2008; Tavecchio et al. 2010; Neronov et al. 2012; Zhang et al. 2012; Madejski & Sikora 2016; Zheng et al. 2017).

Various variability timescales, e.g., from minutes to decades, have been found in most BL Lacs and these timescales can help us to investigate the properties of the radiation region (e.g., Xie et al. 1999, 2002, 2005; Covino et al. 2015; Liu & Bai 2015; Wierzcholska et al. 2015; Feng et al. 2017; Liu et al. 2019). The variability timescales are usually divided into three classes: the timescales less than one day are regarded as intra-day variability (IDV) or microvariability (e.g., Wagner & Witzel 1995; Falomo et al. 2014); the timescales from days to a few months are short-term variability (STV; e.g., Li et al. 2017); and the timescales larger than several months are known as long-term variability (LTV; e.g., Dai et al. 2015). Different variability timescales may originate from different emission regions. Thus, we can study different radiation mechanisms via variability with different timescales. Furthermore, the flux variability often follows different spectral behavior and the correlation between the variability of flux and spectral index (or magnitude and color) will shed light on the physical processes of radiation for BL Lacs. A common phenomenon has been found in most BL Lac objects. The bluer spectral index usually arises at the brighter phase in most BL Lac objects (e.g., Villata et al. 2004; Bonning et al. 2012; Bhatta et al. 2016), i.e., bluer-when-brighter (BWB). The BWB trend is often regarded as evidence of a shock-in-jet model (e.g., Marscher & Gear 1985; Gupta et al. 2008; Bonning et al. 2012). However, many observations do not show any correlation between colors and magnitudes (e.g., Agarwal et al. 2016; Hong et al. 2017), or...
they show only weak correlations (e.g., Wierzcholska et al. 2015). The discrepancy of the color–magnitude correlations is a crucial issue that can help us to understand more detailed radiation properties in jets.

S5 0716+714 is a typical BL Lac object at a redshift of 0.31 ± 0.08 (Nilsson et al. 2008). It was first discovered by Kühr et al. (1981) and was widely studied on the whole electromagnetic spectrum (e.g., Ostroéro et al. 2006; Abdo et al. 2010; Hu et al. 2014; Dai et al. 2015; Gaur et al. 2015; Feng et al. 2017; Hong et al. 2017; Sandrinelli et al. 2017; Liu et al. 2019). It is one of the most active and bright BL Lacs in the optical band and shows a completely featureless spectrum (e.g., Biermann et al. 1981; Danforth et al. 2013). A number of groups have focused on the broadband photometric study of S5 0716+714 in the optical regime. Almost, all of them have found the variability with timescales from minutes to years (e.g., Nesì et al. 2002; Hu et al. 2014; Dai et al. 2015; Agarwal et al. 2016; Hong et al. 2017; Li et al. 2017). Many studies reported high IDV duty cycles (DCs; Wagner & Witzel 1995), i.e., DCs >70% for S5 0716+714. Variation amplitudes are larger than 0.05 mag for 80% of 52 nights (Nesì et al. 2002). Hu et al. (2014) gave a DC of 83.9% on 42 nights. Agarwal et al. (2016) obtained a DC of ~90% by 23 night observations. The probability of variability in S5 0716+714 is nearly daily. The various (strong, weak, or non) BWB trends have also been reported in many observations. Dai et al. (2013) found that the source exhibited strong BWB chromatism in LTV, STV, and IDV. Hu et al. (2014) showed strong and mild BWB trends on IDV and STV, respectively. Agarwal et al. (2016) did not find any correlations between colors and magnitudes. Recently, Hong et al. (2017) reported an outburst state during 2012 and they found both BWB chromatism and weak BWB trend in most nights. However, in a few nights, the data did not show any correlations between colors and magnitudes. The observational characteristics mentioned above indicate that S5 0716+714 is a natural laboratory for studying the radiation properties of BL Lac objects.

Almost all of the previous studies only used a few broadband photometric observations. Bandwidths of broadband filters are usually larger than 1000 Å and different filters have different bandwidths. Therefore, the relationship between brightness and spectral behavior is only roughly studied. The broad bandwidths might also influence the relationship during some phases (e.g., might decrease the correlation coefficient during weak phases). Moreover, the adjacent bands will partly overlap each other, which will further influence the correlation between the brightness and spectral behavior. In order to investigate the relationships of index–flux, index variability–flux variability, color–magnitude, and color variability–magnitude variability, and shed some light on the radiation processes of BL Lac objects, we simultaneously monitored S5 0716+714 with spectroscopic observations and broadband photometry. The spectral data can provide the light curves (LCs) at narrow enough wavelength coverage which allow us to study the above relationships in detail. Besides, comparing photometric LCs to spectral integral LCs will help us probe the effect of bandwidth. The correlations of variability among different bands and different wavelength ranges could also help us to limit the relative location of radiation.

In Section 2, we describe the detailed information of observations and data reductions. The results and our analyses are presented in Section 3. Finally, a discussion and our conclusion are presented in Section 4.

2. Observations and Data Reduction

All the spectroscopic and photometric observations of S5 0716+714 were carried out with the 2.4 m alt-azimuth telescope, which is located at Lijiang Observatory of Yunnan Observatories, Chinese Academy of Science. The longitude, latitude, and altitude of the observatory are 100°01′48″, 26°42′42″, and 3193 m, respectively. From mid-September to May, the observatory is dry and most nights are clear. The average seeing of the telescope obtained by the FWHM of stars is ~1.5″ (e.g., Du et al. 2014). For the 2.4 m telescope, the pointing accuracy is about 2″, and the closed-loop tracking accuracy is better than 0.05″ h−1. In 2010, the telescope was mounted with an Yunnan Faint Object Spectrograph and Camera (YFOSC) at Cassegrain focus. This is an all-purpose CCD for low/medium dispersion spectroscopy and photometry. The CCD can keep low readout noise under high readout speed, which benefits from all-digital hyper-sampling technology. During our observations, the readout noise and gain are 9.4 electrons and 0.35 electrons/ADU, respectively. The CCD chip covers a field of view (FOV) of 9′6 × 9′6 with 2048 × 4096 pixels, and the pixel scale is 0.283 pixel−1. YFOSC can quickly switch from photometry to spectroscopy (≤1 s), and we can also choose the binning mode to reduce the photometric readout time. The detailed parameters of the telescope and YFOSC were described in Wang et al. (2019).

The monitoring campaign started in 2018 November and spanned ~106 days. For most clear dark or gray nights, we basically performed photometric and spectroscopic observations of S5 0716+714 within 10 minutes. Thus, the photometry and spectroscopy can be considered to be quasi-simultaneous. During our observations, we successfully obtained the photometric data in 42 nights and spectral data in 47 nights. The cadence of spectroscopy is ~2.08 days. The complete observation information is listed in Table 1.

2.1. Photometry

The photometric observations were performed using Johnson $B V$ and Cousins $R I$ filters. In order to obtain the accurate magnitude calibration of the target, we always set several comparison stars in the observed FOV. The comparison stars were presented in Villata et al. (1998), who have calibrated the magnitudes in the $B V R$ bands. We found that star2, star3, star5, and star6 are closest to the target (see Figure 3 in Villata et al. 1998). Besides, the four comparison stars were also used in Ghisellini et al. (1997), who gave the data of the $I$ band. Thus, these stars are selected as comparison stars in our observations. The magnitude of S5 0716+714 is calibrated as follows:

$$\text{Mag} = -2.5 \log \frac{1}{N} \sum_{i}^{N} 10^{-0.4(M_{\text{std}}^i - M_i)}$$

where $N$ is the number of comparison stars, $M_{\text{std}}^i$ is the standard magnitude of the $i$th comparison star, and $M_i$ and $M_i^\text{std}$ are the instrumental magnitudes of the target and the $i$th comparison star, respectively. Figure 1 shows the calibrated LCs of S5 0716+714. The calibration errors include two components. The first is the Poisson errors of the target and comparison stars, and it can propagate through Equation (1). The second is
Table 1
Observation Logs of S5 0716+714

| Date       | Spectral Exposure (s) | Photometric Exposure (s) | Date       | Spectral Exposure (s) | Photometric Exposure (s) |
|------------|-----------------------|--------------------------|------------|-----------------------|--------------------------|
|            |                       | B V R I                  |            |                       | B V R I                  |
| 2018 Nov 29| ...                   | 30 20 15 15              | 2019 Jan 21| 200                   | ... ...                 |
| 2018 Dec 7 | 120                   | ... ... ... ... ... ...   | 2019 Jan 24| 120                   | 30 20 15 10            |
| 2018 Dec 10| 200                   | 30 20 15 15              | 2019 Jan 25| 120                   | 30 20 15 10            |
| 2018 Dec 12| 120                   | 30 20 15 15              | 2019 Jan 27| 120                   | 30 20 15 10            |
| 2018 Dec 13| 120                   | 30 20 15 15              | 2019 Jan 31| 120                   | 30 20 15 10            |
| 2018 Dec 15| 120                   | 30 20 15 15              | 2019 Feb  2| 120                   | 30 20 15 10            |
| 2018 Dec 16| 120                   | 30 20 15 15              | 2019 Feb  5| 120                   | 30 20 15 10            |
| 2018 Dec 19| 120                   | 30 20 15 15              | 2019 Feb  8| 120                   | 30 20 15 10            |
| 2018 Dec 20| 120                   | 30 20 15 15              | 2019 Feb 10| 120                   | 30 20 15 10            |
| 2018 Dec 21| 120                   | 30 20 15 15              | 2019 Feb 12| 120                   | 30 20 15 10            |
| 2018 Dec 22| ...                   | 30 20 15 15              | 2019 Feb 15| 120                   | 30 20 15 10            |
| 2018 Dec 23| ...                   | 30 20 15 15              | 2019 Feb 19| 200                   | ... ...                 |
| 2018 Dec 24| 120                   | 30 20 15 15              | 2019 Feb 20| 200                   | 30 20 15 10            |
| 2018 Dec 25| 120                   | 30 20 15 15              | 2019 Feb 22| 200                   | 30 20 15 10            |
| 2018 Dec 26| 120                   | 30 20 15 15              | 2019 Feb 24| 300                   | 30 20 15 10            |
| 2018 Dec 30| 120                   | 30 20 15 15              | 2019 Feb 26| 300                   | 30 20 15 10            |
| 2018 Dec 31| 120                   | 30 20 15 15              | 2019 Mar  2| 300                   | 30 20 15 10            |
| 2019 Jan 2 | 120                   | 30 20 15 15              | 2019 Mar  3| 180                   | 30 20 15 10            |
| 2019 Jan 6 | 120                   | 30 20 15 15              | 2019 Mar  6| 180                   | 30 20 15 10            |
| 2019 Jan 10| 120                   | 30 20 15 15              | 2019 Mar  9| 120                   | 30 20 15 10            |
| 2019 Jan 11| 120                   | 30 20 15 15              | 2019 Mar 11| 180                   | 30 20 15 10            |
| 2019 Jan 13| 120                   | 30 20 15 15              | 2019 Mar 13| 120                   | 30 20 15 10            |
| 2019 Jan 16| 120                   | 30 20 15 15              | 2019 Mar 14| 900                   | 30 20 15 10            |
| 2019 Jan 18| 200                   | ... ... ... ... ... ...   | 2019 Mar 15| 180                   | 30 20 15 10            |
| 2019 Jan 19| 200                   | ... ... ... ... ... ...   |            | ...                   | ... ...                 |

Table 2
Photometric Data in the B Band

| JD         | Object         | Star3          |
|------------|----------------|----------------|
| 2458452.42872 | 14.563 ± 0.009 | 13.286         |
| 2458463.25048 | 14.339 ± 0.002 | 13.295         |
| 2458465.23931 | 14.189 ± 0.002 | 13.295         |
| 2458466.24818 | 14.047 ± 0.001 | 13.294         |
| 2458468.34552 | 14.219 ± 0.008 | 13.302         |

Note. JD: Julian dates. Object: magnitudes and errors of S5 0716+714. Star3: magnitudes of the comparison star.

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

To avoid the contamination of the host galaxy mentioned in Feng et al. (2017), we tested two different aperture types: dynamic apertures (several times FWHM) and fixed apertures. For each type of aperture, we chose 10 different apertures. The aperture radii of fixed apertures and dynamic apertures are 1")5–8"0 and 1.3–3.5 x FWHM, respectively. The results are almost the same in different apertures. However, the best signal-to-noise ratio (S/N) could be obtained with the aperture radius of 6"0, and we adopted the photometry under this aperture as the final result.

2.2. Spectroscopy

Considering the featureless spectra of BL Lac objects, the spectroscopic observations were carried out with Grism 3, which provides a relatively low dispersion (2.93 Å pixel−1) and wide wavelength coverage (3400–9100 Å). We found that the spectrum of Grism 3 might be slightly contaminated by the second-order spectrum as wavelength is longer than ∼7000 Å, and the second-order spectrum is ∼5% times intensity of the 1st order spectrum. To avoid the effect of the second-order spectrum, we use a UV-blocking filter which cuts off at ∼4150 Å. Thus, the secondary spectrum will be rejected shorter than ∼8300 Å. The final spectra cover the observed frame of 4250–8050 Å. To improve the flux calibration, we simultaneously put the target and star3 in the long slit. This method was used widely (e.g., Kaspi et al. 2000; Du et al. 2014; Lu et al. 2016), and can obtain the relatively high quality spectra even in poor weather. To minimize the effects of seeing, we use a wide slit with a projected width of 5"05. For each night, we also observe a spectrophotometric standard star, which can calibrate the absolute fluxes of the target and comparison star.

The raw spectral data are also reduced with IRAF. After correcting the bias and flat-field, we calibrate the wavelength of...
the two-dimensional spectral image using standard helium and neon lamps. We extract the spectra of the target and star3 after removing the cosmic-rays. The extraction aperture radius is 21 pixels (∼5.943), nearly the same with photometry. We calibrate the absolute fluxes of the target and star3 using the spectrophotometric standard star. Note that miscentering of the object in slit will cause the shift of wavelength and then will influence the calibration of flux. We correct the shift by the absorption lines from 6400 to 7100 Å. In the end, we recalibrate the spectra using the template spectrum of the comparison star. Table 3 is the mean spectrum and an individual spectrum.

Table 3
Photometric Data in the V Band

| JD       | Object   | Star3 |
|----------|----------|-------|
| 2458452.42915 | 13.796 ± 0.014 | 12.424  |
| 2458463.25093 | 13.529 ± 0.002 | 12.438  |
| 2458465.23978 | 13.393 ± 0.001 | 12.437  |
| 2458466.24862 | 13.258 ± 0.001 | 12.437  |
| 2458468.34611 | 13.402 ± 0.005 | 12.442  |

Note. The meaning of each column is the same as in Table 2. (This table is available in its entirety in machine-readable form.)

Table 4
Photometric Data in the R Band

| JD       | Object   | Star3 |
|----------|----------|-------|
| 2458452.42950 | 13.396 ± 0.011 | 12.056  |
| 2458463.25130 | 13.089 ± 0.002 | 12.064  |
| 2458465.24019 | 12.967 ± 0.003 | 12.064  |
| 2458466.24899 | 12.849 ± 0.005 | 12.062  |
| 2458468.34655 | 12.965 ± 0.004 | 12.063  |

Note. The meaning of each column is the same as in Table 2. (This table is available in its entirety in machine-readable form.)

Table 5
Photometric Data in the I Band

| JD       | Object   | Star3 |
|----------|----------|-------|
| 2458452.42980 | 12.911 ± 0.008 | 11.779  |
| 2458463.25164 | 12.536 ± 0.025 | 11.762  |
| 2458465.24049 | 12.459 ± 0.001 | 11.787  |
| 2458466.24932 | 12.352 ± 0.002 | 11.788  |
| 2458468.34704 | 12.437 ± 0.004 | 11.786  |

Note. The meaning of each column is the same as in Table 2. (This table is available in its entirety in machine-readable form.)
and 7925 Å are used for analysis. The six bins are denoted in the top panel of Figure 2, and the relevant LCs are shown in Figure 3.

2.3. Fractional Variability Amplitude and Spectral Index

The variability amplitude of each light curve is calculated by the rms fractional variability amplitude $F_{\text{var}}$ (e.g., Rodriguez-Pascual et al. 1997; Edelson et al. 2002; Vaughan et al. 2003). The fractional variability amplitude $F_{\text{var}}$ is defined as

$$F_{\text{var}} = \frac{\sqrt{S^2 - \langle \sigma_{\text{err}}^2 \rangle}}{\langle F \rangle},$$

where $S^2$ denotes the total variance for the $N$ data points in a light curve, $\langle F \rangle$ is the mean flux of the light curve, and $\langle \sigma_{\text{err}}^2 \rangle$ denotes the measured mean square error of the $N$ data points:

$$S^2 = \frac{1}{N - 1} \sum_{i=1}^{N} (F_i - \langle F \rangle)^2,$$

$$\langle F \rangle = \frac{1}{N} \sum_{i=1}^{N} F_i,$$

$$\langle \sigma_{\text{err}}^2 \rangle = \frac{1}{N} \sum_{i=1}^{N} \sigma_{\text{err},i}^2.$$

Edelson et al. (2002) gave the error $\sigma_{F_{\text{var}}}$ on $F_{\text{var}}$:

$$\sigma_{F_{\text{var}}} = \frac{1}{F_{\text{var}}} \sqrt{\frac{1}{2N} \frac{S^2}{\langle F \rangle^2}}.$$

First, we convert all the photometric data to flux. Then, we measure both spectral and photometric variability amplitude.
The variability amplitudes of different LCs are listed in Table 7. The spectral indices and amplitudes of S5 0716+714 are obtained by fitting the spectra via a power law ($f_\lambda = A\lambda^{-\alpha}$). Figure 2 shows the best fit to the mean spectrum and individual spectrum. The variability of spectral index is shown in the left top panel of Figure 3.

### 3. Results and Analysis

During our observations, the amplitudes of variability are ∼40%, calculated from Equation (3). The photometric and spectroscopic results of $F_{var}$ are consistent with each other and show that the variability amplitudes of S5 0716+714 in the blue side are consistent with those in the red side as considering the relevant uncertainties (see Table 7). The bandwidths of the filters are hundreds to thousands of angstroms, and the variability amplitudes of photometry are the average results of broad bands. The width of the spectral bin is much more narrow than the filter bandwidth. Though there are differences between the photometric and spectroscopic bandwidths and bins, the very close wavelength coverage should result in their consistent $F_{var}$ for the photometric and spectroscopic observations.

To compare the variability of different bands, we shift each photometric LC to the same level depending on the magnitude at JD ∼ 2458545.12 (the median magnitude of each LC). Figure 4 shows the shifted results. In addition to the differences of the variability amplitudes of valleys, the LCs of different filters are nearly the same as each other. We measure the time delay among different photometric LCs. However, we do not find any reliable time lags. The result of the interpolated cross-correlation function (ICCF; White & Peterson 1994; Wang et al. 2016) between $I$ and $B$ is shown in the right bottom panel of Figure 5. We also test the time delays between the photometric and spectroscopic LCs (see Figure 3), and the LCs are consistent with each other. Therefore, the variability in different wavelength ranges should originate from the same region, and the variations of brightness might cause the changes of color and spectral index.

We find that the variability of different colors is similar to that of the photometric LCs (see Figure 5). The spectral index variability is also similar to that of the LC of each bin (see Figure 3). We test correlations between different colors and different magnitudes. Figures 5 and 6 show the test results. The results indicate that the bluer spectra usually occur at brighter phases, i.e., BWB. The Spearman rank correlation between $B - I$ and $B$ is significant, and other colors are also correlated with $B$. The BWB trend was often found in S5 0716+714 (see Section 1) and can be explained with a shock-in-jet model. The larger variability amplitude is inclined to occur at the shorter wavelength. Thus, the BWB trend will be more significant when the interval of effective wavelengths between two bands is larger. As mentioned in Section 1, there are some groups that do not find any correlations between the colors and...
Figure 4. Offset photometric light curves of S5 0716+714.

Figure 5. The left panel shows color–magnitude diagrams of S5 0716+714. The right panel shows interpolation cross-correlation functions of color vs. magnitude, and $I$ and $B$ LCs.
The discrepancy might be caused by the following reasons:

1. For some extended sources, the contamination of the host galaxies might lead to some fake variability because of the change of seeing (e.g., Feng et al. 2017, 2018). As a result, the observed correlation of the color–magnitude may not be related to the radiation processes. For point sources, the strong host galaxies may dilute the variability amplitudes of AGNs, and then influence the correlation between flux and spectral index, especially during the weak states. S5 0716+714 is a point source and its host galaxy is more than four times darker than the target itself (Nilsson et al. 2008). Thus, the discrepancy should not be caused by the effect of the host galaxy.

2. The accuracy of photometry may also influence the variability of colors. Most photometric studies are based on the small telescopes (≤1 m). For most BL Lacs, the typical variability amplitudes of colors are ~0.05 mag (e.g., Stalin et al. 2006; Hu et al. 2014; Agarwal & Gupta 2015). Furthermore, the variability amplitudes might be less than 0.02 mag for some adjacent bands. When the photometric accuracy is larger than 0.01 mag, the color–magnitude correlations will be seriously affected. The accuracy of our photometric measurement is less than 1% on most nights. So, the adjacent bands can show the mild BWB trends (see Figure 6).

During our observations, all of the data show that the BWB trend exists in S5 0716+714. The S/N and sampling frequency of the data are high enough. Therefore, the BWB trend may be an intrinsic phenomenon of the source. The color–magnitude data roughly obey the BWB trend, but the data scatter is visible as well (see Figure 6). The variability of flux density and spectral index are similar to each other (see Figures 3 and 5). Thus, the variability rate of flux might influence the variability of spectral index. Another possibility is that the variability of flux density and spectral index may result from changes of relativistic electron distribution emitting the observed photons and may have a correlation between the relevant variability rates. Thus, we test whether a correlation exists between the variability rates of flux density and spectral index. The sampling of observational data is nearly homogeneous and the variability magnitudes of AGNs, and then influence the correlation between flux and spectral index, especially during the weak states. S5 0716+714 is a point source and its host galaxy is more than four times darker than the target itself (Nilsson et al. 2008). Thus, the discrepancy should not be caused by the effect of the host galaxy.

Figure 6. Color–magnitude diagrams of S5 0716+714. In each panel, the solid line is the best fitting.

\[ A = \frac{A_{i+1} - A_i}{T_{i+1} - T_i} \]  

where \( F_\lambda \), \( \alpha \), and \( A_i \) are the flux density, spectral index, and spectral amplitude observed at the time series \( T_i \), respectively. Figure 7 shows a positive correlation between \( \dot{\alpha} \) and \( \dot{F_\lambda} \) for Bin1. Most of the data of BWB behavior is distributed in I and III quadrants of the coordinate system (see Figure 7). At the same time, there are strong positive correlations of \( \dot{\alpha} \sim \dot{A} \) and \( \dot{F_\lambda} \sim \dot{A} \) for Bin1 (see Table 8). Also, there is a correlation between the variability rates of \( B \) and \( B - I \) and the data of BWB behavior are distributed in I and III quadrants (see Figure 8). Hereafter, spectral index–flux density and color–magnitude relations are called the “color-brightness” relation. These correlations indicate that the variability rates of color and brightness are likely dominated by the cooling and accelerating processes of the relativistic electrons that generate the observed photons and the relevant variability. In Equations 6(a)–(c), the variability rates are calculated from the differences of adjacent data points. The adjacent data points may be considered to originate from the same flare.

In order to compare the color–magnitude variability rate correlations with the spectral index–flux density variability rate correlation, a relative variability rate of flux density is defined as

\[ \frac{\dot{F_\lambda}}{F_\lambda} = \left( \frac{F_\lambda}{F_\lambda^{\text{ref}}} - 1 \right) \frac{1}{T_{i+1} - T_i}. \]
If the flux variability is mainly caused by the variability of spectrum $F_{\lambda} = A \lambda^{-\alpha}$, $\dot{F}_{\lambda}/F_{\lambda}$ will be a function of $\dot{A}/A$ and $\dot{\alpha}$, where

$$\frac{\dot{A}}{A} = \left( \frac{A_{i+1}}{A_i} - 1 \right) \frac{1}{T_{i+1} - T_i}. \quad (8)$$

The observational data of $\dot{F}_{\lambda}/F_{\lambda}$ and $\dot{\alpha}$ can be linearly fitted with $\dot{F}_{\lambda}/F_{\lambda} = B + C\dot{\alpha}$. The Spearman’s rank correlation test shows a strong positive correlation between $\dot{F}_{\lambda}/F_{\lambda}$ and $\dot{\alpha}$ (see Table 8), and the BWB data of S5 0716+714 are mostly distributed in I and III quadrants (see Figure 9). $B$ is almost close to zero, and $C = 3.29 \pm 0.23$. The Spearman’s rank
correlation analyses show strong positive correlations of \( \dot{\alpha} - \dot{A}/A \) and \( \dot{A}/A - \dot{F}_y/F_y \) (see Table 8). Since three correlations exist among \( \dot{\alpha}, \dot{F}_y/F_y, \) and \( \dot{A}/A, \) there should be a correlation like as \( \dot{F}_y/F_y(\dot{A}/A, \dot{\alpha}) \) (see Figure 10). In fact, there is a correlation among \( \dot{\alpha}, \dot{A}/A, \) and \( \dot{F}_y/F_y \) at the confidence level of \( >99.99\% \), \( \dot{F}_y/F_y = 0.001 + 0.012\dot{A}/A + 1.839\dot{\alpha} \). Since I and III quadrants in Figures 7–9 correspond to the BWB, II and IV quadrants in Figures 7–9 should correspond to redder-when-brighter (RWB), which likely have \( F_y = DX \) in the optical band. Spectroscopic and photometric observations show consistent BWB trends in the color-brightness diagrams (Figures 7–9). In order to confirm the Spearman’s rank test results listed in Table 8, a Monte Carlo (MC) simulation is used to reproduce these parameters presented in Table 8. For each pair of these parameters, each data array generated by the MC simulation is fitted with the SPEAR (Press et al. 1992) and the fitting gives the relevant \( r_s \) and \( P_s \) the Spearman’s rank correlation coefficient and the p-value of the hypothesis test. Considering the errors of \( X \) and \( Y \) and assuming Gaussian distributions of \( X \) and \( Y, r_s \) and \( P_s \) distributions are generated by the SPEAR fitting to the data of \( X \) and \( Y \) from \( 10^4 \) realizations of the MC simulation. Averages, \( r_s(MC) \) and \( P_s(MC) \), are calculated by the \( r_s \) and \( P_s \) distributions, respectively. Standard deviations of these two distributions are taken as the relevant uncertainties of \( r_s(MC) \) and \( P_s(MC) \) (see Table 8). These results given by the MC simulation confirm the ordinary Spearman’s rank test results listed in Table 8. Thus, these correlations will be reliable.

Table 8

| X       | Y       | \( r_s \) | \( P_s \) | \( r_s(MC) \) | \( -\log P_s(MC) \) |
|---------|---------|-----------|-----------|---------------|---------------------|
| \( \dot{\alpha} \) | \( \dot{F}_y \) | 0.800 | \(<10^{-4}\) | 0.70 \pm 0.05 | 7.3 \pm 1.5 |
| \( \dot{\dot{A}} \) | \( \dot{F}_y \) | 0.864 | \(<10^{-4}\) | 0.79 \pm 0.05 | 10.5 \pm 1.9 |
| \( \dot{\dot{\alpha}} \) | \( \dot{A} \) | 0.856 | \(<10^{-4}\) | 0.76 \pm 0.05 | 9.4 \pm 1.8 |
| \( \dot{\dot{\alpha}} \) | \( \dot{F}_y/F_y \) | 0.787 | \(<10^{-4}\) | 0.69 \pm 0.06 | 7.2 \pm 1.5 |
| \( \dot{\dot{A}}/A \) | \( \dot{F}_y/F_y \) | 0.875 | \(<10^{-4}\) | 0.77 \pm 0.05 | 9.8 \pm 2.0 |
| \( \dot{\dot{\alpha}} \) | \( \dot{A}/A \) | 0.971 | \(<10^{-4}\) | 0.85 \pm 0.05 | 13.4 \pm 2.8 |
| \( \Delta B/\Delta T \) | \( \Delta(B - I)/\Delta T \) | 0.781 | \(<10^{-4}\) | 0.78 \pm 0.02 | 8.6 \pm 0.8 |
| 0.553 | 2 \times 10^{-4} | 0.54 \pm 0.02 | 3.6 \pm 0.2 |
| 0.395 | 1 \times 10^{-2} | 0.41 \pm 0.06 | 2.2 \pm 0.6 |
| 0.470 | 2 \times 10^{-3} | 0.44 \pm 0.06 | 2.5 \pm 0.6 |
| 0.492 | 1 \times 10^{-3} | 0.49 \pm 0.04 | 3.0 \pm 0.5 |

Note. \( X \) and \( Y \) are the relevant quantities of spectra fitted in Section 2 and those presented in Figures 6 and 8.

Figure 9. \( \dot{F}_y/F_y \) vs. \( \dot{\alpha} \) within Bin1. The FITEXY estimator gives the best linear fitting \( y = 1.1(\pm 0.7) \times 10^{-3} + 3.29(\pm 0.23) \times x \).
The variability of BL Lac objects should be caused by the shock process. If the particles in the jet are homogeneous, caused by the propagation of shocks in the jet; another factor depend on the brightness. Thus, the relevant radiation of the jet will be produced at different distances. The synchrotron peak frequency depends on the relativistic electron distribution and the magnetic field, i.e., the distances behind the shock front, and the radiation cooling will make the synchrotron radiation peak decrease at the intensity and the frequency. Thus, frequency dependence of the duration of a flare corresponds to an energy-dependent cooling length behind the shock front, which will cause color variations in blazars. Papadakis et al. (2007) proposed that the observations during the early rising phase of the flux will give a bluer color while those taken during later phases of the same flare will show more enhanced redder fluxes. The synchrotron peak of SED of S5 0716+714 is located very close to the optical wavelengths, and the corresponding broadband SED can be well explained by the synchrotron self-Compton (SSC) and the external radiation Compton (ERC) models, where the SSC soft photons are the synchrotron photons and the ERC soft photons in the IC scattering are emission from a broad-line region (BLR) and/or infrared (IR) emission from a dust torus (e.g., Liao et al. 2014). No emission lines were detected in the IR, optical, and UV spectra of S5 0716+714 (Shaw et al. 2009; Chen & Shan 2011; Danforth et al. 2013), and this may result from the fact that thermal emission from an accretion disk is not found in a multiwavelength SED of S5 0716+714 (e.g., Liao et al. 2014). The ionizing radiation from the accretion disk is so weak that broad emission lines are not observable, even though a BLR exists in S5 0716+714. Also, the dust emission is not observable because of very weak emission of the accretion disk, even though a dust torus exists in S5 0716+714.

The observational frequency band is at the left of the synchrotron radiation peak because $F_\lambda \propto A \lambda^{-\alpha}$ ($\alpha > 0$). This corresponds to the BWB behavior data in the I(++,+) and III(−,−) quadrants of the coordinate system. If the observational frequency band is at the right of the synchrotron radiation peak, we may have $F_\lambda \propto D \lambda^{-\alpha}$ ($\alpha > 0$). This may correspond to the RWB behavior in the II(−,+) and IV(++,−) quadrants of the coordinate system. The first case is observed in our observations and the second one is not observed in our observations. The BWB trends usually arise in most BL Lac objects (e.g., Villata et al. 2004; Bonning et al. 2012), and this is probably because the synchrotron peaks are at optical–UV–X-ray bands for most BL Lac objects and the optical observations are usually on the left of the synchrotron radiation peak. No, or only weak, BWB trends are observed in many observations (e.g., Wierzcholska et al. 2015; Agarwal et al. 2016; Hong et al. 2017), and this may result from the observational frequency ranges spanning the synchrotron peak frequencies. Also, the optical variability may be produced by a superposition of optical variability from different regions in jets for BL Lac objects without the color-brightness correlations. The BL Lac objects with the BWB trends may have a single emitting region of optical variability. The relativistic electrons in a single emitting region can produce the broadband SED containing the synchrotron and IC components (e.g., Liao et al. 2014). This single emitting region of optical variability will avoid superposing of optical variability from different regions and weakening of the color-brightness correlations. Thus, the variability of brightness, color, and spectral index is likely caused by the change of the underlying relativistic electron distribution that generates the relevant radiation behavior observed in S5 0716+714 as a shock passes through a high density region in the jet. This passing of shock will produce the

4. Discussion and Conclusion

We also test the BWB trend using the bin flux and spectral index (see Figure 11). This BWB trend is slightly different from that of color–magnitude. The data are fitted with a fifth-order polynomial and a monotonically increasing trend appears in Figure 11. Figure 11 shows that the BWB trend might depend on the brightness. Thus, the relevant radiation of the BWB at least includes two components: one component is caused by the propagation of shocks in the jet; another component is the underlying radiation that is not related to the shock process. If the particles in the jet are homogeneous, the variability of BL Lac objects should be caused by the disturbance of the magnetic field (e.g., Chandra et al. 2015), the precession of the jet (e.g., Camenzind & Krockenberger 1992), the inhomogeneous region of the jet, etc. The variations of the underlying radiation of the jet may not cause the change of spectral index. But, during a weaker phase the BWB trend caused by the shock will be more significant and during a brighter phase the underlying radiation might dilute the BWB trend. This possibility needs more observation evidence to test. There is a possible discrepant point, the one at the lower left quarter in Figure 11, that might affect the fitting result. We exclude this point and refit the rest data. The result is very similar to the previous one. The reason that one flux may correspond to several $\alpha$ values is that the spectrum fitting includes two parameters A and $\alpha$. Different A and $\alpha$ combinations may give the same flux. This will result in the data point scatter of BWB for both spectroscopic and photometric observations. Though the dispersion of $\alpha$ exists, the BWB trend roughly holds (see the best fittings in Figure 11).

The BWB behavior is observed in our monitoring epoch with the 2.4 m optical telescope located at Lijiang Observatory of Yunnan Observatories. The BWB behavior can be explained by the shock-jet model. A relativistic shock propagating down a jet will accelerate electrons to higher energies, where the shock interacts with a nonuniform region of high magnetic field and/or electron density, likely observed to be knots in jets. The shock acceleration will cause radiations at different frequencies being produced at different distances. The synchrotron peak frequency depends on the relativistic electron distribution and the magnetic field, i.e., the distances behind the shock front, and the radiation cooling will make the synchrotron radiation peak decrease at the intensity and the frequency. Thus, frequency dependence of the duration of a flare corresponds to an energy-dependent cooling length behind the shock front, which will cause color variations in blazars. Papadakis et al. (2007) proposed that the observations during the early rising phase of the flux will give a bluer color while those taken during later phases of the same flare will show more enhanced redder fluxes. The synchrotron peak of SED of S5 0716+714 is located very close to the optical wavelengths, and the corresponding broadband SED can be well explained by the synchrotron self-Compton (SSC) and the external radiation Compton (ERC) models, where the SSC soft photons are the synchrotron photons and the ERC soft photons in the IC scattering are emission from a broad-line region (BLR) and/or infrared (IR) emission from a dust torus (e.g., Liao et al. 2014). No emission lines were detected in the IR, optical, and UV spectra of S5 0716+714 (Shaw et al. 2009; Chen & Shan 2011; Danforth et al. 2013), and this may result from the fact that thermal emission from an accretion disk is not found in a multiwavelength SED of S5 0716+714 (e.g., Liao et al. 2014). The ionizing radiation from the accretion disk is so weak that broad emission lines are not observable, even though a BLR exists in S5 0716+714. Also, the dust emission is not observable because of very weak emission of the accretion disk, even though a dust torus exists in S5 0716+714.

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SED’s variability, such as the SED’s shape, peak frequency, and peak intensity.

In order to research short timescale optical variability of γ-ray blazar S5 0716+714, quasi-simultaneous spectroscopic and multiband photometric observations were performed from 2018 November to 2019 March with the 2.4 m optical telescope located at Lijiang Observatory of Yunnan Observatories. As the BWB trends are detected in the photometric observations, what will the optical spectra show and how will they vary? First, the observed spectra can be well fitted with a power law $F_{\lambda} = A\lambda^{-\alpha}$. Then we study $\alpha$, $A$, $A/A_i$, $F_{\lambda}$, and $F_{\lambda}/F_{\lambda_i}$ for spectroscopic observations. We find correlations between these quantities, which are consistent with the BWB trends. Interestingly, $\alpha$ is correlated to $F_{\lambda_i}$ and the variations of $\alpha$ lead those of $F_{\lambda_i}$. The variations of $\alpha$ indicate variations of relativistic electron distribution producing these optical spectra. A correlation among $\alpha$, $A/A_i$, and $F_{\lambda}/F_{\lambda_i}$ is found as well. Colors, magnitudes, color variation rates, and magnitude variation rates are studied for photometric observations. We also find correlations between these quantities, which are consistent with the BWB trends. Moreover, the color variations lead to the magnitude variations. The data of spectroscopic and photometric observations are mostly distributed in the I(++,+) and III(--,-) quadrants of coordinate system (see Figures 1–9).

The observed BWB may be explained by the shock-jet model. Whether there are BWB trends may depend on the relative locations of the synchrotron peak frequencies with respect to the observational frequency ranges, e.g., at the left of the synchrotron peak frequencies. Both spectroscopic and photometric observations give $F_{\text{var}} \sim 40\%$ which show violent variations in S5 0716+714. Moreover, the range of $\alpha$ is similar to those of colors computed from magnitudes and this similarity implies the reliability of BWB observed in our observations. There are similarities and differences for BWB observed in the spectroscopic and photometric observations. These differences indicate the bandwidth effect on BWB.

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Figure 11. Spectral index vs. flux density within Bin1. The solid and dashed lines are the best fitting for all the data and these data excluding the lowest point, respectively.
