

Postprint: Multi-epoch Spectroscopic Variability Analysis of Broad Absorption Lines in SDSS J142225.03+535901.7

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Abstract

Broad absorption lines (BALs) in quasars represent one of the strongest observational evidences for the existence of outflows. BALs commonly exhibit variability, and analyzing BAL variability helps constrain physical models of outflows. Variations in the ionizing continuum incident along the line of sight from the quasar central engine constitute the primary mechanism driving most BAL variability. If a quasar's BAL absorption troughs at different velocities vary simultaneously in the same direction (weakening or strengthening), then its BAL variability is likely dominated by changes in the ionizing continuum. The quasar SDSS J142225.03+535901.7 possesses 55 epochs of high signal-to-noise ratio spectroscopic observations, and its BALs show variability. Significant negative correlations exist between the equivalent widths of different velocity components of this source's BALs and the continuum luminosity (Spearman correlation test, probability of no correlation $p < 0.05$). The absence of significant negative correlations between the equivalent widths of each component and the continuum spectral index can rule out the possibility that the negative correlation between equivalent width and continuum luminosity is caused by dust-bearing gas moving perpendicular to the line of sight. Therefore, the BAL variability of this source is primarily driven by changes in the ionizing continuum.

Full Text

Preamble

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Multi-epoch Spectral Variability Analysis of Broad Absorption Lines in SDSS J142225.03+535901.7

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Abstract

Broad absorption lines (BALs) in quasars represent some of the strongest observational evidence for the existence of outflows. BALs commonly exhibit variability, and analyzing these variations helps constrain the physical models of outflows. Changes in the ionizing continuum incident along the line of sight from the quasar's central engine are thought to be the primary mechanism driving most BAL variability. If a quasar's BAL absorption troughs vary simultaneously in the same direction (either weakening or strengthening) at different velocities, the BAL variability is likely dominated by changes in the ionizing continuum. The quasar SDSS J142225.03+535901.7 has 55 epochs of high signal-to-noise spectral observations that reveal BAL variability. There exists a significant anticorrelation (Spearman correlation test, with a non-correlation probability p-value less than 0.05) between the equivalent widths of different velocity components of the BAL and the continuum luminosity. No significant anticorrelation is found between the equivalent widths of these components and the continuum spectral index, which rules out the possibility that the observed anticorrelation between equivalent width and continuum luminosity is caused by dusty gas moving perpendicular to the line of sight. Therefore, the BAL variability in this source is primarily driven by changes in the ionizing continuum.

Keywords: galaxies: active, ISM: jets and outflows, quasars: absorption lines, spectral line: profiles

1. Introduction

It is widely believed that supermassive black holes co-evolve with their host galaxies. The primary evidence for this includes: (1) correlations between supermassive black hole mass and host galaxy properties such as luminosity and stellar velocity dispersion, most notably the $M_{\text{BH}} - \sigma$ relation; and (2) the close synchronization between black hole growth and star formation throughout cosmic history. However, black holes and their host galaxies differ by several orders of magnitude in both spatial scale and mass, suggesting that some physical mechanism must connect them. Additionally, observations reveal far fewer massive galaxies than predicted by galaxy evolution models without active galactic nucleus (AGN) feedback, prompting astronomers to incorporate AGN feedback mechanisms.

AGN-driven outflows may constitute an important form of such feedback. The

strongest observational evidence for these outflows is the presence of broad absorption lines (BALs) in quasar spectra. Common BAL species include C IV, Si IV, N V, O VI, and Mg II. BALs are generally considered intrinsic absorption systems, with blueshifted line widths reaching tens of thousands of kilometers per second, indicating that material in the host galaxy is moving toward the observer at speeds approaching 0.1 times the speed of light. Certain BAL properties (such as absorption trough equivalent width EW and maximum velocity V_{\max}) correlate with quasar physical properties (such as luminosity), suggesting that BALs are absorption features produced by outflows driven by the AGN.

BALs commonly exhibit variability. In Capellupo et al.'s study, 39% of quasars showed variability over short timescales (4-9 months), while 65% displayed variability over longer periods (3.8-7.7 years). Typical variability timescales range from months to years, though some studies indicate that significant variations within days are not particularly rare. Variability amplitudes can be substantial; in extreme cases, absorption troughs may disappear entirely. Research suggests that the gas producing BALs may be distributed anywhere from sub-parsec to kiloparsec scales from the galactic center.

AGN-driven outflows carry enormous energy that can significantly impact galaxy evolution, with the magnitude of this effect depending on the outflow's scale, mass, energy, and degree of interaction. BAL variability serves as a probe for studying these outflows, and identifying the variability mechanism is a prerequisite for using variability to constrain outflow physical models. The scientific community generally recognizes two primary causes of BAL variability: (1) changes in the ionization state of the absorbing gas due to variations in the ionizing continuum along the line of sight; and (2) motion of the absorbing gas, where movement into or out of the line of sight alters the covering factor. Some studies suggest that changes in the ionization state of the absorbing gas itself can also alter the covering factor, making these two mechanisms not entirely independent, and both may contribute to variability simultaneously.

Systematic studies of the dominant variability mechanisms have only emerged in recent years due to the lack of large samples. Gibson et al. examined a small sample of 13 sources at redshifts $1.7 \leq z \leq 2.8$ with two observations separated by 3-6 years (rest-frame) and found no clear correlation between absorption trough variability and continuum changes. Filiz Ak et al. studied a larger sample of 291 sources from the Sloan Digital Sky Survey (SDSS) and found some correlation between changes in BAL equivalent width ΔEW and luminosity, suggesting that BAL variability might be caused by ionizing continuum changes (though they did not consider this strong evidence). Wang et al. used a large sample of 452 sources to confirm at the 14.1σ confidence level that BAL variability correlates with continuum flux variations at 1400 \AA , and also found that different velocity components within the same BAL trough can show different variability trends, supporting the notion that BAL variability is dominated by ionizing continuum changes. Meanwhile, some astronomers argue

that covering factor variations are the primary cause of BAL variability. The debate was largely settled in 2017 when He et al., using an ultra-large sample of 2005 sources from SDSS, concluded that at least 80% of BAL variability is caused by ionizing continuum changes. However, for individual sources, both ionization state changes and covering factor changes may play roles.

He et al. proposed that if a quasar's BAL absorption troughs vary simultaneously at different velocities, the variability is likely dominated by ionizing continuum changes. They also identified a small sample of 46 sources from the SDSS BAL quasar sample that showed simultaneous variability at different velocities. This paper selects one source from this sample with 55 epochs of high signal-to-noise spectral observations to fit its continuum and emission lines, calculate the equivalent widths of different velocity components of its BAL trough, and analyze the relationships between equivalent width and continuum luminosity and spectral index to investigate whether its BAL variability is caused by ionizing continuum changes.

2. Data and Methods

2.1 Target Selection

He et al. merged the SDSS DR7 BAL quasar sample from Shen et al. with the SDSS DR12 BAL quasar sample from Paris et al., removed duplicate entries, and applied the following selection criteria: (1) three or more observations in the SDSS DR16 spectral database; (2) redshift $1.9 < z < 4.7$ to cover the C IV $\lambda 1548$, 1551 absorption lines for variability studies; (3) at least one spectrum with g-band signal-to-noise ratio (S/N) greater than 10 to ensure detection of absorption features; and (4) simultaneous detection of BAL variability in three velocity intervals: low (0-5000 km/s), intermediate (5000-10000 km/s), and high (>10000 km/s).

This yielded a sample of 46 quasars with three or more epochs of high signal-to-noise spectral observations. The BAL variability in this sample is believed to be caused by ionizing continuum changes. Considering both high signal-to-noise ratio and a large number of observational epochs, we selected SDSS J142225.03+535901.7 as our target for analyzing the cause of its BAL variability.

SDSS J142225.03+535901.7 has 55 epochs of BOSS (Baryon Oscillation Spectroscopic Survey) observations, all with $S/N > 18$, redshift $z = 2.69$, right ascension $RA = 215.6043$, and declination $Dec = 53.9838$. Table 1 lists the Plate, Modified Julian Date (MJD), FiberID, and S/N information for its 55 spectral epochs (columns 1-4). Columns 5-22 contain the continuum spectral index α , continuum flux density at 1700 \AA $f_{\text{con},1700}$, C IV emission line center wavelength λ_0 , emission line velocity dispersion σ , emission line intensity A , equivalent widths of the low-velocity component EW_{low} , intermediate-velocity component EW_{mid} , high-velocity component EW_{high} , and the entire trough EW_{whl} , with odd columns showing the values and even columns showing their errors. This source is unusual in that its absorption is relatively shallow at low velocities

and deeper at high velocities, opposite to the typical statistical trend for BAL quasars (where absorption troughs are usually deeper at low velocities and shallower at high velocities). Therefore, it is particularly important to investigate whether its BAL variability mechanism also exhibits special characteristics.

2.2 Spectral Fitting

After obtaining the spectral data for our target, we first applied redshift correction and Galactic extinction correction (using parameters from Fitzpatrick 1999). Due to strong absorption features, identifying appropriate windows free of both emission and absorption lines for continuum fitting proved challenging. To address this, we convolved the original spectra with a Gaussian kernel of width 3 Å. Based on these smoothed spectra, we selected 1355–1370 Å, 1580–1595 Å, and 1705–1725 Å as windows for continuum fitting. Figure 1 [Figure 1: see original paper] shows wavelength λ on the horizontal axis and Galactic extinction-corrected spectral flux density f_λ on the vertical axis, with gray lines representing six corrected spectra from the 55 epochs. Except for the bottom spectrum, each successive spectrum is vertically offset by six units. The three fitting windows are indicated by shaded regions. The blue end of the spectrum (1300–1400 Å) contains absorption trough features that make it difficult to determine the intrinsic continuum, which affects continuum fitting. We combined visual inspection with adjustments to ensure the fitted continuum appeared reasonable overall.

We fitted the continuum using a single power-law function:

$$f_{\text{con}}(\lambda) = f_{\text{con},1700} \left(\frac{\lambda}{1700 \text{ \AA}} \right)^{-\alpha}$$

where λ is wavelength, $f_{\text{con}}(\lambda)$ is the continuum flux density, α is the spectral index, and $f_{\text{con},1700}$ is the fitted continuum flux density at 1700 Å. The fitting results were obtained by minimizing:

$$\chi^2 = \sum_i \frac{[f_{\text{obs},i} - f_{\text{con}}(\lambda_i)]^2}{\sigma^2(f_{\text{obs},i})}$$

where i indexes each wavelength data point, $f_{\text{obs},i}$ is the Galactic extinction-corrected flux density, $f_{\text{con}}(\lambda_i)$ is the continuum fit, and $\sigma(f_{\text{obs},i})$ is the error. Before fitting, we checked the errors of data points within the windows and excluded those with inverse variance $ivar < 2$ or unusually large errors. After each fitting iteration, we masked data points where the absolute difference between measured and fitted values exceeded three times the error, then refit until the results converged. Spectra that did not achieve good fits during batch processing were manually adjusted. The fitted spectral index α and continuum flux density at 1700 Å $f_{\text{con},1700}$ with their errors are listed in Table 1 (columns 5–8). Figure 2 [Figure 2: see original paper] shows an example of continuum

and C IV emission line fitting, with black lines indicating the fitted continuum (top panel) and C IV emission line (bottom panel), black vertical dashed lines marking the C IV $\lambda 1550$ emission line position, and gray short horizontal lines indicating the fitting windows.

The fitting can be easily implemented using the mpfit program, which returns both fitted parameters and their errors $\sigma(\alpha)$ and $\sigma(f_{\text{con},1700})$. The error in the continuum fit is calculated as:

$$\sigma(f_{\text{con}}(\lambda)) = f_{\text{con}}(\lambda) \sqrt{\left[\frac{\sigma(f_{\text{con},1700})}{f_{\text{con},1700}} \right]^2 + [\ln(\lambda/1700 \text{ \AA})]^2 \sigma^2(\alpha)}$$

Emission line fitting was performed on the residual spectrum after continuum subtraction using a single Gaussian function:

$$f_{\text{emi}}(\lambda) = A \exp \left[-\frac{(\lambda - \lambda_0)^2}{2\sigma^2} \right]$$

which provides good fits as shown in Figure 2 (bottom panel). We used a C IV emission line fitting window of 1520–1580 \AA , indicated by gray horizontal lines. Given the presence of absorption troughs in this region, after each fit we masked data points where measured values fell more than three times the error below the fitted values, then refit until convergence. Data points with $ivar < 2$ were excluded before fitting. The fitted parameters λ_0 (line center wavelength), σ (velocity dispersion), and A (line intensity) with their errors are listed in Table 1 (columns 9–14).

Figure 3 [Figure 3: see original paper] illustrates C IV absorption trough variability between two spectral epochs. After further subtracting the emission line from the residual spectrum, a broad C IV absorption trough is visible with multi-component absorption features at different velocities. Based on the absorption trough profile, we divided the BAL into three regions: 1405–1460 \AA , 1460–1520 \AA , and 1520–1560 \AA , corresponding to high-velocity (18000–27700 km/s), intermediate-velocity (5400–18000 km/s), and low-velocity (0–5400 km/s) components, distinguished by different shades of gray in the figure. The equivalent width of the BAL trough is calculated as:

$$EW = \int \left[1 - \frac{f_{\text{obs}}(\lambda)}{f_{\text{con}}(\lambda) + f_{\text{emi}}(\lambda)} \right] d\lambda$$

The equivalent widths of the different velocity components (EW_{low} , EW_{mid} , EW_{high}) and the entire trough (EW_{whl}) with their errors are listed in Table 1 (columns 15–22). The error in equivalent width is:

$$\sigma(EW) = \sqrt{\sum_i \left[\frac{\sigma^2(f_{\text{obs},i}) + \sigma^2(f_{\text{emi},i})}{(f_{\text{con},i} + f_{\text{emi},i})^2} + \frac{(f_{\text{obs},i} + f_{\text{emi},i})^2 \sigma^2(f_{\text{con},i})}{(f_{\text{con},i} + f_{\text{emi},i})^4} \right] \Delta\lambda^2}$$

3. Analysis and Discussion

3.1 Correlation Between BAL Equivalent Width and Continuum Luminosity

If BAL variability is caused by changes in the ionizing continuum, the equivalent width of BAL troughs should correlate with continuum luminosity. Here we use the continuum flux density at 1700 Å, $f_{\text{con},1700}$, as a proxy for continuum luminosity. Figure 4 [Figure 4: see original paper] shows the relationship between the equivalent widths of the three velocity components and the entire trough of SDSS J142225.03+535901.7 and the continuum flux density at 1700 Å. Each point represents one observational epoch, with Spearman correlation coefficients r and p -values annotated on each subplot. The low-velocity component shows a significant anticorrelation with $r = -0.563$ and $p = 7.7 \times 10^{-6}$. The intermediate- and high-velocity components show moderate anticorrelations, both with p -values less than 0.05. If the continuum fit is overestimated relative to the intrinsic value, the measured BAL equivalent width will be overestimated, and vice versa. This uncertainty in continuum fitting would weaken the observed anticorrelation between continuum luminosity and BAL equivalent width. From this perspective, the intrinsic anticorrelation should be even stronger. These results suggest that the BAL variability in this source is likely caused by ionizing continuum changes. SDSS J142225.03+535901.7 was selected from a sample of quasars whose variability is believed to be driven by ionizing continuum changes, which validates the selection method.

Figure 5 [Figure 5: see original paper] shows simulations using Cloudy that demonstrate how Si IV and C IV column densities initially increase then decrease with increasing ionization parameter U . The ionization parameter is defined as:

$$U = \frac{Q_H}{4\pi R^2 n_H c}$$

where Q_H is the rate of ionizing photons emitted by the central source, R is the distance from the absorber to the radiation source, n_H is hydrogen number density, and c is the speed of light. When U is small, ionized gas (such as C IV) is under-ionized, and its column density increases with the ionization parameter, meaning the absorption trough equivalent width increases as continuum radiation strengthens. When the continuum radiation reaches a certain intensity, the ionized gas column density reaches its maximum. If continuum intensity continues to increase, the column density decreases because some of the ionized gas transitions to higher ionization states (such as C V), becoming over-ionized. In Figure 4, all components show decreasing equivalent widths

with increasing continuum radiation, indicating that the gas in each component is in an over-ionized state, consistent with previous studies.

3.2 Correlation Between BAL Equivalent Width and Spectral Index

Dust in absorbing gas scatters blue light more strongly than red light, making the continuum flatter (decreasing the spectral index α). If BAL variability were caused by dusty gas moving perpendicular to the line of sight (changing the covering factor), continuum luminosity and BAL equivalent width should also be anticorrelated: as dusty gas moves out of (into) the line of sight, continuum luminosity increases (decreases) while BAL equivalent width decreases (increases). In this scenario, BAL equivalent width EW should be anticorrelated with spectral index α : as dusty gas moves out of (into) the line of sight, α increases (decreases) while EW decreases (increases).

Figure 6 [Figure 6: see original paper] shows the relationship between the equivalent widths of the three velocity components and the entire trough of SDSS J142225.03+535901.7 and the spectral index α . We find not only no negative correlation but even a weak positive correlation between the equivalent widths of BAL components and the spectral index. This analysis rules out the scenario where BAL variability is caused by changes in covering factor due to dusty gas moving perpendicular to the line of sight.

3.3 Relationships Between Equivalent Widths of Different Velocity Components

If BAL variability is driven by ionizing continuum changes, the equivalent widths of different velocity components should theoretically vary coherently—either all increasing or all decreasing together. Figure 7 [Figure 7: see original paper] shows the correlations between equivalent widths of different velocity components and the entire trough. In SDSS J142225.03+535901.7, we find statistically significant positive correlations ($p < 0.05$) only between low- and intermediate-velocity components and between low-velocity and the entire trough. The correlation between intermediate- and high-velocity components is weaker. Several factors could contribute to these poor correlations: (1) Different velocity components of the outflow can have substantially different densities, column densities, ionization levels, and distances from the central source, leading to different responses to central radiation. For example, (a) gas densities differ, with low-density gas having longer recombination timescales and less responsive to central radiation; (b) column densities differ, leading to different response amplitudes; (c) ionization levels differ, causing different responses—under-ionized gas responds positively to the ionizing continuum, over-ionized gas responds negatively, and gas in a critical state shows no response. (2) Variability may not be entirely caused by ionizing continuum changes; covering factor variations may also play a role, and different covering factor changes among components can lead to inconsistent equivalent width variations. (3) Statistical significance

depends on the number of observations; confidence levels might improve with more epochs.

4. Summary and Outlook

We selected SDSS J142225.03+535901.7 from a sample of quasars whose BAL variability is believed to be caused by ionizing continuum changes. This source has 55 epochs of high signal-to-noise spectral observations. We fitted its continuum and C IV emission line, calculated the equivalent widths of three velocity components and the entire C IV absorption trough, and analyzed the relationships between equivalent width EW and continuum flux density $f_{\text{con},1700}$ and spectral index α . We found significant anticorrelations ($p < 0.05$) between the equivalent widths of all components and continuum luminosity, while no significant anticorrelations exist between equivalent widths and spectral index. These results support the conclusion that BAL variability in this source is driven by ionizing continuum changes and rule out the scenario where variability is caused by covering factor changes due to dusty gas moving perpendicular to the line of sight. Our findings validate the method of selecting sources with simultaneous variability at different velocities to identify those dominated by ionizing continuum changes. The anticorrelation between component equivalent widths and continuum luminosity implies that higher luminosity leads to lower C IV column density, indicating that the absorbing gas is in an over-ionized state.

Future work will systematically analyze the causes of BAL variability in other sources from the sample. Building upon this foundation, we can use photoionization simulations with Cloudy to analyze recombination timescales and derive physical properties of the outflowing gas such as density, distance, and energy. Additionally, by selecting sources with relatively constant continuum but dramatic BAL changes, we can attempt to construct a sample of BAL quasars whose variability is caused by covering factor changes for comparative analysis with the ionizing continuum-driven sample.

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