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We investigate the relationship between the variability of broad absorption lines (BALs) or narrow absorption lines (NALs) and that of continuum using a data set of two-epoch SDSS spectra containing 134 C iv NAL-BAL pairs. Our analysis reveals an anti-correlation between the fractional equivalent width (EW) variations in NALs (or BALs) and the fractional flux variations of the continuum, with Spearman rank correlation coefficients of r = −0.47 (p = 1E-08) and r = −0.58 (p = 1E-13), respectively. In addition, we find a positive correlation between the fractional EW variations in NALs and BALs (r = 0.72, p = 1E-22), and derive a regression equation ΔEWNAL/⟨EWNAL⟩= 0.803ΔEWBAL/⟨EWBAL⟩ + 0.008, with an intrinsic scatter of 0.14. These results suggest that the variability in the ionizing continuum may play a significant role in the observed changes in C iv NALs and BALs, supporting the idea of photoionization-driven variability. The co-variability between C iv NALs and BALs may imply that they originate from outflows with similar physical conditions.

Full Text

Preamble

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Co-variability Between the Broad Absorption Lines and Narrow Absorption Lines

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Abstract

We investigate the relationship between the variability of broad absorption lines (BALs) and narrow absorption lines (NALs) and that of the continuum using a dataset of two-epoch SDSS spectra containing 134 C IV NAL-BAL pairs.

Our analysis reveals an anti-correlation between the fractional equivalent width (EW) variations in NALs (or BALs) and the fractional flux variations of the continuum, with Spearman rank correlation coefficients of $r = -0.47$ ($p = 1E\text{-}08$) and $r = -0.58$ ($p = 1E\text{-}13$), respectively. In addition, we find a positive correlation between the fractional EW variations in NALs and BALs ($r = 0.72$, $p = 1E\text{-}22$), and derive a regression equation $\Delta EWNAL/\langle EWNAL\rangle = 0.803\Delta EWBAL/\langle EWBAL\rangle + 0.008$, with an intrinsic scatter of 0.14. These results suggest that variability in the ionizing continuum may play a significant role in the observed changes in C IV NALs and BALs, supporting the idea of photoionization-driven variability. The co-variability between C IV NALs and BALs may imply that they originate from outflows with similar physical conditions.

Key words: (galaxies:) quasars: absorption lines – (galaxies:) quasars: general – galaxies: active

1. Introduction

Absorption lines are instrumental in the spectral observation of quasars, providing insight into the physical and chemical composition of media that is either non-luminous or not directly observable due to technological limitations (e.g., Weymann et al. 1998). Based on their physical connection to the quasars, intervening absorption lines are divided into two categories: intervening absorption lines and intrinsic absorption lines.

Intervening absorption lines arise from absorbers that are not physically associated with quasars, such as the interstellar medium and intervening galaxies. Intrinsic absorption lines arise from absorbers that are physically associated with quasars, such as gases in the vicinity of outflows or accretion disks (e.g., Barlow et al. 1997; Savage et al. 1998; Chen et al. 2018). These absorption lines are further classified by their line widths: narrow absorption lines (NALs), which have widths of a few hundred km s^{-1}; broad absorption lines (BALs), with widths exceeding 2000 km s^{-1} and depths greater than 10% below the continuum (e.g., Weymann et al. 1991); and mini-BALs, which exhibit line widths between those of NALs and BALs (e.g., Hamann & Sabra 2004; Chen et al. 2021). Intrinsic absorption lines, including BALs, mini-BALs, and NALs, present diverse characteristics, with underlying mechanisms of considerable complexity. Previous studies indicate that the predominant physical mechanisms are likely linked to the diverse inclination angles of the quasar line of sight relative to the accretion disk axis, as well as the distinct evolutionary stages of the quasar outflow or host galaxy (e.g., Murray et al. 1995; Hamann et al. 2009, 2012; Rodríguez Hidalgo et al. 2013; Chen et al. 2022; Peng et al. 2024).

Absorption lines in quasars exhibit significant variability, a phenomenon observed in both BALs and NALs. Studies have found that the profiles and intensities of BALs can undergo substantial changes on timescales ranging from days to years (e.g., Capellupo et al. 2011, 2012, 2013; Filiz et al. 2012, 2013; Grier et al. 2015; He et al. 2015; Wang et al. 2015), while the strength of intrinsic NALs has also been observed to fluctuate notably over periods of months to years (e.g., Wise et al. 2004; Hamann et al. 2011; Chen & Qin 2013; Hacker et al. 2013; Wang et al. 2015; He et al. 2015; Hemler et al. 2019). BALs are typically associated with high-velocity outflows that are physically connected to the central regions of quasars, such as the accretion disk and the dusty torus (e.g., He et al. 2022; Naddaf et al. 2023). In contrast, NALs may be located further away, such as in the disk or halo of the galaxy, and their variations may require longer timescales to respond to changes in the central region (e.g., Barlow et al. 1997).

Investigating the correlation between changes in BALs and NALs can enhance our understanding of the physical relationship between these two types of absorption lines. Although numerous studies have examined the variability of BALs and NALs over the years, investigations into the correlation between the variability of these two absorption line types remain scarce.

It is acknowledged that two primary mechanisms underlie the changes observed in absorption lines: variations in the ionization state of the absorbing gas (e.g., Barlow 1994; Hamann et al. 2011; Filiz et al. 2014; He et al. 2015; Wang et al. 2015; Lu et al. 2017; Chen et al. 2018b; Vivek 2019; Zhao et al. 2021; Lin et al. 2024) and alterations in the covering factor of the absorbers relative to the central continuum source (e.g., Narayanan et al. 2004; Lundgren et al. 2007; Hamann et al. 2008; Krongold et al. 2010; Hall et al. 2011; Filiz et al. 2012; Capellupo et al. 2013; Vivek et al. 2016; Capellupo et al. 2017). Changes in the ionization state of absorbers can directly affect their absorption properties. Quasar variability significantly affects the ambient environment, modifying the absorbers' physical properties, including ionization state, density, and temperature. The intrinsic absorbers' close association with the quasar center means that variations in quasar activity directly alter the ionization structure of the absorbers, leading to changes in their ionization states and densities, and thus in the absorption lines. In addition, alterations in the covering factor of the absorbing gas relative to the central continuum source can also impact the strength and profile of the absorption lines. The bulk motion or rotational motion of outflows, or changes in the internal velocity structure of the outflows, can induce variations in the covering factor, which in turn affect the characteristics of the absorption lines. Determining the predominant mechanism between these two is currently difficult, as some sources may be primarily influenced by the first mechanism, while others are more likely influenced by the second. The possibility that both mechanisms contribute to the observed variations cannot be ruled out (e.g., Lundgren et al. 2007; Capellupo et al. 2011; Vivek et al. 2014).

In this paper, we first study the correlation between the variability of the C IV BALs and the continuum, as well as between the variability of the C IV NALs and the continuum. Then we analyze the correlation between the variability of the C IV BALs and NALs. In addition, we explore the physical processes that lead to changes in quasar absorption lines and the mechanisms that classify them into BAL, mini-BAL, and NAL categories. Section 2 provides a description of the sample, Section 3 entails an analysis of the data, and Section 4 presents the results and discussion. In Section 5 we draw conclusions.

2. Sample

The sample for this study is derived from the previous works of He et al. (2017) and Chen et al. (2018b). He et al. (2017) provided a catalog containing 9918 pairs of spectra with C IV BALs, which were obtained from a sample of 2005 BAL quasars selected from the Sloan Digital Sky Survey (SDSS). Chen et al. (2018b) presented a catalog consisting of 21,239 C IV NAL systems, detected from the spectra of 13,769 quasars observed by SDSS.

In this study, we first cross-matched these two catalogs to identify common quasars. Then, we selected the quasars with two-epoch observations and obtained the corresponding spectra. Subsequently, we selected spectra that contain both C IV NALs and C IV BALs to form NAL-BAL pairs. We finally obtained 2119 NAL-BAL pairs from 1059 quasars with two-epoch observations.

To obtain reliable analytical results, we require the data to have a high signal-to-noise ratio (SNR). As shown in Figure 1, the peak SNRs for F1350 across the two observations approximate 25 and 40, respectively. For the EW of C IV NALs, the peak SNRs for both observations are approximately 6, as shown in Figure 2 [Figure 2: see original paper]. For the EW of C IV BALs, the peak SNRs for the previous and later observations are approximately 13 and 20, respectively, as shown in Figure 3 [Figure 3: see original paper]. In subsequent analyses, we only adopted data with an SNR greater than the distribution peak. Furthermore, we performed a data filtering process to eliminate measurements with fractional variations smaller than their uncertainties, as these data were considered unreliable. After the filtering process, we retained a total sample of 134 NAL-BAL pairs for further analysis.

At the same time, we identified two types of NAL-BAL pairs through visual inspection, as illustrated in Figure 2. One type consists of an NAL located outside the BAL trough, while the other type includes an NAL positioned within the BAL trough. We categorized these two types of NAL-BAL pairs as Type I and Type II, respectively.

3.1. The Variability of NALs and BALs

He et al. (2017) has shown that the equivalent width (EW) of C IV NALs is influenced by the ionization parameter U, with a pattern of initially increasing, reaching a peak, and subsequently decreasing. Following Lu et al. (2018), we utilized the fractional variations of EW to estimate the variability of NALs and BALs. The fractional variation of equivalent width is defined as:

$$\frac{\Delta \mathrm{EW}}{\langle \mathrm{EW} \rangle} = \frac{\mathrm{EW}_2 - \mathrm{EW}_1}{\langle \mathrm{EW} \rangle}$$

where $\langle \mathrm{EW} \rangle = 0.5(\mathrm{EW}_1 + \mathrm{EW}_2)$, and EW_1 and EW_2 represent the EW of the previous and later observations, respectively. Correspondingly, the uncertainty of $\Delta \mathrm{EW}/\langle \mathrm{EW} \rangle$ is defined as:

$$\sigma_{\Delta \mathrm{EW}/\langle \mathrm{EW} \rangle} = \frac{\sqrt{\sigma^2_{\mathrm{EW1}} + \sigma^2_{\mathrm{EW2}}}}{\langle \mathrm{EW} \rangle}$$

where $\sigma\{EW\}_1\ and\ \sigma\{\mathrm{EW}\}_2$ represent the uncertainties of EW in the previous and later observations, respectively. The EW and σ_{EW} measurements of C IV BALs and NALs were derived from He et al. (2017) and Chen et al. (2018b), respectively.

3.2. The Variability of Power-law Continuum

Similarly, we computed the fractional variations of continuum flux at 1350 Å in the rest-frame (F_{1350}) to estimate the variability of the power-law continuum. The fractional variation of the continuum is defined as:

$$\frac{\Delta F_{\mathrm{cont}}}{\langle F_{\mathrm{cont}} \rangle} = \frac{F_{\mathrm{cont},2} - F_{\mathrm{cont},1}}{\langle F_{\mathrm{cont}} \rangle}$$

where $\langle F_{\mathrm{cont}} \rangle = 0.5(F_{\mathrm{cont},1} + F_{\mathrm{cont},2})$, and F_{cont}$_{,1}$ and F_{cont}$_{,2}$ represent the F_{1350} of the previous and later observations, respectively. Correspondingly, the uncertainty of $\Delta F_{\mathrm{cont}}/\langle F_{\mathrm{cont}} \rangle$ is defined as:

$$\sigma_{\Delta F_{\mathrm{cont}}/\langle F_{\mathrm{cont}} \rangle} = \frac{\sqrt{\sigma^2_{F_{\mathrm{cont},1}} + \sigma^2_{F_{\mathrm{cont},2}}}}{\langle F_{\mathrm{cont}} \rangle}$$

where $\sigma F\{\mathrm{cont}\}_{,1}$ and $\sigma F\{\mathrm{cont}\}_{,2}$ represent the uncertainties of F_{1350} in the previous and later observations, respectively. We also adopted the F_{cont} and $\sigma F\{\mathrm{cont}\}$ measurements from He et al. (2017) and Chen et al. (2018b).

4. Results and Discussion

Based on the sample obtained in Section 2, we plotted the fractional EW variation of C IV NALs (or BALs) versus the fractional variation of F_{1350}, as well as the fractional EW variation between C IV NALs and C IV BALs, as shown in Figure 3 [Figure 3: see original paper]. The Spearman rank correlation analyses for different samples are presented in Table 1 .

First, we find that the fractional EW variations of both the C IV NALs and C IV BALs are inversely correlated with the fractional flux variations of the continuum across all samples, as demonstrated in the left and middle column subfigures of Figure 3. This inverse correlation has been previously reported. Several studies discovered an inverse correlation between the fractional EW variations of NALs and the fractional flux variations of the continuum (e.g., Lu et al. 2017; Chen et al. 2018b). Meanwhile, some studies reported similar relationships for BALs (e.g., Lu & Lin 2018b; Lu et al. 2018; Huang et al. 2019; Mishra et al. 2021; Lin et al. 2024). In our study, we consider that the variations in both BALs and NALs are primarily driven by changes in the ionizing continuum, which alter the ionization state or column density of the relevant ions (e.g., Crenshaw et al. 2003; Wise et al. 2004; Hamann et al. 2011; Misawa et al. 2014; Wang et al. 2015; He et al. 2017; Vivek 2019). Photoionization simulations show that the EWs of absorption lines first rise, reach a peak, and then decline with increasing ionization parameter (U), dividing into low and high ionization states. In the low ionization states, the absorption lines positively respond to central source variations, while in the high ionization states they show a negative response. This suggests that the majority of BALs and NALs investigated herein might reside in a relatively highly ionized state, originating from absorption clouds dominated by high-ionization gas. Relevant research shows that the detectability of NAL or BAL variations hinges on the gas recombination timescale being shorter than the detection interval (e.g., Krolik & Kriss 1995; He et al. 2019). The variations in BALs and NALs are negatively correlated with changes in central radiation, possibly due to asymmetric recombination timescale effects. According to He & Wang (2023), absorbers with high ionization states exhibit shorter response timescales compared to those with low ionization states, leading to the detection of more negative responses. The NALs and BALs that can be detected may represent only the portions with extremely high ionization states and therefore shorter recombination timescales. Our results are consistent with previous studies.

Second, we present the correlation between the EW variations of BALs and NALs, as illustrated in the right column of Figure 3. Although previous works have explored the relationship between variations in BALs and changes in the continuum, as well as the relationship between NAL variations and continuum changes, there remains a gap in research concerning the relationship between variations in BALs and those of NALs. In our results (the right column of Figure 3), the EW variations of BALs and NALs exhibit a significant positive correlation. This correlation suggests that BALs and NALs may originate from outflows with similar physical conditions. According to the inclination hypothesis, different types of absorption lines represent the same outflow observed at different angles, with BALs forming in the main body of the outflow close to the accretion disk plane, while NALs and mini-BALs form along sightlines that graze the edges of the outflows at higher latitudes above the disk plane (e.g., Murray et al. 1995; Proga & Kallman 2004; Ganguly et al. 2001; Chartas et al. 2009; Hamann et al. 2012). If the inclination hypothesis holds, the simultaneous presence of BALs and NALs within the same spectrum in our sample may suggest that there might not be a distinct boundary between sightline angles that produce solely BALs or solely NALs. Instead, there could be a region where both BALs and NALs are observed, as reported by Itoh et al. (2020). According to the evolution hypothesis, NALs and mini-BALs might represent either the initial or late phases of a powerful outflow, implying that BALs and NALs may denote different evolutionary stages of the same outflow (e.g., Hamann et al. 2008; Gibson et al. 2010; Rodríguez Hidalgo et al. 2013). Given our previous discussion that the observed variations in both BALs and NALs are primarily influenced by photoionization, and that C IV BALs and NALs are in similar ionized states, it is unlikely that these two types of absorption lines arise from absorbers at different stages of evolution. Consequently, our findings are more conducive to the inclination hypothesis rather than the evolution hypothesis.

Third, our results show that the EWs of Type I pairs and Type II pairs exhibit consistency in their variations with changes in the continuum flux. This indicates that there may be some physical relationship between them, such as originating from high-ionization outflow gases close to the central engine. The difference is that BALs typically originate from the large-scale clumpy structure or a large number of small-scale clumpy structures of the outflow, while NALs primarily stem from the small-scale clumpy structure of the outflow (e.g., Hamann et al. 2011; Itoh et al. 2020). In addition, Lu & Lin (2018a) and Lu & Lin (2019) identified NALs within broad absorption troughs, suggesting that there may be two types of BALs: one that cannot be decomposed into NALs and another that is a blend of NALs, which can be decomposed into NALs with similar intrinsic properties. Our findings are in agreement with this perspective.

5. Conclusion

We have studied the correlation between the variability of NALs (or BALs) and the continuum's variability using a sample of two-epoch SDSS spectra containing 134 NAL-BAL pairs. The fractional EW variations in NALs and BALs correlate with the fractional variations in the continuum flux, with Spearman rank correlation coefficients $r = -0.47$ ($p = 1E\text{-}08$) and $r = -0.58$ ($p = 1E\text{-}13$), respectively. Additionally, there is a correlation between the fractional EW variations in NALs and BALs ($r = 0.72$, $p = 1E\text{-}22$). A regression equation $\Delta EWNAL/\left\langle EWNAL\right\rangle = 0.803\Delta EWBAL/\left\langle EWBAL\right\rangle + 0.008$ with an intrinsic scatter of 0.14 has been obtained. Based on these results, we draw the following conclusions:

(1) The fractional EW variations of both C IV NALs and BALs in our study are inversely correlated with the fractional flux variations of the continuum, suggesting that the variations in both NALs and BALs are primarily driven by changes in the ionizing continuum, which alter the ionization state or column density of the relevant metal ions.

(2) Utilizing data from quasars exhibiting both NALs and BALs, our results indicate a significant positive correlation between the fractional EW variations of BALs and NALs, suggesting that BALs and NALs may originate from outflows with similar physical conditions, which favors the inclination hypothesis rather than the evolution hypothesis.

(3) Our results show consistency in the fractional variations of the EWs of Type I pairs and Type II pairs with changes in the continuum flux, which may indicate some physical relationship between them.

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