THE OPTICAL VARIABILITY OF SDSS QUASARS FROM MULTI-EPOCH SPECTROSCOPY. I. RESULTS FROM 60 QUASARS WITH ≥ SIX-EPOCH SPECTRA

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ABSTRACT

In a sample of 60 quasars selected from the Sloan Digital Sky Survey with at least six-epoch spectroscopy, we investigate the variability of emission lines and continuum luminosity at various aspects. A strong anti-correlation between the variability and continuum luminosity at 2500 Å is found for the sample, which is consistent with previous works. In individual sources, we find that half of the sample objects follow the trend of being bluer when brighter, while the remaining half follow the redder-when-brighter (RWB) trend. Although the mechanism for RWB is unclear, the effects of host galaxy contribution due to seeing variations cannot be completely ruled out. As expected from the photoionization model, the positive correlations between the broad emission line and continuum luminosity are found in most individual sources, as well as for the whole sample. We confirm the Baldwin effect in most individual objects and the whole sample, while a negative Baldwin effect is also found in several quasars, which can be at least partly (if not all) due to the host galaxy contamination. We find positive correlations between the broad emission line luminosity and line width in most individual quasars, as well as the whole sample, implying a line base that is more variable than the line core.

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

Online-only material: color figures

1. INTRODUCTION

Active galactic nuclei (AGNs) are characterized by variability at almost all wavelengths (Ulrich et al. 1997). Investigating the variability is a very important approach to probing the physical properties of AGNs. There have been many systematic studies on the variability of AGNs using photometric data, although such measurements are subject to the line contributions in photometric bands (e.g., Vanden Berk et al. 2004). Several interesting results have been obtained from various AGN samples. The well-known anti-correlation between the variability and continuum luminosity was first discovered by Angione & Smith (1972), and it was later confirmed by many other works (Hook et al. 1994; Wilhite et al. 2008; Zuo et al. 2012). Although there are other possibilities that can explain this result (Cid Fernandes et al. 2000), Li & Cao (2008) explained that the anti-correlation could be qualitatively explained by the standard accretion disk model assuming the variability was caused by the change of accretion rate.

A positive correlation was found between the variability and redshift (e.g., Trevese et al. 1994; Hook et al. 1994; Cid Fernandes et al. 1996), which was later confirmed in a sample of over 25,000 Sloan Digital Sky Survey (SDSS) quasars (Vanden Berk et al. 2004; Zuo et al. 2012). The correlation can be caused by the variability–wavelength relation (Cristiani et al. 1996), which is likely related to the variability mechanism (Vanden Berk et al. 2004). The positive relation between the optical–UV variability and black hole mass was first reported by Wold et al. (2007), which can be explained by the fact that the more massive black holes were gasless and produce larger flux variations because they do not have a steady inflow of gaseous fuel. Alternatively, Li & Cao (2008) argued that this relation could be triggered by the change of the accretion rate in their accretion disk model.

Mostly because the spectroscopic observations are time-consuming, there are only a few investigations on the variability of AGNs from multi-epoch spectroscopy, which either focused on reverberation mapping analysis for extensively monitored sources (e.g., Kaspi et al. 2000) or were based on spectroscopic observations at a few epochs (e.g., Wilhite et al. 2005). However, multi-epoch spectroscopy has advantages compared to photometric data. The continuum can be well constrained by excluding the emission line contamination, and the spectral shape can be measured by carefully fitting the continuum on a wide wavelength coverage. Moreover, the line measurements can be obtained, which enable us to study the variability of emission lines.

There have been extensive investigations on the quasar spectral shape, Baldwin effect, and line width (e.g., Fan et al. 1998; Gu & Ai 2011a, 2011b; Wu et al. 2005; Zuo et al. 2012; Baldwin 1977; Wills et al. 1993; Wilhite et al. 2005). The bluer-when-brighter (BWB) trend is very common in AGNs; however, the redder-when-brighter (RWB) trend has also been found, for example, in a sample of 544 quasars with two-epoch spectroscopy (Bian et al. 2012b). The anti-correlation between the emission line equivalent width (EW) and the continuum luminosity, the so-called the Baldwin effect (Baldwin 1977), was originally found in the broad emission lines in the UV/optical band (see Shields 2007, for a review), and was also detected in narrow lines (e.g., Zhang et al. 2013). Recently, a strong Baldwin effect for CIV and MgII and a weak negative Baldwin effect for Hβ were presented by Shen et al. (2011) in the data release seven (DR7) quasar catalog. There is still no definitive conclusion on the correlation between the emission line luminosity and line width. A negative correlation was found by Wills et al. (1993) in a sample of 123 quasars with single-epoch spectroscopy, while a positive correlation was discovered by Wilhite et al. (2005) based on a sample of 315 quasars with...
two-epoch spectroscopy. We note that all these works focused on studies of entire samples; not much work has been done on individual quasars. Moreover, usually only two-epoch spectroscopy was used in individual sources. To further study the Baldwin effect, the variability of the spectral shape and line width, especially in individual objects, quasar samples with multi-epoch spectroscopy data are needed.

In this paper, we investigate quasar variabilities by constructing a sample of quasars with multi-epoch spectroscopy from the SDSS\(^3\) (Abazajian et al. 2009; Ahn et al. 2012). The multi-epoch spectroscopic data enables us not only to study the continuum variability but also the effects that involve line variations relative to the continuum and the line width, for both individual quasars and the whole sample. In order to increase the probability of detecting variabilities, and to improve the correlation analysis for individual QSOs, quasars with at least six-epoch spectroscopy were selected. In Section 2, we describe the quasar sample, and the spectroscopic data analysis is 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, a cosmology with \(H_0 = 70\, \text{km s}^{-1} \text{Mpc}^{-1}\), \(\Omega_\text{m} = 0.3\), and \(\Omega_\Lambda = 0.7\) is adopted, and the spectral index \(\alpha_i\) is defined as \(f_\lambda \propto \lambda^{\alpha_i}\) with \(f_\lambda\) being the flux density at wavelength \(\lambda\).

### 2. SAMPLE

The SDSS DR7 quasar catalog consists of 105,783 quasars selected to be brighter than \(M_i = -22.0\) and to have at least one broad emission line with FWHM larger than 1000 km s\(^{-1}\) (Schneider et al. 2010). These quasars were selected for spectroscopic observation according to the quasar target selection algorithm (Richards et al. 2002; Schneider et al. 2010), which selects objects with \(i < 19.1\) (for \(i\)-band apparent magnitude \(i\)) and with nonstellar colors similar to redshift \(\lesssim 3\) quasars, and unresolved objects with \(i < 20.2\) and colors similar to higher-redshift quasars. Moreover, all \(15 < i < 19.1\) unresolved sources within 2\(^\circ\) of a Faint Images of the Radio Sky at Twenty Centimeters (FIRST) radio detection were also chosen.

The spectral wavelength coverage is 3800–9200 Å with spectral resolution \(R \sim 1850–2200\), and the five-band \(u, g, r, i, z\) magnitudes have typical errors of about 0.03 mag. A comprehensive compilation of quasar properties is presented for DR7 quasars in Shen et al. (2011), including the continuum and emission line measurements, black hole masses, and radio properties, etc. To study the variabilities, the quasars with at least two-epoch spectroscopic observations were selected by searching the number of spectroscopic observations given in Shen et al. (2011), which results in a sample of 7063 quasars. The multi-epoch spectroscopic observations are mainly from the overlap survey areas between adjacent plates and were sometimes used to monitor the system (Dawson et al. 2013). As the first of a series papers, we present in this work the results for 60 quasars with at least six-epoch spectroscopic observations. The redshift covers 0.08–3.78 for these 60 objects. Eight quasars were detected in the FIRST 1.4 GHz radio survey (Becker et al. 1995). Radio loudness is available for all eight sources in Shen et al. (2011), seven of which are radio-loud according to the definition of radio loudness \(R = f_{60\text{cm}}/f_{2500\text{Å}} \geq 10\) (\(f_{60\text{cm}}\) and \(f_{2500\text{Å}}\) are the flux density at rest-frame 6 cm and 2500 Å, respectively). When available, we include in our analysis the spectra from SDSS data release nine (DR9), which is the first spectroscopic data from the SDSS-III Baryon Oscillation Spectroscopic Survey (Ahn et al. 2012). The spectra of DR9 cover a wider wavelength range 3600–10,500 Å than those of DR7. The biggest advantage of our sample is that each of our sample sources have at least six-epoch spectroscopy. Therefore, we will mainly focus on the results for individual objects instead of the global sample as our sample size is relatively small compared to previous works.

Since different emission lines are covered in SDSS spectra for sources at different redshifts, our sample sources are separately listed in Tables 1–3. Table 1 lists the quasars at \(z \leq 0.4\), while the objects at \(0.4 < z < 0.8\), and \(z > 0.8\) are presented in Tables 2 and 3, respectively.

### 3. SPECTROSCOPIC ANALYSIS

Data reduction on the SDSS spectra follows the procedure in Chen et al. (2009), which is illustrated in Figure 1. After correcting the Galactic extinction with the reddening map of Schlegel et al. (1998), we shifted the spectra to the rest-frame wavelength. In order to obtain reliable line parameters, line-free wavelength ranges were first selected to be pseudo-continua. In addition to the emission lines, three components are considered: (1) a power-law continuum derived from the emission-line-free windows; (2) UV and optical Fe \(\text{II}\) emission fitted using the templates of Vestergaard & Wilkes (2001) and Véron-Cetty et al. (2004), respectively; (3) a Balmer continuum generated in the same way as in Dietrich et al. (2002). The modeling of these three components was performed by minimizing the \(\chi^2\) in the fitting process. The final multicomponent fit was then subtracted from the observed spectrum.

The broad emission lines were measured from the continuum-subtracted spectra. We mainly focus on several prominent emission lines, i.e., H\(\alpha\), H\(\beta\), Mg\(\text{II}\), and C\(\text{IV}\). The Mg\(\text{II}\), H\(\beta\), and H\(\alpha\) lines were fitted with two Gaussian components, with one for the narrow component with an upper limit of FWHM \(\lesssim 1200\, \text{km s}^{-1}\), and the other for a broad profile with a lower limit of FWHM \(\geq 1200\, \text{km s}^{-1}\) (see, e.g., Shen et al. 2011). Although it is still unclear whether there is a narrow component, we fitted C\(\text{IV}\) with two Gaussians.

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\(^3\) [http://dr9.sdss3.org/bulkSpectra](http://dr9.sdss3.org/bulkSpectra)
### Table 1

Quasars at $z \leq 0.4$

| Object (SDSS J) | $z$  | $i$   | $N$  | log $M_{bh}$ | $n_{H}$ | $R$     | $L_{con} - \alpha_{\lambda}$ | $L_{con} - L_{H\beta}$ | $L_{con} - L_{H\alpha}$ | $L_{con} - \text{EWH}_{\beta}$ | $L_{con} - \text{EWH}_{\alpha}$ | $L_{H\beta} - \text{FWHM}$ | $L_{H\alpha} - \text{FWHM}$ |
|-----------------|------|-------|------|--------------|---------|---------|-------------------------------|--------------------------|--------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
|                 |      |       |      |              |         |         | (mag)                         | (5$_{\odot}$)             | (5$_{\odot}$)             | (5$_{\odot}$)             | (5$_{\odot}$)             | (5$_{\odot}$)             | (5$_{\odot}$)             | (5$_{\odot}$)             |
| 030639.57+000343.1 | 0.107| 16.83 | 9    | 7.50         | 0.24    | 5.3     | $-0.89$                       | $5E-4$                   | $0.86$                   | $1E-3$                       | $0.86$                       | $2E-3$                       | $0.50$                       | $0.17$                       |
| 031027.82-004950.7 | 0.081| 15.63 | 8    | 7.92         | 0.10    | $...$   | $-0.59$                       | $0.11$                   | $0.92$                   | $8E-4$                       | $-0.14$                      | $0.73$                       | $-0.07$                      | $0.86$                       |
| 031142.02-005918.9 | 0.281| 18.69 | 6    | 8.37         | 0.04    | $...$   | $0.37$                        | $0.46$                   | $0.60$                   | $0.20$                       | $0.71$                       | $0.11$                       | $0.54$                       | $0.26$                       |
| 031427.45-011152.3 | 0.387| 18.33 | 8    | 7.86         | 0.53    | $...$   | $-0.16$                       | $0.66$                   | $0.73$                   | $0.02$                       | $0.63$                       | $0.06$                       | $-0.51$                      | $0.15$                       |

**Notes.** The quasars at $z \leq 0.4$ in our sample. Column 1: object name, Column 2: redshift, Column 3: $i$-band apparent magnitude, Column 4: number of spectroscopic observations, Column 5: black hole mass, Column 6: Eddington ratio, defined as $L_{bol}/L_{\text{Edd}}$, Column 7: radio loudness, $R = f_{6cm}/f_{2500 \ Å}$, Columns 8–21: the Spearman rank correlation coefficients and probability level for $L_{con} - \alpha_{\lambda}$, $L_{con} - L_{H\beta}$, $L_{con} - L_{H\alpha}$, $L_{con} - \text{EWH}_{\beta}$, $L_{con} - \text{EWH}_{\alpha}$, $L_{H\beta} - \text{FWHM}$, and $L_{H\alpha} - \text{FWHM}$. 
Table 2
Quasars at 0.4 < z ≤ 0.8

| Object (SDSS J) | z | i | N | log M_h | a_1 | R | L_{con} - a_1 | L_{con} - L_{M_{edd}} | L_{con} - L_{H_β} | L_{con} - EW_{MgII} | L_{con} - EW_{H_β} | L_{M_{edd}} - FWHM | L_{H_β} - FWHM |
|-----------------|---|---|---|---------|----|---|-------------|----------------|----------------|----------------|----------------|-----------------|---------------|
|                |   |   |   |         |    |   |            |                |                |                |                |                 |               |
| 021953.04-004434.2 | 0.686 | 19.60 | 6 | 8.25 | -0.76 | ... | -0.08 | 0.87 | 0.43 | 0.39 | 0.20 | 0.70 | -0.54 | 0.27 | -0.02 | 0.95 | 0.02 | 0.96 | 0.60 | 0.20 |
| 022214.38-001745.3 | 0.773 | 21.18 | 6 | 8.42 | -1.06 | ... | -0.60 | 0.28 | 0.89 | 0.03 | 0.80 | 0.10 | -0.70 | 0.19 | 0.50 | 0.39 | -0.20 | 0.74 | 0.40 | 0.50 |
| 022331.90-001605.5 | 0.771 | 19.00 | 6 | 8.27 | -0.46 | ... | -0.09 | 0.87 | -0.10 | 0.87 | 0.99 | 1E-4 | -0.90 | 0.03 | -0.90 | 0.03 | 0.70 | 0.18 | -0.50 | 0.40 |
| 022335.84+002351.8 | 0.774 | 19.07 | 9 | 8.25 | -0.64 | ... | -0.11 | 0.76 | -0.08 | 0.83 | 0.25 | 0.52 | -0.08 | 0.83 | -0.07 | 0.86 | -0.51 | 0.15 | 0.11 | 0.76 |
| 022556.34+001345.3 | 0.709 | 19.51 | 7 | 8.81 | -1.12 | ... | 0.46 | 0.29 | 0.78 | 0.04 | 0.82 | 0.02 | -0.03 | 0.93 | -0.11 | 0.82 | 0.82 | 0.02 | 0.57 | 0.18 |
| 030458.96+000235.7 | 0.564 | 18.36 | 10 | 9.03 | -1.17 | 404.4 | -0.76 | 9E-3 | 0.01 | 0.98 | 0.08 | 0.83 | -0.50 | 0.13 | -0.43 | 0.21 | 0.83 | 3E-3 | 0.72 | 0.01 |
| 030745.95+000833.4 | 0.427 | 19.02 | 9 | 8.50 | 0.05 | ... | -0.59 | 0.11 | -0.26 | 0.53 | 0.26 | 0.50 | -0.45 | 0.26 | -0.26 | 0.53 | 0.90 | 2E-3 | 0.59 | 0.11 |
| 030911.64+002358.8 | 0.611 | 17.22 | 10 | 9.05 | -0.62 | ... | -0.66 | 0.07 | 0.38 | 0.35 | 0.26 | 0.53 | -0.69 | 0.05 | -0.21 | 0.61 | 0.97 | 4E-5 | -0.17 | 0.69 |
| 030939.45-000339.2 | 0.769 | 17.11 | 8 | 8.92 | -0.36 | ... | 0.16 | 0.69 | -0.02 | 0.95 | 0.54 | 0.16 | -0.19 | 0.65 | 0.33 | 0.41 | -0.88 | 3E-3 | 0.73 | 0.03 |
| 031022.10+004130.0 | 0.656 | 19.47 | 7 | 7.90 | -0.31 | ... | 0.67 | 0.09 | -0.46 | 0.29 | 0.18 | 0.70 | -0.42 | 0.33 | -0.32 | 0.48 | 0.96 | 1E-4 | 0.71 | 0.01 |
| 031226.12-003708.9 | 0.621 | 18.98 | 10 | 9.06 | -1.51 | 1227.7 | -0.06 | 0.86 | 0.28 | 0.46 | 0.92 | 5E-4 | -0.87 | 2E-3 | -0.47 | 0.20 | -0.16 | 0.66 | -0.06 | 0.86 |
| 032142.83-003225.7 | 0.648 | 19.14 | 6 | 8.17 | -0.46 | ... | 0.30 | 0.62 | 0.00 | 1.00 | 0.99 | 1E-4 | -0.70 | 0.18 | -0.10 | 0.87 | 0.69 | 0.18 | -0.10 | 0.87 |
| 032205.04+001201.4 | 0.471 | 17.48 | 6 | 8.70 | -0.71 | ... | -0.71 | 0.11 | 0.42 | 0.39 | 0.94 | 4E-3 | -0.37 | 0.46 | 0.09 | 0.87 | 0.25 | 0.62 | 0.37 | 0.46 |

Notes. The quasars at 0.4 < z ≤ 0.8 in our sample. Column 1: object name, Column 2: redshift, Column 3: i-band apparent magnitude, Column 4: number of spectroscopic observations, Column 5: black hole mass, Column 6: Eddington ratio, defined as \( L_{bol}/L_{edd} \), Column 7: radio loudness, \( R = J_0c_\text{cm} / J_{2500 \lambda} \), Columns 8–21: the Spearman rank correlation coefficients and probability level for \( L_{con} - \alpha_1 \), \( L_{con} - L_{M_{edd}} \), \( L_{con} - L_{H_β} \), \( L_{con} - EW_{MgII} \), \( L_{con} - EW_{H_β} \), \( L_{M_{edd}} - \text{FWHM} \), and \( L_{H_β} - \text{FWHM} \).
### Table 3
Quasars at \( z > 0.8 \)

| Object (SDSS J) | \( z \) | \( i \) | \( N \) | \( \log M_{\text{BH}} \) | \( m \) | \( R \) | \( L_{\text{con}} - \alpha_{ \text{K29}} \) | \( L_{\text{con}} - L_{\text{CIV}} \) | \( L_{\text{con}} - L_{\text{MgII}} \) | \( L_{\text{con}} - \text{EW}_{\text{CIV}} \) | \( L_{\text{con}} - \text{EW}_{\text{MgII}} \) | \( L_{\text{CIV}} - \text{FWHM} \) | \( L_{\text{MgII}} - \text{FWHM} \) |
|----------------|-----|-----|-----|-----------------|-----|-----|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 021754.30+000234.0 | 2.044 | 19.07 | 6 | 9.17 | 0.22 | ... | 0.37 | 0.46 | 0.82 | 4E−3 | ... | ... | ... | 0.92 | 2E−3 | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | 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| ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |...
The blended narrow lines, e.g., [O iii] \( \lambda \lambda 4959, 5007 \) and [He ii] \( \lambda 4686 \) blending with H\( \beta \), and [S ii] \( \lambda \lambda 6716, 6731 \), [N ii] \( \lambda \lambda 6548, 6583 \) and [O i] \( \lambda 6300 \) blending with H\( \alpha \), are included as one Gaussian component for each line at the fixed line wavelength. The details of spectral analysis were given in Chen et al. (2009). The spectral index of the continuum, the continuum flux, the line width, and flux of broad H\( \beta \), Mg\( ii \) and C iv lines were obtained from the final fits for our sample, from which the variations of both the continuum and line emission can be investigated for individual sources and whole sample.

4. RESULTS

4.1. The Variability in Continuum Luminosity

The variability of continuum emission is investigated with the rest luminosity at 2500 Å. This wavelength is selected because it is covered in the SDSS spectra for most sources, and the variations at shorter wavelength are known to be larger than those at longer wavelength (e.g., Cristiani et al. 1997). The luminosity at 2500 Å is directly calculated from the fitted power-law continuum if 2500 Å is covered in the spectrum, otherwise it is extrapolated from the power-law continuum, which is the case in seven quasars. We define the continuum variability amplitude for each source to be \( \Delta \log L_\lambda = \log L_{\lambda, \text{max}} - \log L_{\lambda, \text{min}} \), in which \( L_{\lambda, \text{max}} \) and \( L_{\lambda, \text{min}} \) are the highest and lowest luminosities at 2500 Å measured from multi-epoch spectra, respectively. To evaluate the significance of the variability, two uncertainties are taken into account. The first one is the measurement uncertainties in two involved spectra \( \sigma_s = \sqrt{\sigma_{s,1}^2 + \sigma_{s,2}^2} \), in which \( \sigma_{s,1} \) and \( \sigma_{s,2} \) are uncertainties in two spectra. The other is the uncertainties from the power-law fitting \( \sigma_1 = \sqrt{\sigma_{1,1}^2 + \sigma_{1,2}^2} \). The total uncertainty in \( \Delta \log L_\lambda \) is \( \sigma = \sqrt{\sigma_s^2 + \sigma_1^2} \). We found that \( \Delta \log L_\lambda \) is larger than 3\( \sigma \) for all our sources, implying significant continuum variations in our sample. As an example, the continuum variation is shown in Figure 2 for the nine-epoch spectra of SDSS J031003.01−004645.7 (\( z = 2.115 \)), in which the C iv line variation is also presented.

The relationship between the continuum variability amplitude and various parameters are presented in Figure 3 for our sample. We find a significant anti-correlation between the continuum variability amplitude and the multi-epoch-averaged 2500 Å luminosity with a Spearman rank correlation coefficient \( r_s = -0.38 \) at \( \sim 99.7\% \) confidence level (see Figure 3(a)). This anti-correlation is more apparent in binned 2500 Å luminosity. In Figure 3(b), we find a mild anti-correlation between the redshift and the continuum variability amplitude with a Spearman correlation coefficient \( r_s = -0.27 \) at \( \sim 96.6\% \) confidence level. In redshift bins, the continuum variability amplitude decreases with the redshift at \( z < 2.5 \), while it increases at higher redshift, where, however, there are only a few objects. For our objects, the variability was obtained from the luminosity at the same rest frame wavelength 2500 Å, which naturally eliminates the selection effect of the rest wavelength. However, our result is in contrast to the positive correlations reported in previous works (e.g., Cristiani et al. 1996; Vanden Berk et al. 2004).

Using the black hole mass \( M_{bh} \) and the Eddington ratio \( L_{bol}/L_{edd} \) from Shen et al. (2011; see Tables 1–3), their relations with the continuum variability amplitude were studied for our sample (see Figures 3(c) and (d)). From the Spearman correlation analysis, we failed to find a significant correlation between the continuum variability amplitude and the black hole mass. Similarly, there is no strong correlation between the continuum variability amplitude and the Eddington ratio, although the trend of decreasing variability amplitude with increasing \( M_{bh} \) and \( L_{bol}/L_{edd} \) can be seen from the binned values.

In Figure 3, it can be clearly seen that one quasar (SDSS J022214.38−001745.3, \( z = 0.773 \)) has a much larger variability amplitude than all other objects. In order to evaluate its influence on the correlations, we performed the correlation...
analysis after excluding the object and found similar correlation results.

4.2. The Spectral Variation

The multi-epoch spectroscopic observations enable us to investigate the relationship between the \(2500\,\text{Å} \) continuum luminosity and the spectral shape (\(\alpha_{\lambda} \)) for individual sources. The Spearman correlation coefficient and the confidence level are shown for each source in Tables 1–3. We find that 30 sources follow the RWB trend with positive correlations, while the rest of the 30 objects show a BWB trend with a negative correlation coefficient. While the correlation confidence level is quite low for most objects, we find significant anti-correlations in three quasars at a confidence level of \(\geq 99\% \) and mild anti-correlations in six objects at the \(90\% < p < 99\% \) confidence level. In contrast, none of the sources have significant positive correlations, and only three quasars have mild positive correlations (SDSS J022518.36−001332.3 at \(z = 3.63\), SDSS J030907.49+002419.0 at \(z = 2.08\), and SDSS J031022.10+004130.0 at \(z = 0.65\); see Tables 2–3). The correlations are illustrated in Figure 4 with two examples, SDSS J030639.57+000343.1 (BWB, \(r_s = -0.89\) at \(>99.5\% \)) and SDSS J031022.10+004130.0 (RWB, \(r_s = 0.67\) at \(<91\%)\).

4.3. Line Emission

The correlation between the variations in the broad emission line luminosity with the continuum luminosity is explored for each object, and the results from the Spearman correlation analysis are shown in Tables 1–3, in which the continuum luminosity at \(1350\,\text{Å}, 3000\,\text{Å}, 5100\,\text{Å}, \) and \(5100\,\text{Å} \) correspond to broad \(\text{C}\ IV, \text{Mg}\ II, \text{H}\beta, \) and \(\text{H}\alpha \) lines, respectively.

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Figure 3. (a) Variability amplitude vs. continuum luminosity at \(2500\,\text{Å} \). The continuum luminosity is the multi-epoch averaged value. (b) Variability amplitude vs. redshift. (c) Variability amplitude vs. black hole masses. (d) Variability amplitude vs. Eddington ratio. In each panel, the squares represent the mean variability amplitude in bins of \(x\) axis parameters. The different bins are divided by (a) 44.5, 45, 46; (b) 1, 2, 3; (c) 8.0, 8.5, 9.0, 9.5; (d) \(-1.1, -0.6, -0.2\).
We find positive correlations between the line and continuum luminosity in most cases (74 of 92 emission lines, \(\sim 80\%\)), consistent with the photoionization model (Yee 1980), of which \(\sim 26\%\) (24 of 92) have a \(\geq 90\%\) correlation confidence level. As an example, the correlation between the broad H\(\alpha\) luminosity and the continuum luminosity at 5100 Å is plotted in Figure 5 for SDSS J030639.57+000343.1. A significant correlation is found with \(r_s = 0.867\) at a confidence level of 99.7% (see also Guo & Gu 2014). The linear fit gives
\[
\log L_{H\alpha} = (1.03 \pm 0.13) \log(\lambda L_{\lambda,5100}) - (2.83 \pm 5.81). \tag{1}
\]

Interestingly, we find anti-correlations between the line and continuum luminosity in the rest of the cases. However, the anti-correlations are usually very weak (see Tables 1–3). Only one object (SDSS J021754.80+000234.0) exhibits a mild anti-correlation with \(r_s = -0.77\) at the \(\sim 93.0\%\) confidence level (see Table 3), which is shown in Figure 5 for the broad Mg \(\text{II}\) luminosity and the continuum luminosity at 3000 Å. The linear fit yields
\[
\log L_{\text{Mg} \text{II}} = (-0.50 \pm 0.32) \log(\lambda L_{\lambda,3000}) + (70.91 \pm 14.66). \tag{2}
\]

When putting the multi-epoch line measurements of all our sample sources together, we find significant positive correlations between each line emission and the corresponding continuum luminosity for whole sample (see Figure 6).

### 4.4. Baldwin Effect

Measurements of emission lines from multi-epoch spectra also enable us to study the Baldwin effect for both individual sources and the whole sample. In Tables 1–3, we list the Spearman correlation coefficient and corresponding confidence level between the EW (broad C\(\text{IV}\), Mg \(\text{II}\), H\(\beta\), and H\(\alpha\)) and the continuum luminosity for individual sources. We find that 61 of 92 (\(\sim 66\%)\) emission lines show anti-correlations, with 13 cases (\(\sim 14\%)\) at a confidence level of \(\geq 90\%). Two sources are found to have significant anti-correlations at a confidence level \(> 99\%), i.e., SDSS J031156.45−004157.0 and SDSS J031156.45−004157.0 (see Tables 2 and 3). Strikingly, positive correlations, namely, the negative Baldwin effect, are also found in 31 cases; however, the correlations are usually weak (confidence level \(< 90\%)\). Examples of anti-correlation and positive correlation are shown in Figure 7 for SDSS J031027.82−004950.7 and SDSS J030639.57+000343.1, respectively.
Figure 7. Examples of the positive correlation (SDSS J030639.57+000343.1, for Hα, top) and negative correlation (SDSS J031027.82−004950.7, for Hα, bottom) between the broad-line equivalent width and continuum luminosity. The errors of the EW and continuum luminosity are indicated by the vertical and horizontal lines, respectively, which are not evident when smaller than the symbol size.

Figure 8. Broad emission line equivalent width and continuum luminosity from all multi-epoch spectra of our sample. The measurements from multi-epoch spectra for the same object are connected with solid lines for Hα in four sources and Hβ in four sources. (A color version of this figure is available in the online journal.)

We further study the Baldwin effect for whole sample by plotting all line EW measurements and the corresponding continuum luminosity in Figure 8. Although the scatter is large, significant Baldwin effect, i.e., a strong anti-correlation between the line EW and continuum luminosity, is found with a Spearman correlation coefficient of 0.14 at 99.9% confidence level for the broad Mg II line, which is covered in SDSS spectra for most sources.

4.5. Line Emission and Width

With multi-epoch spectroscopy, we investigate the relationship between the variability of the broad-line width FWHM and the broad-line luminosity (broad C IV, Mg II, H β, and Hα) for individual sources. In Tables 1–3, we show the Spearman correlation coefficient and confidence level for various emission lines in each source. While 69 of 92 (∼75%) emission lines show a positive correlation, with 24 cases (∼26%) at a confidence level of ∼90%, anti-correlations were also found, although the anti-correlations are usually weak, with only three sources at ∼90% confidence level (C IV in SDSS J022230.28+001844.5, Mg II in SDSS J030911.64+002358.8, and Hα in SDSS J031027.82−004950.7; see Tables 1–3). In Figure 9, the positive correlation and anti-correlation are illustrated with two examples, SDSS J031131.41−002127.4 and SDSS J031027.82−004950.7, for broad C IV and Hα, respectively.

The relationship between broad-line width and luminosity is also explored for the whole sample when putting all multi-epoch measurements together (see Figure 10). Strong correlations are found with Spearman correlation coefficients of 0.14, 0.16, 0.42, and 0.41, all at >99% confidence level, for C IV, Mg II, H β, and Hα, respectively. Correlation analysis is not performed for Hα, since only four sources have Hα measurements. In Figure 10, irrespective of large scatters, the mean values for line FWHM imply that systematically H β and Mg II are at similar regions, while C IV are relatively closer to central nuclei, with the mean FWHM of 41 Å (∼7900 km s⁻¹), 48 Å (∼5100 km s⁻¹), and 90 Å (∼5500 km s⁻¹) for broad C IV, Mg II, and H β, respectively.

5. DISCUSSIONS

5.1. The Color Variation

As mentioned in Section 2, the quasars are selected to be candidates for spectroscopic observations according to various criteria. While most sources are chosen from their color, some are selected because they were detected in the FIRST...
survey. We find that the mean spectral index of all sample $\langle \alpha_i \rangle = -1.37 \pm 0.18$ is generally consistent with that of the composite spectrum ($\alpha_c = -0.44$; Vanden Berk et al. 2001), which indicates no severe reddening for the whole sample. There are 15 quasars with $i > 19.1$ (see Tables 1–3), and their mean spectral index is $-1.34$, similar to the value of the rest of the 45 bright objects $-1.38$. This implies that the reddening is not strong in faint sources, consistent with the color selection criterion. In contrast, we find that the mean spectral index of the eight FIRST-detected quasars, $-1.07$, is evidently redder than that of non-FIRST detections, $-1.42$. This can be likely due to the higher reddening or the contamination of FIRST.
sources with synchrotron emission. However, none of these FIRST sources exhibits significant positive correlation between the spectral index and continuum luminosity, indicating that the reddening or synchrotron emission may not be necessarily related with the RWB trend.

The anti-correlation of the variability amplitude with the rest wavelength has been found in quasars (e.g., Cristiani et al. 1997; Vanden Berk et al. 2004; Zuo et al. 2012). The spectrum shortward of 2500 Å shows a steeper slope and is more variable, while the spectrum longward of 2500 Å is relatively flat and less variable for quasars dominated by Balmer emission and Fe II emission lines. This variance mainly comes from the changing of the temperature of the accretion disk (Bian et al. 2012b). It is reasonable to assume that most variability occurs in the inner part of the AGNs, so when the accretion disk becomes hotter, it will produce more high energy photons and the continuum emission peak will move to the short wavelength, which yields a bluer spectra when AGNs become brighter (see Bian et al. 2012b), i.e., the commonly observed BWB trend in AGNs (e.g., Gu & Ai 2011a, 2011b; Zuo et al. 2012). Indeed, we find a BWB trend in half of our sample sources; however, we also find an RWB trend in the remaining half of the sources. In flat-spectrum radio quasars (FSRQs), Gu et al. (2006) proposed that the varying contribution of the thermal emission from the disk relative to the synchrotron jet emission can qualitatively explain the RWB trend. However, this scenario cannot be used to explain three quasars with mild RWB correlations (see Section 4.2) because none of them are detected in FIRST.

It is still unclear what causes the RWB trend in radio-quiet quasars (e.g., Bian et al. 2012b). The line contribution in a broad photometric band could somewhat explain the RWB color variability in photometric data (Schmidt et al. 2012; Wilhite et al. 2005); nevertheless, it is hardly applicable to our sample since it is the continuum flux in a spectrum that resolves the quasar emission lines and there is no contamination from line emission. Alternatively, the variations of the contribution of the host galaxy could qualitatively produce the RWB trend in multi-epoch spectroscopy with a fixed fiber size (3 arcsec in SDSS-I/II) when seeing varies. The influence of variable seeing conditions on the observed variations has already been noticed in aperture photometry (e.g., Cellone et al. 2000). Since luminous quasars are usually hosted in the bright elliptical galaxies, the host galaxies will be more extended in poor seeing conditions, then their contribution will be relatively smaller within a fixed aperture compared to light from the quasar. This will result in an RWB trend when seeing varies because the host galaxies are usually redder than quasars. We checked the correlations between the spectral index and seeing for three RWB sources with mild correlations. With the available seeing, we found correlations at a confidence level similar to RWB correlations in two sources, SDSS J030907.49+002419.0 ($z = 2.083$) and SDSS J031022.10+004130.0 ($z = 0.656$). Therefore, the effects of host galaxy contribution cannot be completely ruled out, although it is hard to quantitatively evaluate this possibility, and the contribution of the host galaxy may not be significant at the rest frame wavelength for these two objects.

### 5.1.1. Comparison with Previous Works

There have been extensive investigations on the relationship between the spectral shape and continuum variability, especially in radio-loud AGNs (e.g., Fan et al. 1998; Gu & Ai 2011a, 2011b). Two trends of color variations have been found. The BWB trend is commonly found in blazars, as well as in radio-quiet AGNs (e.g., Wu et al. 2005; Gu & Ai 2011a, 2011b; Zuo et al. 2012). However, the RWB trend has also been found (e.g., Gu et al. 2006; Bian et al. 2012b), which can be caused by the contribution of thermal emission in the case of FSRQs (Gu et al. 2006). Based on the two-epoch spectroscopy for a sample of quasars, which consists of 312 radio-loud and 232 radio-quiet sources, Bian et al. (2012b) found that half of the objects follow the RWB trend, and no obvious difference can be found between sub-samples of radio-quiet and radio-loud quasars. Therefore, our results are consistent with Bian et al. (2012b) with the fact that half of our quasars exhibit an RWB trend, and this RWB trend seems to have no relation with the radio detection. The results will be further investigated in a sample of about 2000 SDSS quasars with pronounced variations from multi-epoch spectroscopy (H. Guo & M. Gu 2014, in preparation).

### 5.2. Line Emission

While most sources show positive correlations between the broad line and continuum luminosity, some quasars exhibit anti-correlations, an effect not expected in the photoionization model. This anti-correlation could be qualitatively explained by the time delay between the line and continuum variability because the continuum emission needs a finite amount of time to reach the broad-line region clouds. This is actually why reverberation mapping works for long-term monitoring of AGNs (e.g., Kaspi et al. 2000). When we are observing the increased continuum emission, the observed line emission actually happens to correspond to the past declining phase due to the time delay. Therefore, an anti-correlation will be obtained.

### 5.3. Baldwin Effect

Despite the fact that the Baldwin effect has been extensively studied, its origin is still unclear (e.g., Netzer et al. 1992; Dietrich et al. 2002; Baskin & Laor 2004; Wu et al. 2009), and several causes of possible correlations (hence, possible physical causes) have been proposed: correlations with the black hole mass, the Eddington ratio, and the luminosity (e.g., Bian & Zhao 2004; Vestergaard & Peterson 2006). It could most likely be explained by the trend that more luminous sources have a softer spectral energy distribution (Netzer et al. 1992; Dietrich et al. 2002), which produces fewer less ionizing photons.

While the Baldwin effect has been studied extensively for AGN samples (e.g., Bian et al. 2012a), there have been few works on the Baldwin effect in individual sources. With multi-epoch spectroscopy, we investigate the Baldwin effect for our sample objects. As described in Section 4, most sources exhibit an anti-correlation between EW and continuum luminosity, as expected from the Baldwin effect, although the correlations are usually weak. As claimed in Wilhite et al. (2005), the broad lines are less variable than the underlying continuum, resulting in a relationship known as the intrinsic Baldwin effect, which is intrinsic to each object (Kinney et al. 1990). However, the intrinsic Baldwin effect in each object will be altered by the light-travel time effects in the broad-line region. Indeed, it has been shown that the scatter in the continuum-emission-line correlations is greatly reduced by removing light-travel time effects so that the emission-line flux are relative to the continuum that is driving the effects (e.g., Pogge & Peterson 1992). Unfortunately, we are unable to remove the light-travel time effects for our quasars due to the limited spectroscopic data. Interestingly, we also found a strong positive correlation...
between the EW and continuum luminosity (i.e., negative Baldwin effect) in SDSS J030639.57+000343.1 (broad Hα; see Figure 7) at the ∼99% confidence level. This however is most likely caused by increasing host contamination toward fainter luminosities (see Shen et al. 2011).

5.3.1. Comparison with Previous Works

As shown in Figure 8, a strong anti-correlation has been found for the Mg II line when all the measurements from multi-epoch spectra are put together, suggesting a Baldwin effect for the whole sample. However, some scatter is also found, which is likely, at least partly, caused by the mixture of the intrinsic Baldwin effect and light-travel time effects in each object. The Baldwin effect in the Mg II line is consistent with previous works. In a comprehensive study of the DR7 quasar catalog (105,783 quasars), strong Baldwin effects were found in both Mg II and CIV (Shen et al. 2011). In contrast, the Baldwin effect in Hβ is still unclear. The weak negative Baldwin effect was found for Hβ in the forms of EW ∝ L^{0.2} and EW ∝ L^{0.1} from ∼22,000 quasars in the 2dF+6dF surveys (Croom et al. 2002), and from ∼40,000 SDSS quasars (Greene & Ho 2005; Netzer & Trakhtenbrot 2007), respectively. It was suggested that this unexpected effect is likely caused by the luminosity-dependent change in the ratio of disk to non-disk continuum components (Croom et al. 2002). Indeed, although our sample is rather small compared to their samples, we found a strong negative Baldwin effect in Hβ EW ∝ L^{0.14} with a Spearman correlation coefficient r_s = 0.5 at the ∼99.9% confidence level, consistent with their results. The negative Baldwin effect between the broad Hβ EW and L_{5100} has also been found below L_{5100} ∼ 10^{45} erg s^{-1} in DR7 quasars (see their Figure 12, Shen et al. 2011). However, the authors argued that it can be most likely due to the contamination from the host galaxy. When we restrict L_{5100} ∼ 10^{45} erg s^{-1}, we did not find a pronounced Baldwin effect in Hβ for our sample. However, the small sample size with only 13 quasars at L_{5100} ∼ 10^{45} erg s^{-1} prevents us from drawing firm conclusions. Similarly, we failed to find the Baldwin effect in CIV, which may be caused by the narrow L_{1350} coverage (Shields 2007; see Figure 8).

5.4. Line Width

An anti-correlation between the FWHM and luminosity of emission lines has been found in previous works (e.g., Wills et al. 1993). An intermediate-line region is hypothesized to explain the anti-correlation, which is located between the narrow-line region and the very-broad-line region, i.e., there are two distinct portions of the broad-line region. In the empirical relation of black hole mass estimations (e.g., Kaspi et al. 2000), the black hole mass can be obtained from

\[ M_{\text{BH}} \propto V^2 \times R_{\text{BLR}} \propto \text{FWHM}^2 \times L^\beta, \]  

where the \( M_{\text{BH}} \) is the black hole mass, \( V \) is the velocity of the BLR gas clouds, \( R_{\text{BLR}} \) is BLR radius, \( \beta \) is the index of the empirical \( R_{\text{BLR}}-L \) relation, and \( L \) is either the continuum or emission line luminosity (e.g., Wu et al. 2004). Therefore, an anti-correlation between the emission line luminosity and line width would be expected in individual sources, which indeed has been found in some quasars. However, we find a positive correlation between the FWHM and line luminosity in most sources (see Tables 1–3). The positive correlations become even more evident when putting all quasars together in Figure 10, which is consistent with Wilhite et al. (2005). This result can be explained with two components in BLR, with the broad-line base (the inner BLR) being more variable than the line core, which is expected because with the radius increasing, the characteristics of the variation will be diluted and the reprocessing of the seed photons will consume the energy of the variability (see Wilhite et al. 2005). In the double-peaked broad Hα source 3C 390.3, Zhang (2013) argued that this unexpected positive correlation can be naturally explained due to the different time delays for different parts of the disk-like BLRs in one short period with the theoretical accretion disk model.

6. CONCLUSIONS

We have investigated the optical variability at various aspects for a sample of 60 SDSS quasars with at least six-epoch spectroscopic observations. The main results are summarized as follows.

1. We verify the strong anti-correlation between the variability and continuum luminosity, consistent with previous works. A mild anti-correlation is discovered between the variability and redshift. However, we find no significant correlations between the variability and black hole mass or Eddington ratio. In individual sources, half of the sample objects follow the RWB trend, while the other half exhibit the RWB trend. Although the mechanism of the RWB trend is unclear, the effects of host galaxy contribution due to seeing variations cannot be completely ruled out.

2. As expected from the photoionization model, positive correlations between the broad emission line and continuum luminosity are found in most individual sources, as well as for the whole sample. We confirm the Baldwin effect in most individual objects and the whole sample, while the positive Baldwin effect was also found in several quasars, which can be at least partly (if not all) due to the host galaxy contamination.

3. We find positive correlations between the broad emission line luminosity and line width in most individual quasars, as well as in the whole sample, implying that the line base is more variable than the line core.

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