THE OPTICAL MICROVARIABILITY AND SPECTRAL CHANGES OF THE BL LACERTAE OBJECT S5 0716+714

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ABSTRACT

We 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. Four fast flares were observed with amplitudes ranging from 0.3 to 0.75 mag. The source remained active during the whole monitoring campaign, showing microvariability in all days except for one. The overall variability amplitudes are $\Delta B \sim 0^{m}89$, $\Delta V \sim 0^{m}80$, $\Delta R \sim 0^{m}73$, and $\Delta I \sim 0^{m}51$. 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. However, a different spectral behavior was found on intranight timescales. A possible time lag of $\sim 11$ minutes between $B$ and $I$ bands was found on one night. The shock-in-jet model and geometric effects can be applied to explain the source’s intranight behavior.

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

Online-only material: machine-readable tables

1 INTRODUCTION

Blazars represent an extreme subclass of active galactic nuclei (AGNs). They are characterized by rapid and strong variability throughout the entire electromagnetic waveband, and high and variable polarization ($\sim 3\%$) from the radio to the optical wavelengths. In the unified model of AGNs, blazars make an angle of less than $10^\circ$ from the line of sight (Urry & Padovani 1995). For low-energy-peaked (or radio-selected) blazars, the continuum from the radio through the UV or soft X-ray is mainly contributed by synchrotron radiation, while a second hump in the spectrum at higher energies usually peaks in the GeV $\gamma$-ray band. Blazars exhibit variability on different timescales, from years down to hours or less (see Fan et al. 2005). Understanding blazar variability is one of the major issues of AGNs studies. There may be different behavior on different timescales. Periodicity may be found in the long term, as in the case of OJ 287 (Sillanpaa et al. 1988) and other blazars (Fan et al. 2002, 2007). The periodicity of OJ 287 can be explained by a binary black hole model, with the secondary black hole passing through the accretion disk of the primary black hole twice per revolution (Sillanpaa et al. 1998; Lehto & Valtonen 1996). On shorter timescales, 3C 66A was claimed to have an optical period of $\sim 65$ days during its bright state (Lainela et al. 1999), while Mkn 501 may have displayed a period of 23 days in high energy data (Osone 2006). Recently, analyses of X-ray data have yielded excellent evidence for a quasi-period of about an hour for 3C 273 (Espaillat et al. 2008) and very good evidence for near periods of $\sim 16$ days for AO 0235+164 and $\sim 420$ days for 1ES 2321+419 (Rani et al. 2009). This may be due to a shock wave moving along a helical path in the relativistic jet (e.g., Marscher 1996) or the instability in the accretion disk (Fan et al. 2008) for Mkn 501. Different viewing angles may also result in different levels of brightness, with the source being dimmer at larger viewing angles. BL Lacertae shows variability on both intranight and internight timescales with different spectral behaviors. It shows an intranight strongly chromatic trend and an internight mildly chromatic trend, indicating two different components operating in the engine (Villata et al. 2004; Hu et al. 2006). Understanding the shortest variability timescale is of special importance. Brightness changes of up to a few tenths of a magnitude over the course of a night or less is known as intranight optical variability (Wagner & Witzel 1995) or the so-called microvariability. It can bring new insight into the understanding of the nature of blazars, probing into the innermost structure down to microparsecs, and putting constraints on the size of the source and its physical environments.

Microvariability was first discovered in the 1960s by Matthews & Sandage (1963), who found 3C 48 changed $0^{m}04$ in the V band in 15 minutes. But their results were not taken seriously and were considered to be due to instrumental errors. However, with the development of CCD, microvariability was confirmed to be the intrinsic nature of AGNs, especially for blazars (e.g., Miller et al. 1989). From a complete sample of BL Lac objects (Stickel et al. 1991), Heidt & Wagner (1996) found that 80% exhibited microvariability, proving it to be the nature of BL Lac objects. Romero et al. (1999) detected microvariability in 60% of their selected sample of 23 southern AGNs. Microvariability has become extensively observed since the 1980s. Up to now, the reasons for it are still unclear. Many different models have been proposed to explain this phenomenon. It may conceivably be due to eclipses if there is a binary black hole system (Xie et al. 2002). The interaction of relativistic shock waves and an inhomogeneous jet can also cause microvariability in the jet (Maraschi et al. 1989; Qian et al. 1991; Marscher & Bloom 1992; Marscher 1996). Other models like instabilities and perturbations in the accretion disk can explain some of the microvariability phenomena (e.g., Mangalam & Wiita 1993; Fan et al. 2008). In order to understand the radiation mechanism and the structure of the radiating region, long-term and multiwavelength observations are needed. The BL Lac object S5 0716+714 is one of the brightest BL Lac objects noted for its microvariability. Its high duty cycle means that it is always in an active state (Wagner & Witzel 1995). It has been the target of many monitoring programs (e.g., Wagner et al. 1996; Qian et al. 2002; Raiteri et al. 2003). Montagni et al. (2006) reported the fastest variabil-
Five major outbursts have been observed so far, occurring at the beginning of 1995, in late 1997, in the fall of 2001, in 2004 March, and at the beginning of 2007 (Raiteri et al. 2003; Foschini et al. 2006; Gupta et al. 2008). These five outbursts indicate a long-term variability timescale of ∼3.0 yr (e.g., Raiteri et al. 2003). Correlated radio/optical variability has been observed for the source. In a four-week monitoring program, Quirrenbach et al. (1991) discovered a period change of 1–7 days in both radio and optical bands. Heidt & Wagner (1996) reported a period of 4 days in the optical band while Qian et al. (2002) derived a 10-day period from their 5.3 yr optical monitoring. Recently Gupta et al. (2009) have found good evidence for quasi-periods in five of the 20 best quality nightly data sets of Montagni et al. (2006); these ranged from ∼23 to ∼75 minutes.

The spectral change of S5 0716+714 has been observed extensively (e.g., Ghisellini et al. 1997; Raiteri et al. 2003; Villata et al. 2004; Gu et al. 2006; Wu et al. 2005). Different behaviors have been reported. Raiteri et al. (2003) reported different chromatism in different timescales in their eight-year monitoring program. Sometimes the source was bluer when brighter (BWB), sometimes the opposite, and sometimes no spectral change was seen despite changes in brightness. Ghisellini et al. (1997) and Wu et al. (2005) found that the source exhibited a BWB chromatism when it was in fast flares. However, Stalin et al. (2006) found that even if the source was in fast flare, there was no color change with brightness. In this paper, we concentrate on the microvariability and spectral changes of S5 0716+714. We monitored the source from 2008 October 25–30, 2008 December 23–29, and 2009 February 3–10. The temporal resolution was around 5–8 minutes in the four optical bands (BVRI). Because of the high temporal resolution, we can provide high-quality data with accurate results.

The paper is organized as follows: Section 2 describes observations and data reduction procedures. Section 3 presents the results. Discussions are reported in Section 4. A summary is given in Section 5.

## 2. OBSERVATIONS AND DATA REDUCTIONS

Our photometric observations were carried out at the 85 cm telescope located at the Xinglong Station of the National Astronomical Observatories of China (NAOC). This telescope is equipped with a standard Johnson–Cousin–Bessel multicolor CCD photometric system built on the primary focus (Zhou et al. 2009). The PI1024 BFT camera has 1024 × 1024 square pixels, a field of view of 165′ × 165′ at a focal ratio of 3.27 (f = 2780 mm) with a scale of 0.96 arcsec per pixel.

After flat-fielding, bias, and dark corrections, aperture photometry was performed using the apphot task of IRAF. The instrumental magnitudes of the source and comparison stars were then collected and then processed in order to obtain the standard magnitudes of S5 0716+714 and the relevant errors (note that data in the I band were not calibrated due to large photometric errors). Two standard stars in the blazar field, stars 5 and 6 in the finding chart of Villata et al. (1998), were compared to check that any reported variations were intrinsic to the blazar and that each standard star was non-variable. The magnitude difference between the two stars in the B, V, R, and I bands are

| Julian Date | Magnitude | σ |
|------------|-----------|---|
| 2454824.05104 | 14.191 | 0.010 |
| 2454824.05473 | 14.204 | 0.010 |
| 2454824.05844 | 14.203 | 0.009 |
| 2454824.06213 | 14.209 | 0.009 |
| 2454824.06583 | 14.210 | 0.009 |
| 2454824.06953 | 14.224 | 0.009 |
| 2454824.07322 | 14.222 | 0.009 |
| 2454824.07692 | 14.230 | 0.011 |
| 2454824.08061 | 14.238 | 0.010 |
| 2454824.08431 | 14.244 | 0.013 |
Figure 1. Light curves of S5 0716+714 in the VR bands from 2008 October 25 to 2009 February 10.

Our monitoring program for S5 0716+714 was divided into three periods. The first period was from 2008 October 25–30, the second from 2008 December 23–29, and the third from 2009 February 3–10. As a result of weather conditions, 14 nights of data were obtained. In the first period of our observations, only filters V and R were used. In the second and third periods, longer observation times allowed us to usually use four filters: B, V, R, and I. The typical exposure times for BVRI measurements were 100 s, 70 s, 50 s, and 30 s, respectively. The readout time is about 10 s, resulting in a temporal resolution of around 5 minutes for the best weather conditions. Because of the dense sampling and high quality (photometric error \(\sim 0.004\) mag), the data set can provide highly reliable results.

3. RESULTS

3.1. Light Curves

The overall light curves in bands V and R are displayed in Figure 1. The light curves of the two bands for individual periods are displayed in Figures 2–4. The source remained active during the whole period of monitoring. The variations in BVRI are \(\Delta B \sim 0^\circ 89\), \(\Delta V \sim 0^\circ 80\), \(\Delta R \sim 0^\circ 73\) mag, and \(\Delta I \sim 0^\circ 51\). One can see four flares during our period of observation for four months (from JD 2454765 to JD 2454873) from Figure 1. The first flare peaked on JD 2454766, with \(V \sim 13^\circ 41 \pm 0^\circ 01\),...
and $R \sim 13^{m}01 \pm 0^{m}01$. It is quite likely that the actual peak was even higher since the blazar's brightness was declining monotonically throughout the period observed that night. After that, the magnitude dropped about 0.4 mag in 4 days. In the second flare, the source brightness rose since the first day (JD 2454824) of our second period of observation, reaching a maximum on JD 2454825 ($V \sim 13^{m}59 \pm 0^{m}01, R \sim 13^{m}16 \pm 0^{m}01$) and then quickly dropped about 0.5 mag in the following 3 days, reaching a minimum on JD 2454828 ($V \sim 14^{m}11 \pm 0^{m}04, R \sim 13^{m}65 \pm 0^{m}03$). The source brightness then rose again until the end of our second period of observation, resulting in another flare with a magnitude change of about 0.5 mag in 2 days. In the third period of observations, the fourth flare showed the source reaching the maximum brightness seen in our entire data set, with $R \sim 12^{m}95 \pm 0^{m}01$ and $V \sim 13^{m}35 \pm 0^{m}01$ on JD 2454867. The source then rapidly dropped about 0.8 mag in 6 days until the end of our observation on JD 2454873.

Clear intranight variations can be seen during the whole monitoring campaign. We detected significant brightness changes in a large fraction of nights: only in 1 night (marked with an asterisk in Table 5) did the source remain stable during the observation time window. The intranight variability amplitude ranges from $\sim0.04$ to $0.28$ mag with a typical duration of a few hours. The light curves of microvariability are generally irregular, except for those of JD 2454825 and JD 2454826 of period 2, which are symmetric, and may show one possible cycle of $\sim8$ hr, respectively. In the first period, the source usually displayed microvariability of large amplitude ($>0.1$ mag). Some examples of the light curves are shown in Figure 5. On JD 2454765, the source brightened gradually by 0.183 $\pm 0.01$ mag in 192 minutes in the $R$ band. On the next day, after reaching the peak of the first flare, the brightness of the source began to fall. The magnitude change was 0.157 $\pm 0.01$ mag in 248 minutes in the $R$ band. On the last day of period one, which was JD 2454770, the brightness rose 0.116 $\pm 0.01$ mag in 185 minutes in the $R$ band.

In the second period of our observations, noticeable microvariability was observed on JD 2454824 and JD 2454825. On
the former day, the brightness first dropped $0.110 \pm 0.01$ mag in 149 minutes in the $R$ band and then became somewhat steady (Figure 6). On JD 2454825, the light curves are symmetric. The source first brightened by $0.105 \pm 0.008$ mag in 259 minutes, reaching the peak of the second flare, and then gradually dropped $0.137$ mag $\pm 0.01$ in 301 minutes ($R$ band; see Figure 7). The light curves on JD 2454826 are sawtooth-like and have sharp turnoffs, showing a complete period. The brightness of the source first dropped $0.054 \pm 0.01$ mag in 172 minutes and then rose $0.07 \pm 0.01$ mag in 268 minutes ($R$ band). It then dropped again with an amplitude of $0.0461 \pm 0.01$ mag, in a timescale of 117 minutes, forming a complete cycle (Figure 8).

The light curves of JD 2454825 and JD 2454826 are of particular interest and are discussed further in Section 4.

In the third period of our observations, the source showed substantial brightness changes in all the four days of observations. On JD 2454865–2454866, it first dropped $0.112 \pm 0.02$ mag in 258 minutes and then rose $0.073 \pm 0.01$ in 206 minutes ($R$ band; see Figure 9). On JD 2454866–2454867, in the $R$ band, the source brightened steadily by $0.152 \pm 0.02$ mag in 145 minutes, reaching the peak of the fourth flare, and then it dropped $0.07 \pm 0.01$ mag in 463 minutes (Figure 10). The source displayed the greatest magnitude change on JD 2454871–2454872. The brightness dropped $0.245 \pm 0.03$ mag over the course of the night in 480 minutes ($R$ band; see Figure 11). On the last night of our whole observation campaign, JD 2454872–2454873, the source displayed a rather regular light curve. At the beginning, the brightness dropped $0.082 \pm 0.01$ mag in 274 minutes and then rose $0.113 \pm 0.01$ mag in 240 minutes ($R$ band; see Figure 12).

From Figures 5–12, one can see that the light curves of microvariability of different bands are consistent with each other.

### 3.2. Spectral Variability

Based on our observations of high temporal resolution, the spectral variability with brightness is investigated in this section. Magnitudes have been dereddened by using a galactic extinction coefficient $A_B = 0.132$, $A_V = 0.102$, and $A_R = 0.082$ (Schlegel...
Figure 5. Intranight differential light curves of period 1 in $V$ and $R$ bands. The observation dates are JD 2454765 (top left for the $V$ band and top right for the $R$ band), JD 2454766 (middle left for the $V$ band and middle right for the $R$ band), and JD 2454770 (bottom left for the $V$ band and bottom right for the $R$ band). Crosses represent the differential magnitude between the source and star 5 while plus signs represent the differential magnitude between star 5 and star 6 shifted by an arbitrary offset.

et al. 1998). We concentrate on the $V - R$ index, the best sampled one. The overall $V - R$ color index ranges from 0.380 to 0.485. For individual nights showing microvariability, the spectral behavior varies from night to night (see Figure 13). A
Figure 6. Intranight differential light curves on JD 2454824 in $B$ (top left), $V$ (top right), $R$ (bottom left), and $I$ (bottom right) bands. Crosses represent the differential magnitude between the source and star 5 while plus signs represent the differential magnitude between star 5 and star 6 shifted by an arbitrary offset.

Figure 7. Intranight differential light curves on JD 2454825 in $V$ (top left), $R$ (top right), and $I$ (bottom left) bands. Crosses represent the differential magnitude between the source and star 5 while plus signs represent the differential magnitude between star 5 and star 6 shifted by an arbitrary offset.
clear BWB chromatism is evident in the long-term trend. The changes in the color index with brightness during the whole monitoring campaign are shown in Figure 14. The solid line is the unweighted least-squares fit to the data points, which has a slope of 0.02 and a correlation coefficient of 0.753, indicating a strong correlation between color and magnitude. However, the color–magnitude correlation is complex in the three observation periods.
Those nights showing strong correlation between color and magnitude are shown in Figure 15. In the first period of our observations (JD 2454765–JD 2454770), the source displayed the strongest BWB behavior. Clear microvariability was observed on all nights, with variability amplitude ranging from \( \sim 0.04 \) to 0.2 mag (see Table 5). On the first night of observations of period 1, JD 2454765, the variability amplitude in the \( R \) band was 0.183 mag and the correlation coefficient was 0.859. The mean \( R \) magnitude was \( \sim 13^m.12 \). On the next day, the variability amplitude was somewhat smaller, \( \Delta R = 0.157 \) mag (\( R \sim 13^m.09 \)), and the correlation coefficient \( r = 0.827 \). On JD 2454767, the variability amplitude was the smallest among all days of observations in period 1, \( \Delta R = 0.048 \) mag (\( R \sim 13^m.15 \)) and \( r = 0.430 \). On JD 2454770, the amplitude was \( \Delta R = 0.116 \) mag (\( R \sim 13^m.32 \)) and \( r = 0.749 \). One can see a noticeable trend that the source showed a stronger BWB chromatism when the amplitude change became larger in period 1. However, this trend does not seem to be related to brightness. BWB chromatism can be found both when the source was at the brightest state (\( R \sim 13^m.09 \) on JD 2454766) and the dimmest state (\( R \sim 13^m.32 \) on JD 2454770) of period 1.

In the second period of our observations (JD 2454824–JD 2454830), BWB is still noticeable on the first two nights of observation. The variability amplitude of these two nights were 0.127 and 0.137 mag, respectively (\( R \) band), the corresponding mean \( R \) magnitudes were \( \sim 13^m.36 \) and \( \sim 13^m.21 \) and the corresponding correlation coefficients were 0.563 and 0.618. However, on subsequent nights with smaller variability amplitude, an achromatic trend is noticed. On JD 2454826, JD 2454828, and JD 2454829, the amplitude changes in the \( R \) band were 0.070, 0.043, and 0.071 mag, respectively, and the corresponding correlation coefficients \( r \) were 0.150, −0.187, and 0.323, indicating no clear relationship between color and brightness. The source was at a rather dim state during these 3 days, with \( R \sim 13^m.34 \) on JD 2454826, \( R \sim 13^m.50 \) on JD 2454828, and \( R \sim 13^m.40 \) on JD 2454829. The trend that the source displayed stronger BWB chromatism with increasing variability amplitude is still noticeable in period 2 but not as obvious as in period 1, and again, the color change does not seem to be related to brightness.

In the third period of observations (JD 2454865–JD 2454873), each night showed a variability magnitude of >0.1 mag. The source was observed for four nights in this period. It showed an achromatic trend on the first three nights of observations with \( \Delta R = 0.112 \) (\( R \sim 13^m.35 \)) on JD 2454865–JD 2454866, \( \Delta R = 0.152 \) (\( R \sim 12^m.99 \), the brightest state in the whole monitoring campaign) on JD 2454866–JD 2454867,
Figure 11. Intranight differential light curves on JD 2454871–JD 2454872 in B (top left), V (top right), R (bottom left), and I (bottom right) bands. Crosses represent the differential magnitude between the source and star 5 while plus signs represent the differential magnitude between star 5 and star 6.

and $\Delta R = 0.245$ ($R \sim 13^{m}34$) on JD 2454871–JD 2454872. The corresponding correlation coefficients are $-0.198$, $0.333$, and $0.115$, respectively, indicating no clear correlation between color and brightness. However, on JD 2454873, the source was at the dimmest state in the whole monitoring campaign, with $R \sim 13^{m}64$ and $\Delta R = 0.113$; a BWB trend is noticeable with correlation coefficient $r = 0.516$. Obviously, spectral change is related to neither brightness nor variability amplitude in period 3.

On the whole, we find no consistent relation between color versus magnitude and also color versus variability amplitude on an intranight timescale. BWB chromatism and achromatism can be found when the source is bright or faint, showing large variability amplitude or small variability amplitude. This suggests that even on intranight timescales, different mechanisms may be at work.

4. DISCUSSIONS

The microvariability of S5 0716 + 714 has been observed by many authors. Some ultra-rapid fluctuations on timescale $\leq 1.0$ hr were reported. Qian et al. (2002) recorded a brightness increase of $\Delta V \sim 0.78$ mag in 9 minutes in their 5.3-year monitoring program. Xie et al. (2004) reported $\Delta B \sim 0.55$ mag on a timescale of 36 minutes. On longer timescales, Gu et al. (2006) found a magnitude change of $\Delta V = 0.28$ mag in $\sim 5$ hr. In our monitoring program, no ultra-rapid fluctuations were detected. The shortest timescale was $\sim 2$ hr, corresponding to $\Delta R \sim 0.046$ mag on JD 2454826 while the longest timescales were $\sim 8$ hr, corresponding to $\Delta R \sim 0.245$ mag, which happened on JD 2454871–JD 2454872. In our whole monitoring campaign, the timescales are generally a few hours with an amplitude of $\sim 0.04$–$0.28$ mag.

Time lags between different optical bands have also been reported. Stalin et al. (2006) found possible time lags of $\sim 6$ and $\sim 13$ minutes between the $V$ and $R$ bands in their two nights of observations of the source. Qian et al. (2000) reported similar results in which they found a time lag of $\sim 6$ minutes between the $V$ and $I$ bands. From densely sampling data, Villata et al. (2000) presented a time lag with a strict upper limit of $\sim 10$ minutes between the $B$ and $I$ bands. In this work, we tried to find out the time lag between the $B$ band and the $I$ band using the discrete cross-correlation function, DCF, suggested by Edelson & Krolik (1988) for unequally spaced data. It was performed only on the
Figure 12. Intranight differential light curves on JD 2454872–JD 2454873 in B (top left), V (top right), and R (bottom left) bands. Crosses represent the differential magnitude between the source and star 5 while plus signs represent the differential magnitude between star 5 and star 6.

day with high-quality data (error \(\sim 0.003\) and \(\sim 0.005\) for B and I bands, respectively) and a dense sampling rate (temporal resolution \(\sim 5\) minutes), which is JD 2454826, the day with a hint of periodicity in its light curve. Figure 16 presents the results of the calculations. The dashed line indicates the centroid that was calculated using the method proposed by Peterson (2001), and we found the barycenter using data points located near the peak value, DCF\(_{\text{peak}}\), specifically, those greater than 0.8 DCF\(_{\text{peak}}\). The expression is

\[
\text{DCF}_{\text{centroid}} = \frac{\sum \tau \text{DCF}(\tau)}{\sum \text{DCF}(\tau)}. \tag{3}
\]

We found a time lag of \(\sim 11\) minutes, with the B band leading the I band. However, given the sampling rate of \(\sim 5\) minutes and the negligible difference between the DCF values at \(\sim 20\) minutes and 0 minutes, this cannot be considered a convincing measurement of a lag. This result is consistent with Villata et al. (2000), who presented a strict upper limit of \(\sim 10\) minutes to a possible delay between B- and I-band variations using high-quality, densely sampled data on a single night. This result is expected in the shock-in-jet model but not in most disc-based variability models (e.g., Wiita 2006).

In order to quantitatively analyze possible periods, we performed a structure function (SF) on JD 2454826, the only day with a light curve that shows a hint of a period. SF, discussed fully by Simonetti et al. (1985), is a common tool for searching periodicities and timescales of variation. It identified a timescale of 259 minutes, 287 minutes, 280 minutes, and 263 minutes and a period of 482 minutes, 497 minutes, 498 minutes, and 491 minutes were found for the B, V, R, and I bands, respectively. All these results are consistent with visual inspection. The results are shown in Figure 17. Of course, since only one “cycle” is present that night, the presence of a period is no more than speculative; such a possible period does not appear to extend to the previous night, for which there are also data. Only observations made with multiple ground-based telescopes at different longitudes (or space-based telescopes) can convincingly find intranight periods that substantially exceed \(\sim 1\) hr.

The spectral variability of blazars has been investigated by many authors (e.g., Ghisellini et al. 1997; Fan & Lin 1999; Romero et al. 2000; Raiteri et al. 2003; Villata et al. 2000, 2004). Raiteri et al. (2003) found different spectral behaviors
for S5 0716+714 in short timescales. Sometimes the source was BWB, sometimes the opposite, and sometimes no spectral change was seen. Stalin et al. (2006) found no clear evidence of color variation with brightness in either their internight or intranight monitoring of the source for a fortnight. Ghisellini et al. (1997) and Wu et al. (2005) reported a BWB trend during fast flares but this trend is insensitive in the long term. However, Wu et al. (2007) noticed that the source is BWB on both intranight and internight timescales but this trend was not present in the long-term data.

In our monitoring campaign, the source also showed different spectral change behaviors. In the long term, the source showed a BWB behavior. Unlike previous studies which reported consistent trends on spectral behavior on intranight timescales (e.g., Ghisellini et al. 1997; Stalin et al. 2006; Wu et al. 2005), no consistent spectral behavior is found among all those nights displaying microvariability in our present study. The source displayed BWB chromatism when it was either bright or dim, or when showing large or small variability amplitudes. Achromatism was also found when the source...
Figure 15. Some examples of S5 0716+714 showing the relationship between the $V-R$ color index vs. source brightness (top panel), color index vs. time (middle panel), and the corresponding brightness change with time (bottom panel). Solid lines are the best fit to the data points. Here $r$ indicates the linear Pearson correlation coefficient of the best fit. Dates of observations are 2008 October 28 (top left), 2008 October 26 (top right), 2008 October 30 (bottom left), and 2008 December 23 (bottom right).

was in the same conditions, suggesting different mechanisms for microvariability. The BWB behavior is consistent with the shock-in-jet model (Wagner & Witzel 1995). In this model, shocks form at the base of the jet and propagate downstream, accelerating electrons, and compressing magnetic fields, thus resulting in the observed variability. The model predicts a BWB
phenomenon and an irregular light curve, as observed in our cases showing this phenomenon. In the case of JD 2454825 and JD 2454826, a symmetric light curve was observed for the former case while a periodic light curve was observed for the latter. Such regular light curves are rarely found. Wu et al. (2005) reported a single "period" of a sine-like light curve on intranight timescales for two nights during their observations of S5 0716+714. Using more sophisticated techniques, Gupta et al. (2009) found multiple oscillations to be present during five nights out of the 20 highest quality light curves of a total sample of 102 nights of data by Montagni et al. (2006). Unlike ours, their light curves are sine-like with smooth turns while ours are sawtooth-like with sharp turnoffs. The symmetric light curves on JD 2454825 showed a correlation between color and magnitude, with the correlation coefficient $r = 0.616$. Hence, the variation may still be due to intrinsic reasons. However, for the periodic light curve on JD 2454826, no strong correlation between color and magnitude is found, with the correlation coefficient $r = 0.150$. Such achromatic light curves may be produced by geometric effects like microlensing or a lighthouse effect produced by different amounts of Doppler boosting induced by a helical structure to the jet (e.g., Wagner & Witzel 1995). Microlensing predicts a strictly symmetric light curve, which cannot explain the concave shape of the second halves of the light curves in our case. Therefore, a lighthouse effect is the most probable mechanism for explaining periodic components.

Figure 16. Discrete correlation functions between $B$ and $I$ bands. The dashed line indicates the centroid.

Figure 17. Structure function of S5 0716+714 on JD 2454826 in $B$ (top left), $V$ (top right), $R$ (bottom left), and $I$ (bottom right) bands. The dashed lines indicate timescales at the maxima and periods at the minima of the structure function.
in blazar light curves as this type of variation is likely to be achromatic (e.g., Camenzind & Krokenberger 1992; Gopal-Krishna & Wiita 1992).

5. SUMMARY

We monitored S5 0716+714 during the period of 2008 October to 2009 February. The object remained active during the whole campaign, showing microvariability on all nights of observations except for one. The timescales ranged from ~2–8 hr, and the variability amplitude ranged from ~0.04–0.28 mag. Four flares of amplitude of ~0.4 mag, 0.5 mag, 0.3 mag, and 0.75 mag were observed, each lasting for a few days. The long-term spectral change is evidently BWB. Among those nights displaying microvariability, the source displayed different spectral behaviors. Sometimes the source seemed to become bluer with increasing variability amplitude while sometimes not. In a bright state, it displayed a BWB chromatism but this was also found when the source was in a dim state. Achromaticism was also observed when the source was both bright and dim. The BWB behavior can be explained by the shock-in-jet model while the achromatic trend may be due to geometric effects. A possible time lag of ~11 minutes between the \( B \) and \( I \) bands was seen during one night.

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REFERENCES

Camenzind, M., & Krokenberger, M. 1992, A&A, 255, 59
Edelson, R. A., & Krolik, J. H. 1988, ApJ, 333, 646
Espaillat, C., Bregman, J., Hughes, P., & Lloyd-Davies, E. 2008, ApJ, 679, 182
Fan, J. H., & Lin, R. G. 1999, ApJS, 121, 131
Fan, J. H., Lin, R. G., Xie, G. Z., Zhang, L., Mei, D. C., Su, C. Y., & Peng, Z. M. 2002, A&A, 381, 1
Fan, J. H., Romero, G. E., Wang, Y. X., & Zhang, J. S. 2005, Chin. J. Astron. Astrophys., 5, 457
Fan, J. H., et al. 2007, A&A, 462, 547
Fan, J. H., et al. 2008, Astropart. Phys., 28, 508
Foschini, L., et al. 2006, A&A, 455, 871
Ghisellini, G., et al. 1997, A&A, 327, 61
Gopal-Krishna, & Wiita, P. J. 1992, A&A, 259, 109
Gu, M. F., Lee, C. U., Pak, S., Yim, H. S., & Fletcher, A. B. 2006, A&A, 450, 39
Gupta, A. C., Fan, J. H., Bai, J. M., & Wagner, S. J. 2008, AJ, 135, 1384
Gupta, A. C., Srivastava, A. K., & Wiita, P. J. 2009, ApJ, 690, 216
Heidt, J., & Wagner, S. J. 1996, A&A, 305, 42
Hu, S. M., Wu, J. H., Zhao, G., & Zhou, X. 2006, MNRAS, 373, 209
Jiang, M., & Miller, H. R. 1997, AJ, 114, 565
Lai, M., et al. 1999, ApJ, 521, 561
Lehto, H. J., & Valtonen, M. J. 1996, ApJ, 460, 207
Mangalam, A. V., & Wiita, P. J. 1993, ApJ, 406, 420
Maraschi, L., Celotti, A., & Treves, A. 1989, in Proc. 23rd ESLAB Symp. Two Topics in X-Ray Astronomy, ed. J. J. Hunt & K. Battrick (Vol. 2; Paris: ESA), 825
Marscher, A. P. 1996, in ASP Conf. Ser. 110, Blazar Continuum Variability, ed. H. R. Miller, J. R. Webb, & J. C. Noble (San Francisco, CA: ASP), 248
Marscher, A. P., & Bloom, S. D. 1992, in Proc. Compton Observatory Science Workshop, ed. C. R. Schrader, N. Gehrels, & B. Dennis (Washington, DC: NASA), 346
Matthews, T. A., & Sandage, A. R. 1963, ApJ, 138, 30
Miller, H. R., Carini, M. T., & Goodrich, B. D. 1989, Nature, 337, 627
Montagni, F., Maselli, A., Massaro, E., Nesci, R., Sclavi, S., & Maesano, M. 2006, A&A, 451, 435
Osoe, S. 2006, ApJ, 26, 209
Peterson, B. M. 2001, in Advanced Lectures on the Starburst-AGN Connection, ed. I. Aretxaga, D. Kunth, & R. Mujica (Singapore: World Scientific), 3
Qian, S. J., Quirrenbach, A., Witzel, A., Krichbaum, T. P., Hummel, C. A., & Zensus, J. A. 1991, A&A, 241, 15
Qian, B. C., Tao, J., & Fan, J. H. 2000, PASJ, 52, 1075
Qian, B., Tao, J., & Fan, J. 2002, AJ, 123, 678
Quirrenbach, A., et al. 1991, A&A, 372, 71
Raiteri, C. M., et al. 2003, A&A, 402, 151
Rani, B., Wiita, P. J., & Gupta, A. 2009, ApJ, 696, 2170
Romero, G. E., Cellone, S. A., & Combi, J. A. 1999, A&AS, 135, 477
Romero, G. E., Cellone, S. A., & Combi, J. A. 2000, A&A, 306, L47
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Sillanpaa, A., Haarala, S., Valtonen, M. J., Sundelius, B., & Byrd, G. G. 1988, ApJ, 325, 628
Simonetti, J. H., CorDES, M. J., & Heeschen, D. S. 1985, ApJ, 296, 46
Stalin, C., Gopal-Krishna, Sagar, R., Wiita, P. J., Mohan, Y., & Pandey, A. K. 2006, MNRAS, 366, 1337
Stickel, M., Fried, W., Kuehr, H., Padovani, P., & Urry, C. M. 1991, ApJ, 374, 431
Urry, C. M., & Padovani, P. 1995, PASP, 107, 803
Villata, M., Raiteri, C. M., Lanteri, L., Sobrito, G., & Cavallone, M. 1998, A&AS, 130, 305
Villata, M., et al. 2000, A&A, 363, 108
Villata, M., et al. 2004, A&A, 421, 103
Wagner, S. J., & Witzel, A. 1995, ARA&A, 33, 163
Wagner, S. J., et al. 1996, AJ, 111, 2187
Wiita, P. J. 1996, in ASP Conf. Ser. 110, Blazar Continuum Variability, ed. H. R. Miller, J. R. Webb, & J. C. Noble (San Francisco, CA: ASP), 42
Wiita, P. J. 2006, in ASP Conf. Ser. 350, Blazar Variability Workshop II: Entering the GLAST Era, ed. H. R. Miller et al. (San Francisco, CA: ASP), 423
Wu, J., Peng, B., Zhou, X., Ma, J., Jiang, Z., & Chen, J. 2005, AJ, 129, 1818
Wu, J., Zhou, X., Ma, J., Wu, Z., Jiang, Z., & Chen, J. 2007, AJ, 133, 1599
Xie, G. Z., Liang, E. W., Zhou, S. B., Li, K. H., Dai, B. Z., & Ma, L. 2002, MNRAS, 334, 459
Xie, G. Z., Zhou, S. B., Li, K. H., Dai, H., Chen, L. E., & Ma, L. 2004, MNRAS, 348, 831
Zhou, A. Y., Jiang, X. J., Zhang, Y. P., & Wei, J. Y. 2009, Res. Astron. Astrophys., 9, 349