The Correlated Variations of C IV Narrow Absorption Lines and Quasar Continuum

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Received 2018 February 1; revised 2018 March 28; accepted 2018 April 3; published 2018 June 1

Abstract

We assemble 207 variable quasars from the Sloan Digital Sky Survey, all with at least 3 observations, to analyze C IV narrow absorption doublets, and obtain 328 C IV narrow absorption line systems. We find that 19 out of 328 C IV narrow absorption line systems were changed by \( |\Delta W_{\lambda 1548}| \geq 3\sigma_{\Delta W_{\lambda 1548}} \) on timescales from 15.9 to 1477 days at rest-frame. Among the 19 obviously variable C IV systems, we find that (1) 14 systems have relative velocities \( v_r > 0.01c \) and 4 systems have \( v_r > 0.1c \), where \( c \) is the speed of light; (2) 13 systems are accompanied by other variable C IV systems; (3) 9 systems were changed continuously during multiple observations; and (4) 1 system with \( v_r = 16,862 \) km s\(^{-1}\) was enhanced by \( \Delta W_{\lambda 1548} = 2.7\sigma_{\Delta W_{\lambda 1548}} \) in 0.67 day at rest-frame. The variations of absorption lines are inversely correlated with the changes in the ionizing continuum. We also find that large variations of C IV narrow absorption lines are form differently over a short timescale.

Key words: galaxies: active – galaxies: halos – methods: data analysis – quasars: absorption lines

Supporting material: machine-readable table

1. Introduction

It is now widely accepted that feedback is a very important mechanism during the formation and evolution of galaxies. Outflow is a foundational component of active galactic nuclei, and is related to the gas lifted off the central accretion disk. In addition to regulating the growth of supermassive black holes, through feedback the outflow affects the multiphase distribution of the surrounding gas, influences the chemical and dynamical evolution of the galaxy, regulates the enrichment of the intergalactic medium, and enhances/quenches star formation within the host galaxy.

It is found that many AGN spectra exhibit asymmetric or even double-peaked features in the emission-line profiles (e.g., Liu et al. 2010; Barrows et al. 2013; Shi et al. 2014; Lyu & Liu 2016; Kharb et al. 2017), which can be ascribed to (1) outflows (e.g., Baskin & Laor 2005; Komossa et al. 2008); (2) binary supermassive black holes (e.g., Boroson & Lauer 2009; Gaskell 2010; Shen & Loeb 2010); and (3) accretion disk emission lines (e.g., Chen et al. 1989; Cao & Wang 2006; Luo et al. 2009). The emission lines with asymmetric profiles are a powerful and fashionable tool to investigate the properties of outflows. We also note that quasar absorption lines with \( z_{\text{abs}} \leq z_{\text{em}} \) are very common, which could originate in (1) foreground galaxies that are beyond the gravitational well of the quasar system (e.g., Bergeron 1986; Bergeron & Boissé 1991; Bowen et al. 2006; Farina et al. 2014; Landoni et al. 2016); (2) quasar outflows (e.g., Hamann et al. 2011, 2013; Chen & Qin 2015; Perrotta et al. 2016); and (3) quasars’ surrounding environments, such as a quasar’s host galaxy, circumgalactic medium, and galaxy cluster. The foreground galaxies generally produce absorption lines with \( z_{\text{abs}} \leq z_{\text{em}} \). Quasars’ surrounding environments often make absorption lines with \( z_{\text{abs}} \approx z_{\text{em}} \). Due to the relative motion of the clumpy clouds ejected by the quasar, absorption lines formed in quasar outflows generally show an absorption redshift \( z_{\text{abs}} \leq z_{\text{em}} \). Blueshifted absorption lines are common in the quasar spectra and their detections do not depend on quasar emissions, so they are a very popular tool for studying the outflow as well.

Broad absorption lines (BALs), which have line widths larger than a few thousand km s\(^{-1}\) at depth >10% below the continuum (e.g., Weymann et al. 1979), are undoubtedly related to quasars and likely formed in quasar outflows; narrow absorption lines (NALs), which have line widths of less than a few hundred km s\(^{-1}\), can originate in a wide variety of media. No matter what the relationship between the medium producing NALs and the quasar is, NALs often exhibit similar line profiles, especially in low- or middle-resolution spectra. Therefore, it is not easy to distinguish outflow NALs from NALs originating in other media in a single-epoch spectra. It has long been known that the quasar NALs can vary in equivalent width on timescales from months to years (e.g., Narayan et al. 2004; Wise et al. 2004; Hamann et al. 2011; Chen & Qin 2013; Misawa et al. 2014, 2016; Boissé et al. 2015; Chen et al. 2015). The variations of NALs can be interpreted by (1) the change in the background ionizing continuum; (2) the change in the shielding gas located between the continuum source and absorbing clouds; and (3) clumpy clouds moving across the continuum source. Line variation can be a good characteristic to assess whether the NALs are formed in the outflow or not, since, based on the above scenarios, it is unrealistic to expect obvious variation in the intervening and environmental NALs on a timescale of years.

While the origin of the variation in NALs is still an open question, the variations of absorption lines are a useful tool to constrain the physical and geometrical conditions, and/or kinematics of the absorbing clouds. In the photoionization scheme, the line variation is related to the flux density of the incident ionizing continuum, thus the timescale of the variation can set a limit on the recombination or ionization timescale. In the scheme of the absorbing cloud moving across our sightline, the timescale of the variation can help to limit the transverse velocity of a clumpy cloud across the ionizing continuum source. In this paper, using quasars with multi-epoch spectra from the Sloan Digital Sky Survey (SDSS; York et al. 2000), we will examine the variations of C IV NALs, and investigate...
the relationship between the variations of the NALs and continuum. The Mg II and Si IV NALs, and the BALs will be studied in our future work.

In Section 2, we describe the data sample and spectral analysis. We present the properties of variable C IV NALs and discussions in Section 3. A summary is presented in Section 4. In this paper, we adopt the $\Lambda$CDM cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2. Quasar Sample and Spectral Analysis

2.1. Quasar Sample

Through the ancillary science programs of the Baryon Oscillation Spectroscopic Survey (BOSS; Dawson et al. 2013, 2016) and the Extended Baryon Oscillation Spectroscopic Survey (eBOSS; Dawson et al. 2016), some quasars are repeatedly observed by the SDSS. The quasar catalog for Data Release 14 of eBOSS (DR14Q; Pâris et al. 2017) is the latest SDSS catalog of spectroscopically confirmed quasars, and also includes previously spectroscopically confirmed quasars from the SDSS. We select quasars from the DR14Q catalog, all with three- to six-epoch observations. Here, we do not consider the quasars with more than six observations, since they generally have very short observation time intervals. The purpose of this paper is to analyze the variation of C IV NALs, so in our sample we only consider quasars with $z_{\text{em}} > 1.32$. Then, we download the quasar spectra from https://data.sdss.org/sas/dr14/. We aim to investigate the relationship between the variations of quasar radiation and absorption lines, thus we further limit the quasar sample to $\Delta f_{1350} \geq 4\sigma_{1350}$, where $f_{1350}$ is the spectral flux at rest-frame 1350 Å. After these screenings, we obtain a sample of 207 quasars, which includes 675 spectra. For these 207 quasars, we determine the emission redshifts in the following sequence: (1) adopt the redshifts from our measurements of [O II] $\lambda$3728 narrow emission lines when available; (2) use the improved redshifts of the SDSS quasars from Hewett & Wild (2010); (3) adopt the Mg II emission-line-based redshifts from Pâris et al. (2017) when available; and (4) or otherwise utilize the visual inspection redshifts of Pâris et al. (2017).

2.2. Spectral Analysis and Parameter Measurements

In order to identify C IV NALs, we adopt methods consistent with our previous works (e.g., Chen et al. 2014a, 2014b, 2015) to analyze the quasar spectra, which are briefly described as follows:

1. For each spectrum, we model a pseudo-continuum with a combination of cubic spline and multi-Gaussian functions in an iterative fashion, which is utilized to normalize the spectral flux and flux uncertainty. The NALs generally have line widths of less than a few hundred km s$^{-1}$. Therefore, we first mark the continual absorption features with line widths larger than 1200 km s$^{-1}$ at depths larger than 20% under the pseudo-continuum fit (e.g., Chen et al. 2015). In the same spectral region, if no quasar spectrum shows an absorption feature less than 1200 km s$^{-1}$ at depths larger than 20% under the pseudo-continuum fit, we get rid of the marked absorption features. This step was carried out to account for NALs that might have evolved into mini-BALs or BALs.

2. The pairs of Si II $\lambda$1304 and O I $\lambda$1302 NALs at higher redshifts often lead to misidentifications of C IV NALs at lower redshifts. In order to reduce the confusions arising from the Ly $\alpha$, O I $\lambda$1302, and Si II $\lambda$1304 absorption features, we consider the spectra data, which are used to search for C IV NALs, from 1310 Å at rest-frame to the red wing of the CIV $\lambda$1549 emission lines. The C IV NALs are identified in the normalized spectra data, which are the spectral fluxes divided by the pseudo-continuum fit. A pair of Gaussian functions is invoked to model a C IV doublet and the best fit is carried out with $\chi^2$ minimization. The model results are visually inspected one-by-one.

3. The redshifts ($z_{\text{obs}}$) of C IV NALs are yielded by the Gaussian function fitting centers of the C IV $\lambda$1548 lines, and the equivalent widths ($W_r$) of absorption lines at rest-frame are determined by the integrations of the Gaussian function fitting profiles. The error ($\sigma_r$) of $W_r$, which is contributed from the spectra flux uncertainty, is estimated by

$$ (1 + z_{\text{abs}})\sigma_r = \sqrt{\sum_{i=1}^{n} P^2 \left( \frac{\lambda_i - \lambda_0}{\sigma_{\text{flux},i}} \right)} \Delta \lambda, $$

where $P(\lambda_i - \lambda_0)$ is the absorption line profile centered at $\lambda_0$, $\lambda_i$ is the wavelength, $\sigma_{\text{flux},i}$ is the spectra flux, $\sigma_r$ is the spectra flux uncertainty, and $N$ is the pixel number over $\pm 3\sigma$, where $\sigma$ is determined by the fitting result of the Gaussian function. Due to the evolution of absorption lines or the signal-to-noise ratio of the spectra, we find that some C IV NALs are remarkable in the spectra obtained at some times, but there are inconspicuous absorption features in the spectra obtained at other times. For these inconspicuous absorption lines, we estimate their $\sigma_r$ within 200 km s$^{-1}$; these estimates are also considered upper limits of absorption strengths.

Among the 207 quasars, there are 166 quasars that at least one C IV NAL system with $W_r^{1548} \geq 3\sigma_{\text{flux}}$ and $W_r^{1551} \geq 2\sigma_{\text{flux}}$ was detected in one of the multi-epoch spectra. We obtain 328 C IV NAL systems, which comprise 1210 C IV NAL pairs. Here, a C IV NAL pair is defined as the same C IV NAL system that is observed in two-epoch spectra. The observed timescales of the 1210 C IV NAL pairs are shown in Figure 1, and their parameters are listed in Table 1.

3. The Properties of Variable C IV NALs and UV Continuum

3.1. The Variations of C IV NALs and UV Continuum

Section 2.1 claims that our data sample is limited to the quasars with $f_{1350} \geq 4\sigma_{1350}$, which is the most significant variation among the multiple-spectra pairs of a quasar. We note that some authors might fit a power-law continuum for each spectrum and derive the continuum flux at a band by directly measuring the fitting power-law continuum, which is unnecessary for this paper. We can derive the continuum flux at 1350 Å ($f_{1350}$) by directly measuring the SDSS original spectra. We believe that the SDSS original spectra and a fitting power-law continuum would not produce obviously different $f_{1350}$, especially for the differences between the $f_{1350}$ measured from the two-epoch spectra of a quasar. Now we start to compute the flux variations of the 1350 Å continuum for our 1210 C IV
NAL pairs. Here, we converse the fluxes to magnitudes, and define the basic variation as

$$\Delta m = -2.5 \times \log \left(\frac{f_{1530}}{f_{1350}}\right)$$

(2)

and the corresponding error as

$$\sigma_{\Delta m} = \sqrt{\left(\frac{\sigma_{f_{1350}}}{f_{1350}}\right)^2 + \left(\frac{\sigma_{f_{1530}}}{f_{1530}}\right)^2}$$

(3)

where $f_{1350}$, $f_{1530}$ are the observed flux of the 1350 Å continuum at two epochs, and $\sigma_{f_{1350}}$, $\sigma_{f_{1530}}$ are the corresponding errors. The normalized differences of the 1350 Å continuum fluxes are shown in the left panel of Figure 2. We find that a significant variation of $|\Delta m| \geq 3\sigma_{\Delta m}$ happened for about 58% of the 1210 C IV NAL pairs. We note that the spectro-photometric calibration of the SDSS has an error of about 5% at the $r$-band (e.g., Adelman-McCarthy et al. 2008; Margala et al. 2016; Yan et al. 2016; Abolfathi et al. 2017). Considering 5% of spectral flux as the error of flux calibration, we also find that 49% of the 1210 C IV NAL pairs show variations with $|\Delta m| \geq 3\sigma_{\Delta m}$. This paper aims to investigate the relationship between the variations of absorption lines and quasar continuum, which is expected to be diminished rather than enhanced by the flux calibration uncertainty. Therefore, we do not consider flux calibration uncertainty throughout this paper.

To investigate the variations of C IV NALs, we compute the differences of absorption strengths via

$$\Delta W^\lambda_r = W^\lambda_{r,1} - W^\lambda_{r,2}$$

(4)

and corresponding errors via

$$\sigma_{\Delta W^\lambda_r} = \sqrt{\sigma_{W^\lambda_{r,1}}^2 + \sigma_{W^\lambda_{r,2}}^2}$$

(5)

where $W^\lambda_{r,1}$, $W^\lambda_{r,2}$ are the equivalent widths at rest-frame at two epochs, and $\sigma_{W^\lambda_{r,1}}$, $\sigma_{W^\lambda_{r,2}}$ are the corresponding errors. The normalized differences of the absorption strengths are shown in the right panels of Figure 2. We find that there are 19 C IV NAL systems with $|\Delta W^\lambda_{1548}| \geq 3\sigma_{\Delta W^\lambda_{1548}}$, which are imprinted in the spectra of 16 quasars. These 19 C IV NAL systems with significant variations comprise 72 C IV NAL pairs, of which 27 pairs have variations of $|\Delta W^\lambda_{1548}| \geq 3\sigma_{\Delta W^\lambda_{1548}}$.

Wise et al. (2004) investigated the variations of associated C IV, N V, and O VI NALs with $v_r \leq 5000$ km s$^{-1}$, and found that 4 out of 15 quasars, or 4 out of 19 NALs, contained variable NALs, which indicates that about 21% associated NALs are variable. With a limit of $v_r \leq 5000$ km s$^{-1}$, our sample contains 7 out of 80 quasars, or 7 out of 100 NALs, including variable C IV NALs, which means that about 7% C IV NALs are variable. The fraction of variable NALs is much less than that reported by Wise et al. (2004), which might be mainly ascribed to the reason that Wise et al. (2004) contained C IV, N V, and O VI NALs, while we only consider C IV NALs.

3.2. The Variable C IV Narrow Absorption Line Systems

In this section, one-by-one we describe the 19 obviously variable C IV NALs with $|\Delta W^\lambda_{1548}| \geq 3\sigma_{\Delta W^\lambda_{1548}}$, whose spectra are shown in Figure 3.

1. Quasar SDSS J003135.57+003421.2 with $z_{em} = 2.2300$. It was spectroscopically observed by the SDSS on MJD = 52,262, 55,182, 55,443, and 57,006. In the quasar spectra, we detect 4 C IV NALs with $z_{abs} = 1.7333, 1.9979, 2.0082$, and 2.0246, and $v_r = 49,588, 22,329, 21,306$, and 19,682 km s$^{-1}$ from the quasar system. A weakened system with $W^\lambda_{1548} = -3.9\sigma_{\Delta W^\lambda_{1548}}$ had $v_r = 21,306$ km s$^{-1}$. The system with $v_r = 22,329$ km s$^{-1}$ also showed a variation of $W^\lambda_{1548} = -2.8\sigma_{\Delta W^\lambda_{1548}}$. Note that a negative value of the significance level indicates a weakened system, and vice versa for a positive value. These two variable C IV systems were weakened on the same timescale.

2. Quasar SDSS J004323.43–001522.4 with $z_{em} = 2.8200$. It was spectroscopically observed by the SDSS on MJD = 55,184, 55,186, 55,444, and 57,016. In the quasar spectra, we detect 5 C IV NALs with $z_{abs} = 2.4501, 2.7882, 2.7993, 2.8145$, and 2.8342, and $v_r = 30,448, 2507, 1630, 432$, and $-1,113$ km s$^{-1}$ from the quasar system. A system with $v_r = 2507$ km s$^{-1}$ was enhanced first by $W^\lambda_{1548} = 2.6\sigma_{\Delta W^\lambda_{1548}}$ from MJD = 55,184 to 55,444, and then was weakened by $W^\lambda_{1548} = -3.4\sigma_{\Delta W^\lambda_{1548}}$ from MJD = 5444 to 57,106. The other system with $v_r = -1,113$ km s$^{-1}$ also showed a variation of $W^\lambda_{1548} = -2.2\sigma_{\Delta W^\lambda_{1548}}$ from MJD = 55,184 to 57,106, whose weakened timescale was longer than that of the system with $v_r = 2507$.

3. Quasar SDSS J004856.34+005648.1 with $z_{em} = 2.3230$. It was spectroscopically observed by the SDSS on MJD = 51,913, 55,201, and 55,451. In the quasar spectra, we detect 3 C IV NALs with $z_{abs} = 1.8929, 2.2651$, and 2.3052, and $v_r = 43,318, 5272$, and 1611 km s$^{-1}$ from the quasar system. The system with $v_r = 1611$ km s$^{-1}$ was weakened first by $W^\lambda_{1548} = -3.8\sigma_{\Delta W^\lambda_{1548}}$ from MJD = 51,913 to 55,201, and then was enhanced by $W^\lambda_{1548} = 1.6\sigma_{\Delta W^\lambda_{1548}}$ from MJD = 55,201 to 55,451.

4. Quasar SDSS J015017.70+002902.4 with $z_{em} = 2.9980$. It was spectroscopically observed by the SDSS on MJD = 51,793, 55,182, 55,447, and 56,900. In the quasar spectra, we detect 4 C IV NALs with $z_{abs} = 2.8121, 2.8345, 3.0066$, and 3.0189, and $v_r = 14,218, 12,519$, $-644$, and $-1,564$ km s$^{-1}$ from the quasar system. The obviously variable system had $v_r = 14,218$ km s$^{-1}$, which first emerged during MJD = 51,793 and 55,182, and then was weakened by $W^\lambda_{1548} = -4.3\sigma_{\Delta W^\lambda_{1548}}$ from MJD =
| ID          | SDSS NAME | PLATE | MJD | FIBER | $z_{\text{em}}$ | $z_{\text{abs}}$ | $W_{1548}\lambda1548$ | $W_{1551}\lambda1551$ | $f_{\lambda1550}$ | $v_r$ | ID | Symbol | SL |
|-------------|-----------|-------|-----|-------|---------------|----------------|-------------------|-----------------|--------------|------|-----|--------|----|
| 001142.72+255537.1 | 6880 | 56543 | 865 | 2.2944 | 2.2466 | 0.43 ± 0.09 | 0.34 ± 0.09 | 3.805 ± 0.523 | 4384 | 1 | 0 | 0.4 |
| 001142.72+255537.1 | 6276 | 56269 | 370 | 2.2944 | 2.2462 | 0.38 ± 0.08 | 0.47 ± 0.10 | 5.124 ± 0.622 | 4421 | 1 | 0 | 2.3 |
| 001142.72+255537.1 | 7664 | 57367 | 859 | 2.2944 | 2.2467 | 1.15 ± 0.33 | 0.35 ± 0.15 | 1.027 ± 0.383 | 4375 | 1 | 0 | 2.1 |
| 001142.72+255537.1 | 6276 | 56269 | 370 | 2.2944 | 2.2462 | 0.38 ± 0.08 | 0.47 ± 0.10 | 5.124 ± 0.622 | 4421 | 1 | 0 | 2.3 |
| 001142.72+255537.1 | 7664 | 57367 | 859 | 2.2944 | 2.2467 | 1.15 ± 0.33 | 0.35 ± 0.15 | 1.027 ± 0.383 | 4375 | 1 | 0 | 2.1 |
| 001142.72+255537.1 | 6880 | 56543 | 865 | 2.2944 | 2.2466 | 0.43 ± 0.09 | 0.34 ± 0.09 | 3.805 ± 0.523 | 4384 | 1 | 0 | 0.4 |
| 001142.72+255537.1 | 6276 | 56269 | 370 | 2.2944 | 2.2475 | 0.38 ± 0.08 | 0.47 ± 0.10 | 5.124 ± 0.622 | 4421 | 1 | 0 | 2.3 |
| 001142.72+255537.1 | 7664 | 57367 | 859 | 2.2944 | 2.2475 | 0.38 ± 0.08 | 0.47 ± 0.10 | 5.124 ± 0.622 | 4421 | 1 | 0 | 2.3 |

**Note.** Column (1): identification number of a C IV NAL pair. Column (2): SDSS object name. Columns (3)–(5): PlateID, MJD, and FiberID of the SDSS spectra. Column (6): emission-line redshift of the quasar. Column (7): absorption line redshift of the C IV NAL system. Column (8): rest-frame equivalent width and corresponding error of the C IV $\lambda1548$. Column (9): rest-frame equivalent width and corresponding error of the C IV $\lambda1551$. Column (10): the 1350 Å continuum flux and flux uncertainty measured from the original spectra of the SDSS. Column (11): velocity offset of the C IV NAL system with respect to the quasar emission-line redshift. Column (12): identification number of the C IV NAL system. Column (13): 1 indicates enhanced C IV NALs with $|\Delta W_{1548}| \geq 3\sigma_{\Delta W_{1548}}$; -1 indicates weakened C IV NALs with $|\Delta W_{1548}| \geq 3\sigma_{\Delta W_{1548}}$; 2 indicates emerged C IV NALs; -2 indicates disappeared C IV NALs; and 0 indicates C IV NALs with $|\Delta W_{1548}| < 3\sigma_{\Delta W_{1548}}$. See Equations (4) and 5 for the calculations of $\Delta W_{1548}$ and $\sigma_{\Delta W_{1548}}$. Column (14): the significance level (SL) of the variation, which is equated to $|\Delta W_{1548}|/\sigma_{\Delta W_{1548}}$. Note that if the rest-frame equivalent widths and corresponding errors of both lines of a C IV doublet are the same, these values are the 1σ upper limits of absorption strengths and indicate that the C IV NALs are not observed in the corresponding spectra.

(This table is available in its entirety in machine-readable form.)
55,182 to 56,900. The variations of the system with $v_r = 12,519$ km s$^{-1}$ were consistent with the system with $v_r = 14,218$ km s$^{-1}$. Another variable system with $v_r = -644$ km s$^{-1}$ was enhanced first by $\Delta W_{1548}^{\text{r}} = 2\sigma_{\Delta W_{1548}}$ from MJD = 51,793 to 55,447, and then weakened by $\Delta W_{1548}^{\text{r}} = -2.5\sigma_{\Delta W_{1548}}$ from MJD = 55,447 to 56,900.

5. Quasar SDSS J024457.18–010809.8 with $z_{\text{em}} = 3.9780$. It was spectroscopically observed by the SDSS on MJD = 51,871, 55,247, 55,455 and 57,041. In the quasar spectra, we detect 3 C IV NALs with $z_{\text{abs}} = 3.3209$, 3.6049 and 3.8078, and $v_r = 42,187, 23,324$ and 10,432 km s$^{-1}$ from the quasar spectra. The significantly variable C IV system with $\Delta W_{1548}^{\text{r}} = -3\sigma_{\Delta W_{1548}}$ was located at $z_{\text{abs}} = 3.3209$ and had $v_r = 42,187$ km s$^{-1}$.

6. Quasar SDSS J025011.85+001812.8 with $z_{\text{em}} = 2.8630$. It was spectroscopically observed by the SDSS on MJD = 53,742, 55,476, and 56,984. In the quasar spectra, we detect 3 C IV NALs with $z_{\text{abs}} = 2.7836$, 2.8225, and 2.8369, and $v_r = 6229, 3161$, and 2033 km s$^{-1}$ from the quasar spectra. The system with $v_r = 2033$ km s$^{-1}$ was enhanced by $\Delta W_{1548}^{\text{r}} = 3.2\sigma_{\Delta W_{1548}}$ from MJD = 53,742 to 55,476.

7. Quasar SDSS J081435.19+502946.3 with $z_{\text{em}} = 3.8800$. It was spectroscopically observed by the SDSS on MJD = 55,180, 55,517, and 55,590. In the quasar spectra, we detect 3 C IV NALs with $z_{\text{abs}} = 3.2818, 3.3361$, and 3.5576, and $v_r = 39,009, 35,286$, and 20,472 km s$^{-1}$ from the quasar spectra. The significantly variable system with $\Delta W_{1548}^{\text{r}} = -4\sigma_{\Delta W_{1548}}$ and $v_r = 20,472$ km s$^{-1}$ was continuously weakened during MJD = 55,180 and 55,590. The other slightly weakened system had $v_r = 35,286$ km s$^{-1}$.

8. Quasar SDSS J081435.19+502946.3 with $z_{\text{em}} = 2.3270$. It was spectroscopically observed by the SDSS on MJD = 52,964, 55,893, and 55,946. In the quasar spectra, we detect 2 C IV NALs with $z_{\text{abs}} = 2.0293$ and 2.3134, and $v_r = 28,039$ and 1228 km s$^{-1}$ from the quasar system. The system with $v_r = 1228$ km s$^{-1}$ was enhanced first by $\Delta W_{1548}^{\text{r}} = 2.9\sigma_{\Delta W_{1548}}$ from MJD = 52,964 to 55,893, and then was weakened by $\Delta W_{1548}^{\text{r}} = -3.1\sigma_{\Delta W_{1548}}$ during MJD = 55,893 and 55,964. The other one significantly variable system with $v_r = 28,039$ km s$^{-1}$ was enhanced by $\Delta W_{1548}^{\text{r}} = 2.4\sigma_{\Delta W_{1548}}$ from MJD = 52,964 to 55,893.

9. Quasar SDSS J115911.52+313427.2 with $z_{\text{em}} = 3.0380$. It was spectroscopically observed by the SDSS on MJD = 53,474, 55,589, and 56,363. In the quasar spectra, we detect 3 C IV NALs with $z_{\text{abs}} = 2.8624, 2.9900$, and 3.0272, and $v_r = 13,329, 3587$, and 803 km s$^{-1}$ from the quasar spectra. The significantly variable system with $\Delta W_{1548}^{\text{r}} = 3.5\sigma_{\Delta W_{1548}}$ and $v_r = 3587$ km s$^{-1}$ was continuously enhanced during MJD = 53,474 and 56,363.

10. Quasar SDSS J120206.80+370919.5 with $z_{\text{em}} = 2.4782$. It was spectroscopically observed by the SDSS on MJD = 53,467, 55,621, and 57,428. In the quasar spectra, we detect 2 C IV NALs with $z_{\text{abs}} = 2.3444$ and 2.3737, and $v_r = 11,762$ and 9148 km s$^{-1}$ from the quasar spectra. The significantly variable system with $\Delta W_{1548}^{\text{r}} = 3.5\sigma_{\Delta W_{1548}}$ and $v_r = 11,762$ km s$^{-1}$ was continuously enhanced during MJD = 53,467 and 57,428. The system with $v_r = 9148$ km s$^{-1}$ was also slightly enhanced by $\Delta W_{1548}^{\text{r}} = 1.7\sigma_{\Delta W_{1548}}$ during the same timescale.

11. Quasar SDSS J121347.74+373726.8 with $z_{\text{em}} = 1.7980$. It was spectroscopically observed by the SDSS on MJD = 53,472, 55,621, and 57,426. In the quasar spectra, we detect one C IV NAL with $z_{\text{abs}} = 1.7976$ and $v_r = 42$ km s$^{-1}$ from the quasar system. This system was weakened first by $\Delta W_{1548}^{\text{r}} = -2.5\sigma_{\Delta W_{1548}}$ during MJD = 53,472 and 55,621, and then obviously weakened by $\Delta W_{1548}^{\text{r}} = 3.8\sigma_{\Delta W_{1548}}$ during MJD = 55,621 and 57,426.

12. Quasar SDSS J121400.79+3730936.7 with $z_{\text{em}} = 1.9233$. It was spectroscopically observed by the SDSS on MJD = 53,472, 55,591, and 57,476. In the quasar spectra, we detect 2 C IV NALs with $z_{\text{abs}} = 1.8162$ and 1.8671, and $v_r = 11,191$ and 5822 km s$^{-1}$ from the quasar system. The C IV NALs with $v_r = 5822$ km s$^{-1}$ did not show continuous variation. The C IV NALs with $v_r = 11,191$ km s$^{-1}$ were continuously weakened from...
Figure 3. Quasar spectra with at least one C IV NAL meeting $|\Delta \lambda_{1548}| \geq 5\lambda_{1548}$. In each figure, the upper panel is the SDSS spectra, and the lower panel is the SDSS spectra normalized by the pseudo-continuum fits. The different line colors indicate the spectra obtained at different times. The significantly variable C IV NALs are marked by cyan lines. The values in the top right corners are the spectra MJD.
MJD = 53,472 to 57,426. A pair of Gaussian functions with FWHM = 566 km s\(^{-1}\) and 729 km s\(^{-1}\) can model the absorption features imprinted in the spectra obtained on MJD = 53,472 and 55,591, respectively. Although we do not detect absorption features of other transitions at the same redshift, the variable absorption and good fits suggest that the continuous variation absorption feature could be possibly produced by the associated C IV absorber with high velocity.

13. Quasar SDSS J141334.38+421201.7 with \(z_{\text{em}} = 2.8130\). It was spectroscopically observed by the SDSS on MJD = 52,823, 56,093, and 57,519. In the quasar spectra, we detect 2 C IV NALs with \(z_{\text{abs}} = 2.3968\) and 2.8070, and \(v_r = 34,521\) and 472 km s\(^{-1}\) from the quasar system. The system with \(v_r = 34,521\) was significantly enhanced by \(\Delta W_r^{\text{1548}} = 3.2 \sigma_{\Delta W^{\text{1548}}}\) during MJD = 56,093 and 57,519.

14. Quasar SDSS J142500.24+494729.2 with \(z_{\text{em}} = 2.2600\). It was spectroscopically observed by the SDSS on MJD = 52,460, 56,416, and 57,513. In the quasar spectra, we detect 4 C IV NALs with \(z_{\text{abs}} = 1.8425\), 1.8725, 1.9312, and 2.2665, and \(v_r = 40,857\) to 37,751, 31,774, and 597 km s\(^{-1}\) from the quasar system. The systems with \(v_r = 40,857\) were weakened first by \(\Delta W_r^{\text{1548}} = -2.2 \sigma_{\Delta W^{\text{1548}}}\) during MJD = 52,460 and 56,416, and then enhanced by \(\Delta W_r^{\text{1548}} = 5.5 \sigma_{\Delta W^{\text{1548}}}\) from MJD = 56,416 to 57,513. Another two systems with 37,751 and 31,774 km s\(^{-1}\) were simultaneously enhanced during MJD = 56,416 and 57,513 as well.

15. Quasar SDSS J154857.86+141440.9 with \(z_{\text{em}} = 2.4753\). It was spectroscopically observed by the SDSS on MJD = 54,570, 55,333, and 55,739. In the quasar spectra, we detect 4 C IV NALs with \(z_{\text{abs}} = 2.3127\), 2.3832, 2.4222, and 2.4683, and \(v_r = 16,364\), 8055, 4618, and 604 km s\(^{-1}\) from the quasar system. The systems with \(v_r = 16,364\) and 8055, and 4618 km s\(^{-1}\) were simultaneously varied during the same observation times.

16. Quasar SDSS J235454.30—092603.2 with \(z_{\text{em}} = 1.9810\). It was spectroscopically observed by the SDSS on MJD = 52,201, 56,602, and 56,604. In the quasar spectra, we detect 4 C IV NALs with \(z_{\text{abs}} = 1.6278\), 1.8179, 1.8786, and 1.9169, and \(v_r = 37,634\), 16,862, 10,482, and 6520 km s\(^{-1}\) from the quasar system. The system with \(v_r = 16,862\) km s\(^{-1}\) was stable between MJD = 52,201 and 56,602, while it was significantly enhanced by \(\Delta W_r^{\text{1548}} = 2.7 \sigma_{\Delta W^{\text{1548}}}\) during MJD = 56,602 and 56,604. The other one variable system with \(v_r = 10,482\) km s\(^{-1}\) was also slightly enhanced by \(\Delta W_r^{\text{1548}} = 2.1 \sigma_{\Delta W^{\text{1548}}}\) from MJD = 52,201 to 56,604.

3.3. Correlated Variations of Absorption Lines and Continuum

Both the fluctuations of incident photons and the absorber motions can give rise to variable NALs. The scheme of absorber motion cannot explain the coherent variation of multiple absorption line systems, which requires coordinated motion between multiple absorbers. In addition, the initially enhanced and then weakened systems, or the opposite case, are very difficult to explain using absorber motions. For example, the C IV system with \(z_{\text{abs}} = 2.3134\), which was imprinted in the spectra of quasar SDSS J084525.84+072223.3, was enhanced first by \(\Delta W_r^{\text{1548}} = 2.9 \sigma_{\Delta W^{\text{1548}}}\) from MJD = 52,964 to 55,893, and then was weakened by \(\Delta W_r^{\text{1548}} = -3.1 \sigma_{\Delta W^{\text{1548}}}\) during MJD = 55,893 and 55,964. These complex variations require an absorber moving first into and then out of the quasar sightline, in the scheme of the absorber motion driving variable NALs. Nevertheless, fluctuations of incident photons can reasonably interpret the coherence variations of multiple absorption line systems and the complex variations of a single system.

Among the 19 obviously variable C IV NAL systems described in Section 3.2, 13 systems are cases in which multiple systems change together. In terms of the above discussions, the variations of these C IV NALs were likely caused by the fluctuations of the incident continuum. Changes in the incident photons into the absorbing clouds can be caused by the intrinsic variation of the background ionizing continuum, and by the variation of the column density or ionization of the shielding gas located between the absorbing clouds and the ionizing continuum source (e.g., Murray...
et al. 1995; Misawa et al. 2007). To further investigate the origins of the variations of C IV NALs, we explore the relationship between the variations of the quasar continuum and the C IV NALs. Our results are shown in Figure 4, which clearly exhibits a tight correlation between the variations of the 1350 Å continuum and the C IV NALs. For all the 27 C IV NAL pairs with |ΔW_r^{1548}| > 3σ_ΔW_r^{1548} (the black and red symbols in Figure 4), the Spearman’s correlation test yields a correlation coefficient ρ = 0.63 and a probability P < 10^{-3} of no correlation. When excluding the disappeared and emergent C IV systems (the red symbols in Figure 4), the Spearman’s correlation test suggests a stronger correlation (ρ = 0.89 and P < 10^{-9}). This tight correlation is consistent with the results reported by previous works (e.g., He et al. 2015, 2017; Lu et al. 2018; Lu & Lin 2018). An increase or decrease of the column density of the shielding gas would not result in an obviously correlated variation between the ionizing continuum and the absorption lines. In addition, the variations of the ionization of the shielding gas, which are introduced by the alterations in the ionization state, indeed reflect the changes in the ionizing continuum. Therefore, combining with the coordinated variations of multiple C IV systems, the significant correlation between the variations of the continuum fluxes and the absorption strengths of C IV NALs suggests that the variations of C IV NALs are mainly driven by the changes of the ionizing continuum.

Except for one enhanced C IV NAL shown in the top left corner and two disappeared C IV NALs shown in the bottom right corner, Figure 4 indicates that the variations of absorption lines are inversely related to the changes of the ionizing continuum, namely, the brighter the objects, the weaker the absorption lines. Figure 11 of Wang et al. (2015) demonstrated that the responses of the ionic column density to the changes in the ionizing continuum are connected to the ionization state of the absorbing gas. Below the critical value of the ionization parameter, the fraction of the C^+ increases as the ionization parameter increases, and the variations of the C IV absorption lines positively respond to the changes in the ionizing continuum. Nevertheless, they are opposite cases when the ionization parameter is larger than the critical value. The variations of the C IV NALs shown in Figure 4 are inversely correlated with the continuum fluxes, which implies that our 19 obviously variable C IV systems may be dominated by the gas with high ionization phase.

3.4. Relative Velocity and Timescales of Variable Absorption Line Systems

Figure 5 shows the relative velocities of the 19 obviously variable C IV NALs. In general, associated NALs are limited to v ≤ 5000 km s^{-1} (e.g., Wise et al. 2004), while here we find that there are 14 systems with v > 0.01c, and 4 systems with v > 0.1c, where c is the speed of light. This suggests that some of our C IV NALs might be related to quasar outflows with high velocities.

Coordinated variations of the ionizing continuum and absorption lines require a recombination time of recombining gas that is shorter than the timescale of continuum fluctuations and the time interval between two observations (e.g., Barlow et al. 1992); otherwise, one cannot observe obvious variations in the absorption lines. The time intervals of the 72 C IV NAL pairs of the 19 obviously variable C IV NALs are from ΔMJD = 0.52 to 1550 days at rest-frame; these intervals are shown in the left and middle panels of Figure 6. We note that a C IV system with v_r = 16,862 km s^{-1}, which was imprinted in the spectra of the quasar SDSS J235454.30–092603.2, was enhanced by ΔW_r^{1548} = 2.7σ_ΔW_r^{1548} on a very short time interval of 0.67 day at rest-frame.

Although there is not a tightly linear correlation between changes in absorption lines and time intervals, it has been discovered for both the NALs (e.g., Hacker et al. 2013; Chen et al. 2015) and BALs (e.g., Filiz et al. 2013; Misawa et al. 2014) that the variations of absorption lines depend on the time intervals. We show the changes in W_r^{1548} of C IV NALs in the right panel of Figure 6, which clearly indicates that a large variation of absorption lines is very difficult to form on a short time interval, though there is a C IV NAL enhanced by ΔW_r^{1548} = 2.7σ_ΔW_r^{1548} in 0.67 day at rest-frame. In addition, the middle panel of Figure 6 shows that in the same systems, the obvious variations are not positively related to the time intervals.

4. Summary

Using the SDSS spectra of 207 quasars with at least 3 observations and the 1350 Å continuum variations Δf_{1350} ≥

![Figure 6. Distributions of time intervals and |ΔW_r^{1548}| of the 19 obviously variable C IV NALs. Left panel: the black solid line represents the time intervals of all 72 C IV NAL pairs, and the red dashed line only represents the time intervals of the 27 C IV NAL pairs with |ΔW_r^{1548}| ≥ 3σ_ΔW_r^{1548}. Middle panel: the x-axis indicates the serial numbers of the 19 obviously variable C IV NALs, the red open circles represent the NA-pairs with |ΔW_r^{1548}| ≥ 3σ_ΔW_r^{1548}, the black filled circles represent the NAL pairs with |ΔW_r^{1548}| < 2σ_ΔW_r^{1548}, and the blue unfilled squares represent the NAL pairs with 2σ_ΔW_r^{1548} ≤ |ΔW_r^{1548}| < 3σ_ΔW_r^{1548}. Right panel: changes in W_r^{1548} = 2.7σ_ΔW_r^{1548} on a very short timescale of 0.67 day at rest-frame.
4σ_{1550}, we analyze C IV NALs and investigate their variations. Our results and conclusions are as follows:

1. There are 166 quasars for which at least 1 C IV NAL system with $W_r^{1548} > 3\sigma_{W_r^{1548}}$ and $W_r^{1551} > 2\sigma_{W_r^{1551}}$ was detected in one of the multi-epoch spectra. We obtain 328 C IV NAL systems, comprising 1210 C IV NAL pairs. We find that 19 out of 328 C IV NAL systems were changed by $|\Delta W_r^{1548}| > 3\sigma_{\Delta W_r^{1548}}$. Among these 19 obviously variable C IV systems, 13 systems are accompanied by other variable C IV systems, and 9 systems were changed continuously during multiple observations. In addition, 4 out of 19 systems have $v_r > 0.1c$, which are significantly larger than the boundary of 5000 km s$^{-1}$ that is generally used to define associated C IV NALs. This suggests that some of our C IV NALs might be related to quasar outflows with high velocities.

2. The variations of absorption lines are tightly and inversely correlated with the changes in the ionizing continuum. Therefore, our 19 obviously variable C IV systems negatively respond to the fluctuations of the ionizing continuum, and might be dominated by gas with high ionization phases.

3. We find that a C IV system with $v_r = 16,862$ km s$^{-1}$, which was imprinted in the spectra of quasar SDSS J235454.30−092603.2, was enhanced by $\Delta W_r^{1548} = 2.7\sigma_{\Delta W_r^{1548}}$ on a very short time interval of 0.67 day at rest-frame.

4. Large variations of C IV NALs are difficult to form on short timescales.

We thank the anonymous referee for very helpful comments. This work was supported by the National Natural Science Foundation of China (No. 11763001; No. 11363001; No. 11661012), and the Guangxi Natural Science Foundation (2015GXNSFBA139004).

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