THE OPTICAL VARIABILITY OF SDSS QUASARS FROM MULTI-EPOCH SPECTROSCOPY.

II. COLOR VARIATION

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ABSTRACT

We investigated the optical/ultraviolet (UV) color variations for a sample of 2169 quasars based on multi-epoch spectroscopy in the Sloan Digital Sky Survey data releases seven (DR7) and nine (DR9). To correct the systematic difference between DR7 and DR9 due to the different instrumental setup, we produced a correction spectrum by using a sample of F-stars observed in both DR7 and DR9. The correction spectrum was then applied to quasars when comparing the spectra of DR7 with DR9. In each object, the color variation was explored by comparing the spectral index of the continuum power-law fit on the brightest spectrum with the faintest one, and also by the shape of their difference spectrum. In 1876 quasars with consistent color variations from two methods, we found that most sources (1755, ~94%) show the bluer-when-brighter (BWB) trend, and the redder-when-brighter (RWB) trend is detected in only 121 objects (~6%). The common BWB trend is supported by the composite spectrum constructed from bright spectra, which is bluer than that from faint spectra, and also by the blue composite difference spectrum. The correction spectrum is proven to be highly reliable by comparing the composite spectrum from corrected DR9 and original DR7 spectra. Assuming that the optical/UV variability is triggered by fluctuations, 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.

Key words: galaxies: active – quasars: general – techniques: spectroscopic

1. INTRODUCTION

Quasars are the most luminous active galactic nuclei (AGNs) and they provide the opportunity to explore far across the universe. The study of variability is one of the most effective and important tools for revealing the nature of quasars (Ulrich et al. 1997, and references therein). The variability can happen on different timescales, from as short as hours, as usually occurs in jets of blazars, weeks for thermal changes in an accretion disk, months for stochastic processes, to several years for global changes in accretion rate or lens intersecting time (Rees 1984; Kroll et al. 1991; Hawkins 1996; Kawaguchi et al. 1998; Gupta & Joshi 2005; Kelly et al. 2009). However, the mechanism of variability is still uncertain. By investigating the spectral variability of the optical/UV continuum, changes in global accretion rate have been proposed to explain the optical/UV variability in accretion disk models (Pereyra et al. 2006; Li & Cao 2008; Sakata et al. 2011; Zuo et al. 2012; Gu & Li 2013). In line with these models, Gaskell (2008) argued that the variability may propagate at close to the speed of light, rather than on a viscous timescale. The variability can also be due to hot spots (Abramowicz et al. 1991; Zhang & Bao 1991; Pecháček et al. 2008, 2013) or localized coronal flares (Galeev et al. 1979; Merloni & Fabian 2001; Cymer et al. 2004) in an accretion disk caused by the enhancement of mass accretion or disk instabilities. Alternatively, it could be caused by the thermal fluctuations driven by an underlying stochastic process (Kelly et al. 2009; MacLeod et al. 2010), which is related to generally accepted magnetorotational instability (Balbus & Hawley 1991), or by large localized temperature fluctuations (Dexter & Agol 2011; Ruan et al. 2014; Sun et al. 2014).

The color variations can give us clues to the emission mechanisms, and they have been studied extensively by using surveys with large sky coverage, such as photometric and spectroscopic data from the Sloan Digital Sky Survey (SDSS) (Wilhite et al. 2005; Gu & Ai 2011a, 2011b; Meusinger et al. 2011; Sakata et al. 2011; Bian et al. 2012; Zuo et al. 2012; Guo & Gu 2014; Ruan et al. 2014). There seems to be general consensus in the community that the bluer-when-brighter (BWB) trend is common in radio-quiet quasars (Webb & Malkan 2000; Wilhite et al. 2005; Schmidt et al. 2012; Sun et al. 2014) and also in blazars (Gu et al. 2006; Rani et al. 2010; Gu & Ai 2011a; Zhang et al. 2015). However, the redder-when-brighter (RWB) trend, first discovered in a optically violent optically variable quasar 3C 446 (Miller 1981), has been found in flat-spectrum radio quasars (FSRQs) (Gu et al. 2006; Rani et al. 2010). Interestingly, based on the study of two-epoch spectra of 312 radio-loud (RL) and 232 radio-quiet (RQ) quasars, Bian et al. (2012) found that half of the sources follow the BWB trend, while the other half show the RWB trend. Moreover, there is no obvious difference in color variation between their subsamples of RL and RQ quasars. In a sample of 9093 quasars in SDSS Stripe 82, Schmidt et al. (2012) confirmed the BWB trend and suggested that the color variation is remarkably uniform and independent of redshift, luminosity, and black hole mass. In addition, they claimed that relatively strong color variations were usually accompanied by fast variabilities of low amplitude and brightness. In a similar sample, Sun et al. (2014) found that the color variation on shorter timescales was bluer than that on longer timescales, implying that the RWB trend may more likely occur in long-timescale variabilities.
Although the color variations have been studied extensively, the fraction of RWB is still unclear, with different results from different samples and databases, not to mention the mechanism of RWB (e.g., Bian et al. 2012; Schmidt et al. 2012). While most works were based on massive photometric data (Schmidt et al. 2012; Zuo et al. 2012), there are few based on spectroscopic data. The biggest spectroscopic sample consists of only about 600 quasars based on either early SDSS spectroscopy or spectra taken from multiple telescopes (Bian et al. 2012; Ruan et al. 2014). The SDSS spectra enable us to study the color variations for large samples and with broader wavelength coverage than photometry, and more importantly, they avoid the contaminations of strong emission lines in photometric filters. Moreover, the large database in SDSS enables us to study the color variation at high significance by carefully selecting samples that have spectra with high signal-to-noise ratio (S/N) and minimizing the effects of contamination (e.g., host galaxies). Therefore, to further study the color variation, we compiled a large sample of 2169 quasars with multi-epoch spectroscopy from SDSS. In Section 2, we describe the quasar sample. The spectroscopic data analysis, and the correction of the systematic difference between SDSS data release seven (DR7) and data release nine (DR9) due to the different instrumental setup are given in Section 3. We show the results and discussions in Sections 4 and 5, respectively. Finally, we draw our conclusions in Section 6. Throughout this paper, the spectral index $\alpha_\lambda$ is defined as $f_\lambda \propto \lambda^{\alpha_\lambda}$ with $f_\lambda$ being the flux density at wavelength $\lambda$.

2. SAMPLE

In SDSS, some plates were entirely or partially observed multiple times. This usually occurred when the S/N of the first epoch was not sufficient to reach the lower limit required by the survey, or it was inherently a part of the survey plan (Pâris et al. 2012; Dawson et al. 2013; Guo & Gu 2014). Consequently, many sources have multi-epoch spectroscopy in SDSS, which can be used to study quasar variability. In this paper, we combined SDSS DR7 and DR9 to enlarge the quasar sample with multi-epoch spectroscopy. We started by searching the SDSS DR9 quasar catalog for objects observed in DR7 previously as indicated in the catalog (Pâris et al. 2012). By adding quasars observed at least twice in the SDSS DR7 quasar catalog (Shen et al. 2011), although not included in the DR9 quasar catalog, we constructed our parent sample of about 17,000 quasars. All these sources have been observed at least twice in DR9 and/or DR7.

Further refinements of the sample were made in several ways. First, sources with a non-zero ZWARNING flag or broad absorption lines were excluded due to their uncertain redshift determination and contamination of absorption lines (Reichard et al. 2003). Second, only those spectra with high S/N $\geq 10$ were selected to ensure the data quality. Third, a redshift cutoff is set at $z \geq 0.3$ to reduce the contamination of the host galaxy. Instead of using the flux density at a fixed rest-frame wavelength, we used the integrated flux density of the overall spectrum to study the source variability. We define the integrated flux density for the studied spectrum as $f_{\text{int}} = \sum f_\lambda$, in which $f_\lambda$ is the flux density at wavelength $\lambda$, and $n$ is the total number of wavelength points. To increase the significance of variability in individual quasars, we consider only the spectra with the brightest and faintest integrated flux density. The variability between these two epochs is defined as $\Delta f = (f_{\text{int},b} - f_{\text{int},f})/f_{\text{int},f}$, where $f_{\text{int},b}$ and $f_{\text{int},f}$ are the integrated flux density at the brightest and faintest epochs, respectively. To ensure the reliability of variations, we selected those sources with $\Delta f > 10\%$. Moreover, 20 objects were excluded due to their significantly convex spectral shape, usually at the faintest epoch. The convex shape is difficult to fit with a single power law. These features are possibly caused by dust extinction, and a systematic study of these sources will be given in a forthcoming paper (Guo & Gu 2016). Our final sample consists of 2169 quasars, of which 789 objects have both bright and faint spectra in DR7, while 1380 sources have one epoch in DR7 and the other in DR9. The redshift of our sample sources ranges from 0.3 to 4.1. In our sample, 202 quasars (~9.3%) are radio-loud according to the radio loudness $R = f_{6cm}/f_{2500\AA} \geq 10$ obtained directly from Shen et al. (2011), with $f_{6cm}$ and $f_{2500\AA}$ being the flux density at rest-frame 6 cm and 2500 Å, respectively.

3. RECALIBRATION ON BOSS SPECTRA AND DATA ANALYSIS

The DR9 quasar catalog is the first quasar catalog of the Baryon Oscillation Spectroscopic Survey (BOSS, Dawson et al. 2013). Compared to SDSS DR7, there are two main modifications in BOSS: (1) original SDSS spectrographs were replaced by BOSS spectrographs in 2009; these are fed by 1000 fibers of 2″ entrance aperture, rather than 640 fibers of 3″ aperture. The CCDs were replaced by new devices with higher throughput and smaller pixels. The gratings were changed into volume-phase holographic gratings; (2) new target selection algorithms with a larger range of luminosities and colors were used, which mainly focus on high-redshift objects to measure the baryon acoustic oscillation. Different devices and algorithms in BOSS lead to substantial differences in calibration from that of SDSS DR7 targets. Two effects are crucial for the calibration: (1) excess flux in the blueward end of the BOSS spectrum; (2) the application of washers and the focal-plane offsets in plate position for the BOSS quasar fibers, which accounts for a warping of the quasar target spectrophotometry relative to the standard stars (Pâris et al. 2012; Dawson et al. 2013; Margala et al. 2015). Both effects will lead to bluer spectra. The excess light is about 10% at an observed wavelength of 3600 Å, and decreases with increasing wavelength in BOSS spectra (Pâris et al. 2012). The fiber offsets were originally designed to improve throughput in the Ly$\alpha$ forest and reduce the atmospheric differential refraction for quasar targets, but these offsets are not applied to the standard stars (Dawson et al. 2013). Moreover, the current pipeline for DR9 (idlspec2d v5_4_45) has not taken this into account. Such systematic flux differences between BOSS and DR7 are therefore nontrivial and must be corrected in order to study quasar variability when comparing DR9 with DR7 spectra. Instead of using standard stars, we selected a sample of about 30,000 objects with a QSO_LIKE flag from DR9, which were quasar candidates based on the target selection criteria of BOSS (Pâris et al. 2012), but were finally proved to be stars (usually called “failed quasars”). These sources were then cross-matched to be stars (usually called “failed quasars”). These sources were then cross-matched with the DR9 catalog, of which 80 objects are

\[ \text{http://dr9.sdss3.org/bulkSpectra} \]

\[ \text{https://www.sdss3.org/dr9/whatsnew.php} \]
F-type stars. The systematic correction spectrum was generated by averaging the correction spectrum of individual F-stars, which is the flux ratio of the BOSS spectrum to the DR7 spectrum (see Figure 1). The reason to use only F-type stars is that they are usually blue, stable, observed at high S/N, and selected from high Galactic latitude. Moreover, they are often used in the calibration procedure of SDSS. In fact, we find that the systematic correction spectrum generated from 80 F-type stars is very similar to that from all 400 stars, which includes various types of stars.

As shown in Figure 1, the systematic correction spectrum is fitted with a fourth-order polynomial,

$$f_{c,\lambda} = a + b\lambda + c\lambda^2 + d\lambda^3 + e\lambda^4,$$

where $f_{c,\lambda}$ is the average flux ratio at observed wavelength $\lambda$, $a = 0.81$, $b = 3.40 \times 10^{-4}$, $c = -1.12 \times 10^{-7}$, $d = 1.23 \times 10^{-11}$, and $e = -4.38 \times 10^{-16}$. This, however, can only be applied in the range 3800–9200 Å, since the wavelength coverages are 3800–9200 Å and 3600–10,500 Å for DR7 and BOSS, respectively. Our systematic correction spectrum indeed shows that BOSS spectra are systematically bluer at short wavelengths, consistent with the differences in the composite spectra generated for DR7 and DR9 quasars (see Figure 5 in Pâris et al. 2012). Since the correction spectrum is essential in our study, it needs to be carefully checked whether it depends on source luminosity. By separating the F-stars into two groups with luminosity larger (19 stars) or smaller (61 stars) than the mean value, we found that the correction spectra of two groups are in good consistency (see Figure 1). This strongly indicates that our correction spectrum is independent of source luminosity.

In this paper, we focus on the variation of continuum shape when flux varies. Therefore, only the continuum was fitted, and measurements on the emission lines were not performed. When BOSS spectra are involved, we first corrected the systematic difference between BOSS and DR7 by dividing the BOSS spectrum by the systematic correction spectrum, i.e., Equation (1). Then, all the spectra were transferred into the source rest frame after correction for Galactic extinction using the extinction map (Schlegel et al. 1998) and reddening law (Cardelli et al. 1989). Several line-free windows were selected to obtain a pseudo-continuum, then fitted with a power-law continuum, UV/optical Fe II emission, and a Balmer continuum together (see also Chen et al. 2009; Guo & Gu 2014). The $\chi^2$ minimization was applied to obtain the best fit by using the IDL package mpfitexpr. The spectral index $\alpha_\lambda$ of the power-law continuum can be obtained from the best fit, as shown in Figure 2 for example.

### 4. RESULTS

#### 4.1. Color Variation

The distribution of the variability $\Delta f$ with redshift is shown in Figure 3. The variability ranges from 10% to 170% with most sources below 50%. Most objects with redshift higher than 2.15 are from BOSS as expected, since it was designed to detect the Ly$\alpha$ forest in high-redshift quasars.

The color variation in individual quasars was first determined from the difference in the spectral index between the bright and faint epochs $\Delta \alpha = \alpha_B - \alpha_F$, in which $\alpha_B$ and $\alpha_F$ are spectral indices at bright and faint epochs, respectively. We found that 1782 quasars show the BWB trend ($\Delta \alpha < 0$), while the remaining 387 objects exhibit the RWB trend ($\Delta \alpha > 0$). The color variations were further checked by the power-law fit to the difference spectrum between bright and faint epochs (i.e.,

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This performs a Levenberg–Marquardt least-squares fit to an arbitrary expression.
Figure 2. Examples of color variations. The left column shows the BWB trend in three objects, while the right column is for three RWB sources. In each panel, the red and green curves are spectra at two epochs, and the blue one is their difference spectrum. The optical/UV Fe II emission lines and Balmer continuum were subtracted from the spectra. The black lines are power-law fits to the continuum.

Figure 3. Variability vs. redshift. As designed, our sources are limited to have redshift $z \geq 0.3$ and variability $\Delta f > 10\%$ (see the text for details). Most sources at $z > 2.15$ are from BOSS.
bright spectrum minus faint spectrum, see Figure 2). The spectral index of the difference spectrum $\alpha_d$ shows that 1755 quasars are confirmed to have the BWB trend ($\Delta \alpha < 0$ and $\alpha_d < 0$) and 121 objects the RWB trend ($\Delta \alpha > 0$ and $\alpha_d > 0$, see Figures 2 and 5). By considering only quasars with consistent color variations from the two methods, we found that the majority of sources (1755/1876, ~94%) show the BWB trend, consistent with previous results based on SDSS (e.g., Zuo et al. 2012; Ruan et al. 2014). This result is also supported by the spectra at the bright epoch being bluer than at the faint epoch, with mean values of the spectral index of $-1.72$ for the former and $-1.55$ for the latter (see Figure 4).
4.2. Composite Spectra

To further study the color variations in our sample, we constructed composite spectra separately for bright and faint epochs. In this work, we used the geometric mean spectrum in order to preserve the global continuum shape, instead of the arithmetic mean spectrum, which preserves the relative fluxes of emission features. The geometric mean spectrum was generated following the procedure in Vanden Berk et al. (2001), including rebinning the individual spectra to the source rest frame, scaling the spectra, and finally stacking the spectra into the composite with \( f_\lambda = \left( \prod_{i=1}^{n} f_{\lambda,i} \right)^1/n \), where \( f_{\lambda,i} \) is the flux of each spectrum at wavelength \( \lambda \) and \( n \) is the total number of spectra in spectral bins (see Figure 6). The composite difference spectrum was also derived in a similar way. The composite spectra for both bright and faint epochs were first scaled at 2250 Å. However, to distinguish the two composites, we multiply the faint epoch by 0.76, which is the mean value of the flux ratio of bright to faint spectra at 2250 Å (see Figure 6).

We fitted composite spectra with a power law to several line-free regions, which were selected as 1350–1370 Å, 1455–1470 Å, 1680–1720 Å, 2160–2180 Å, 2225–2250 Å, 4000–4050 Å, and 4210–4230 Å. The region bluer than Ly\( \alpha \) 1216 Å was not used because of the contamination of the absorption features. Moreover, wavelengths longer than H\( \beta \) were also excluded, since they might be better fitted by a different power law, perhaps due to the host galaxy (Vanden Berk et al. 2001). As shown in Figure 6, the bright composite spectrum is steeper than the faint one, with spectral indices of \( \alpha_{c,b} = -1.72 \pm 0.07 \) and \( \alpha_{c,f} = -1.54 \pm 0.03 \), respectively. This strongly supports our finding that most of our sources show the BWB trend. While the faint composite is consistent with the composite spectrum in Vanden Berk et al. (2001) \((\alpha_\lambda = -1.56)\), the bright one is bluer. We found that the composite difference spectrum is much steeper than any composite, with a spectral index of \( \alpha_{c,diff} = -2.01 \pm 0.02 \), consistent with previous results (e.g., Wilhite et al. 2005; Ruan et al. 2014). Its blue color gives additional support to the general BWB trend in our sample.

5. DISCUSSION

5.1. Correction Spectrum

DR9 spectra have been used for more than half the sources in our sample; therefore, the reliability of the correction spectrum is crucial in our study. It can be checked by comparing the composite spectra at the faint epoch constructed from BOSS-only and DR7-only spectra. As shown in Figure 7, the composite spectrum from original BOSS spectra is obviously bluer than that from DR7 spectra, consistent with results of Pâris et al. (2012, see their Figure 5). Interestingly, the composite spectrum based on the corrected BOSS spectra is nearly identical to that of DR7. This strongly proves that the correction spectrum is highly reliable. It can be seen from Figure 1 that the blue excess is about 10% at 3800 Å; however, the flux could be underestimated by ~10% at 9000 Å, which is qualitatively consistent with recent analysis (Margala et al. 2015).

To further check the reliability of the correction spectrum, we constructed the composite difference spectrum only for quasars with both bright and faint epochs in DR7, and compared it with that of all sources. We found that two spectra are very similar (see Figure 6), again indicating that the correction spectrum is highly reliable. Both spectra show significant variations in emission lines for both broad and narrow components (e.g., narrow Mg\( \text{II} \) and [O\( \text{II} \)] 5007 Å...
lines). The stronger line variations compared to Wilhite et al. (2005) are likely due to our larger sample size and the fact that we maximized the variability by selecting the brightest and faintest epochs. The correction spectrum is essential to correct the calibration difference between SDSS DR7 and BOSS, even for the most recent data release 12, in which the calibration difference still remains (see Alam et al. 2015). It could be widely applied in future work to correct the systematic difference, especially in studies of variability.

5.2. Uncertain Color Variation

As shown in Figure 5, the color variations are uncertain in 293 quasars with either $\Delta \alpha < 0$ and $\alpha_d > 0$, or $\Delta \alpha > 0$ and $\alpha_d < 0$. This may be caused by several factors. The power-law fit to the quasar continuum depends strongly on the selected line-free windows, but these are contaminated by optical/UV Fe II (mainly at 2200–3800 $\AA$) and the Balmer continuum (<4000 $\AA$). Although Fe II and the Balmer continuum were also added in the overall fitting, the uncertainties in the spectral index will result in a large uncertainty in the color variation $\Delta \alpha$. In contrast, most of the Fe II, Balmer continuum, and emission lines are removed in the difference spectra of individual quasars. This will greatly reduce the uncertainty in $\alpha_d$. Moreover, although we performed a single power-law fit to the continuum, a better fit can be obtained with a broken power law in many cases, such as a flattening at 3000 $\AA$ due to a small blue bump (Vanden Berk et al. 2004). This will also result in a large $\Delta \alpha$ uncertainty, but it has little influence on the general trend of the difference spectrum. In addition, the uncertain color variations will occur when one spectrum intersects with the other, since the color variation depends wholly on the recognition of bright and faint spectra, which is defined from the integrated flux density. One spectrum can be regarded as a bright spectrum because of its higher integrated flux although the flux at a fixed wavelength is smaller than in the other spectrum. For these reasons, we required consistent color variations for individual objects from two methods. Although this will reduce the number of sources, it can give more reliable results on the color variations.

5.3. Comparison between BWB and RWB Quasars

The physical properties of RWB quasars are compared with those of BWB objects in Figure 8, in which the variability $\Delta f$ is plotted for 1755 BWB and 121 RWB quasars against black hole mass, redshift, Eddington ratio, and continuum luminosity at 2500 $\AA$, respectively. We find positive correlations in $\Delta f - M_{\text{bh}}$ and $\Delta f - z$ for both BWB and RWB sources (see Figures 8(a) and (b)), while negative correlations in $\Delta f - L_{\text{bol}}/L_{\text{Edd}}$ and $\Delta f - L_{2500}$ are present for both subsamples (see Figures 8(c) and (d)). These correlations are consistent with previous results (Vanden Berk et al. 2004; Wold et al. 2007; Meusinger & Weiss 2013; Guo & Gu 2014). For each parameter, RWB and BWB quasars have similar median values, indicating no significant differences in these two populations (see Figure 8). This is further studied using a $\chi^2$ test assuming all quasars come from the same distribution. From BWB quasars, we randomly selected samples with the same size as the RWB sample 100 times. Each randomly selected sample was compared with BWB quasars using a $\chi^2$ test. The averaged probabilities from a $\chi^2$ test performed 100 times ($p$, see Figure 8) indicate that there is no reason to reject the proposed hypothesis at the 0.05 significance level. This strongly favors similar distributions of the four parameters in two populations. Therefore, the behavior of color variation is generally uniform in our sample, and independent of black hole mass, redshift, Eddington ratio, and luminosity.
5.4. RWB Trend

The common BWB trend is consistent with previous results based on either photometric or spectroscopic data (e.g., Zuo et al. 2012; Ruan et al. 2014). There are several scenarios related to color variations. The spectral change may occur if two components with different spectra and timescales of variability make up the continuum, for example the relatively stable small blue bump and the more variable primary continuum (Ulrich et al. 1997). Li & Cao (2008) proposed that the change in accretion rate in the accretion disk model can be responsible for the observed optical/UV variability, including the correlation of the amplitude of optical/UV variability with rest-frame wavelength, which is tightly related to the BWB trend. In contrast, Kelly et al. (2009) suggested that the variability is caused by thermal fluctuations driven by a stochastic process in the accretion disk, e.g., a turbulent magnetic field, and that their thermal timescale is about $10^{10}$ days. Recently, a time-dependent inhomogeneous disk model with large temperature fluctuations was constructed, which can naturally explain the color variation and power-law composite difference spectrum (Dexter & Agol 2011; Ruan et al. 2014). However, Kokubo (2015) argued that the intrinsic scatter of magnitude–magnitude plots for the light curves of Stripe 82 quasars is too small in comparison with the simulated scatter, and their inhomogeneous model cannot explain the tight interband correlation.

While most sources show the BWB trend, the RWB trend is clearly present in our sample, although very rare (see Figures 2 and 5). In our sample, DR7 epochs usually span about four years, while the time coverage extends to about ten years when adding BOSS spectra. We found a positive correlation between $\alpha_d$ and the time separation $\Delta MJD$ of bright and faint epochs with a Spearman correlation coefficient $r_s = 0.10$ at 99.99% confidence level (see Figure 9). Moreover, we found a trend of increasing RWB source fraction for longer time separation. The results imply that variable emission on longer timescales possibly has a higher probability of showing the RWB trend than that on short timescales. The result is consistent with previous work based on 9258 photometric quasars in Stripe 82 (Sun et al. 2014), which is expected by the time-dependent inhomogeneous disk model (Dexter & Agol 2011).

If it is assumed that variability occurs in the inner region of AGNs, then when the accretion disk becomes hotter, it will produce more high-energy photons and the continuum

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Figure 8. Variability vs. (a) black hole mass, (b) redshift, (c) Eddington ratio, and (d) continuum luminosity at 2500 Å. The blue dots and lines are for BWB quasars, while the red dots and lines are for RWB ones. The results of Spearman correlation analysis (correlation coefficient and confidence level) are shown in each panel for BWB and RWB objects. In the side panels, histograms of the four parameters are shown for both BWB and RWB quasars, along with their median values. The average probabilities $p$ are also given for a $\chi^2$ test performed 100 times that compares the randomly selected RWB samples with BWB quasars.
emission peak will move to shorter wavelength, yielding bluer spectra when AGNs become brighter (Bian et al. 2012). While this can generally explain the BWB trend, the reason for the RWB trend is still unclear. Based on the optical variability study of eight red blazars, Gu et al. (2006) suggested that the different relative contributions of the thermal versus non-thermal radiation in optical emission can be responsible for the observed color variations. The RWB trend observed in FSRQs can be explained by the significant contribution of thermal emission in the optical/UV band, especially in a low-flux state. In FSRQs, the flux variations are usually dominated by the variable jet emission. When the source gets brighter, the jet emission will become gradually dominant, resulting in a RWB trend since jet emission is redder than thermal emission from the accretion disk. However, we found that radio-loud quasars in our sample, especially objects with $R \geq 100$, do not show a significantly higher probability of the RWB trend since jet emission is redder than thermal emission from the accretion disk. The RWB trend observed in the present sample. On the other hand, since luminous quasars are usually hosted in bright elliptical galaxies, the host galaxies will be more extended in poor seeing conditions, and then the contribution of host galaxies will be smaller in a fixed aperture. This will lead to an RWB trend when seeing varies, because the host galaxies are usually redder than quasars (see, e.g., Guo & Gu 2014). In order to check the effect of seeing, we performed correlation analysis between the spectral index and seeing for a subsample of RWB quasars at redshifts of 0.3–0.8. However, no significant correlation was found from Spearman correlation analysis ($r_s = -0.04$ at ~76% confidence level). This shows that the RWB trend is likely not much related to the variation in seeing. Actually, this could be a natural result of our sample selection. Our sample is selected at redshifts of $z > 0.3$ in order to reduce the contamination of host galaxies. At such redshifts, the contribution of host galaxies is expected to be rather small, and it is unlikely to change much when seeing varies.

In an accretion disk, the optical/UV radiation originates from the hot inner region, and the light is bluer than that from the cool outer region. The radiation regions may play an important role in color variation as shown in Shields (1978). Regardless of the detailed mechanism of variability (e.g., localized thermal fluctuations or large temperature fluctuations), when the variation occurs first in the outer disk region, it will take a certain time for the fluctuation to propagate inward. The RWB trend will happen when the inner disk region has not yet fully responded. In contrast, if fluctuations happen first in the inner region, the BWB trend will be observed. Since most of our sources show the BWB trend, it is likely that the fluctuations more often happen first in the inner region, while occurring rarely in the outer disk, although the details are unknown. Obviously, further investigation of the color variations on a much larger sample will be needed to improve our understanding of variability, such as using the massive amount of data from the Large Synoptic Survey Telescope.

5.5. Comparison with Previous Work

While the result of BWB in most of our sources is consistent with SDSS-based works (e.g., Ruan et al. 2014), it is different from Bian et al. (2012), in which half of the quasars appear redder during their brighter phases, not only for variable radio-

![Figure 9](image-url)
quiet quasars but also for variable radio-loud objects. The difference may be related to several factors. First, their sample is from the FIRST Bright Quasar Survey (FBQS, White et al. 2000), and therefore is basically a radio-selected sample. All their sources were detected in FIRST, and there are 312 radio-loud and 232 radio-quiet quasars. However, our sample is optically selected, with only 246 objects included in the FIRST catalog. The jet contribution in continuum emission has been proposed to explain the RWB found in blazars (e.g., Gu et al. 2006). The presence of a radio jet thus likely affects the color variations toward RWB to some extent, although not completely. Indeed, the RWB source fraction is about 11% in our 246 FIRST-detected quasars, higher than that in whole sample (~6%). Second, a significant number of sources in their sample are at low redshift, with about one third of quasars at $z \leq 0.5$. The original spectra of the FBQS used to compare with SDSS spectra in their work are from observations at five different observatories, in a wide variety of atmospheric conditions, ranging from photometric to cloudy, with both good and bad seeing, and different resolutions (White et al. 2000). The variations of the host galaxy contribution when seeing varies were proposed to be at least partly responsible for the RWB trend (Guo & Gu 2014). This effect could be more significant at low redshift, especially when comparing the spectra taken with long slit and fiber. While our analysis shows that the RWB trend is likely not much related with the variation in seeing (see Section 5.4), it is unclear in their sample. Finally, while we found a trend of increasing fraction of RWB with longer spectral duration (Figure 9), their sample concentrates more on larger time separations (i.e., >3 years, see their Figure 1). This could partly account for the high RWB fraction.

6. CONCLUSIONS

We investigated the optical/UV color variations for a sample of 2169 quasars based on the multi-epoch spectroscopy in DR7 and DR9 by correcting their systematic difference. The color variation was explored by comparing the difference in power-law spectral index of the continuum between the brightest and the faintest spectra, and by the shape of the difference spectrum. In 1876 quasars with consistent color variations from two methods, we found that most sources (1755, ~94%) show the BWB trend, and the RWB trend is detected in only 121 objects (~6%). The color variations are generally uniform and independent of black hole mass, redshift, Eddington ratio, and luminosity. The common BWB trend is supported by the composite spectrum constructed from bright spectra, which is bluer than that from faint spectra, and also by the blue composite difference spectrum. The correction spectrum is proved to be highly reliable by comparing the composite spectrum from corrected DR9 and original DR7 spectra. It can thus be widely applied in future work to correct the systematic difference between SDSS DR7 and BOSS. Assuming that the optical/UV variability is triggered by fluctuations, the RWB trend can likely be explained if fluctuations occur first in the outer disk region, and the inner disk region has not yet fully responded when fluctuations are propagated inward. The common BWB trend implies that fluctuations likely more often happen first in the inner disk region.

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